Astro-Ballistic Chronostratigraphic Sequencing IV

Astro-Ballistic Chronostratigraphic Sequencing Versus Plate Tectonics

Direct Causal Comparison, Explanatory Coverage, Model Complexity, Prediction, and Replacement Adjudication

The Formal Replacement Test

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Paper: IV of V

Companion: Paper V, Claims, Equations, Data, and Falsification Atlas

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Canonical Corpus Freeze Notice

This manuscript is part of the five-paper Canonical Corpus Freeze 1.0. Its freeze identifier is

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and its freeze date is August 7, 2026. The freeze fixes the current manuscript wording, equations, citations, epistemic statuses, dependencies, falsifiers, and declared scope. It does not upgrade any item marked unresolved, not established, disfavored, not yet executed, draft, or to-be-preregistered into empirical support. Any substantive scientific revision requires a new corpus version and a new freeze identifier.

Declaration of Purpose

Papers I–III define the event-audit, mechanical, chronological, material, kinematic, structural, and geophysical eligibility burdens of Astro-Ballistic Chronostratigraphic Sequencing . Paper IV does not add another causal narrative. It defines the matched adjudication required to compare surviving model versions.

> Does any eligible astro-ballistic event-sequence model explain and predict the shared global evidence more successfully, with no greater unjustified flexibility, than Plate-Tectonic, regional, null, or hybrid alternatives?

Observed motion, boundaries, structures, chronology, gravity, seismology, magnetics, and heat flow are shared evidence. The comparison concerns causal organization.

Formal replacement thesis under adjudication.
Astro-Ballistic Chronostratigraphic Sequencing accepts observed continental drift and plate motion while challenging Plate Tectonics as the primary causal framework of global crustal organization. Paper IV separates physical eligibility from comparative replacement qualification and permits rejection, disfavor, equivalence, regional support, complementarity, hybrid preference, unresolved status, or primary replacement as distinct outcomes.

Source Status and Citation Policy

External references support measurements, dated constraints, standard methods, regional context, comparison-model components, and reproducibility requirements. They do not independently verify an astro-ballistic event assignment, event sequence, causal interpretation, or replacement claim unless the cited source directly tests that claim. Internal Ontomics documents establish developmental provenance, not independent confirmation. Manuscript-derived values remain consequences of their declared inputs and methods. External chronology constrains observations and marker compatibility; it is not imported as a substitute causal narrative. The complete source taxonomy, verification fields, and conflict rules are maintained in Paper V.

Data, Evidence, and Provenance Convention

Every factual input, model input, reconstruction, simulation output, and calculated result must retain an explicit evidentiary origin. Scientific authority, publication status, or institutional custody does not by itself upgrade an item from model-derived to observed, from observed to causal, or from internally reproduced to independently validated.

The corpus uses the following evidence-origin classes:

Measurement-proximal
: A directly measured, sampled, mapped, or instrument-recorded quantity, together with its reported uncertainty and acquisition method.

Curated primary dataset
: A maintained collection of observations. The dataset may include processing, but its raw sources, version, and transformations must remain traceable.

Reference model
: A community or institutional model derived from observations and assumptions. It is not identical to the underlying measurements.

Reconstructed or inverted
: A past state, field, geometry, or parameter estimated through an explicit inversion or reconstruction method.

Author-declared input
: A coordinate, age, range, threshold, branch, or other value selected for the present investigation. It is a model input rather than an independent observation.

Internal provenance
: An Ontomics manuscript, author working document, or earlier source file establishing the developmental history of the hypothesis. Internal provenance is not independent confirmation.

Manuscript-derived result
: A reproducible consequence of declared inputs, equations, algorithms, and numerical conventions.

Simulated model output
: A quantity produced by an implemented physical or statistical model.

Interpretive inference
: A geological, causal, or historical interpretation assigned to one or more observations or model outputs.

Unverified, unavailable, or missing
: An item whose source, version, access path, lineage, uncertainty, or required observation has not yet been established.

For item i, the minimum provenance record is

$$\mathbf{P}_i = (\mathrm{ID}_i, \mathrm{origin}_i, \mathrm{custodian}_i, \mathrm{version}_i, \mathrm{locator}_i, \mathrm{acquisition}_i, \mathrm{hash}_i, \\ \mathrm{transformations}_i, \mathrm{units}_i, \mathrm{uncertainty}_i, \mathrm{use}_i, \mathrm{dependencies}_i, \mathrm{status}_i).$$

For a derived result R_j, the complete lineage must identify the exact input records and method version:

$$R_j = \mathcal{M}_j(\mathbf{D}_{j1}, \ldots, \mathbf{D}_{jn}; \boldsymbol{\theta}_j, \nu_j)\,,$$

where ν_j identifies the equation, code, solver, or calculation version. Rounding, unit conversion, coordinate transformation, filtering, interpolation, exclusion, and manual transcription are transformations and must be logged rather than treated as invisible clerical steps.

A located source is not automatically passage-verified. A verified passage is not automatically data-verified. A data-verified input does not by itself validate the causal interpretation built from it. Missing evidence remains explicitly missing; it may not be filled by a preferred reconstruction, model narrative, or uncited numerical convention.

Paper-IV Comparison-Provenance Snapshot

The same provenance burden applies to every competing model family.

Table 1: Paper-IV comparison data and provenance snapshot.

ID	Item	Origin and role	Current provenance status
P4-IN-001	ABC reconstruction package	Model outputs and status records from Papers I–III	Candidate-model predictions and reconstructions, not observations
P4-IN-002	Plate-Tectonic comparison implementations	Published or independently implemented reference models and force models [4, 5]	Exact model versions, parameters, and fitted freedoms must be frozen
P4-DAT-001	Boundary, motion, strain, gravity, seismic, magnetic, and chronology observations	External data package	Each release, subset, transformation, and covariance model must be versioned before scoring
P4-CTL-001	Null and randomized catalogs	Generated controls	Random seed, generation algorithm, admissibility constraints, and number of trials must be archived

ID	Item	Origin and role	Current provenance status
P4-MOD-001	Hybrid models	Generated combinations of registered parent models	Parent provenance, limiting behavior, interaction terms, and added freedoms must remain explicit
P4-PAR-001	Weights, score normalizations, penalties, and decision thresholds	Author-declared comparison design	T3 and T4 values remain to be preregistered before final data inspection
P4-TEST-001	Held-out and replication datasets	Independent validation evidence	Cannot have been used to select events, parameters, branches, scores, or thresholds

Conditional Adjudication Statement

Paper IV receives conditional results from Papers I through III.

It does not assume that the preceding papers have established:

- the flagship event;
- the broader event catalog;
- mechanically viable Earth transmission;
- event-created global boundaries;
- event-derived plate motion;
- event-derived continental displacement;
- event-derived mountains or trenches;
- or causal replacement.

If the Paper-III global model-family viable set is empty after all preregistered eligible event sequences have been tested,

$$\mathcal{V}_{\mathrm{III}} = \varnothing, \tag{1}$$

then no eligible global astro-ballistic reconstruction remains for the primary replacement comparison.

Paper IV must record failure of that global model family. Failure of one event, one mechanism branch, or one candidate sequence does not trigger this result while an independently specified eligible sequence remains.

It may still compare:

- regional event hypotheses;
- complementary event forcing;
- isolated inherited structures;
- or secondary predictive applications.

It may not restore a failed global model by redefining the comparison after the result is known.

Epistemic Status and Claim-Language Convention

This paper distinguishes observation, curated data, reference model, author-declared input, manuscript-derived calculation, simulated output, interpretive inference, prediction, unresolved item, negative result, and falsified claim. These statuses are not interchangeable. Reproducible arithmetic does not establish historical causation; physical admissibility does not establish occurrence; and regional compatibility does not establish global replacement. Missing evidence is reported as unresolved rather than silently completed. Paper V contains the authoritative machine-readable status vocabulary and item-level records.

Prediction, Falsification, and Decision-Threshold Convention

Predictions must identify the claim tested, data required, comparison or null, uncertainty treatment, decision threshold, and bounded consequence. Thresholds are classified as physical-admissibility conditions (T0), measurement or convergence conditions (T1), exploratory working thresholds (T2), preregistered confirmatory thresholds (T3), or preregistered comparative thresholds (T4). A claim is rejected only after a valid, completed test crosses its frozen rejection rule. An unrun test, unavailable dataset, or unfrozen threshold is unresolved. Failure to earn superiority or replacement status is a comparative non-qualification, not retroactive falsification of every upstream result.

Causal-Chain, Assumption, and Alternative-Explanation Convention

Causal language follows a seven-level ladder: association (L0), temporal compatibility (L1), mechanical admissibility (L2), modeled contribution (L3), causal necessity (L4), primary or dominant causation (L5), and replacement qualification (L6). Each proposed transition must identify its assumptions, mediators, counterfactual intervention, and credible alternatives. For claim c with preregistered support paths $\mathcal{P}_c$, viability is

$$\mathcal{V}_{\text{causal},c} = \bigcup_{p \in \mathcal{P}_c} \bigcap_{e \in p} \mathcal{V}_e.$$

One failed edge rejects every path that requires that edge, but does not erase an independent surviving path. One failed branch, event, regional assignment, or event sequence therefore has only its registered downstream consequence. Confounding, equifinality, circular use of outputs as inputs, and unequal assumption burdens remain explicit audit failures. Paper V preserves the full causal-edge, assumption, alternative, and intervention registries.

Abstract

This paper defines the matched causal-comparison and replacement-adjudication protocol for Astro-Ballistic Chronostratigraphic Sequencing , Plate Tectonics , regional-event models, null models, and hybrid models. Observed continental drift, measured plate motion, mapped boundaries, structural systems, chronology, and deep geophysical data are shared evidence. The disputed question is causal organization, not whether plates move.

Paper IV receives status-qualified outputs from Papers I–III and separates two questions. *Eligibility* asks whether a frozen model version survives its own physical, chronological, conservation, material-lineage, and mandatory prediction requirements. *Replacement qualification* asks whether an eligible model achieves superior held-out prediction, causal necessity, realistic null performance, effective-complexity control, and independent replication under a common comparison contract. A comparative loss or failure to qualify for replacement does not retroactively erase an upstream geometric calculation, mechanically admissible branch, or sequence-specific reconstruction.

The paper specifies matched data vectors, model families, priors and likelihoods, proper predictive scores, multiple-testing controls, hidden flexibility and search penalties, counterfactual ablations, hybrid parent-limit checks, and preregistered decision gates. Allowed outcomes include model-version rejection, regional or complementary support, hybrid preference, causal equivalence, comparative disfavor, unresolved status, and primary replacement qualification. Paper IV is an adjudication architecture; no numerical winner is declared until the frozen comparison, held-out tests, and replication program have actually been completed.

Keywords

Astro-Ballistic Chronostratigraphic Sequencing; Plate Tectonics; continental drift; causal replacement; model comparison; plate motion; plate boundaries; geodynamics; tectonic reconstruction; Bayesian model comparison; falsification; counterfactual analysis; predictive validation.

Contents

1 The Adjudication Mandate

1.1 Canonical Corpus Terminology

The authoritative nomenclature registry is maintained in Paper V. Throughout this paper, *continental drift* and *plate motion* name observed motion classes, whereas Plate Tectonics names the competing causal model family. An *event catalog* is the registered set of candidate events; an *event sequence* is a chronologically ordered selection from that catalog. The *flagship candidate relationship* is the declared Aegean–Everest–Mariana geometry, while the *flagship candidate event* is its broader causal interpretation. *Midpoint* is geometric; *midpoint response* is physical. *Terminal response* is the general scientific term; *exit* is retained in the Paper-I title and only where a specific mechanism branch predicts literal outward passage. The *replacement thesis* is the proposition under test; a *replacement candidate* is an outcome that can be earned only through the complete Paper-IV comparison and replication program.

1.2 Paper IV Defines the Decision Protocol

Papers I through III ask whether the candidate framework can be made:

- geometrically explicit;
- mechanically admissible;
- chronologically coherent;
- kinematically predictive;
- structurally comprehensive;
- statistically testable;
- and independently reproducible.

Paper IV defines how a surviving model would be classified as a replacement, supplement, hybrid component, equivalent alternative, or rejected candidate relative to the comparison framework.

1.3 The Comparison Is Not Between Motion and No Motion

The model comparison is not

$$\text{moving plates} \quad \text{versus} \quad \text{stationary continents.} \tag{2}$$

Both model families must explain the observed motion field

$$\mathbf{D}_V^{\text{obs}}. \tag{3}$$

The comparison is

$$\mathcal{M}_{\text{PT}} \quad \text{versus} \quad \mathcal{M}_{\text{ABC}} \quad \text{versus} \quad \mathcal{M}_{\text{HYB}}, \tag{4}$$

where:

$$\mathcal{M}_{\text{PT}} = \text{Plate-Tectonic comparison model,} \tag{5}$$
$$\mathcal{M}_{\text{ABC}} = \text{Astro-ballistic causal model,} \tag{6}$$
$$\mathcal{M}_{\text{HYB}} = \text{hybrid event-inheritance and geodynamic model.} \tag{7}$$

1.4 Replacement Requires More Than Compatibility

A model is compatible with an observation when it does not contradict that observation.

A model explains an observation when the observation follows from the model's physical and historical state.

A model predicts an observation when the relevant output is specified before the observation is used for calibration.

A model replaces another model only when it explains at least the same observation domain with equal or greater accuracy, physical coherence, and predictive power.

1.5 Adjudication Questions

Paper IV asks:

A1. Which model predicts the global boundary network?

A2. Which model predicts the direction and magnitude of plate motion?

A3. Which model predicts plate and continental reconstruction through time?

A4. Which model predicts major mountains, trenches, ridges, basins, plateaus, volcanic provinces, sutures, and terranes?

A5. Which model predicts deep gravity, seismic, magnetic, and heat-flow structure?

A6. Which model satisfies conservation and material continuity?

A7. Which model survives chronological testing?

A8. Which model survives spatial and statistical null models?

A9. Which model survives causal ablation?

A10. Which model predicts withheld observations?

A11. Which model uses fewer effective degrees of freedom?

A12. Which model depends less on post hoc assignment?

A13. Does the hybrid model outperform both parent models?

A14. Is the astro-ballistic contribution primary, complementary, regional, negligible, or incompatible?

1.6 Allowed Final Outcomes

Paper IV permits the following conclusions:

Outcome IV-A: Rejected
The astro-ballistic model fails mechanical, chronological, statistical, or global reconstruction requirements.

Outcome IV-B: Regional
One or more event-derived hypotheses survive locally, but no global replacement is supported.

Outcome IV-C: Complementary
Astro-ballistic events improve selected explanations while Plate Tectonics remains the primary causal framework.

Outcome IV-D: Hybrid preferred
A combined model outperforms both isolated model families.

Outcome IV-E: Causal equivalence
The models remain statistically and predictively indistinguishable within available evidence.

Outcome IV-F: Replacement candidate
The astro-ballistic model explains the shared evidence more accurately, parsimoniously, and predictively.

2 Conditional Handoff From Papers I Through III

2.1 Paper-I Handoff

Paper I supplies

$$\mathbf{Q}_I = (\mathbf{G}_I, \mathbf{T}_I, \mathbf{R}_I, \mathbf{S}_I, \mathbf{F}_I)\,, \tag{8}$$

where:

$$\mathbf{G}_I = \text{audited geometry}, \tag{9}$$
$$\mathbf{T}_I = \text{chronological constraints}, \tag{10}$$
$$\mathbf{R}_I = \text{regional evidence}, \tag{11}$$
$$\mathbf{S}_I = \text{statistical and selection analysis}, \tag{12}$$
$$\mathbf{F}_I = \text{Paper-I falsification status}. \tag{13}$$

2.2 Paper-II Handoff

For candidate sequence $\mathcal{S}$, Paper II supplies

$$\mathbf{H}_{II\to IV}(\mathcal{S}) = \left\{ \left(\mathcal{V}_{II,k}, \mathbf{Q}^{(k)}_{\text{post}}, \mathbf{J}^{(k)}, \Delta T^{(k)}, \Delta\rho^{(k)}, \mathbf{D}^{(k)}, \Delta\phi^{(k)}, \chi^{(k)}_m, \Delta\boldsymbol{\sigma}^{(k)}, \Delta\mathbf{g}^{(k)} \right) : k \in \mathcal{S} \right\}. \tag{14}$$

Each $\mathcal{V}_{II,k}$ is the mechanically admissible parameter set for event k.

2.3 Paper-III Handoff

Paper III supplies

$$\mathbf{H}_{III\to IV} = \left(\mathcal{E}^*, \mathcal{V}_{\text{III}}, \widehat{\mathcal{B}}, \widehat{\mathbf{V}}, \widehat{\mathcal{P}}, \widehat{\mathcal{G}}_S, \widehat{\mathbf{D}}_G, \mathcal{J}_{\text{III}}, \mathbf{L}_{\text{III}}, \mathbf{F}_{\text{III}} \right), \tag{15}$$

where:

$$\mathcal{E}^* = \text{surviving event sequence}, \tag{16}$$
$$\mathcal{V}_{\text{III}} = \text{integrated viable parameter set}, \tag{17}$$
$$\widehat{\mathcal{B}} = \text{predicted boundary network}, \tag{18}$$
$$\widehat{\mathbf{V}} = \text{predicted plate-motion field}, \tag{19}$$
$$\widehat{\mathcal{P}} = \text{predicted plate and continental reconstruction}, \tag{20}$$
$$\widehat{\mathcal{G}}_S = \text{predicted surface structures}, \tag{21}$$
$$\widehat{\mathbf{D}}_G = \text{predicted global geophysical observations}, \tag{22}$$
$$\mathcal{J}_{\text{III}} = \text{integrated Paper-III score}, \tag{23}$$
$$\mathbf{L}_{\text{III}} = \text{claim and dependency ledger}, \tag{24}$$
$$\mathbf{F}_{\text{III}} = \text{falsification state}. \tag{25}$$

2.4 Combined Handoff

The complete Paper-IV initial state is

$$\mathbf{Q}_{IV,0} = \left(\mathbf{Q}_I, \mathbf{H}_{II\to IV}(\mathcal{S}), \mathbf{H}_{III\to IV}, \mathbf{D}_{\text{shared}}, \mathfrak{M}_{\text{comparison}} \right), \tag{26}$$

where $\mathfrak{M}_{\text{comparison}}$ is the frozen comparison-model family.

2.5 Handoff Integrity

Paper IV may not:

- alter event coordinates to improve comparison;
- replace failed Paper-II mechanics;
- change the event catalog without a new model version;

- fit different astro-ballistic models to different observation classes;
- omit unfavorable Paper-III results;
- or redefine success after seeing comparison outcomes.

2.6 Handoff Eligibility

A frozen global sequence $\mathcal{S}^*$ is eligible only if every event it requires has survived event-specific geometry, chronology, and mechanics:

$$\forall k \in \mathcal{S}^*, \qquad \mathcal{V}_{I,k} \cap \mathcal{V}_{II,k} \neq \varnothing. \tag{27}$$

The sequence must also occupy a nonempty Paper-III reconstruction set:

$$\mathcal{V}_{\mathrm{III},\mathcal{S}^*} \neq \varnothing. \tag{28}$$

The global replacement model family is ineligible only if no preregistered sequence satisfies both conditions. A failed flagship event rejects every model version that requires it, but does not automatically reject independently specified alternate sequences.

3 Model-Family Definitions

3.1 Plate-Tectonic Comparison Family

Define the Plate-Tectonic model family as

$$\mathfrak{M}_{\mathrm{PT}} = \{\mathcal{M}_{\mathrm{PT},1}, \mathcal{M}_{\mathrm{PT},2}, \ldots, \mathcal{M}_{\mathrm{PT},N_{\mathrm{PT}}}\}. \tag{29}$$

A member may contain:

$$\mathcal{M}_{\mathrm{PT},q} = (\mathbf{Q}_0, \mathcal{B}_0, \mathbf{F}_g, \mathbf{F}_b, \mathbf{F}_m, \mathbf{F}_{\partial P}, \mathbf{R}_{\mathrm{rheo}}, \mathbf{U}_{\mathrm{PT}}), \tag{30}$$

where:

$$\mathbf{Q}_0 = \text{initial material and thermal state,} \tag{31}$$
$$\mathcal{B}_0 = \text{initial or inherited boundary state,} \tag{32}$$
$$\mathbf{F}_g = \text{gravity-related forcing,} \tag{33}$$
$$\mathbf{F}_b = \text{buoyancy forcing,} \tag{34}$$
$$\mathbf{F}_m = \text{mantle coupling and flow,} \tag{35}$$
$$\mathbf{F}_{\partial P} = \text{boundary and plate interaction,} \tag{36}$$
$$\mathbf{R}_{\text{rheo}} = \text{rheological architecture,} \tag{37}$$
$$\mathbf{U}_{\text{PT}} = \text{state-evolution operator.} \tag{38}$$

Paper IV must state which specific Plate-Tectonic implementations are being tested.

It must not compare Astro-Ballistic Chronostratigraphic Sequencing against a vague or weakened caricature.

3.2 Astro-Ballistic Model Family

Define

$$\mathfrak{M}_{\text{ABC}} = \{\mathcal{M}_{\text{ABC},1}, \ldots, \mathcal{M}_{\text{ABC},N_{\text{ABC}}}\}\,. \tag{39}$$

A member is

$$\mathcal{M}_{\text{ABC},q} = (\mathcal{E}, \mathbf{Q}_0, \mathbf{Q}_{\text{inherit}}, \mathcal{B}_{\text{event}}, \mathbf{F}_g, \mathbf{F}_b, \mathbf{F}_m, \mathbf{F}_{\partial P}, \mathbf{R}_{\text{rheo}}, \mathbf{U}_{\text{ABC}})\,. \tag{40}$$

3.3 Hybrid Model Family

Define

$$\mathfrak{M}_{\text{HYB}} = \{\mathcal{M}_{\text{HYB},1}, \ldots, \mathcal{M}_{\text{HYB},N_{\text{HYB}}}\}\,. \tag{41}$$

A hybrid model includes event-derived inheritance while allowing later geodynamic evolution to dominate selected outputs.

$$\mathcal{M}_{\text{HYB}} = \mathcal{M}_{\text{PT}} + \mathbf{Q}_{\text{inherit}}^{\text{ABC}} + \mathcal{E}. \tag{42}$$

The symbolic addition does not imply linear superposition.

3.4 Regional Event Model

Define regional model family

$$\mathfrak{M}_{\text{REG}} = \{\mathcal{M}_{\text{REG},1}, \ldots, \mathcal{M}_{\text{REG},N_{\text{REG}}}\}. \tag{43}$$

A regional model attributes one or more structures to event inheritance without claiming global replacement.

3.5 No-Event Baseline

Define

$$\mathcal{M}_0 \tag{44}$$

as the corresponding comparison model with

$$\mathcal{E} = \varnothing \tag{45}$$

and

$$\mathbf{Q}^{\text{ABC}}_{\text{inherit}} = \mathbf{0}. \tag{46}$$

3.6 Randomized-Event Models

Define randomized catalog family

$$\mathfrak{M}_{\text{RAND}} = \left\{\mathcal{M}^{(r)}_{\text{RAND}}\right\}_{r=1}^{N_R}. \tag{47}$$

These models retain selected nuisance structure while randomizing the proposed causal sequence.

3.7 Model Nesting

Where possible, define nested hierarchy

$$\mathcal{M}_0 \subset \mathcal{M}_{\text{HYB}} \supset \mathcal{M}_{\text{ABC}}. \tag{48}$$

The exact nesting depends on whether the model families share the same governing equations and differ only by event-derived state.

3.8 No Undefined Umbrella Model

The statement

> Plate Tectonics explains the observation

is not sufficient for quantitative comparison unless the relevant mechanism, parameters, boundary conditions, and predicted observation are specified.

The same restriction applies to the statement

> Astro-ballistic inheritance explains the observation.

3.9 Alternative-Explanation Family Completeness

The model registry is incomplete unless it contains a defensible member of each explanation class relevant to the target:

1. a no-event or null baseline;
2. a strongest defensible Plate-Tectonic family;
3. regional process models for structures that need not share one global origin;
4. astro-ballistic event and sequence models;
5. event-reactivation models in which pre-existing structures are modified rather than created;
6. and hybrid models with explicit interaction terms.

An omitted plausible family is recorded as `ALTERNATIVE-SPACE-INCOMPLETE`. No primary causal ranking may be issued while that omission could reasonably change the result.

4 The Shared Observation Domain

The shared plate-boundary, plate-motion, and strain components are anchored to independently published kinematic and geodetic products [1, 2, 3].

4.1 Complete Observation Vector

Define the shared observation vector

$$\mathbf{D}_{\text{shared}} = (\mathbf{D}_B, \mathbf{D}_V, \mathbf{D}_C, \mathbf{D}_S, \mathbf{D}_T, \mathbf{D}_G, \mathbf{D}_M, \mathbf{D}_P)\,, \tag{49}$$

where:

$$\mathbf{D}_B = \text{plate and block boundaries,} \tag{50}$$
$$\mathbf{D}_V = \text{motion, rotation, and strain,} \tag{51}$$
$$\mathbf{D}_C = \text{continental and paleogeographic reconstruction,} \tag{52}$$
$$\mathbf{D}_S = \text{surface structures,} \tag{53}$$
$$\mathbf{D}_T = \text{chronology,} \tag{54}$$
$$\mathbf{D}_G = \text{gravity, seismic, magnetic, and heat-flow fields,} \tag{55}$$
$$\mathbf{D}_M = \text{material identities and mass transfer,} \tag{56}$$
$$\mathbf{D}_P = \text{advance-prediction outcomes.} \tag{57}$$

4.2 Boundary Observations

The boundary vector is

$$\mathbf{D}_B = (\mathbf{x}_B, \gamma_B, \kappa_B, \tau_B, a_B, H_B, v_n, v_t, \mathcal{G}_B) \,. \tag{58}$$

4.3 Motion Observations

The motion vector is

$$\mathbf{D}_V = (\mathbf{v}_{\text{present}}, \boldsymbol{\omega}, \mathbf{R}_{\text{finite}}, \mathbf{v}_{\text{boundary}}, \dot{\boldsymbol{\epsilon}}, \mathbf{d}_{\text{PM}}) \,. \tag{59}$$

4.4 Continental Reconstruction Observations

The continental vector is

$$\mathbf{D}_C = (\mathbf{x}_C, \Gamma_C, \mathbf{R}_C, \mathbf{A}_C, \mathbf{M}_C, \mathbf{X}_C, \mathbf{T}_C) \,. \tag{60}$$

4.5 Surface-Structure Observations

The surface vector is

$$\mathbf{D}_S = (\mathbf{D}_O, \mathbf{D}_{TR}, \mathbf{D}_R, \mathbf{D}_{BA}, \mathbf{D}_{PL}, \mathbf{D}_{VO}, \mathbf{D}_{SU}, \mathbf{D}_{TE}) \,, \tag{61}$$

representing:

- orogens;
- trenches;
- ridges and rifts;
- basins;
- plateaus;
- volcanic provinces;
- sutures;
- and terranes.

4.6 Deep Geophysical Observations

The geophysical vector is

$$\mathbf{D}_G = \left(\mathbf{g}, N, V_P, V_S, Q^{-1}, \mathbf{A}_{\text{seis}}, \mathbf{B}, q_H, \rho, \eta\right) . \tag{62}$$

4.7 Shared Data Freeze

The comparison requires one frozen data release

$$\mathbf{D}^*_{\text{shared}}. \tag{63}$$

All models must be evaluated against the same:

- spatial masks;
- time intervals;
- observation uncertainties;
- coordinate systems;
- reference frames;
- held-out datasets;
- and scoring rules.

4.8 Observation Independence

Let observation groups a and b satisfy

$$\text{Cov}\left(\mathbf{D}_a, \mathbf{D}_b\right) \neq \mathbf{0}. \tag{64}$$

They cannot be treated as independent evidence without including the cross-covariance.

4.9 Shared Evidence Principle

Shared-evidence principle.
No observation receives greater evidentiary weight for one model merely because it is traditionally associated with that model.
Every model must predict the same frozen observation vector.

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5 Observational, Kinematic, and Causal Levels

5.1 Level L0: Observation

Level L0 contains measurements and mapped structures:

$$L_0 = \mathbf{D}_{\text{shared}}. \tag{65}$$

Examples include:

- plate velocities;

- boundary positions;
- mountain geometry;
- trench depth;
- crustal thickness;
- gravity anomalies;
- and dated material relationships.

5.2 Level L1: Representation

Level L1 organizes observations through:

- plate polygons;
- Euler rotations;
- boundary graphs;
- reconstruction time slices;
- structural catalogs;
- and geophysical fields.

A representation may summarize observations without establishing their cause.

5.3 Level L2: Kinematic Reconstruction

Level L2 predicts how positions and boundaries change through time:

$$\mathbf{Q}(t_2) = \mathcal{U}_K \left[\mathbf{Q}(t_1), \mathbf{V}(t) \right]. \tag{66}$$

5.4 Level L3: Dynamic Maintenance

Level L3 identifies forces, torques, rheology, and dissipation that maintain or alter motion:

$$\mathbf{F}_{\text{net}} \to \mathbf{V}(t). \tag{67}$$

5.5 Level L4: Boundary-Origin Causation

Level L4 explains why the global boundary architecture exists:

$$\mathbf{Q}_0 \to \mathcal{B}(t). \tag{68}$$

5.6 Level L5: Historical Global Organization

Level L5 explains the joint chronology of:

- boundary initiation;
- plate fragmentation;
- motion direction;
- continental displacement;
- mountain building;
- trench development;
- basin evolution;
- and terrane assembly.

5.7 Level L6: Predictive Replacement

Level L6 requires advance prediction of observations not used in construction.

5.8 Comparison by Level

A model may succeed at one level and fail at another.

For model $\mathcal{M}_q$, define level score

$$S_{q,\ell}, \qquad \ell = 0, \ldots, 6. \tag{69}$$

The level vector is

$$\mathbf{S}_q^L = (S_{q,0}, S_{q,1}, \ldots, S_{q,6}). \tag{70}$$

5.9 No Kinematic-to-Causal Shortcut

Accurately reproducing observed motion does not by itself establish why the plates or boundaries formed.

Similarly, generating an event path does not establish that the path created the global motion field.

Each causal level requires its own test.

6 Fair-Comparison Rules

6.1 Rule 1: Same Observation Domain

All model families must predict the same data vector

$$\mathbf{D}^*_{\text{shared}}. \tag{71}$$

6.2 Rule 2: Same Data Partition

Let

$$\mathbf{D}^* = \mathbf{D}_{\text{train}} \cup \mathbf{D}_{\text{validation}} \cup \mathbf{D}_{\text{test}}. \tag{72}$$

The partition must be identical across model families.

6.3 Rule 3: Same Uncertainty Standards

Each model is evaluated using the same observation covariance

$$\mathbf{\Sigma}_D. \tag{73}$$

Model-specific uncertainty may be added, but observation uncertainty cannot be selectively inflated or reduced.

6.4 Rule 4: Same Reference Frames

Plate velocities, rotations, and event paths must be transformed into a declared common frame before comparison.

6.5 Rule 5: Same Chronology Standards

All models must satisfy the same dating constraints and age uncertainties.

6.6 Rule 6: Same Physical Constraints

All models must satisfy:

- mass conservation;
- momentum conservation;
- angular-momentum conservation;
- energy accounting;
- nonnegative dissipation where required;
- material continuity;
- and planetary-survival constraints.

6.7 Rule 7: Same Prediction Freeze

A prediction counts as advance only if it was frozen before validation data were examined.

6.8 Rule 8: Same Complexity Accounting

Model complexity must include:

- numerical parameters;
- event count;
- initial-condition flexibility;
- boundary-condition flexibility;
- manually selected structures;
- branch switching;
- revisions;
- spatial masks;
- chronological windows;
- and hidden preprocessing decisions.

6.9 Rule 9: Same Failure Visibility

Failed runs, rejected events, poor regional fits, and unstable solutions must be retained in the audit record.

6.10 Rule 10: Strongest Defensible Comparison

The Plate-Tectonic model must be represented by its strongest defensible implementations.

The astro-ballistic model must use its frozen surviving Paper-III implementation.

Neither model may be weakened to create an artificial result.

6.11 Rule 11: No Gap-Based Proof

An unresolved question in one framework is not evidence for the other framework.

Support must come from positive prediction and comparative performance.

6.12 Rule 12: No Asymmetric Burden

The astro-ballistic model may not be required to predict every local detail while the comparison model is credited for qualitative compatibility.

The comparison model may not be required to derive event-like structures that its model family does not contain.

Each model must be judged according to the same declared observation and causal burdens.

6.13 Rule 13: Assumption and Intervention Parity

The comparison must expose assumptions at the same level of detail for all model families. A background structure, rheology, force field, event coordinate, or preservation rule cannot be counted as a free physical fact for one family and as an adjustable parameter for another.

Ablations must also be symmetric. Removing a defining component from one model while allowing its functional equivalent to remain hidden in the initial conditions of another model is not a valid necessity test.

6.14 Rule 14: No Strawman or Gap Filling

Each family must be represented by the strongest version that can be implemented from the frozen literature, data, and declared scope. The target model does not win because a comparison implementation is weak, and a comparison model does not win because an astro-ballistic bridge has simply been left unimplemented. Missing implementation produces `COMPARISON-INCOMPLETE`.

6.15 Rule 15: Measurement-Proximal Evidence Is Not a Reconstruction Output

Dated samples, stratigraphic order, paleomagnetic measurements, provenance relations, pressure–temperature–time paths, present geodesy, and mapped structures may enter the shared observation domain with declared uncertainty. Restored plate polygons, rotation trees, inferred vanished boundaries, and reconstructed paleogeographic maps remain model-conditioned products.

A model may not receive credit for reproducing its own reconstruction when that reconstruction was used as the observation target.

6.16 Rule 16: No Privileged Paleogeography

No conventional or astro-ballistic paleogeographic history is treated as fixed ground truth. Each model family must either:

1. predict the measurement-proximal constraints from its own frozen history; or
2. be evaluated across the same preregistered reconstruction ensemble.

A conflict with one model-derived map rejects compatibility with that map. It does not automatically reject the competing causal model unless the conflict is also a conflict with the underlying observations.

6.17 Rule 17: Material-Lineage Parity

All model families must declare how present observation domains connect to older material parcels. Fragmentation, accretion, terrane transfer, subduction, recycling, deformation, and overprint cannot be explicit costs for one family and hidden preprocessing for another.

The comparison records the number of lineage branches, missing lineage edges, and post hoc lineage changes for every family.

6.18 Rule 18: Chronology-Branch Accounting

Event age, marker age, reactivation age, and visible-expression age are separate quantities. A young visible structure may be compatible with an older inherited carrier, but only when the carrier and the intermediate lineage are specified and tested.

A chronology result is reported by scope:

- branch-incompatible;
- lineage-incompatible;
- event-incompatible;
- sequence-incompatible;
- or globally disqualifying.

No broader consequence is assigned without a required dependency edge.

6.19 Rule 19: No Side-by-Side Causal Substitution

Paper IV compares implemented predictions and residuals. It does not replace missing physics in either model family with narrative summaries of what that family is generally said to explain. Literature-derived interpretations may define candidate implementations, priors, or alternatives, but the decision is made from frozen equations, data, uncertainties, interventions, and held-out predictions.

6.20 Rule 20: Specific Initiating-Age Integrity

The flagship astro-ballistic implementation uses the frozen nominal initiating age

$$a_{\text{init},F} = 256 \text{ Ma}. \tag{74}$$

A preregistered uncertainty envelope may represent chronometric and reconstruction uncertainty, but the comparison may not tune the event age after seeing which value improves geometric, mechanical, or regional fit. Younger marker, reactivation, uplift, trench, basin, or visible-expression ages are evaluated through explicit response kernels and material lineage. They do not replace the initiating-event parameter.

If the specific initiating-age assignment fails a completed valid test, the flagship age claim and the event sequences that require it are rejected. Independent candidate events, unrelated regional claims, and the broader model family retain their own evidence states.

6.21 Rule 21: No Credit or Penalty for Scope-Reserved Hypotheses

A directional, terrain, or material-displacement hypothesis explicitly reserved for later research is absent from the current comparison vector. It receives zero explanatory credit, cannot repair a current residual, and cannot be invoked as an auxiliary causal path after model evaluation.

A current model version is likewise not penalized for failing to explain a phenomenon it explicitly did not claim to explain, unless that phenomenon belongs to a mandatory observation class already frozen for the decision being made. In particular, a global replacement decision may not evade a mandatory coverage failure by moving the failed class into future work.

This rule permits a deliberately narrow base-framework test without turning unpublished follow-on hypotheses into either hidden evidence or hidden liabilities.

6.22 Rule 22: Compare Implementations, Not Literature Narratives

The adjudication is performed on explicit model implementations, frozen input contracts, forward predictions, residuals, uncertainty, complexity, and held-out performance. It is not a requirement to place the ABC narrative side by side with every historical or regional explanatory paper. Published work may supply measurements, constraints, or defensible comparison-model components, but narrative volume is not a score.

7 Parameter, Prior, and Model-Input Registry

7.1 Model Parameter Vectors

For model family q, define

$$\boldsymbol{\Theta}_q = \left(\boldsymbol{\Theta}_{q,\text{initial}}, \boldsymbol{\Theta}_{q,\text{boundary}}, \boldsymbol{\Theta}_{q,\text{force}}, \boldsymbol{\Theta}_{q,\text{rheology}}, \boldsymbol{\Theta}_{q,\text{history}}, \boldsymbol{\Theta}_{q,\text{numerical}}\right). \tag{75}$$

7.2 Astro-Ballistic Event Parameters

The event parameter vector is

$$\boldsymbol{\Theta}_E = \left(N_E, t_k, \mathbf{x}_{A,k}, \mathbf{x}_{M,k}, \mathbf{x}_{H,k}, E_k, \mathbf{p}_k, \mathbf{L}_k, \mathbf{Q}_k^+, \boldsymbol{\Sigma}_k\right). \tag{76}$$

7.3 Plate-Tectonic Initial-State Parameters

The Plate-Tectonic comparison vector may include

$$\boldsymbol{\Theta}_{\text{PT},0} = \left(T_0, \rho_0, \eta_0, \mathcal{B}_0, H_{\ell,0}, \mathbf{C}_0, \phi_0, \mathbf{v}_{m,0}, \mathbf{Q}_{\text{composition}}\right). \tag{77}$$

The exact registry depends on the selected model implementation.

7.4 Prior Distribution

For model q,

$$p\left(\boldsymbol{\Theta}_q \mid \mathcal{M}_q\right) \tag{78}$$

must be declared before final evaluation.

7.5 Prior Sources

A prior may be based on:

- independent measurement;
- prior literature;
- constitutive experiments;
- physical bounds;
- geometric bounds;
- numerical stability;
- or explicitly weak prior knowledge.

The source of each prior must be recorded.

7.6 No Fit-Dependent Physical Bound

A parameter bound derived only because it produces favorable agreement is not an independent physical prior.

Such a bound is part of model fitting and must be counted as flexibility.

7.7 Parameter Identifiability

For prediction vector $\widehat{\mathbf{D}}_q$, define sensitivity matrix

$$\mathbf{J}_q = \frac{\partial \widehat{\mathbf{D}}_q}{\partial \boldsymbol{\Theta}_q}. \tag{79}$$

The information matrix is

$$\mathbf{F}_q = \mathbf{J}_q^{\mathsf{T}} \boldsymbol{\Sigma}_D^{-1} \mathbf{J}_q. \tag{80}$$

Poorly identifiable combinations correspond to small eigenvalues.

7.8 Shared Parameter Audit

Where two models use conceptually equivalent quantities, such as density, viscosity, temperature, plate geometry, or mantle coupling, the priors should be comparable unless the model physics justifies a difference.

8 Likelihood and Observational Adequacy

8.1 Model Prediction

For model $\mathcal{M}_q$,

$$\widehat{\mathbf{D}}_q = \mathcal{F}_q\left[\mathbf{\Theta}_q\right]. \tag{81}$$

8.2 Residual Vector

The residual is

$$\boldsymbol{\epsilon}_q = \mathbf{D}^*_{\text{shared}} - \widehat{\mathbf{D}}_q. \tag{82}$$

8.3 Gaussian Observation Likelihood

Where a Gaussian approximation is justified,

$$\ln \mathcal{L}_q = -\frac{1}{2}\boldsymbol{\epsilon}_q^{\top}\mathbf{\Sigma}_q^{-1}\boldsymbol{\epsilon}_q - \frac{1}{2}\ln|\mathbf{\Sigma}_q| + C. \tag{83}$$

8.4 Observation-Class Likelihoods

The global likelihood may be decomposed as

$$\mathcal{L}_q = \mathcal{L}_{B,q}\mathcal{L}_{V,q}\mathcal{L}_{C,q}\mathcal{L}_{S,q}\mathcal{L}_{T,q}\mathcal{L}_{G,q}\mathcal{L}_{P,q} \tag{84}$$

only when dependence among classes is handled correctly.

8.5 Class-Specific Misfits

Define

$$\chi^2_{g,q} = \boldsymbol{\epsilon}_{g,q}^{\top}\mathbf{\Sigma}_g^{-1}\boldsymbol{\epsilon}_{g,q}, \tag{85}$$

where

$$g \in \{B, V, C, S, T, G, P\}. \tag{86}$$

8.6 No Global-Score Concealment

A favorable total likelihood must not conceal catastrophic failure in a required observation class.

Define required class thresholds

$$\chi^2_{g,q} \le \chi^2_{g,\text{crit}}. \tag{87}$$

A model fails global adequacy if any mandatory class exceeds its predeclared rejection threshold.

8.7 Residual Structure

Residuals must be tested for:

- spatial clustering;
- chronological clustering;
- directional bias;
- scale dependence;
- regional dependence;
- reference-frame dependence;
- and observation-class dependence.

8.8 Residual Autocorrelation

For residual field $\epsilon(\mathbf{x})$, define correlation

$$C_\epsilon(d) = \langle \epsilon(\mathbf{x})\epsilon(\mathbf{x}') \rangle_{d(\mathbf{x},\mathbf{x}')=d} . \tag{88}$$

A model with low total error but strongly structured residuals may be missing a causal component.

8.9 Observational Adequacy

Define normalized adequacy score

$$A_q = 1 - \frac{\|\boldsymbol{\epsilon}_q\|_\Sigma}{\|\mathbf{D}^*_{\text{shared}} - \mathbf{D}_{\text{baseline}}\|_\Sigma + \epsilon}. \tag{89}$$

The baseline must be explicitly defined.

9 Physical and Causal Adequacy

9.1 Physical Residual Vector

Define

$$\mathbf{R}_{\text{phys},q} = (R_{M,q}, R_{P,q}, R_{L,q}, R_{E,q}, R_{\text{diss},q}, R_{\text{material},q}, R_{\text{chron},q}, R_{\text{survival},q}) , \tag{90}$$

where the entries represent residuals in:

- mass;
- linear momentum;
- angular momentum;

- energy;
- dissipation;
- material identity;
- chronology;
- and planetary survival.

9.2 Physical Penalty

Define

$$\mathcal{P}_{\mathrm{phys},q} = \sum_{a} \lambda_a \Psi_a \left(R_{a,q} \right), \tag{91}$$

where Ψ_a penalizes violations.

For a hard constraint,

$$\Psi_a(R) = \begin{cases} 0, & R \leq R_{\mathrm{crit}}, \\ \infty, & R > R_{\mathrm{crit}}. \end{cases} \tag{92}$$

9.3 Causal Necessity

Let the full model prediction be

$$\widehat{\mathbf{D}}_q^{+}. \tag{93}$$

Let the prediction after removing causal component c be

$$\widehat{\mathbf{D}}_{q,-c}. \tag{94}$$

The causal contribution is

$$\Delta \mathbf{D}_{q,c} = \widehat{\mathbf{D}}_q^{+} - \widehat{\mathbf{D}}_{q,-c}. \tag{95}$$

9.4 Causal Necessity Score

Define

$$N_{q,c} = \mathcal{J}_{q,-c} - \mathcal{J}_q^{+}. \tag{96}$$

If

$$N_{q,c} \approx 0, \tag{97}$$

component c is not required by the observation vector.

9.5 Astro-Ballistic Necessity Test

For the hybrid model, remove event-derived inheritance:

$$\mathbf{Q}_{\text{inherit}}^{\text{ABC}} \to \mathbf{0}. \tag{98}$$

The change is

$$\Delta \mathbf{D}_{\text{ABC}} = \widehat{\mathbf{D}}_{\text{HYB}} - \widehat{\mathbf{D}}_{\text{HYB},-\text{ABC}}. \tag{99}$$

9.6 Plate-Tectonic Component Ablation

For the hybrid model, remove selected internal geodynamic components:

$$\mathbf{F}_m \to \mathbf{0}, \tag{100}$$

or

$$\mathbf{F}_g \to \mathbf{0}, \tag{101}$$

or

$$\mathbf{F}_{\partial P} \to \mathbf{0}, \tag{102}$$

only where the modified model remains physically interpretable.

9.7 Intervention-Coherence Gate

Before a component ablation contributes to a causal-necessity score, the reduced model must satisfy:

$$I_{\text{coh}}^{(-c)} = I_{\text{equations}} I_{\text{initial state}} I_{\text{boundary state}} I_{\text{numerics}} I_{\text{interpretability}} = 1. \tag{103}$$

If this gate fails, the ablation is not evidence that component c is necessary. It shows only that the selected reduced implementation is invalid. A coherent replacement or reparameterized counterfactual must be tested where one exists.

9.8 Mediation and Interaction Accounting

When component c acts through mediator m, the analysis must separate direct, mediated, and interaction contributions. A component may be causally important even when its direct effect is small, or may appear important only because another fitted component compensates for its removal. The result must therefore report component ablations, mediator ablations, and parent-plus-interaction ablations rather than one undifferentiated score.

9.9 Causal Dominance

For competing causal components a and b, define

$$D_{a:b} = \frac{N_a}{N_b + \epsilon}. \tag{104}$$

This ratio is meaningful only when the ablations are comparably defined.

9.10 Causal Adequacy Principle

Causal-adequacy principle.
A model does not establish primary causal status merely by fitting the observations.
Its defining causal components must be necessary for the successful prediction.

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10 Model Complexity and Causal Compression

10.1 Raw Parameter Count

For model q, define raw parameter count

$$k_q = \dim\left(\boldsymbol{\Theta}_q\right). \tag{105}$$

10.2 Effective Parameter Count

Raw count may underestimate flexibility.

Define effective complexity

$$k_{\mathrm{eff},q} = k_q + k_{\mathrm{selection},q} + k_{\mathrm{branch},q} + k_{\mathrm{initial},q} + k_{\mathrm{boundary},q} + k_{\mathrm{revision},q} + k_{\mathrm{numerical},q}. \tag{106}$$

10.3 Event Complexity

For the astro-ballistic model,

$$k_E = k_{N_E} + \sum_{k=1}^{N_E} \left(k_{t,k} + k_{x,k} + k_{d,k} + k_{E,k} + k_{M,k} + k_{Q,k}\right), \tag{107}$$

where the terms represent age, location, direction, energy, mechanism, and post-event state flexibility.

10.4 Initial-Condition Complexity

For any model, flexible initial conditions contribute

$$k_{\mathrm{IC}} = \operatorname{rank}\left(\mathbf{Q}_0\right)_{\text{adjustable}}. \tag{108}$$

10.5 Boundary-Condition Complexity

Define

$$k_{\mathrm{BC}} = \operatorname{rank}\left(\mathcal{B}_0, \partial\mathbf{Q}\right)_{\text{adjustable}}. \tag{109}$$

A model that receives the observed boundary architecture as an initial condition must count that information.

10.6 Manual-Assignment Complexity

Let

$$N_{\text{assign},q} \tag{110}$$

be the number of manually selected links between causal elements and observed structures.

Define

$$\mathcal{P}_{\text{assign},q} = \lambda_{\text{assign}} N_{\text{assign},q}. \tag{111}$$

10.7 Mechanism-Switching Complexity

If the model changes mechanism after examining each target,

$$\mathcal{P}_{\text{switch},q} = \lambda_{\text{switch}} N_{\text{switch},q}. \tag{112}$$

10.8 Model Revision Complexity

For major revisions after outcome inspection,

$$\mathcal{P}_{\text{rev},q} = \lambda_{\text{rev}} N_{\text{rev},q}. \tag{113}$$

10.9 Information Criteria

A generic penalized score is

$$\mathrm{IC}_q = -2 \ln \mathcal{L}_q + \kappa k_{\text{eff},q}, \tag{114}$$

where κ depends on the selected criterion.

10.10 Bayesian Evidence

The model evidence is

$$\mathcal{Z}_q = \int \mathcal{L}\left(\mathbf{D} \mid \mathbf{\Theta}_q, \mathcal{M}_q\right) p\left(\mathbf{\Theta}_q \mid \mathcal{M}_q\right)\, d\mathbf{\Theta}_q. \tag{115}$$

The evidence ratio is

$$K_{ij} = \frac{\mathcal{Z}_i}{\mathcal{Z}_j}. \tag{116}$$

10.11 Causal Compression

Let observation-information measure be

$$I_D. \tag{117}$$

Let effective model-description length be

$$L_q. \tag{118}$$

Define causal compression

$$C_q = \frac{I_D}{L_q}. \tag{119}$$

A model has greater causal compression when a smaller shared description predicts a larger observation domain.

10.12 Compression Failure

A model fails causal compression if:

- each boundary requires a separate cause;
- each plate requires a separate force law;
- each mountain requires a separate event;
- each trench requires a different unregistered mechanism;
- each chronology mismatch receives an independent delay;
- or each failed region is removed after inspection.

11 Predictive Performance

11.1 Prediction Versus Reconstruction

A reconstruction uses known data to estimate a prior state.

An advance prediction specifies an unknown or withheld observation from the fitted model.

These evidentiary classes must remain separate.

11.2 Training, Validation, and Test Data

Define

$$\mathbf{D} = \mathbf{D}_{\text{train}} \cup \mathbf{D}_{\text{validation}} \cup \mathbf{D}_{\text{test}}. \tag{120}$$

The final comparison uses

$$\mathbf{D}_{\text{test}} \tag{121}$$

only after model and parameter decisions are frozen.

11.3 Predictive Distribution

For model q,

$$p\left(\mathbf{D}_{\text{test}} \mid \mathbf{D}_{\text{train}}, \mathcal{M}_q\right) = \int p\left(\mathbf{D}_{\text{test}} \mid \boldsymbol{\Theta}_q, \mathcal{M}_q\right) p\left(\boldsymbol{\Theta}_q \mid \mathbf{D}_{\text{train}}, \mathcal{M}_q\right)\, d\boldsymbol{\Theta}_q. \tag{122}$$

11.4 Predictive Log Score

The predictive log score is

$$S_{\text{pred},q} = \ln p\left(\mathbf{D}_{\text{test}} \mid \mathbf{D}_{\text{train}}, \mathcal{M}_q\right). \tag{123}$$

11.5 Spatial Holdout

Let withheld geographic domain be

$$\mathcal{D}_{\text{geo}}^{\text{test}}. \tag{124}$$

The model must predict:

- boundary structure;
- motion;
- subsurface anomalies;

- surface structures;
- and chronology

without geographic retuning.

11.6 Temporal Holdout

Fit using time interval

$$t \leq t_c \tag{125}$$

in forward-time coordinates.

Predict

$$t > t_c. \tag{126}$$

11.7 Observation-Type Holdout

Fit without one observation class, such as seismic anisotropy, and predict that class from the remaining model.

11.8 Negative Prediction

Each model must specify regions where a predicted structure should not occur.

For feature g, define control domain

$$\mathcal{D}_g^0. \tag{127}$$

A false positive occurs when

$$\widehat{g} \in \mathcal{D}_g^0 \tag{128}$$

but

$$g^{\text{obs}} \notin \mathcal{D}_g^0. \tag{129}$$

11.9 Calibration

For predicted probability p_j and binary outcome y_j, calibration requires

$$\Pr(y_j = 1 \mid p_j = p) \approx p. \tag{130}$$

11.10 Predictive Superiority

Model i predictively outperforms model j when

$$S_{\mathrm{pred},i} - S_{\mathrm{pred},j} > \Delta S_{\mathrm{crit}} \tag{131}$$

under a frozen T4 decision threshold justified before the final test data are inspected. Without a frozen superiority margin, the result may be reported continuously but cannot be classified as confirmatory superiority.

11.11 Decision-Threshold Freeze

Before the final comparison, Paper IV must freeze:

- the observational-equivalence interval δ_{equiv};
- the causal-necessity threshold N_{crit};
- the predictive-superiority margin ΔS_{crit};
- the effective-complexity rule;
- the mandatory observation classes and their uncertainty-aware acceptance regions;
- the hybrid-preference margin;
- and the replication agreement criterion.

Until those T4 values are frozen, Paper IV may compare continuous scores but may not declare replacement, equivalence, or hybrid preference.

12 Replacement Standards

12.1 Standard R0: Compatibility

The candidate model does not contradict the shared evidence.

This is necessary but weak.

12.2 Standard R1: Observational Equivalence

The candidate model reproduces the observation vector at least as well as the comparison model:

$$\mathcal{J}_{\mathrm{ABC}} \leq \mathcal{J}_{\mathrm{PT}} + \delta_{\mathrm{equiv}}. \tag{132}$$

12.3 Standard R2: Causal Necessity

Removing astro-ballistic inheritance materially degrades the model:

$$N_{\mathrm{ABC}} > N_{\mathrm{crit}}. \tag{133}$$

12.4 Standard R3: Novel Prediction

The candidate predicts withheld observations better:

$$S_{\text{pred,ABC}} > S_{\text{pred,PT}} + \Delta S_{\text{crit}}. \tag{134}$$

12.5 Standard R4: Complexity Control

The performance gain survives effective-complexity penalties:

$$\text{IC}_{\text{ABC}} < \text{IC}_{\text{PT}}\,. \tag{135}$$

12.6 Standard R5: Physical Coherence

The candidate satisfies all hard physical constraints:

$$\mathbf{R}_{\text{phys,ABC}} \in \mathcal{R}_{\text{admissible}}. \tag{136}$$

12.7 Standard R6: Global Coverage

The candidate succeeds across required observation classes rather than isolated regions:

$$\chi^2_{g,\text{ABC}} \leq \chi^2_{g,\text{crit}} \tag{137}$$

for every mandatory class g.

12.8 Standard R7: Replication

Independent teams reproduce the principal comparative result.

12.9 Primary Replacement Condition

Let $I_{Rj} \in \{0,1\}$ indicate whether replacement standard R_j has been satisfied under its frozen decision rule. The astro-ballistic model qualifies as a primary replacement candidate only if

$$\prod_{j=1}^{7} I_{Rj} = 1. \tag{138}$$

An untested standard, missing T4 threshold, or data-insufficient standard sets the replacement decision to unresolved or not established; it is not converted into a falsification by assigning zero evidence.

12.10 Complementarity Condition

The hybrid model is preferred when

$$\text{Score}\left(\mathcal{M}_{\text{HYB}}\right) < \min\left[\text{Score}\left(\mathcal{M}_{\text{PT}}\right), \text{Score}\left(\mathcal{M}_{\text{ABC}}\right)\right] \tag{139}$$

by more than a frozen T4 hybrid-preference margin after effective complexity is counted, and both causal components remain necessary under predeclared ablation tests. Otherwise hybrid preference is not established.

12.11 Regional Condition

A regional conclusion is appropriate when

$$\mathcal{V}_{\text{REG}} \neq \varnothing \tag{140}$$

but

$$\mathcal{V}_{\text{GLOBAL}} = \varnothing. \tag{141}$$

12.12 Model-Version Rejection Versus Replacement Non-Qualification

A frozen global astro-ballistic model version is rejected when a valid completed test demonstrates a mandatory contradiction with no declared alternate support path inside that model version, including:

- mechanical impossibility;
- chronological incompatibility;
- a completed empty Paper-III viable-set union;
- violation of conservation, force, torque, power, or other hard physical constraints; or
- direct failure of a mandatory frozen model prediction beyond its stated uncertainty under adequate observation sensitivity.

Primary replacement candidacy is instead *not established* when:

- predictive superiority is absent or remains inside the frozen equivalence interval;
- causal necessity is not demonstrated;
- an apparent advantage disappears after effective-complexity or selection correction;
- randomized event catalogs perform comparably;
- a strong comparison model performs better; or
- independent replication has not been completed.

These comparative outcomes can disfavor the replacement thesis without logically rejecting every event, regional mechanism, or complementary contribution.

13 The Hybrid-Model Question

13.1 Hybrid Models Are Not Automatic Compromises

A hybrid model must be tested rather than accepted because it appears moderate.

It may outperform both parent models.

It may also accumulate the flexibility of both.

13.2 Hybrid State

Define

$$\mathbf{Q}_{\mathrm{HYB}} = (\mathbf{Q}_{\mathrm{PT}}, \mathbf{Q}_{\mathrm{ABC}}, \mathbf{Q}_{\mathrm{interaction}}) . \tag{142}$$

13.3 Interaction Term

The interaction state is

$$\mathbf{Q}_{\mathrm{interaction}} = \mathcal{F}_{\mathrm{int}} [\mathbf{Q}_{\mathrm{PT}}, \mathbf{Q}_{\mathrm{ABC}}] . \tag{143}$$

It may include:

- event-modified mantle flow;
- event-created boundaries acted upon by later geodynamics;
- event-created density anomalies amplified by gravity;
- event-created weakness used by later convergence;
- and event-created plate fragmentation followed by long-time internal evolution.

13.4 Hybrid Complexity

The hybrid effective complexity is not assumed to be

$$k_{\mathrm{HYB}} = k_{\mathrm{PT}} + k_{\mathrm{ABC}}. \tag{144}$$

Shared parameters may reduce it.

Interaction parameters may increase it.

The complete effective count must be calculated.

13.5 Hybrid Ablations

The minimum hybrid ablations are:

$$\mathcal{M}_{\mathrm{HYB},-\mathrm{ABC}} = \text{hybrid model without event inheritance,} \tag{145}$$
$$\mathcal{M}_{\mathrm{HYB},-\mathrm{PT}} = \text{hybrid model without selected internal geodynamics,} \tag{146}$$
$$\mathcal{M}_{\mathrm{HYB},-\mathrm{INT}} = \text{hybrid model without interaction terms.} \tag{147}$$

13.6 Hybrid Identifiability and Parent Recovery

The hybrid model must recover each parent model under a declared limiting case. If no parameter restriction yields a recognizable parent, the hybrid is not a controlled combination but a separate unconstrained family.

Hybrid preference requires all of the following:

1. both parent limits are computationally recoverable;
2. the interaction term is independently defined;
3. each defining component remains necessary under coherent ablation;
4. the hybrid improves held-out prediction by the frozen margin;
5. and its total search and revision flexibility is counted.

Failure of parent recovery or interaction identifiability produces `HYBRID-NON-IDENTIFIABLE`, not evidence for joint causation.

13.7 Hybrid Causal Classification

The hybrid result may indicate:

Event initiated
: Astro-ballistic forcing creates the architecture; later geodynamics maintain it.

Event redirected
: A pre-existing plate system is materially redirected by events.

Event amplified
: Events strengthen or localize processes already operating.

Event incidental
: Events occur but contribute negligibly to global organization.

Event incompatible
: The event model worsens physical or observational agreement.

13.8 Hybrid Preference Falsifier

Hybrid-model falsifier H1.
If the hybrid model improves fit only by accumulating unconstrained parameters from both parent models, while one causal component is unnecessary under ablation, the hybrid does not establish joint causal necessity.

14 Pre-Registration and Model Freeze

14.1 Required Freeze Package

Before final comparison, freeze:

- observation datasets;
- observation covariance;
- event catalog;
- Plate-Tectonic model family;
- astro-ballistic model family;
- hybrid model family;
- priors;
- parameter bounds;
- physical constraints;
- scoring rules;
- complexity penalties;
- holdout data;
- null models;
- and decision thresholds.

14.2 Freeze Record

The model-freeze record is

$$\mathbf{F}_{\text{freeze}} = (v_{\text{model}}, v_{\text{data}}, t_{\text{freeze}}, \boldsymbol{\Theta}, \mathcal{S}, \mathcal{H}, \mathcal{N}, \mathcal{R}), \tag{148}$$

where:

$$v_{\mathrm{model}} = \text{model version}, \tag{149}$$
$$v_{\mathrm{data}} = \text{data version}, \tag{150}$$
$$\mathcal{S} = \text{score definitions}, \tag{151}$$
$$\mathcal{H} = \text{holdout structure}, \tag{152}$$
$$\mathcal{N} = \text{null-model family}, \tag{153}$$
$$\mathcal{R} = \text{decision rules}. \tag{154}$$

14.3 Model Revision After Freeze

A post-freeze revision creates a new model

$$\mathcal{M}_q^{(v+1)}. \tag{155}$$

It may be scientifically justified, but it must be evaluated on new validation data or explicitly labeled exploratory.

14.4 Exploratory and Confirmatory Results

Every result must be labeled:

- exploratory;
- calibration;
- validation;
- confirmatory;
- or post hoc.

14.5 Adjudication Integrity Falsifier

Adjudication-integrity falsifier A1.
If the event catalog, comparison model, observation domain, scoring rules, or decision thresholds are altered after outcome inspection without new validation, the resulting comparison is exploratory rather than confirmatory.

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15 Initial Paper-IV Score Architecture

15.1 Global Fit Score

For model q,

$$\mathcal{J}_{\mathrm{fit},q} = \sum_g w_g \chi^2_{g,q}. \tag{156}$$

15.2 Physical Penalty

$$\mathcal{J}_{\text{phys},q} = \mathcal{P}_{\text{phys},q}. \tag{157}$$

15.3 Complexity Penalty

$$\mathcal{J}_{\text{complex},q} = \kappa k_{\text{eff},q} + \mathcal{P}_{\text{assign},q} + \mathcal{P}_{\text{switch},q} + \mathcal{P}_{\text{rev},q}. \tag{158}$$

15.4 Prediction Score

Let higher predictive score be better. Define a preregistered, dimensionless normalized predictive score $\widetilde{S}_{\text{pred},q}$, such as mean log predictive density per held-out observation relative to a frozen reference model. Convert it to a loss:

$$\mathcal{J}_{\text{pred},q} = -\lambda_{\text{pred}} \widetilde{S}_{\text{pred},q}. \tag{159}$$

15.5 Null-Model Penalty

If model performance is statistically non-distinct from its null family, define

$$\mathcal{P}_{\text{null},q} = \lambda_{\text{null}} \Psi \left(p_{q,\text{null}} \right). \tag{160}$$

15.6 Causal-Necessity Penalty

For defining causal component c_q,

$$\mathcal{P}_{\text{causal},q} = \lambda_{\text{causal}} \Psi \left(N_{q,c_q} \right), \tag{161}$$

where models are penalized when their defining component is not necessary.

15.7 Integrated Score

The total adjudication score is

$$\begin{aligned} \mathcal{J}_{IV,q} = \mathcal{J}_{\text{fit},q} + \mathcal{J}_{\text{phys},q} + \mathcal{J}_{\text{complex},q} + \mathcal{J}_{\text{pred},q} \\ + \mathcal{P}_{\text{null},q} + \mathcal{P}_{\text{causal},q} + \mathcal{P}_{\text{replication},q}. \end{aligned} \tag{162}$$

Lower values indicate stronger penalized performance. Every summed fit component and penalty must be dimensionless or divided by a frozen reference scale; otherwise the weighting is unit-dependent and the integrated score is invalid.

15.8 Score Difference

For models i and j,

$$\Delta\mathcal{J}_{ij} = \mathcal{J}_{IV,i} - \mathcal{J}_{IV,j}. \tag{163}$$

If

$$\Delta\mathcal{J}_{ij} < 0, \tag{164}$$

model i has the lower score.

15.9 Uncertainty in Model Ranking

For posterior or resampled score distributions, define

$$P_{i<j} = \Pr\left(\mathcal{J}_{IV,i} < \mathcal{J}_{IV,j}\right). \tag{165}$$

The comparison must report uncertainty rather than only one ranking.

16 Initial Paper-IV Falsification Architecture

16.1 Paper-IV Primary Falsifier

Paper-IV primary decision rule.
Primary astro-ballistic replacement is not established unless the frozen model satisfies hard physical and chronological admissibility and then outperforms the strongest defensible Plate-Tectonic comparison model under frozen T4 rules for shared observations, causal necessity, effective complexity, held-out prediction, and independent replication.
A mandatory physical contradiction rejects the frozen model version. Comparative equivalence, absence of superiority, or incomplete replication yields non-qualification or causal non-resolution rather than automatic falsification of every underlying event claim.

16.2 Eligibility Falsifier

If the complete Paper-II or Paper-III viable set is empty, the global astro-ballistic replacement model is ineligible.

16.3 Observation-Domain Falsifier

If the candidate succeeds only after excluding required observation classes, it does not establish global replacement.

16.4 Physical Falsifier

If the candidate violates hard conservation, chronology, material continuity, or survival constraints, no statistical fit rescues it.

16.5 Complexity Falsifier

If the candidate's advantage disappears after effective flexibility is counted, replacement is not supported.

16.6 Prediction Falsifier

If the candidate fits known observations but fails held-out data, its replacement claim is weakened or rejected.

16.7 Causal-Necessity Falsifier

If removing event inheritance leaves the successful prediction materially unchanged, astro-ballistic forcing is not the primary cause.

16.8 Hybrid Falsifier

If the hybrid model performs best but astro-ballistic inheritance is unnecessary, the result supports the comparison model rather than a hybrid causal claim.

16.9 Plate-Tectonic Comparison Falsifier

The Plate-Tectonic comparison family is disfavored if it fails the same shared observation, physical, complexity, and predictive standards while the astro-ballistic model survives them.

16.10 Indistinguishability Result

If the models remain within the declared equivalence interval,

$$|\Delta \mathcal{J}_{ij}| \leq \delta_{\text{equiv}}, \tag{166}$$

Paper IV must report causal non-resolution rather than selecting a winner.

17 Comparative Framework Synthesis

This comparative-framework synthesis records:

1. the direct adjudication mandate;
2. the formal replacement thesis;
3. the conditional dependence on Papers I through III;
4. the complete Paper-IV handoff state;
5. global replacement eligibility conditions;
6. Plate-Tectonic, astro-ballistic, hybrid, regional, baseline, and randomized model families;
7. the shared global observation vector;
8. the distinction between observation, representation, kinematics, dynamics, boundary origin, historical organization, and predictive replacement;
9. twelve fair-comparison rules;

10. matched parameter and prior registries;
11. shared likelihood and residual architecture;
12. class-specific failure thresholds;
13. physical residuals and penalties;
14. causal ablation and necessity tests;
15. raw and effective model complexity;
16. event, assignment, switching, and revision penalties;
17. causal-compression criteria;
18. predictive-distribution and held-out-data standards;
19. seven nested replacement standards;
20. the hybrid-model decision architecture;
21. preregistration and model-freeze requirements;
22. the integrated Paper-IV score; and
23. the initial comparative falsification architecture.

The following sections develop the direct comparison of boundary creation and global plate partition:

- Plate-Tectonic boundary-generation classes;
- astro-ballistic boundary-generation classes;
- inherited versus emergent boundaries;
- initial-condition information content;
- boundary-location comparison;
- boundary-orientation comparison;
- boundary-type comparison;
- boundary-age and reactivation comparison;
- global graph topology;
- plate enclosure and plate-count comparison;
- continental-margin and ocean-basin comparison;
- boundary counterfactuals;
- boundary-specific complexity penalties;
- and the complete boundary-replacement decision matrix.

18 Competing Boundary-Generation Mechanisms

18.1 Boundary Origin Is a Primary Replacement Test

A model that receives the observed plate-boundary network as a fixed input may predict later plate motion without explaining the origin of the network.

Paper IV therefore distinguishes:

$$\text{boundary-conditioned prediction} \tag{167}$$

from

$$\text{boundary-generating prediction.} \tag{168}$$

The replacement comparison must determine which parts of the observed network are:

- prescribed as initial conditions;
- inherited from earlier structures;
- generated dynamically;
- reactivated;
- propagated;
- terminated;
- or reconstructed after observing the modern network.

18.2 Observed Boundary State

For boundary element b, define the observed state

$$\mathbf{D}_{B,b}^{\text{obs}} = \left(\mathbf{x}_b, \gamma_b, \kappa_b, \tau_b, a_b, H_b, v_{n,b}, v_{t,b}, \mathbf{Q}_b, \mathcal{N}_b\right), \tag{169}$$

where:

$$\mathbf{x}_b = \text{location}, \tag{170}$$
$$\gamma_b = \text{orientation}, \tag{171}$$
$$\kappa_b = \text{curvature}, \tag{172}$$
$$\tau_b = \text{boundary type}, \tag{173}$$
$$a_b = \text{initiation or reactivation age}, \tag{174}$$
$$H_b = \text{effective thickness or width}, \tag{175}$$
$$v_{n,b} = \text{normal relative velocity}, \tag{176}$$
$$v_{t,b} = \text{tangential relative velocity}, \tag{177}$$
$$\mathbf{Q}_b = \text{material-state vector}, \tag{178}$$
$$\mathcal{N}_b = \text{network and adjacency role}. \tag{179}$$

Each model must predict the same state vector.

18.3 General Boundary-Generation Operator

For model q, define

$$\widehat{\mathcal{B}}_q(t) = \mathcal{H}_{B,q}\left[\mathbf{Q}_{q,0}, \mathbf{F}_q, \mathbf{R}_q, \mathcal{E}_q, t\right], \tag{180}$$

where:

$$\mathbf{Q}_{q,0} = \text{initial planetary state}, \tag{181}$$
$$\mathbf{F}_q = \text{force and torque architecture}, \tag{182}$$
$$\mathbf{R}_q = \text{rheology, damage, and phase laws}, \tag{183}$$
$$\mathcal{E}_q = \text{event catalog, empty for no-event models}. \tag{184}$$

18.4 Plate-Tectonic Boundary-Generation Classes

The Plate-Tectonic comparison family may generate or preserve boundaries through combinations of:

PT-B1. inherited lithospheric weakness;

PT-B2. thermal thinning;

PT-B3. extensional localization;

PT-B4. gravitational instability;

PT-B5. density-driven descent;

PT-B6. convergence and collision;

PT-B7. transform localization;

PT-B8. mantle-flow coupling;

PT-B9. plume- or upwelling-associated weakening;

PT-B10. compositional contrasts;

PT-B11. phase transitions;

PT-B12. stress transfer;

PT-B13. continental-margin inheritance;

PT-B14. and reactivation of earlier structures.

The exact mechanism registry must be defined for each selected Plate-Tectonic implementation.

18.5 Astro-Ballistic Boundary-Generation Classes

The astro-ballistic family may generate or preserve boundaries through:

ABC-B1. direct fracture;

ABC-B2. directional damage;

ABC-B3. excavation margins;

ABC-B4. terminal-response margins;

ABC-B5. displacement discontinuities;

ABC-B6. thermal weakening;

ABC-B7. melt-assisted weakening;

ABC-B8. density contrasts;

ABC-B9. phase-front inheritance;

ABC-B10. residual-stress corridors;

ABC-B11. event-created plate fragmentation;

ABC-B12. and reactivation by later events.

18.6 Hybrid Boundary Generation

The hybrid family may use an event-created initial boundary field

$$\mathcal{B}^0_{\mathrm{ABC}} \tag{185}$$

followed by long-time evolution

$$\widehat{\mathcal{B}}_{\mathrm{HYB}}(t) = \mathcal{U}_{B,\mathrm{PT}}\left[\mathcal{B}^0_{\mathrm{ABC}}, \mathbf{Q}^+_{\mathrm{ABC}}, \mathbf{F}_{\mathrm{later}}, t\right]. \tag{186}$$

This family is favored only if both the event-derived initial state and later geodynamic evolution remain necessary under ablation.

18.7 Boundary-Origin Record

For each observed boundary b, every model must produce a record

$$\begin{aligned}\mathbf{O}_{b,q} = \big(&\text{origin class}, t_{\text{init}}, \text{initial geometry}, \text{driving state},\\ &\text{propagation law}, \text{reactivation history}, \text{termination state}\big).\end{aligned} \tag{187}$$

18.8 Boundary-Generation Burden

The boundary-generation comparison asks whether a model predicts:

- where localization begins;
- why localization occurs there;
- which orientation develops;
- whether the structure propagates;
- which neighboring domains become separated;
- how relative motion begins;
- whether the boundary remains active;
- and what causes later reactivation or termination.

18.9 No Boundary-by-Boundary Mechanism Assignment

A prohibited model is

$$\widehat{\mathcal{B}}_q = \bigcup_{b=1}^{N_B} \mathcal{H}_{B,q}^{(b)}\left[\boldsymbol{\Theta}_b\right], \tag{188}$$

with one independently selected mechanism and parameter vector for each observed boundary.

The preferred model must generate multiple boundaries from shared physical and historical inputs.

19 Inherited Versus Emergent Boundaries

19.1 Boundary Categories

For model comparison, each boundary is classified as:

Prescribed
The boundary is directly supplied as an initial or boundary condition.

Inherited
A pre-existing material contrast is supplied, but later activation or motion is predicted.

Emergent
The boundary forms from the model's initial state and governing dynamics without being supplied in recognizable form.

Event created
The boundary forms from a declared astro-ballistic event output.

Reactivated
A previously inactive structure becomes active under later forcing.

Post hoc reconstructed
The boundary is added or modified after examining the target observation.

19.2 Boundary-Origin Indicator

For boundary b and model q, define indicator vector

$$\mathbf{z}_{b,q} = (z_{\text{pres}}, z_{\text{inh}}, z_{\text{em}}, z_{\text{event}}, z_{\text{react}}, z_{\text{post}}) \,, \tag{189}$$

subject to

$$\sum_a z_{a,b,q} = 1 \tag{190}$$

for exclusive primary classification.

A weighted classification may be used when multiple stages contribute.

19.3 Inherited-State Information

Let the inherited boundary state be

$$\mathbf{Q}_{B,0}^{\text{inh}} = (\mathbf{x}_{B,0}, \gamma_{B,0}, D_{B,0}, \eta_{B,0}, Y_{B,0}, \phi_{B,0}, \Delta\rho_{B,0}, \Delta T_{B,0}, \boldsymbol{\sigma}_{B,0}) \,. \tag{191}$$

A model that receives values close to the observed boundary network contains substantial boundary information before forward evolution.

19.4 Emergence Distance

Let initial boundary-like field be

$$\mathcal{B}_{q,0} \tag{192}$$

and final predicted network be

$$\widehat{\mathcal{B}}_q. \tag{193}$$

Define normalized emergence distance

$$E_{B,q} = \frac{d_{\text{net}}\left(\mathcal{B}_{q,0}, \widehat{\mathcal{B}}_q\right)}{d_{\text{net}}\left(\varnothing, \widehat{\mathcal{B}}_q\right) + \epsilon}. \tag{194}$$

Small values indicate that much of the final network was already encoded.

Large values indicate greater structural emergence.

19.5 Boundary Information Retention

Define retention fraction

$$R_{B,q} = 1 - \frac{d_{\text{net}}\left(\mathcal{B}_{q,0}, \widehat{\mathcal{B}}_q\right)}{d_{\text{net,max}}}. \tag{195}$$

The metric must be interpreted together with the quality and specificity of the initial boundary state.

19.6 Event-Created Boundary Test

For an astro-ballistic model, compare:

$$\widehat{\mathcal{B}}^{+}_{\text{ABC}} = \mathcal{H}_B\left[\mathbf{Q}_0, \mathcal{E}\right] \tag{196}$$

with

$$\widehat{\mathcal{B}}^{0}_{\text{ABC}} = \mathcal{H}_B\left[\mathbf{Q}_0, \mathcal{E} = \varnothing\right]. \tag{197}$$

The event-created contribution is

$$\Delta\mathcal{B}_{\text{event}} = \widehat{\mathcal{B}}^{+}_{\text{ABC}} \ominus \widehat{\mathcal{B}}^{0}_{\text{ABC}}, \tag{198}$$

where $\ominus$ denotes a declared network-difference operator.

19.7 Inherited Plate-Tectonic Boundary Test

For a Plate-Tectonic model, compare the full inherited initial state with an isotropized or boundary-reduced state:

$$\widehat{\mathcal{B}}^{\text{inh}}_{\text{PT}} = \mathcal{H}_{B,\text{PT}}\left[\mathbf{Q}^{\text{inh}}_0\right], \tag{199}$$

$$\widehat{\mathcal{B}}_{\mathrm{PT}}^{\mathrm{iso}} = \mathcal{H}_{B,\mathrm{PT}}\left[\mathrm{Iso}\left(\mathbf{Q}_0^{\mathrm{inh}}\right)\right]. \tag{200}$$

The inherited contribution is

$$\Delta\mathcal{B}_{\mathrm{PT,inh}} = \widehat{\mathcal{B}}_{\mathrm{PT}}^{\mathrm{inh}} \ominus \widehat{\mathcal{B}}_{\mathrm{PT}}^{\mathrm{iso}}. \tag{201}$$

19.8 Origin Attribution Fractions

For boundary b, define attribution fractions

$$\alpha_{b,q}^{\mathrm{pres}} + \alpha_{b,q}^{\mathrm{inh}} + \alpha_{b,q}^{\mathrm{dyn}} + \alpha_{b,q}^{\mathrm{event}} + \alpha_{b,q}^{\mathrm{react}} = 1. \tag{202}$$

The fractions must derive from controlled ablation or sensitivity analysis rather than narrative assignment.

19.9 Inherited-versus-Emergent Decision

A model does not gain boundary-origin credit for information already supplied in a near-observed initial state.

It may gain credit for predicting:

- activation time;
- propagation;
- boundary type;
- relative motion;
- reactivation;
- and later geometry

from that inherited state.

20 Initial-Condition Information Content

20.1 Initial Conditions Are Part of the Model

The initial state is

$$\mathbf{Q}_{q,0} = (\rho_0, T_0, \eta_0, \mathbf{D}_0, \phi_0, \mathbf{C}_0, \boldsymbol{\sigma}_0, \mathbf{u}_0, \mathcal{B}_0, \mathcal{P}_0). \tag{203}$$

Its information content must be included in model complexity.

20.2 Initial-State Description Length

Define encoded description length

$$L_{\mathrm{IC},q} = -\log p\left(\mathbf{Q}_{q,0} \mid \mathcal{M}_q\right). \tag{204}$$

A highly specific initial state has larger description length unless strongly constrained by independent evidence.

20.3 Boundary-Field Information

Let the discretized initial boundary field be

$$\mathbf{b}_{q,0} = \left(b_1, b_2, \ldots, b_{N_g}\right). \tag{205}$$

Its information content under prior $p(\mathbf{b})$ is

$$I_{B,0,q} = -\log p\left(\mathbf{b}_{q,0}\right). \tag{206}$$

20.4 Observed-Network Similarity

Define initial-to-observed similarity

$$S_{B,0,q} = 1 - d_{\mathrm{net}}\,\widetilde{(\mathcal{B}_{q,0}, \mathcal{B}}^{\mathrm{obs}}). \tag{207}$$

A value near one indicates that the observed solution is strongly encoded at initialization.

20.5 Information Gain

Let posterior parameter distribution be

$$p\left(\boldsymbol{\Theta}_q \mid \mathbf{D}\right). \tag{208}$$

The information gained from the data is

$$\mathcal{I}_q = \int p\left(\boldsymbol{\Theta}_q \mid \mathbf{D}\right) \log \frac{p\left(\boldsymbol{\Theta}_q \mid \mathbf{D}\right)}{p\left(\boldsymbol{\Theta}_q\right)}\, d\boldsymbol{\Theta}_q. \tag{209}$$

A model whose posterior barely differs from a highly specific prior may be driven primarily by initial assumptions.

20.6 Event-Catalog Information

For the astro-ballistic model,

$$L_{\mathcal{E}} = -\log p\left(\mathcal{E} \mid \mathcal{M}_{\mathrm{ABC}}\right). \tag{210}$$

This includes information in:

- event count;
- event ages;
- entrance coordinates;
- terminal coordinates;
- path orientations;
- event energies;
- mechanism branches;
- and event-to-boundary assignments.

20.7 Plate-Tectonic Initial-Structure Information

The comparison family must represent the strongest defensible implementations of slab, gravitational, boundary, and mantle-coupling forces rather than a weakened umbrella description [4, 5].

For the Plate-Tectonic family,

$$L_{\mathrm{PT},0} = -\log p\left(\mathcal{B}_0, T_0, \rho_0, \eta_0, \mathbf{D}_0 \mid \mathcal{M}_{\mathrm{PT}}\right). \tag{211}$$

The comparison must count initial heterogeneity when it materially determines the final boundary network.

20.8 Boundary-Origin Compression

Define boundary-origin compression

$$C_{B,q} = \frac{I\left(\mathcal{B}^{\mathrm{obs}}\right)}{L_{\mathrm{IC},q} + L_{\mathrm{dyn},q} + L_{\mathrm{assign},q}}. \tag{212}$$

The numerator measures the information represented by the observed network.

The denominator measures the effective description required to generate it.

20.9 Initial-Condition Ablation

Construct reduced initial state

$$\mathbf{Q}_{q,0}^{(-a)} \tag{213}$$

with component a removed or randomized.

The resulting change is

$$\Delta \mathcal{J}_{\mathrm{IC},a} = \mathcal{J}\left[\mathbf{Q}_{q,0}^{(-a)}\right] - \mathcal{J}\left[\mathbf{Q}_{q,0}\right]. \tag{214}$$

20.10 Initial-Condition Falsifier

Initial-condition falsifier B-C1.
If a model reproduces the observed boundary network only because that network, or a near-equivalent high-information precursor, is inserted as an unconstrained initial condition, the model does not establish independent boundary-origin causation.

21 Boundary Location and Orientation Comparison

21.1 Predicted Boundary Sets

For model q, let the predicted boundary set be

$$\widehat{\mathcal{B}}_q = \bigcup_{b=1}^{N_{B,q}} \widehat{\mathcal{B}}_{b,q}. \tag{215}$$

The observed set is

$$\mathcal{B}^{\mathrm{obs}} = \bigcup_{b=1}^{N_{B,\mathrm{obs}}} \mathcal{B}_b^{\mathrm{obs}}. \tag{216}$$

21.2 Directed Boundary Distance

The observed-to-predicted directed distance is

$$d_{\mathrm{obs}\to q} = \frac{1}{L_{\mathrm{obs}}} \int_{\mathcal{B}^{\mathrm{obs}}} \min_{y\in\widehat{\mathcal{B}}_q} d_{\mathcal{S}}(x,y)\, d\ell. \tag{217}$$

The predicted-to-observed distance is

$$d_{q\to\mathrm{obs}} = \frac{1}{L_q} \int_{\widehat{\mathcal{B}}_q} \min_{x\in\mathcal{B}^{\mathrm{obs}}} d_{\mathcal{S}}(y,x)\, d\ell. \tag{218}$$

21.3 False-Negative Boundary Length

Let tolerance distance be d_{match}.

Observed boundary length not matched by model q is

$$L_{\mathrm{FN},q} = \int_{\mathcal{B}^{\mathrm{obs}}} \mathbf{1}\left[d\left(x, \widehat{\mathcal{B}}_q\right) > d_{\mathrm{match}}\right] d\ell. \tag{219}$$

The false-negative fraction is

$$f_{\mathrm{FN},q} = \frac{L_{\mathrm{FN},q}}{L_{\mathrm{obs}}}. \tag{220}$$

21.4 False-Positive Boundary Length

Predicted boundary length not matched by observations is

$$L_{\mathrm{FP},q} = \int_{\widehat{\mathcal{B}}_q} \mathbf{1}\left[d\left(y, \mathcal{B}^{\mathrm{obs}}\right) > d_{\mathrm{match}}\right] d\ell. \tag{221}$$

The false-positive fraction is

$$f_{\mathrm{FP},q} = \frac{L_{\mathrm{FP},q}}{L_q}. \tag{222}$$

21.5 Boundary Precision and Recall

Boundary precision is

$$P_{B,q} = 1 - f_{\mathrm{FP},q}. \tag{223}$$

Boundary recall is

$$R_{B,q} = 1 - f_{\mathrm{FN},q}. \tag{224}$$

The harmonic score is

$$F_{B,q} = 2\frac{P_{B,q}R_{B,q}}{P_{B,q} + R_{B,q}}. \tag{225}$$

21.6 Orientation Field

For observed tangent $\widehat{\mathbf{t}}^{\mathrm{obs}}(x)$ and matched predicted tangent $\widehat{\mathbf{t}}_q^{\mathrm{pred}}(x)$, define axial agreement

$$A_{\gamma,q}(x) = \left|\widehat{\mathbf{t}}^{\mathrm{obs}}(x) \cdot \widehat{\mathbf{t}}_q^{\mathrm{pred}}(x)\right|. \tag{226}$$

The length-weighted score is

$$\overline{A}_{\gamma,q} = \frac{1}{L_{\mathrm{match}}} \int_{\mathcal{B}_{\mathrm{match}}} A_{\gamma,q}(x)\, d\ell. \tag{227}$$

21.7 Curvature Residual

For observed and predicted geodesic curvature,

$$\epsilon_{\kappa,q} = \kappa^{\text{obs}} - \kappa_q^{\text{pred}}. \tag{228}$$

The normalized curvature score is

$$\chi^2_{\kappa,q} = \sum_b \frac{\left(\kappa_b^{\text{obs}} - \kappa_{b,q}^{\text{pred}}\right)^2}{\sigma^2_{\kappa,b}}. \tag{229}$$

21.8 Boundary-Width Residual

For observed and predicted boundary-zone widths,

$$\epsilon_{H,b,q} = H_b^{\text{obs}} - H_{b,q}^{\text{pred}}. \tag{230}$$

This distinguishes narrow localized boundaries from broad deformation zones.

21.9 Spatially Stratified Scores

Scores must be reported for:

- global network;
- continental boundaries;
- oceanic boundaries;
- convergent boundaries;
- divergent boundaries;
- transform boundaries;
- diffuse deformation zones;
- and held-out geographic regions.

21.10 Location-Orientation Composite

Define

$$\mathcal{J}_{B,\text{geom},q} = w_d \widetilde{d}_{\text{ASD},q} + w_H \widetilde{d}_{H,q} + w_{\text{FP}} f_{\text{FP},q} + w_{\text{FN}} f_{\text{FN},q} + w_\gamma \left(1 - \overline{A}_{\gamma,q}\right) + w_\kappa \widetilde{\chi}^2_{\kappa,q}. \tag{231}$$

All weights and normalization rules must be frozen.

21.11 Boundary-Geometry Decision

Model i has stronger boundary geometry than model j when

$$\mathcal{J}_{B,\mathrm{geom},i} < \mathcal{J}_{B,\mathrm{geom},j} - \delta_{B,\mathrm{geom}} \tag{232}$$

with uncertainty sufficient to distinguish the scores.

22 Boundary Type and Relative-Motion Comparison

22.1 Relative Velocity

At boundary between plates i and j,

$$\mathbf{v}^{\mathrm{rel}}_{ij,q} = \mathbf{v}_{i,q} - \mathbf{v}_{j,q}. \tag{233}$$

Its normal and tangential components are

$$v_{n,ij,q} = \mathbf{v}^{\mathrm{rel}}_{ij,q} \cdot \widehat{\mathbf{n}}_{ij,q}, \tag{234}$$

$$v_{t,ij,q} = \mathbf{v}^{\mathrm{rel}}_{ij,q} \cdot \widehat{\mathbf{t}}_{ij,q}. \tag{235}$$

22.2 Boundary-Type Prediction

The predicted type is

$$\widehat{\tau}_{b,q} = \mathcal{C}_{B,q}\left(v_{n,b,q}, v_{t,b,q}, \mathbf{Q}_{B,b,q}, \mathcal{H}_{B,b,q}\right). \tag{236}$$

22.3 Classification Classes

The minimum shared classification contains:

- convergent;
- divergent;
- transform or shear dominated;
- oblique;
- collision;
- underthrusting or descent;
- collapse;
- diffuse deformation;
- inactive inherited structure;

- and uncertain.

22.4 Type Confusion Matrix

For model q, define

$$N_{ab,q} = \#\left\{\text{observed class } a,\ \text{predicted class } b\right\}. \tag{237}$$

The normalized confusion matrix is

$$C_{ab,q} = \frac{N_{ab,q}}{\sum_b N_{ab,q}}. \tag{238}$$

22.5 Length-Weighted Type Accuracy

Define

$$A_{\tau,q} = \frac{\displaystyle\sum_b L_b \mathbf{1}\left[\tau_b^{\text{obs}} = \widehat{\tau}_{b,q}\right]}{\displaystyle\sum_b L_b}. \tag{239}$$

22.6 Normal-Velocity Residual

The normal-motion residual is

$$\epsilon_{n,b,q} = v_{n,b}^{\text{obs}} - v_{n,b,q}^{\text{pred}}. \tag{240}$$

The tangential residual is

$$\epsilon_{t,b,q} = v_{t,b}^{\text{obs}} - v_{t,b,q}^{\text{pred}}. \tag{241}$$

22.7 Relative-Motion Misfit

Define

$$\chi^2_{\text{rel},q} = \sum_b \begin{pmatrix} \epsilon_{n,b,q} \\ \epsilon_{t,b,q} \end{pmatrix}^{\mathsf{T}} \mathbf{\Sigma}_{v,b}^{-1} \begin{pmatrix} \epsilon_{n,b,q} \\ \epsilon_{t,b,q} \end{pmatrix}. \tag{242}$$

22.8 Kinematic Sign Accuracy

For normal motion, define sign accuracy

$$A^n_{\text{sign},q} = \frac{1}{N_B} \sum_b \mathbf{1}\left[\text{sign}\left(v_{n,b}^{\text{obs}}\right) = \text{sign}\left(v_{n,b,q}^{\text{pred}}\right)\right]. \tag{243}$$

This directly tests whether the model predicts opening rather than closing.

22.9 Obliquity Residual

Define observed and predicted obliquity

$$\psi_b = \operatorname{atan2}\left(v_{t,b}, v_{n,b}\right). \tag{244}$$

The circular residual is

$$\Delta\psi_{b,q} = \operatorname{atan2}\left[\sin\left(\psi_b^{\text{obs}} - \psi_{b,q}^{\text{pred}}\right), \cos\left(\psi_b^{\text{obs}} - \psi_{b,q}^{\text{pred}}\right)\right]. \tag{245}$$

22.10 Boundary-Work Consistency

For model q,

$$\dot{W}_{B,b,q} = \int_{\mathcal{B}_b} \mathbf{t}_{b,q} \cdot \mathbf{v}_{b,q}^{\text{rel}}\, dA. \tag{246}$$

The model must report whether the boundary:

- dissipates mechanical power;
- transfers power between plates;
- contributes positive driving power;
- or requires an unmodeled source.

22.11 Type-Motion Composite Score

Define

$$\mathcal{J}_{B,\text{type},q} = w_\tau\left(1 - A_{\tau,q}\right) + w_{\text{rel}}\widetilde{\chi}^2_{\text{rel},q} + w_{\text{sign}}\left(1 - A^n_{\text{sign},q}\right) + w_\psi\widetilde{\chi}^2_{\psi,q} + w_W\mathcal{P}_{W,q}. \tag{247}$$

22.12 Boundary-Type Falsifier

Boundary-type comparison falsifier B-C2.
A model fails the boundary-type comparison if it predicts boundary locations but systematically assigns the wrong opening, closing, shearing, collision, or descent behavior.

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23 Boundary Age, Reactivation, and Termination

23.1 Boundary Chronology Vector

For boundary b, define

$$\mathbf{T}_{B,b} = \left(t_{\text{precursor}}, t_{\text{init}}, t_{\text{active},1}, t_{\text{inactive}}, t_{\text{react}}, t_{\text{term}}\right). \tag{248}$$

23.2 Initiation-Age Residual

For model q,

$$\epsilon_{t,\text{init},b,q} = \frac{t^{\text{obs}}_{\text{init},b} - t^{\text{pred}}_{\text{init},b,q}}{\sigma_{t,\text{init},b}}. \tag{249}$$

23.3 Reactivation-Age Residual

$$\epsilon_{t,\text{react},b,q} = \frac{t^{\text{obs}}_{\text{react},b} - t^{\text{pred}}_{\text{react},b,q}}{\sigma_{t,\text{react},b}}. \tag{250}$$

23.4 Termination-Age Residual

$$\epsilon_{t,\text{term},b,q} = \frac{t^{\text{obs}}_{\text{term},b} - t^{\text{pred}}_{\text{term},b,q}}{\sigma_{t,\text{term},b}}. \tag{251}$$

23.5 Chronological Likelihood

The boundary chronology likelihood is

$$\mathcal{L}_{B,T,q} = p\left(\left\{\mathbf{T}^{\text{obs}}_{B,b}\right\} \mid \left\{\widehat{\mathbf{T}}_{B,b,q}\right\}, \mathbf{\Sigma}_{B,T}\right). \tag{252}$$

23.6 Reactivation Prediction

A model must predict reactivation from the prior boundary state and later loading:

$$\widehat{\mathcal{R}}_{b,q} = \mathcal{F}_{R,q}\left[\mathbf{Q}^{\text{latent}}_{B,b}, \boldsymbol{\sigma}^{\text{later}}_{q}, \Delta P_q, \Delta T_q, \mathcal{E}^{\text{later}}_{q}\right]. \tag{253}$$

Reactivation occurs when

$$\widehat{\mathcal{R}}_{b,q} \geq \mathcal{R}_{\text{crit},q}. \tag{254}$$

23.7 Reactivation Classification

The predicted reactivation mode may be:

- reopening;
- closing;
- shear reactivation;
- inversion;

- renewed descent;
- uplift;
- or continued inactivity.

23.8 Reactivation Confusion Matrix

For observed mode a and predicted mode b,

$$N^R_{ab,q} = \#\left\{a_{\text{obs}}, b_{\text{pred}}\right\}. \tag{255}$$

23.9 Boundary Lifetime

Predicted lifetime is

$$\tau_{B,b,q} = t_{\text{term},b,q} - t_{\text{init},b,q} \tag{256}$$

in forward-time coordinates.

The lifetime residual is

$$\epsilon_{\tau,b,q} = \tau^{\text{obs}}_{B,b} - \tau^{\text{pred}}_{B,b,q}. \tag{257}$$

23.10 Termination Prediction

Termination must follow from:

- loss of driving force;
- healing;
- encounter with a stronger domain;
- merger with another boundary;
- plate merger;
- boundary consumption;
- event overprint;
- or plate reorganization.

A boundary may not be manually terminated because it is absent from the modern map.

23.11 Survival Analysis

Let boundary survival probability under model q be

$$S_{B,q}(t) = \Pr\left(T_{\text{term}} > t \mid \mathcal{M}_q\right). \tag{258}$$

The hazard function is

$$h_{B,q}(t) = -\frac{d}{dt} \ln S_{B,q}(t). \tag{259}$$

23.12 Chronology Composite Score

Define

$$\mathcal{J}_{B,T,q} = w_i \chi^2_{\text{init},q} + w_r \chi^2_{\text{react},q} + w_t \chi^2_{\text{term},q} + w_\tau \chi^2_{\text{life},q} + w_c \mathcal{P}_{\text{chron viol},q}. \tag{260}$$

23.13 Chronology Falsifier

Boundary chronology falsifier B-C3.
A model fails the boundary chronology test if it reproduces modern boundary geometry only by initiating, reactivating, inverting, or terminating boundaries at times incompatible with the geological record.

---

24 Global Boundary Graph and Plate Partition

24.1 Observed and Predicted Graphs

The observed graph is

$$\mathcal{G}_B^{\text{obs}} = \left(\mathcal{V}_B^{\text{obs}}, \mathcal{E}_B^{\text{obs}}\right). \tag{261}$$

For model q,

$$\widehat{\mathcal{G}}_{B,q} = \left(\widehat{\mathcal{V}}_{B,q}, \widehat{\mathcal{E}}_{B,q}\right). \tag{262}$$

24.2 Node and Edge Residuals

$$\Delta N_{V,q} = N_V^{\text{obs}} - N_{V,q}^{\text{pred}}, \tag{263}$$

$$\Delta N_{E,q} = N_E^{\text{obs}} - N_{E,q}^{\text{pred}}. \tag{264}$$

24.3 Connected Components

The component residual is

$$\Delta N_{C,q} = N_C^{\text{obs}} - N_{C,q}^{\text{pred}}. \tag{265}$$

24.4 Cycle Rank

For model q,

$$\mu_{G,q} = N_{E,q} - N_{V,q} + N_{C,q}. \tag{266}$$

The residual is

$$\Delta\mu_{G,q} = \mu_G^{\text{obs}} - \mu_{G,q}^{\text{pred}}. \tag{267}$$

24.5 Plate-Face Count

The predicted number of enclosed plate or block domains is

$$N_{P,q}^{\text{pred}} = \mathcal{F}_{\text{faces}}\left[\widehat{\mathcal{G}}_{B,q}\right]. \tag{268}$$

The count residual is

$$\Delta N_{P,q} = N_P^{\text{obs}} - N_{P,q}^{\text{pred}}. \tag{269}$$

24.6 Plate-Area Distribution

For plate i, area is

$$A_{P,i}. \tag{270}$$

The observed and predicted distributions are

$$p_{\text{obs}}(A_P), \qquad p_q(A_P). \tag{271}$$

Define distributional distance

$$D_{A_P,q} = \frac{1}{2}\int |p_{\text{obs}}(A_P) - p_q(A_P)|\, dA_P. \tag{272}$$

24.7 Plate-Perimeter Distribution

Similarly,

$$D_{L_P,q} = \frac{1}{2}\int |p_{\text{obs}}(L_P) - p_q(L_P)|\, dL_P. \tag{273}$$

24.8 Degree Distribution

For graph degree distribution,

$$D_{\mathrm{deg},q} = \frac{1}{2} \sum_{d} \left| p_{\mathrm{obs}}(d) - p_q(d) \right| . \tag{274}$$

24.9 Adjacency Matrix

Let adjacency matrices be

$$\mathbf{A}_B^{\mathrm{obs}} \tag{275}$$

and

$$\mathbf{A}_{B,q}^{\mathrm{pred}} . \tag{276}$$

The normalized residual is

$$D_{\mathrm{adj},q} = \frac{\left\| \mathbf{A}_B^{\mathrm{obs}} - \mathbf{A}_{B,q}^{\mathrm{pred}} \right\|_F}{\left\| \mathbf{A}_B^{\mathrm{obs}} \right\|_F} . \tag{277}$$

24.10 Graph Spectral Distance

For graph-Laplacian eigenvalues,

$$D_{\lambda,q} = \left[\sum_{j=1}^{N_\lambda} w_j \left(\lambda_j^{\mathrm{obs}} - \lambda_{j,q}^{\mathrm{pred}} \right)^2 \right]^{1/2} . \tag{278}$$

24.11 Junction Geometry

For junction J, compare:

- degree;
- location;
- incident-boundary orientation;
- incident-boundary type;
- motion compatibility;
- and temporal stability.

The junction residual is

$$\mathcal{J}_{J,q} = w_x d_{J,q} + w_d \left| d_J^{\mathrm{obs}} - d_{J,q}^{\mathrm{pred}} \right| + w_\theta D_{\Theta,J,q} + w_v D_{V,J,q} . \tag{279}$$

24.12 Plate-Enclosure Completeness

For observed plate i, define matched perimeter fraction

$$C_{P,i,q} = \frac{L^{\text{matched}}_{P,i,q}}{L^{\text{obs}}_{P,i}}. \tag{280}$$

The mean completeness is

$$\overline{C}_{P,q} = \frac{\sum_i L^{\text{obs}}_{P,i} C_{P,i,q}}{\sum_i L^{\text{obs}}_{P,i}}. \tag{281}$$

24.13 Manual Gap-Filling Fraction

Let inserted or manually bridged length be

$$L_{\text{manual},q}. \tag{282}$$

Define

$$f_{\text{manual},q} = \frac{L_{\text{manual},q}}{L^{\text{total}}_{B,q}}. \tag{283}$$

24.14 Global Graph Score

Define

$$\begin{aligned}
\mathcal{J}_{B,\text{graph},q} = {} & w_V|\widetilde{\Delta N_{V,q}}| + w_E|\widetilde{\Delta N_{E,q}}| + w_C|\widetilde{\Delta N_{C,q}}| \\
& + w_\mu|\widetilde{\Delta \mu_{G,q}}| + w_P|\widetilde{\Delta N_{P,q}}| + w_A D_{A_P,q} \\
& + w_L D_{L_P,q} + w_D D_{\text{deg},q} + w_{\text{adj}} D_{\text{adj},q} + w_\lambda D_{\lambda,q} \\
& + w_{\text{enc}}\left(1 - \overline{C}_{P,q}\right) + w_{\text{manual}} f_{\text{manual},q}.
\end{aligned} \tag{284}$$

24.15 Graph-Partition Falsifier

Boundary-graph falsifier B-C4.
A model fails the global plate-partition comparison if its predicted boundary network cannot reproduce the observed connectivity, cycles, junctions, plate count, adjacency, and enclosure without extensive manual boundary completion.

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25 Continental Margins and Ocean Basins

25.1 Margin Observation Vector

For continental margin m, define

$$\mathbf{D}_{M,m} = (\mathbf{x}_m, \gamma_m, H_{c,m}, H_{\ell,m}, \beta_m, S_m, a_m, \mathbf{Q}_m, \mathcal{P}_m), \tag{285}$$

where:

$$\beta_m = \text{stretching or thinning factor}, \tag{286}$$
$$S_m = \text{subsidence history}, \tag{287}$$
$$\mathcal{P}_m = \text{paired-margin relationships}. \tag{288}$$

25.2 Basin Observation Vector

For basin b,

$$\mathbf{D}_{O,b} = \left(\mathcal{A}_b, V_b, H_{s,b}, H_{c,b}, \dot{S}_b, \mathbf{A}_b, a_b, \mathbf{Q}_b\right), \tag{289}$$

where:

$$\mathcal{A}_b = \text{basin geometry}, \tag{290}$$
$$V_b = \text{accommodation or basin volume}, \tag{291}$$
$$H_{s,b} = \text{sediment thickness}, \tag{292}$$
$$\mathbf{A}_b = \text{material-age field}. \tag{293}$$

25.3 Competing Margin-Origin Models

For Plate Tectonics,

$$\widehat{\mathcal{M}}_{\text{PT}} = \mathcal{F}_{M,\text{PT}}\left[\text{extension}, \text{thermal evolution}, \text{boundary inheritance}, \text{mantle coupling}\right]. \tag{294}$$

For Astro-Ballistic Chronostratigraphic Sequencing,

$$\widehat{\mathcal{M}}_{\text{ABC}} = \mathcal{F}_{M,\text{ABC}}\left[\text{event damage}, \text{displacement}, \text{thermal state}, \text{later extension}\right]. \tag{295}$$

For the hybrid,

$$\widehat{\mathcal{M}}_{\text{HYB}} = \mathcal{F}_{M,\text{HYB}}\left[\mathbf{Q}^{+}_{\text{event}}, \text{long-time extension}, \text{thermal evolution}, \text{mantle coupling}\right]. \tag{296}$$

25.4 Paired-Margin Prediction

For margins a and b, each model predicts pairing probability

$$p^{\text{pair}}_{ab,q} = p\left(a \leftrightarrow b \mid \mathcal{M}_q\right). \tag{297}$$

The pairing must use:

- reconstructed geometry;
- material age;
- composition;
- structural continuity;
- displacement history;
- and chronology.

25.5 Opening-Width Prediction

For paired margins,

$$W_{ab,q}(t) = d_{\mathcal{S}}\left[\mathcal{M}_{a,q}(t), \mathcal{M}_{b,q}(t)\right]. \tag{298}$$

The opening-rate residual is

$$\epsilon_{\dot{W},ab,q} = \dot{W}^{\text{obs}}_{ab} - \dot{W}^{\text{pred}}_{ab,q}. \tag{299}$$

25.6 Crustal-Thinning Prediction

For model q,

$$H^{\text{pred}}_{c,q}(t) = \mathcal{F}_{H,q}\left[H_{c,0}, \boldsymbol{\epsilon}_{\text{ext}}, \mathbf{Q}_{\text{thermal}}, \mathbf{Q}_{\text{magmatic}}, \mathbf{Q}_{\text{event}}\right]. \tag{300}$$

The residual is

$$\epsilon_{H_c,q} = H^{\text{obs}}_{c} - H^{\text{pred}}_{c,q}. \tag{301}$$

25.7 Basin Subsidence Prediction

Each model predicts

$$S_{b,q}(t) = S_{\text{initial},q} + S_{\text{thermal},q} + S_{\text{flexural},q} + S_{\text{load},q} + S_{\text{dynamic},q} + S_{\text{boundary},q}. \tag{302}$$

For the astro-ballistic and hybrid families,

$$S_{\text{initial},q} = S_{\text{event}} + S_{\text{damage}} + S_{\text{density}} + S_{\text{phase}} + S_{\text{displacement}}. \tag{303}$$

25.8 Subsidence-History Residual

$$\chi^2_{S,b,q} = \left(\mathbf{S}_b^{\mathrm{obs}} - \mathbf{S}_{b,q}^{\mathrm{pred}}\right)^{\mathsf{T}} \mathbf{\Sigma}_{S,b}^{-1} \left(\mathbf{S}_b^{\mathrm{obs}} - \mathbf{S}_{b,q}^{\mathrm{pred}}\right). \tag{304}$$

25.9 Material-Age Prediction

For basin material-age field,

$$\widehat{a}_q(\mathbf{x}) = \mathcal{F}_{a,q}\left[\mathcal{B}_q(t), \mathbf{V}_q(t), \dot{A}_{\mathrm{new},q}(t)\right]. \tag{305}$$

The residual is

$$\epsilon_{a,q}(\mathbf{x}) = a^{\mathrm{obs}}(\mathbf{x}) - \widehat{a}_q(\mathbf{x}). \tag{306}$$

25.10 Margin-Asymmetry Prediction

For paired margins, define asymmetry vector

$$\mathbf{A}_{ab} = (\Delta H_c, \Delta\beta, \Delta S, \Delta H_s, \Delta q_H, \Delta\gamma). \tag{307}$$

Each model predicts

$$\widehat{\mathbf{A}}_{ab,q}. \tag{308}$$

25.11 Margin-Basin Composite Score

Define

$$\begin{aligned} \mathcal{J}_{MB,q} = {} & w_x \mathcal{J}_{\mathrm{margin\,location},q} + w_p \mathcal{J}_{\mathrm{pairing},q} + w_W \chi^2_{\dot{W},q} \\ & + w_H \chi^2_{H_c,q} + w_S \chi^2_{S,q} + w_A \chi^2_{a,q} + w_{\mathrm{asym}} \chi^2_{\mathrm{asym},q} \\ & + w_T \chi^2_{\mathrm{chron},MB,q}. \end{aligned} \tag{309}$$

25.12 Continental-Margin Falsifier

Margin-and-basin comparison falsifier B-C5.
A model fails the continental-fragmentation comparison if it cannot predict paired margins, opening history, crustal thinning, material-age patterns, subsidence, and basin asymmetry from its declared boundary origin and motion field.

26 Boundary Counterfactuals and Causal Necessity

26.1 Purpose

A model may fit the observed boundary network even when its defining causal component is unnecessary.

Boundary counterfactuals determine which components materially generate the solution.

26.2 Astro-Ballistic No-Event Counterfactual

For the astro-ballistic or hybrid family,

$$\mathcal{E} \to \varnothing, \qquad \mathbf{Q}^{\mathrm{ABC}}_{\mathrm{inherit}} \to \mathbf{0}. \tag{310}$$

The resulting network is

$$\widehat{\mathcal{B}}_{q,-E}. \tag{311}$$

The event-boundary necessity is

$$N_{B,E,q} = \mathcal{J}_{B,q,-E} - \mathcal{J}^{+}_{B,q}. \tag{312}$$

26.3 Event-Impulse Ablation

Remove direct impulse while retaining other event-derived fields:

$$\mathbf{J}_E \to \mathbf{0}. \tag{313}$$

The score change is

$$N_{B,J} = \mathcal{J}_{B,-J} - \mathcal{J}^{+}_{B}. \tag{314}$$

26.4 Damage Ablation

$$\mathbf{D}_{\mathrm{event}} \to \mathbf{D}_0. \tag{315}$$

$$N_{B,D} = \mathcal{J}_{B,-D} - \mathcal{J}^{+}_{B}. \tag{316}$$

26.5 Thermal and Phase Ablation

$$\Delta T_{\mathrm{event}} \to 0, \qquad \Delta\phi_{\mathrm{event}} \to 0. \tag{317}$$

26.6 Density Ablation

$$\Delta\rho_{\text{event}} \to 0. \tag{318}$$

26.7 Initial-Weakness Ablation

For a Plate-Tectonic model,

$$\mathbf{D}_0 \to \text{Iso}\left(\mathbf{D}_0\right), \qquad \eta_0 \to \eta_{\text{uniform}}. \tag{319}$$

The necessity is

$$N_{B,\text{weak,PT}} = \mathcal{J}_{B,\text{PT},-\text{weak}} - \mathcal{J}^{+}_{B,\text{PT}}. \tag{320}$$

26.8 Mantle-Forcing Ablation

Where physically interpretable,

$$\mathbf{F}_m \to \mathbf{0} \tag{321}$$

or the event-induced portion alone may be removed.

26.9 Gravity and Buoyancy Ablation

$$\mathbf{F}_g + \mathbf{F}_b \to \mathbf{0} \tag{322}$$

only where the resulting counterfactual remains a meaningful model test.

26.10 Boundary-State Randomization

Randomize the orientation or location of inherited boundary candidates while preserving their total area and strength:

$$\mathbf{Q}^{(r)}_{B,0} = \text{Shuffle}\left[\mathbf{Q}_{B,0}\right]. \tag{323}$$

The randomized score distribution tests whether the specific inherited geometry is necessary.

26.11 Leave-One-Event-Out Boundary Test

For event k,

$$\mathcal{E}_{-k} = \mathcal{E} \setminus \{\mathcal{E}_k\}. \tag{324}$$

Its marginal contribution is

$$N_{B,k} = \mathcal{J}_{B,-k} - \mathcal{J}_{B,\text{full}}. \tag{325}$$

26.12 Leave-One-Mechanism-Out Test

For mechanism m,

$$\mathcal{M}_{q,-m} \tag{326}$$

removes that mechanism from all boundaries rather than only unfavorable ones.

26.13 Boundary Causal Contribution Fractions

For component c,

$$f_{B,c,q} = \frac{\mathcal{J}_{B,q,-c} - \mathcal{J}^{+}_{B,q}}{\mathcal{J}_{B,q,-\text{all}} - \mathcal{J}^{+}_{B,q} + \epsilon}. \tag{327}$$

Nonlinear interactions may prevent the fractions from summing to one.

26.14 Interaction Necessity

For components a and b, define interaction contribution

$$N_{B,a\times b} = \mathcal{J}_{B,-a} + \mathcal{J}_{B,-b} - \mathcal{J}_{B,-a,-b} - \mathcal{J}^{+}_{B}. \tag{328}$$

26.15 Boundary Necessity Rule

A defining causal component is necessary when:

$$N_{B,c,q} > N_{B,\text{crit}} \tag{329}$$

and the degradation appears across held-out boundary observations rather than only calibration targets.

26.16 Causal-Necessity Falsifier

Boundary causal-necessity falsifier B-C6.
If removal, isotropization, or randomization of a model's defining boundary-generating component leaves the predicted network materially unchanged, that component is not established as the primary cause of the boundary architecture.

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27 Boundary Complexity and Predictive Tests

27.1 Boundary-Specific Complexity Vector

For model q, define

$$\mathbf{k}_{B,q} = (k_{\mathrm{IC}}, k_{\mathrm{event}}, k_{\mathrm{threshold}}, k_{\mathrm{prop}}, k_{\mathrm{react}}, k_{\mathrm{term}}, k_{\mathrm{assign}}, k_{\mathrm{bridge}}, k_{\mathrm{regional}}, k_{\mathrm{revision}}) . \tag{330}$$

27.2 Boundary Threshold Complexity

If boundary nucleation depends on threshold θ_B, count whether it is:

- independently measured;
- globally fitted;
- regionally fitted;
- boundary-specifically fitted;
- or altered after inspection.

Define effective threshold count

$$k_{\theta,q}^{\mathrm{eff}} = k_{\theta,\mathrm{global}} + k_{\theta,\mathrm{regional}} + k_{\theta,\mathrm{local}}. \tag{331}$$

27.3 Boundary-Assignment Complexity

Let

$$N_{B\leftarrow c,q} \tag{332}$$

be the number of manually assigned causal links.

The penalty is

$$\mathcal{P}_{B,\mathrm{assign},q} = \lambda_{B,\mathrm{assign}} N_{B\leftarrow c,q}. \tag{333}$$

27.4 Gap-Bridging Complexity

For manually inserted or inferred segments,

$$\mathcal{P}_{B,\mathrm{bridge},q} = \lambda_{B,\mathrm{bridge}} \frac{L_{\mathrm{manual},q}}{L_{B,\mathrm{obs}}}. \tag{334}$$

27.5 Initial-Network Complexity

Define

$$\mathcal{P}_{B,\mathrm{IC},q} = \lambda_{B,\mathrm{IC}} L_{\mathrm{IC},B,q}. \tag{335}$$

27.6 Boundary Information Criterion

A boundary-specific penalized score is

$$\mathrm{IC}_{B,q} = -2\ln \mathcal{L}_{B,q} + \kappa k_{B,\mathrm{eff},q} + \mathcal{P}_{B,\mathrm{assign},q} + \mathcal{P}_{B,\mathrm{bridge},q} + \mathcal{P}_{B,\mathrm{IC},q}. \tag{336}$$

27.7 Boundary Predictive Holdouts

The comparison should include:

BH1. withheld geographic sectors;

BH2. withheld boundary types;

BH3. withheld plate junctions;

BH4. withheld continental margins;

BH5. withheld deep boundary continuations;

BH6. withheld boundary ages;

BH7. and withheld reactivation histories.

27.8 Location Prediction

For held-out region $\mathcal{D}_h$, each model publishes candidate boundary field

$$p_{B,q}\left(\mathbf{x} \mid \mathcal{D}_h\right). \tag{337}$$

27.9 Boundary Detection Score

For binary boundary observation y_j and predicted probability $p_{j,q}$, the log score is

$$S_{B,\log,q} = \sum_j \left[y_j \log p_{j,q} + (1-y_j)\log\left(1-p_{j,q}\right)\right]. \tag{338}$$

27.10 Boundary Distance Prediction

For observed held-out boundary points,

$$S_{B,\mathrm{dist},q} = -\sum_j \frac{d_{\mathcal{S}}^2\left(\mathbf{x}_j^{\mathrm{obs}}, \widehat{\mathcal{B}}_q\right)}{\sigma_{B,j}^2}. \tag{339}$$

27.11 Type Prediction

For class probability $p_q(\tau_j)$,

$$S_{B,\text{type},q} = \sum_j \log p_q\left(\tau_j^{\text{obs}}\right). \tag{340}$$

27.12 Chronology Prediction

For held-out boundary age,

$$S_{B,\text{age},q} = -\frac{1}{2}\sum_j \frac{\left(t_j^{\text{obs}} - t_{j,q}^{\text{pred}}\right)^2}{\sigma_{t,j}^2}. \tag{341}$$

27.13 Negative Boundary Prediction

Each model must identify control regions

$$\mathcal{D}_{B,q}^0 \tag{342}$$

where no major boundary is predicted.

False-positive structure in those regions contributes directly to the predictive score.

27.14 Boundary Calibration

For prediction bins with probability p, calibration requires

$$\Pr\left(B = 1 \mid p_{B,q} = p\right) \approx p. \tag{343}$$

27.15 Boundary Predictive Superiority

Model i predictively exceeds model j when

$$S_{B,\text{test},i} - S_{B,\text{test},j} > \Delta S_{B,\text{crit}} \tag{344}$$

with a predeclared uncertainty threshold.

27.16 Randomized-Boundary Nulls

For the astro-ballistic family, randomized event catalogs generate

$$\left\{\widehat{\mathcal{B}}_{\text{RAND}}^{(r)}\right\}. \tag{345}$$

For models with inherited initial fields, shuffled fields generate

$$\left\{\widehat{\mathcal{B}}^{(r)}_{\mathrm{IC-RAND}}\right\}. \tag{346}$$

The null comparison must preserve comparable initial information and model flexibility.

27.17 Boundary Null Probability

$$p_{B,q,\mathrm{null}} = \frac{1 + \sum_{r=1}^{N_R} \mathbf{1}\left[\mathcal{J}^{(r)}_{B,q} \leq \mathcal{J}^{\mathrm{obs}}_{B,q}\right]}{N_R + 1}. \tag{347}$$

28 Boundary-Replacement Viability and Falsification

28.1 Boundary Comparison Parameter Set

For model q,

$$\mathbf{\Theta}_{B,q} = \left(\mathbf{Q}_{0,q}, \mathcal{E}_q, \mathcal{H}_{B,q}, \mathcal{P}_{B,q}, \mathcal{R}_{B,q}, \mathcal{T}_{B,q}, \mathbf{\Theta}_{\mathrm{motion},q}, \mathbf{\Theta}_{\mathrm{complex},q}\right), \tag{348}$$

where:

$$\mathcal{H}_{B,q} = \text{boundary nucleation and generation}, \tag{349}$$

$$\mathcal{P}_{B,q} = \text{propagation}, \tag{350}$$

$$\mathcal{R}_{B,q} = \text{reactivation}, \tag{351}$$

$$\mathcal{T}_{B,q} = \text{termination}. \tag{352}$$

28.2 Boundary-Model Viable Set

Define

$$\mathcal{V}^{\mathrm{IV}}_{B,q} = \left\{ \mathbf{\Theta}_{B,q} : \begin{array}{l} \text{physical constraints satisfied,} \\ \text{boundary locations compatible,} \\ \text{orientations compatible,} \\ \text{curvature compatible,} \\ \text{boundary types compatible,} \\ \text{relative motion compatible,} \\ \text{chronology compatible,} \\ \text{graph topology compatible,} \\ \text{plate enclosure compatible,} \\ \text{margins and basins compatible,} \\ \text{defining cause necessary,} \\ \text{complexity controlled,} \\ \text{held-out prediction successful} \end{array} \right\}. \tag{353}$$

28.3 Boundary-Replacement Condition

The astro-ballistic boundary model is a replacement candidate only if

$$\mathcal{V}_{B,\mathrm{ABC}}^{\mathrm{IV}} \neq \varnothing \tag{354}$$

and

$$\mathrm{Score}_B\left(\mathcal{M}_{\mathrm{ABC}}\right) < \mathrm{Score}_B\left(\mathcal{M}_{\mathrm{PT}}\right) - \delta_B \tag{355}$$

after uncertainty and complexity correction.

28.4 Hybrid Boundary Preference

The hybrid boundary model is preferred when

$$\mathrm{Score}_B\left(\mathcal{M}_{\mathrm{HYB}}\right) < \min\left[\mathrm{Score}_B\left(\mathcal{M}_{\mathrm{PT}}\right), \mathrm{Score}_B\left(\mathcal{M}_{\mathrm{ABC}}\right)\right] - \delta_B \tag{356}$$

and both parent contributions remain necessary.

28.5 Boundary Equivalence

Models are boundary-equivalent when

$$\left|\mathrm{Score}_{B,i} - \mathrm{Score}_{B,j}\right| \leq \delta_{B,\mathrm{equiv}}. \tag{357}$$

28.6 Boundary Comparison Matrix

Table 2: Paper-IV boundary-replacement falsification matrix.

ID	Comparison claim	Falsifying result	Consequence
IV-B01	Boundary eligibility	The astro-ballistic boundary state requires mechanically excluded Paper-II outputs.	Astro-ballistic boundary model is ineligible.
IV-B02	Boundary generation	The candidate cannot generate persistent connected boundaries.	Reject boundary-origin claim.
IV-B03	Boundary location	Predicted boundaries are systematically misplaced.	Reject spatial boundary replacement.
IV-B04	Boundary orientation	Predicted orientations are systematically incompatible.	Reject directional boundary replacement.
IV-B05	Boundary curvature	Predicted curvature and segmentation fail.	Reject geometric reconstruction.

ID	Comparison claim	Falsifying result	Consequence
IV-B06	Boundary precision	The model produces extensive false-positive boundary length.	Reject predictive specificity.
IV-B07	Boundary recall	The model misses extensive observed boundary length.	Reject global coverage.
IV-B08	Boundary type	The model predicts incorrect convergent, divergent, transform, or descent behavior.	Reject kinematic boundary classification.
IV-B09	Relative motion	Normal and tangential boundary velocities fail.	Reject boundary-motion solution.
IV-B10	Boundary initiation	Predicted boundary initiation ages are incompatible.	Reject origin chronology.
IV-B11	Boundary reactivation	The model cannot predict which latent boundaries reactivate.	Reject reactivation mechanism.
IV-B12	Boundary inversion	The predicted direction of reactivation or inversion is incorrect.	Reject sequenced boundary evolution.
IV-B13	Boundary termination	The model requires manual termination or predicts unobserved continuations.	Reject termination model.
IV-B14	Plate enclosure	The network does not enclose realistic plates or blocks.	Reject global plate partition.
IV-B15	Graph topology	Connectivity, junctions, cycles, or adjacency fail.	Reject global network architecture.
IV-B16	Plate count	The predicted number and scale distribution of plates fail.	Reject lithospheric partition.
IV-B17	Manual bridging	Large boundary fractions require manually inserted connections.	Reject causal network completeness.
IV-B18	Initial-condition information	The observed network is substantially inserted as an unconstrained initial state.	No independent boundary-origin credit.
IV-B19	Event necessity	Removing astro-ballistic inheritance leaves the network unchanged.	Reject primary event causation.
IV-B20	Plate-Tectonic necessity	Removing the defining Plate-Tectonic boundary-generating components leaves the network unchanged.	Reject their claimed primary role.

ID	Comparison claim	Falsifying result	Consequence
IV-B21	Hybrid necessity	The hybrid wins while one parent component is unnecessary.	Reject joint causal attribution.
IV-B22	Continental margins	The model fails paired-margin locations and geometry.	Reject continental-fragmentation explanation.
IV-B23	Ocean-basin opening	The model fails opening rates, crustal thinning, or material ages.	Reject basin-opening explanation.
IV-B24	Basin subsidence	The model fails subsidence and thermal histories.	Reject basin evolution.
IV-B25	Margin asymmetry	The predicted asymmetry pattern is incompatible.	Reject margin-history reconstruction.
IV-B26	Boundary null	Randomized events or shuffled initial fields perform equally well.	Reject special causal organization.
IV-B27	Boundary complexity	The apparent advantage disappears after initial-state, event, assignment, and revision costs are counted.	Reject boundary replacement preference.
IV-B28	Boundary holdout	The model fails withheld regions, types, ages, or continuations.	Reject predictive generality.
IV-B29	Boundary replication	Independent teams cannot reproduce the comparison.	Reject confirmatory status.
IV-B30	Boundary equivalence	Model scores remain within the equivalence interval.	Report boundary causal non-resolution.
IV-B31	Plate-Tectonic superiority	The strongest Plate-Tectonic model predicts the boundary domain better after penalties.	Reject astro-ballistic boundary replacement.
IV-B32	Astro-ballistic superiority	The astro-ballistic model does not achieve a clear penalized advantage.	Primary boundary replacement is unsupported.
IV-B33	Hybrid superiority	The hybrid model does not outperform both parents with both components necessary.	Hybrid boundary preference is unsupported.
IV-B34	Complete boundary viability	The astro-ballistic boundary viable set is empty.	Boundary component of replacement thesis fails.

28.7 Boundary Outcome Classes

The boundary comparison permits:

Boundary Outcome A: Plate-Tectonic preference
The Plate-Tectonic model provides the strongest penalized boundary prediction.

Boundary Outcome B: Astro-ballistic preference
Event-derived boundary generation provides the strongest penalized prediction.

Boundary Outcome C: Hybrid preference
Event-created inheritance and later geodynamic evolution are jointly necessary.

Boundary Outcome D: Regional event contribution
Selected boundaries retain event-derived support without global replacement.

Boundary Outcome E: Equivalence
Available evidence does not distinguish the model families.

Boundary Outcome F: Shared failure
None of the tested model families adequately predicts the boundary domain.

28.8 Boundary Replacement Decision Rule

Boundary-replacement decision rule.
Astro-Ballistic Chronostratigraphic Sequencing can replace Plate Tectonics as the primary explanation of the global plate-boundary architecture only if its mechanically admissible event sequence predicts boundary locations, orientations, types, ages, reactivation, termination, graph topology, plate enclosure, continental margins, and ocean-basin evolution more accurately and predictively after all event, initial-condition, assignment, and model-flexibility costs are counted.
A model does not explain boundary origin merely by receiving the observed network as an initial condition or by assigning a separate event to each boundary after inspection.

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29 Boundary-Comparison Synthesis

This boundary-comparison synthesis records:

1. boundary origin as a primary replacement test;
2. shared observed boundary-state variables;
3. Plate-Tectonic, astro-ballistic, and hybrid boundary-generation classes;
4. prescribed, inherited, emergent, event-created, reactivated, and post hoc boundary categories;
5. explicit boundary-origin records;
6. boundary-emergence and retention metrics;
7. event-created and inherited-boundary ablations;

8. initial-condition description length;
9. event-catalog and initial-boundary information accounting;
10. boundary-origin causal compression;
11. directed spatial boundary distances;
12. false-positive and false-negative boundary length;
13. boundary precision, recall, and harmonic score;
14. orientation, curvature, and width residuals;
15. boundary-type confusion matrices;
16. normal, tangential, and oblique relative-motion residuals;
17. boundary initiation, reactivation, inversion, lifetime, and termination comparison;
18. observed and predicted global boundary graphs;
19. graph nodes, edges, connected components, cycles, adjacency, and spectral metrics;
20. plate-face count and enclosure completeness;
21. manual gap-filling penalties;
22. continental-margin origin comparison;
23. paired-margin prediction;
24. ocean-basin opening, crustal-thinning, material-age, and subsidence comparison;
25. component-specific boundary counterfactuals;
26. leave-one-event-out and leave-one-mechanism-out tests;
27. interaction necessity;
28. boundary-specific complexity accounting;
29. spatial, type, chronology, and continuation holdouts;
30. negative boundary predictions;
31. randomized-event and shuffled-initial-state nulls;
32. the complete boundary-model viable set;
33. the boundary-replacement comparison matrix; and
34. explicit Plate-Tectonic, astro-ballistic, hybrid, regional, equivalence, and shared-failure outcomes.

The following sections compare the global motion systems directly:

- competing plate-driving and motion-maintenance mechanisms;
- initial impulse versus sustained forcing;

- mantle flow, gravity, buoyancy, and boundary traction;
- Euler-pole generation;
- absolute and relative plate velocities;
- acceleration, deceleration, and direction changes;
- plate-speed hierarchy;
- plate circuits and triple-junction closure;
- present-day Global Navigation Satellite System observations;
- finite rotations and deep-time motion;
- force, torque, power, and dissipation comparison;
- motion counterfactuals;
- motion-specific complexity and predictive tests;
- and the complete plate-motion replacement matrix.

30 Competing Plate-Motion Mechanisms

30.1 Motion Is Shared Evidence

The existence of plate and continental motion is not allocated exclusively to either model family.

For plate or block i, the observed motion state is

$$\mathbf{D}_{V,i}^{\mathrm{obs}} = \left(\mathbf{v}_i, \boldsymbol{\omega}_i, \dot{\mathbf{v}}_i, \dot{\boldsymbol{\omega}}_i, \mathbf{R}_i, \dot{\boldsymbol{\epsilon}}_i, \mathbf{v}_{ij}^{\mathrm{rel}}\right), \tag{358}$$

where:

$$\mathbf{v}_i = \text{translational or site-velocity field}, \tag{359}$$
$$\boldsymbol{\omega}_i = \text{Euler angular-velocity vector}, \tag{360}$$
$$\mathbf{R}_i = \text{finite-rotation history}, \tag{361}$$
$$\dot{\boldsymbol{\epsilon}}_i = \text{internal strain-rate field}, \tag{362}$$
$$\mathbf{v}_{ij}^{\mathrm{rel}} = \text{relative motion between adjacent plates}. \tag{363}$$

Every model must predict the same motion state in the same declared reference frame.

30.2 General Plate-Motion Operator

For model q,

$$\widehat{\mathbf{V}}_q(t) = \mathcal{H}_{V,q}\left[\mathbf{Q}_{q,0}, \mathcal{B}_q(t), \mathbf{F}_q(t), \boldsymbol{\tau}_q(t), \mathbf{R}_{q,\mathrm{rheo}}, \mathcal{E}_q, t\right]. \tag{364}$$

The operator must generate:

- plate translations;
- plate rotations;
- Euler poles;
- relative velocities;
- internal deformation;
- acceleration and deceleration;
- and directional changes.

30.3 Plate-Tectonic Motion Classes

The Plate-Tectonic comparison family may generate or maintain motion through combinations of:

PT-V1. gravitational-potential gradients;

PT-V2. density-driven buoyancy;

PT-V3. descent of dense lithospheric material;

PT-V4. topographic and lithospheric pressure gradients;

PT-V5. mantle-flow traction;

PT-V6. plate-driven mantle traction;

PT-V7. boundary-normal traction;

PT-V8. boundary-parallel shear traction;

PT-V9. flexural and bending forces;

PT-V10. collision and underthrusting;

PT-V11. resistance at plate boundaries;

PT-V12. basal resistance;

PT-V13. and inherited material anisotropy.

The selected comparison implementation must specify the relative contribution of each class rather than invoking a generic tectonic force after the motion field is known.

30.4 Astro-Ballistic Motion Classes

The astro-ballistic family may generate or maintain motion through:

ABC-V1. direct linear impulse;

ABC-V2. direct angular impulse;

ABC-V3. event-created plate fragmentation;

ABC-V4. event-created displacement discontinuities;

ABC-V5. event-modified boundary mobility;

ABC-V6. event-created density anomalies;

ABC-V7. event-created thermal and phase anomalies;

ABC-V8. event-modified gravitational potential;

ABC-V9. event-modified mantle flow;

ABC-V10. residual stress;

ABC-V11. later-event reinforcement or redirection;

ABC-V12. and long-time geodynamic response to event-created states.

30.5 Hybrid Motion Classes

The hybrid family combines an event-created state with later geodynamic evolution:

$$\widehat{\mathbf{V}}_{\mathrm{HYB}}(t) = \mathcal{U}_{V,\mathrm{PT}}\left[\mathbf{Q}^{+}_{\mathrm{ABC}}, \mathcal{B}^{+}_{\mathrm{ABC}}, \mathbf{F}_{\mathrm{later}}, \boldsymbol{\tau}_{\mathrm{later}}, t\right]. \tag{365}$$

Possible hybrid causal structures include:

- event initiation followed by geodynamic maintenance;
- event-created boundary guidance followed by gravity-driven motion;
- event-created fragmentation followed by mantle-coupled evolution;
- event-created density anomalies followed by buoyant reorganization;
- or pre-existing motion redirected by later events.

30.6 Motion-Origin Record

For plate i, each model must produce

$$\begin{aligned}\mathbf{O}_{V,i,q} = \big(&\text{initial state}, \text{initiating force}, \text{initial direction}, \text{initial speed},\\ &\text{maintenance forces}, \text{resistance}, \text{rotation history}, \text{later changes}\big).\end{aligned} \tag{366}$$

30.7 Motion-Generation Burden

A complete motion explanation predicts:

- why plate i moves;
- why it moves in its observed direction;

- why it rotates about its observed Euler pole;
- why it moves faster or slower than neighboring plates;
- why motion changes through time;
- why shared boundaries open, close, or shear;
- and why plate circuits remain kinematically consistent.

30.8 No Independent Plate-by-Plate Motion Law

A prohibited model is

$$\widehat{\mathbf{V}}_q = \bigcup_{i=1}^{N_P} \mathcal{H}_{V,q}^{(i)} \left[\mathbf{\Theta}_{V,i} \right], \tag{367}$$

where each plate receives an independently selected force, resistance, memory time, or Euler vector. The preferred model must predict multiple plates from shared physical and historical inputs.

31 Initial Impulse Versus Sustained Forcing

31.1 Impulse and Force Are Distinct

An impulse changes momentum over a finite event interval:

$$\mathbf{I}_{i,k} = \int_{t_k^-}^{t_k^+} \mathbf{F}_{i,k}(t)\, dt. \tag{368}$$

The immediate velocity change is

$$\Delta \mathbf{V}_{i,k} = \frac{\mathbf{I}_{i,k}}{M_i}. \tag{369}$$

Sustained forcing changes momentum over geological time:

$$M_i \frac{d\mathbf{V}_i}{dt} = \mathbf{F}_{i,\mathrm{net}}(t). \tag{370}$$

31.2 Angular Impulse

The angular impulse is

$$\Delta \mathbf{L}_{i,k} = \int_{t_k^-}^{t_k^+} \boldsymbol{\tau}_{i,k}(t)\, dt. \tag{371}$$

For inertia tensor $\mathbf{I}_i$,

$$\Delta\boldsymbol{\omega}_{i,k} = \mathbf{I}_i^{-1}\Delta\mathbf{L}_{i,k} \tag{372}$$

when the inertia tensor is approximately constant across the impulse interval.

31.3 Post-Impulse Evolution

The post-event velocity obeys

$$M_i\frac{d\mathbf{V}_i}{dt} = \mathbf{F}_{i,\mathrm{drive}} - \mathbf{F}_{i,\mathrm{resist}}. \tag{373}$$

The angular evolution is

$$\mathbf{I}_i\frac{d\boldsymbol{\omega}_i}{dt} + \dot{\mathbf{I}}_i\boldsymbol{\omega}_i + \boldsymbol{\omega}_i \times (\mathbf{I}_i\boldsymbol{\omega}_i) = \boldsymbol{\tau}_{i,\mathrm{net}}. \tag{374}$$

31.4 Reduced Velocity-Relaxation Model

A reduced motion model is

$$M_i\frac{d\mathbf{V}_i}{dt} = \mathbf{F}_i^{+}(t) - \mathbf{C}_i\left[\mathbf{V}_i - \mathbf{V}_{i,\mathrm{eq}}(t)\right], \tag{375}$$

where:

$$\mathbf{C}_i = \text{effective resistance tensor}, \tag{376}$$

$$\mathbf{V}_{i,\mathrm{eq}} = \text{instantaneous force-balanced velocity}. \tag{377}$$

31.5 Velocity-Relaxation Time

For scalar effective resistance C_i,

$$\tau_{V,i} = \frac{M_i}{C_i}. \tag{378}$$

For rotational resistance $C_{\omega,i}$,

$$\tau_{\omega,i} = \frac{I_{i,\mathrm{eff}}}{C_{\omega,i}}. \tag{379}$$

31.6 Impulse-Memory Fraction

Let the event-derived velocity component be

$$\mathbf{V}_i^I(t). \tag{380}$$

Define impulse-memory fraction

$$f_{I,i}(t) = \frac{\left\| \mathbf{V}_i^I(t) \right\|}{\left\| \Delta \mathbf{V}_{i,k} \right\|}. \tag{381}$$

31.7 Directional-Memory Fraction

Let initial event direction be

$$\widehat{\mathbf{d}}_{i,k}^0. \tag{382}$$

The directional-memory statistic is

$$f_{\mathrm{dir},i}(t) = \widehat{\mathbf{d}}_{i,k}^0 \cdot \widehat{\mathbf{V}}_i(t). \tag{383}$$

Direction may remain correlated after the original speed contribution has substantially decayed.

31.8 Sustained-Force Fraction

For force component a, define positive power

$$\dot{W}_{i,a}^+ = \max\left[\mathbf{F}_{i,a} \cdot \mathbf{V}_i, 0\right]. \tag{384}$$

The sustained-force fraction is

$$f_{i,a}^{\mathrm{sustain}} = \frac{\dot{W}_{i,a}^+}{\sum_b \dot{W}_{i,b}^+}. \tag{385}$$

31.9 Impulse Sufficiency Ratio

Let present plate kinetic energy be

$$E_{K,i}^{\mathrm{now}}. \tag{386}$$

Let surviving kinetic energy attributable to the event impulse be

$$E_{K,i}^{I,\mathrm{now}}. \tag{387}$$

Define

$$\Pi_{I,i} = \frac{E_{K,i}^{I,\mathrm{now}}}{E_{K,i}^{\mathrm{now}}}. \tag{388}$$

A small value does not eliminate directional inheritance, but it rejects the claim that present speed is maintained primarily by surviving initial kinetic energy.

31.10 Maintenance Sufficiency Ratio

Let integrated positive work from persistent forcing be

$$W_i^{\mathrm{maint}} = \int_{t_k}^{t_{\mathrm{now}}} \dot{W}_i^{+}(t)\, dt. \tag{389}$$

Let integrated dissipative loss be

$$E_i^{\mathrm{diss}} = \int_{t_k}^{t_{\mathrm{now}}} \dot{E}_i^{\mathrm{diss}}(t)\, dt. \tag{390}$$

Define

$$\Pi_{\mathrm{maint},i} = \frac{W_i^{\mathrm{maint}}}{E_i^{\mathrm{diss}} + \Delta E_{K,i} + \epsilon}. \tag{391}$$

A physically sustained solution requires adequate work to balance dissipation and kinetic-energy change.

31.11 No Perpetual-Impulse Assumption

Impulse-maintenance principle.
An ancient impulse may initiate motion, alter direction, fragment a plate, or create guiding boundaries.
It cannot be treated as a perpetual unattenuated power source.
Present motion requires explicit accounting of later driving work, resistance, dissipation, and inherited directional structure.

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32 Gravity, Buoyancy, Mantle Flow, and Boundary Traction

32.1 Complete Force Decomposition

For plate i and model q,

$$\begin{aligned} \mathbf{F}_{i,q}^{\mathrm{net}} = \mathbf{F}_{i,q}^{I} + \mathbf{F}_{i,q}^{g} + \mathbf{F}_{i,q}^{B} + \mathbf{F}_{i,q}^{m} + \mathbf{F}_{i,q}^{\partial P} \\ + \mathbf{F}_{i,q}^{\mathrm{topo}} + \mathbf{F}_{i,q}^{\mathrm{flex}} + \mathbf{F}_{i,q}^{\mathrm{resist}}. \end{aligned} \tag{392}$$

Here:

$$\mathbf{F}^{I}_{i,q} = \text{event or transient impulse-derived force,} \tag{393}$$
$$\mathbf{F}^{g}_{i,q} = \text{gravity-related force,} \tag{394}$$
$$\mathbf{F}^{B}_{i,q} = \text{buoyancy force,} \tag{395}$$
$$\mathbf{F}^{m}_{i,q} = \text{mantle traction,} \tag{396}$$
$$\mathbf{F}^{\partial P}_{i,q} = \text{plate-boundary traction,} \tag{397}$$
$$\mathbf{F}^{\text{topo}}_{i,q} = \text{topographic potential-gradient force,} \tag{398}$$
$$\mathbf{F}^{\text{flex}}_{i,q} = \text{bending and flexural force,} \tag{399}$$
$$\mathbf{F}^{\text{resist}}_{i,q} = \text{net resisting force.} \tag{400}$$

32.2 Gravitational Force

For gravitational potential Φ_q,

$$\mathbf{F}^{g}_{i,q} = -\int_{\mathcal{P}_i} \rho_q \nabla \Phi_q \, dV. \tag{401}$$

The associated torque is

$$\boldsymbol{\tau}^{g}_{i,q} = -\int_{\mathcal{P}_i} \mathbf{r} \times \rho_q \nabla \Phi_q \, dV. \tag{402}$$

32.3 Buoyancy Force

For density anomaly $\Delta\rho_q$,

$$\mathbf{F}^{B}_{i,q} = -\int_{\mathcal{P}_i} \Delta\rho_q \mathbf{g}_q \, dV. \tag{403}$$

The density anomaly may include:

$$\Delta\rho_q = \Delta\rho_{T,q} + \Delta\rho_{C,q} + \Delta\rho_{\phi,q} + \Delta\rho_{m,q} + \Delta\rho_{D,q}. \tag{404}$$

32.4 Mantle Traction

At plate base $\mathcal{A}_i^{\text{base}}$,

$$\mathbf{t}^{m}_{i,q} = \boldsymbol{\sigma}_{m,q} \hat{\mathbf{n}}_i^{\text{base}}. \tag{405}$$

A reduced coupling law is

$$\mathbf{t}^{m}_{i,q} = -\mathbf{K}^{m}_{i,q} \left(\mathbf{V}_i - \mathbf{V}_{m,q} \right). \tag{406}$$

The basal force is

$$\mathbf{F}_{i,q}^{m} = \int_{\mathcal{A}_i^{\text{base}}} \mathbf{t}_{i,q}^{m} \, dA. \tag{407}$$

32.5 Boundary Traction

At boundary $\mathcal{B}_{ij}$,

$$\mathbf{t}_{ij,q}^{\partial P} = \boldsymbol{\sigma}_{ij,q} \widehat{\mathbf{n}}_{ij}. \tag{408}$$

The boundary force on plate i is

$$\mathbf{F}_{i \leftarrow j,q}^{\partial P} = \int_{\mathcal{B}_{ij}} \mathbf{t}_{ij,q}^{\partial P} \, dA. \tag{409}$$

32.6 Action–Reaction Consistency

For a consistently evaluated shared interface,

$$\mathbf{F}_{i \leftarrow j,q}^{\partial P} = -\mathbf{F}_{j \leftarrow i,q}^{\partial P}. \tag{410}$$

The model must report any residual

$$\boldsymbol{\epsilon}_{ij,q}^{AR} = \mathbf{F}_{i \leftarrow j,q}^{\partial P} + \mathbf{F}_{j \leftarrow i,q}^{\partial P}. \tag{411}$$

32.7 Topographic Potential Force

For surface or lithospheric potential-energy density $\mathcal{U}_q$,

$$\mathbf{F}_{i,q}^{\text{topo}} = -\int_{\mathcal{A}_i} \nabla_{\mathcal{S}} \mathcal{U}_q \, dA. \tag{412}$$

32.8 Force Direction Agreement

For observed acceleration direction $\widehat{\mathbf{a}}_i^{\text{obs}}$ and predicted net-force direction,

$$A_{F,i,q} = \widehat{\mathbf{a}}_i^{\text{obs}} \cdot \frac{\mathbf{F}_{i,q}^{\text{net}}}{\left\| \mathbf{F}_{i,q}^{\text{net}} \right\|}. \tag{413}$$

Where acceleration is poorly constrained, force direction must instead be evaluated through forward motion and power consistency.

32.9 Force Contribution Fractions

For positive work component a,

$$f^{+}_{F,i,a,q} = \frac{\max\left[\mathbf{F}_{i,a,q} \cdot \mathbf{V}_i, 0\right]}{\sum_b \max\left[\mathbf{F}_{i,b,q} \cdot \mathbf{V}_i, 0\right]}. \tag{414}$$

32.10 Event-Modified Force Fraction

For the astro-ballistic or hybrid model,

$$f^{\mathrm{event}}_{F,i} = \frac{\left\|\mathbf{F}_i^{\mathrm{full}} - \mathbf{F}_i^{\mathrm{no\,event}}\right\|}{\left\|\mathbf{F}_i^{\mathrm{full}}\right\| + \epsilon}. \tag{415}$$

32.11 Force-Architecture Comparison

A model gains causal force credit only when:

- the force field is generated from its state variables;
- the force has the correct sign and direction;
- the force magnitude is sufficient;
- the associated reaction and dissipation are accounted for;
- and removing the force degrades held-out motion prediction.

33 Euler-Pole Generation and Plate Rotation

33.1 Euler Vectors Must Be Outputs

For approximately rigid plate i,

$$\mathbf{v}_{i,q}(\mathbf{x}, t) = \boldsymbol{\omega}_{i,q}(t) \times \mathbf{x}. \tag{416}$$

The Euler vector must satisfy

$$\boldsymbol{\omega}_{i,q} = \mathcal{F}_{\omega,q}\left[\mathbf{I}_i, \boldsymbol{\tau}_{i,q}, \mathcal{B}_q, \mathcal{E}_q, \mathbf{Q}_{q,0}, t\right]. \tag{417}$$

33.2 Plate Inertia Tensor

The plate inertia tensor is

$$\mathbf{I}_i = \int_{\mathcal{P}_i} \rho\left[\left\|\mathbf{r}'\right\|^2 \mathbf{1} - \mathbf{r}' \otimes \mathbf{r}'\right] dV. \tag{418}$$

The inertia tensor changes with:

- fragmentation;
- terrane transfer;
- deformation;
- new-material production;
- descent;
- and plate merger.

33.3 Euler-Vector Dynamics

For model q,

$$\mathbf{I}_i \dot{\boldsymbol{\omega}}_{i,q} + \dot{\mathbf{I}}_i \boldsymbol{\omega}_{i,q} + \boldsymbol{\omega}_{i,q} \times (\mathbf{I}_i \boldsymbol{\omega}_{i,q}) = \boldsymbol{\tau}_{i,q}^{\text{net}}. \tag{419}$$

33.4 Predicted Euler-Pole Direction

The predicted pole direction is

$$\widehat{\mathbf{e}}_{i,q} = \frac{\boldsymbol{\omega}_{i,q}}{\|\boldsymbol{\omega}_{i,q}\|}. \tag{420}$$

The predicted angular speed is

$$\omega_{i,q} = \|\boldsymbol{\omega}_{i,q}\|. \tag{421}$$

33.5 Euler-Pole Direction Residual

$$\Delta\theta_{\omega,i,q} = \arccos\left[\widehat{\mathbf{e}}_i^{\text{obs}} \cdot \widehat{\mathbf{e}}_{i,q}^{\text{pred}}\right]. \tag{422}$$

33.6 Angular-Speed Residual

$$\Delta\omega_{i,q} = \omega_i^{\text{obs}} - \omega_{i,q}^{\text{pred}}. \tag{423}$$

33.7 Euler-Vector Covariance Misfit

$$\chi^2_{\omega,q} = \sum_i \left(\boldsymbol{\omega}_i^{\text{obs}} - \boldsymbol{\omega}_{i,q}^{\text{pred}}\right)^{\mathsf{T}} \boldsymbol{\Sigma}_{\omega,i}^{-1} \left(\boldsymbol{\omega}_i^{\text{obs}} - \boldsymbol{\omega}_{i,q}^{\text{pred}}\right). \tag{424}$$

33.8 Euler-Pole Drift

The predicted pole-drift rate is

$$\dot{\widehat{\mathbf{e}}}_{i,q} = \frac{1}{\omega_{i,q}} \left[\mathbf{1} - \widehat{\mathbf{e}}_{i,q} \otimes \widehat{\mathbf{e}}_{i,q}\right] \dot{\boldsymbol{\omega}}_{i,q}. \tag{425}$$

33.9 Finite Rotation

The model-predicted finite rotation is

$$\mathbf{R}_{i,q}(t_2, t_1) = \mathcal{T} \exp\left[\int_{t_1}^{t_2} [\boldsymbol{\omega}_{i,q}(t)]_\times \, dt\right]. \tag{426}$$

33.10 Finite-Rotation Residual

Define

$$\mathbf{R}_{i,q}^{\text{res}} = \left[\mathbf{R}_{i,q}^{\text{pred}}\right]^{-1} \mathbf{R}_i^{\text{obs}}. \tag{427}$$

The residual angle is

$$\Delta\theta_{R,i,q} = \arccos\left[\frac{\operatorname{tr}\left(\mathbf{R}_{i,q}^{\text{res}}\right) - 1}{2}\right]. \tag{428}$$

33.11 Rigid-Motion Adequacy

For plate i, define rigid-motion residual energy

$$E_{i,q}^{\text{def}} = \frac{1}{2}\int_{\mathcal{P}_i} \rho \left\|\mathbf{v}_i^{\text{obs}} - \boldsymbol{\omega}_{i,q} \times \mathbf{x}\right\|^2 dV. \tag{429}$$

A plate requiring substantial internal deformation must not be scored as a purely rigid plate.

33.12 No Fitted-Pole Causal Credit

A model may use observed Euler poles as calibration targets.

It receives no causal prediction credit when it assigns

$$\boldsymbol{\omega}_{i,q} = \boldsymbol{\omega}_i^{\text{obs}} \tag{430}$$

as an independent free parameter and then reports agreement.

33.13 Euler-Pole Falsifier

Euler-pole comparison falsifier V-C1.
A model fails the Euler-pole comparison if the observed pole directions, angular speeds, and finite rotations cannot be generated from its declared force, torque, inertia, boundary, and historical state without independent pole fitting.

34 Absolute and Relative Plate Velocities

34.1 Reference-Frame Declaration

For reference frame $\mathcal{R}_f$, a velocity is written

$$\mathbf{v}_{i,q}^{(\mathcal{R}_f)}. \tag{431}$$

The transformation between frames a and b may include rigid rotation

$$\mathbf{v}^{(b)} = \mathbf{v}^{(a)} - \boldsymbol{\omega}_{ab} \times \mathbf{x}. \tag{432}$$

All comparative residuals must be evaluated in a common frame or in frame-invariant relative quantities.

34.2 Absolute Site Velocity

For site j on plate i,

$$\widehat{\mathbf{v}}_{j,q} = \boldsymbol{\omega}_{i,q} \times \mathbf{x}_j + \mathbf{v}_{i,q}^{\mathrm{def}}\left(\mathbf{x}_j\right). \tag{433}$$

The residual is

$$\boldsymbol{\epsilon}_{j,q}^{V} = \mathbf{v}_j^{\mathrm{obs}} - \widehat{\mathbf{v}}_{j,q}. \tag{434}$$

34.3 Absolute-Velocity Misfit

$$\chi^2_{\mathrm{abs},q} = \sum_j \left(\boldsymbol{\epsilon}_{j,q}^{V}\right)^{\mathsf{T}} \boldsymbol{\Sigma}_{j,V}^{-1} \boldsymbol{\epsilon}_{j,q}^{V}. \tag{435}$$

34.4 Relative Euler Vector

For plates i and j,

$$\boldsymbol{\omega}_{ij,q} = \boldsymbol{\omega}_{i,q} - \boldsymbol{\omega}_{j,q}. \tag{436}$$

34.5 Relative Boundary Velocity

At boundary position $\mathbf{x}$,

$$\mathbf{v}_{ij,q}^{\mathrm{rel}}(\mathbf{x}) = \boldsymbol{\omega}_{ij,q} \times \mathbf{x} + \mathbf{v}_{i,q}^{\mathrm{def}} - \mathbf{v}_{j,q}^{\mathrm{def}}. \tag{437}$$

34.6 Relative-Velocity Misfit

$$\chi^2_{\text{rel},q} = \sum_b \left(\mathbf{v}_b^{\text{rel,obs}} - \mathbf{v}_{b,q}^{\text{rel,pred}}\right)^{\mathsf{T}} \boldsymbol{\Sigma}_{b,\text{rel}}^{-1} \left(\mathbf{v}_b^{\text{rel,obs}} - \mathbf{v}_{b,q}^{\text{rel,pred}}\right). \tag{438}$$

34.7 Plate-Mean Speed

For plate i,

$$\bar{v}_{i,q} = \frac{\displaystyle\int_{\mathcal{A}_i} w_i(\mathbf{x}) \, \|\mathbf{v}_{i,q}(\mathbf{x})\| \, dA}{\displaystyle\int_{\mathcal{A}_i} w_i(\mathbf{x}) \, dA}. \tag{439}$$

34.8 Direction Residual

For representative observed and predicted motion directions,

$$\Delta\theta_{V,i,q} = \arccos\left[\widehat{\mathbf{V}}_i^{\text{obs}} \cdot \widehat{\mathbf{V}}_{i,q}^{\text{pred}}\right]. \tag{440}$$

34.9 Magnitude Residual

$$\epsilon_{v,i,q} = \bar{v}_i^{\text{obs}} - \bar{v}_{i,q}^{\text{pred}}. \tag{441}$$

A proportional residual is

$$\epsilon_{\log v,i,q} = \log\left[\frac{\bar{v}_{i,q}^{\text{pred}}}{\bar{v}_i^{\text{obs}}}\right]. \tag{442}$$

34.10 Frame-Robust Score

For defensible frame ensemble $\mathfrak{R}$, define

$$\overline{\mathcal{J}}_{V,q} = \int_{\mathfrak{R}} \mathcal{J}_{V,q}^{(\mathcal{R}_f)} p(\mathcal{R}_f) \, d\mathcal{R}_f. \tag{443}$$

The frame sensitivity is

$$\sigma^2_{\mathcal{R},q} = \int_{\mathfrak{R}} \left[\mathcal{J}_{V,q}^{(\mathcal{R}_f)} - \overline{\mathcal{J}}_{V,q}\right]^2 p(\mathcal{R}_f) \, d\mathcal{R}_f. \tag{444}$$

34.11 Absolute-Relative Motion Principle

A model may perform differently on absolute and relative motion.

Relative boundary kinematics are less sensitive to global rotational frame choices.

Absolute motion may better test mantle coupling and full torque architecture.

Both must be reported.

35 Acceleration, Deceleration, and Direction Change

35.1 Acceleration Field

For model q,

$$\mathbf{a}_{i,q} = \frac{D\mathbf{v}_{i,q}}{Dt}. \tag{445}$$

The along-motion acceleration is

$$a_{\|,i,q} = \mathbf{a}_{i,q} \cdot \widehat{\mathbf{v}}_{i,q}. \tag{446}$$

The turning acceleration is

$$\mathbf{a}_{\perp,i,q} = \mathbf{a}_{i,q} - a_{\|,i,q}\widehat{\mathbf{v}}_{i,q}. \tag{447}$$

35.2 Speed Evolution

$$\frac{d\bar{v}_{i,q}}{dt} = \bar{a}_{\|,i,q}. \tag{448}$$

35.3 Direction-Change Rate

For unit direction $\widehat{\mathbf{v}}_{i,q}$,

$$\frac{d\widehat{\mathbf{v}}_{i,q}}{dt} = \frac{1}{\|\mathbf{v}_{i,q}\|} \left[\mathbf{1} - \widehat{\mathbf{v}}_{i,q} \otimes \widehat{\mathbf{v}}_{i,q}\right] \mathbf{a}_{i,q}. \tag{449}$$

35.4 Motion-Curvature Rate

Define turning-rate magnitude

$$\Omega_{V,i,q} = \left\| \frac{d\widehat{\mathbf{v}}_{i,q}}{dt} \right\|. \tag{450}$$

35.5 Change-Point Times

Let motion change points be

$$\mathcal{T}_{V,i}^{\text{change}} = \left\{ t_{i,1}^*, t_{i,2}^*, \ldots \right\}. \tag{451}$$

A change point may represent:

- acceleration;
- deceleration;
- direction change;

- Euler-pole migration;
- plate fragmentation;
- collision;
- ridge initiation;
- boundary inversion;
- or later-event forcing.

35.6 Change-Point Prediction

For model q,

$$\widehat{\mathcal{T}}_{V,i,q}^{\text{change}} = \mathcal{F}_{\text{change},q}\left[\mathbf{F}_{i,q}, \boldsymbol{\tau}_{i,q}, \mathcal{B}_q, \mathcal{E}_q\right]. \tag{452}$$

35.7 Change-Point Residual

For matched change point a,

$$\epsilon_{t,V,i,a,q} = \frac{t_{V,i,a}^{\text{obs}} - t_{V,i,a,q}^{\text{pred}}}{\sigma_{t,V,i,a}}. \tag{453}$$

35.8 Event-Linked Direction Change

For proposed event k, define directional change before and after the event:

$$\Delta\theta_{i,k}^{V} = \arccos\left[\widehat{\mathbf{V}}_i(t_k^-) \cdot \widehat{\mathbf{V}}_i(t_k^+)\right]. \tag{454}$$

The event model must predict:

- which plates change direction;
- the sign and angle of change;
- the time lag;
- the duration of adjustment;
- and which plates remain comparatively unaffected.

35.9 Event-Linked Speed Change

$$\Delta v_{i,k} = \bar{v}_i(t_k^+) - \bar{v}_i(t_k^-). \tag{455}$$

35.10 No Change-Point Selection After Inspection

An event cannot be credited for a motion change merely because the event age is adjusted to the nearest observed change point.

The event age, uncertainty, and predicted response interval must be frozen independently.

35.11 Acceleration-History Score

Define

$$\mathcal{J}_{A,q} = w_a \chi^2_{a,q} + w_\Omega \chi^2_{\Omega,q} + w_t \chi^2_{t,\mathrm{change},q} + w_\theta \chi^2_{\Delta\theta,q} + w_v \chi^2_{\Delta v,q}. \tag{456}$$

35.12 Acceleration Falsifier

Acceleration-history falsifier V-C2.
A model fails the motion-history comparison if it reproduces present velocity but cannot predict independently constrained acceleration, deceleration, Euler-pole migration, direction changes, or their timing.

36 Plate-Speed Hierarchy

36.1 Observed and Predicted Rankings

Let the observed speed ordering be

$$\bar{v}^{\mathrm{obs}}_{(1)} \geq \bar{v}^{\mathrm{obs}}_{(2)} \geq \cdots \geq \bar{v}^{\mathrm{obs}}_{(N_P)}. \tag{457}$$

For model q,

$$\bar{v}^{\mathrm{pred}}_{(1),q} \geq \bar{v}^{\mathrm{pred}}_{(2),q} \geq \cdots \geq \bar{v}^{\mathrm{pred}}_{(N_P),q}. \tag{458}$$

36.2 Rank Residual

For plate i,

$$\Delta r_{i,q} = r^{\mathrm{obs}}_i - r^{\mathrm{pred}}_{i,q}. \tag{459}$$

36.3 Rank-Correlation Score

$$\rho_{v,q} = 1 - \frac{6\sum_i \left(\Delta r_{i,q}\right)^2}{N_P\left(N_P^2 - 1\right)}. \tag{460}$$

36.4 Speed-Generation Variables

The model may predict plate speed from shared variables:

$$\bar{v}_{i,q} = \mathcal{F}_{v,q}\left[M_i, \mathbf{I}_i, \mathbf{F}_{i,q}, \boldsymbol{\tau}_{i,q}, \mathcal{B}_{i,q}, \mathbf{K}_{m,i,q}, \mathbf{K}_{B,i,q}, \mathbf{R}_{i,q}\right]. \tag{461}$$

36.5 Dimensionless Speed Predictors

Candidate dimensionless predictors include

$$\Pi_{F,i,q} = \frac{F_{i,q}^{\text{drive}}}{F_{i,q}^{\text{resist}} + \epsilon}, \tag{462}$$

$$\Pi_{\tau,i,q} = \frac{\left\|\boldsymbol{\tau}_{i,q}^{\text{drive}}\right\|}{\left\|\boldsymbol{\tau}_{i,q}^{\text{resist}}\right\| + \epsilon}, \tag{463}$$

and

$$\Pi_{P,i,q} = \frac{\dot{W}_{i,q}^{\text{drive}}}{\dot{E}_{i,q}^{\text{diss}} + \epsilon}. \tag{464}$$

36.6 Quasi-Steady Speed

Where acceleration is small,

$$\mathbf{F}_{i,q}^{\text{drive}} + \mathbf{F}_{i,q}^{\text{resist}} \approx \mathbf{0}. \tag{465}$$

For a reduced scalar model,

$$F_{i,q}^{\text{drive}} \approx C_{i,q} v_i + Q_{i,q} v_i |v_i|. \tag{466}$$

36.7 Plate-Specific Flexibility

Define plate-specific parameter count

$$k_{v,i,q}^{\text{local}}. \tag{467}$$

The total local speed flexibility is

$$k_{v,q}^{\text{local}} = \sum_i k_{v,i,q}^{\text{local}}. \tag{468}$$

A model with one fitted resistance coefficient per plate must count each coefficient.

36.8 Leave-One-Plate-Out Prediction

Fit model q without plate i's velocity data.

Predict

$$\widehat{\mathbf{V}}_{i,q}^{(-i)}. \tag{469}$$

The held-out plate score is

$$S_{V,i,q}^{\mathrm{LOPO}} = \log p\left(\mathbf{D}_{V,i}^{\mathrm{obs}} \mid \mathbf{D}_{V,-i}, \mathcal{M}_q\right). \tag{470}$$

36.9 Hierarchy Composite Score

$$\mathcal{J}_{\mathrm{hier},q} = w_r\left(1-\rho_{v,q}\right) + w_v \sum_i \epsilon^2_{\log v,i,q} + w_{\mathrm{LOPO}}\mathcal{J}_{\mathrm{LOPO},q} + w_k k_{v,q}^{\mathrm{local}}. \tag{471}$$

36.10 Speed-Hierarchy Falsifier

Speed-hierarchy comparison falsifier V-C3.
A model fails the shared plate-speed law if it reproduces the observed speed ordering only through independent plate-specific driving, resistance, or memory parameters and cannot predict held-out plate speeds.

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37 Plate Circuits, Junctions, and Global Closure

37.1 Relative Euler-Vector Circuit

For closed plate circuit

$$i_1 \to i_2 \to \cdots \to i_m \to i_1, \tag{472}$$

model q must satisfy

$$\sum_{a=1}^{m} \boldsymbol{\omega}_{i_a i_{a+1},q} = \mathbf{0}, \tag{473}$$

where $i_{m+1} = i_1$.

37.2 Circuit-Closure Residual

$$\boldsymbol{\epsilon}_{\mathrm{circ},q} = \sum_{a=1}^{m} \boldsymbol{\omega}_{i_a i_{a+1},q}. \tag{474}$$

The normalized residual is

$$\epsilon^*_{\mathrm{circ},q} = \frac{\left\|\boldsymbol{\epsilon}_{\mathrm{circ},q}\right\|}{\sum_a \left\|\boldsymbol{\omega}_{i_a i_{a+1},q}\right\| + \epsilon}. \tag{475}$$

37.3 Triple-Junction Closure

For plates i, j, and k,

$$\mathbf{v}_{ij,q}^{\text{rel}} + \mathbf{v}_{jk,q}^{\text{rel}} + \mathbf{v}_{ki,q}^{\text{rel}} = \mathbf{0}. \tag{476}$$

The residual is

$$\boldsymbol{\epsilon}_{J,q} = \mathbf{v}_{ij,q}^{\text{rel}} + \mathbf{v}_{jk,q}^{\text{rel}} + \mathbf{v}_{ki,q}^{\text{rel}}. \tag{477}$$

37.4 Junction Migration

For junction position $\mathbf{x}_J(t)$,

$$\frac{d\mathbf{x}_{J,q}}{dt} = \mathbf{v}_{J,q}. \tag{478}$$

The junction velocity must remain compatible with all incident boundaries.

37.5 Global Surface-Area Accounting

For plate areas $A_i(t)$,

$$\sum_i A_i(t) + A_{\text{deform}}(t) = A_{\oplus}(t). \tag{479}$$

The rate equation is

$$\sum_i \dot{A}_i + \dot{A}_{\text{deform}} = \dot{A}_{\oplus}. \tag{480}$$

For approximately fixed Earth radius over the modeled interval,

$$\dot{A}_{\oplus} \approx 0. \tag{481}$$

37.6 Creation and Removal Balance

Define new-material production

$$\dot{A}_{\text{create},q} \tag{482}$$

and removal, descent, or incorporation

$$\dot{A}_{\text{remove},q}. \tag{483}$$

The global balance residual is

$$\epsilon_{A,q} = \dot{A}_{\text{create},q} - \dot{A}_{\text{remove},q} - \dot{A}_{\text{stored},q}. \tag{484}$$

37.7 Global Angular-Momentum Accounting

The total modeled angular momentum is

$$\mathbf{L}_{\text{tot},q} = \mathbf{L}_{\text{plates},q} + \mathbf{L}_{\text{mantle},q} + \mathbf{L}_{\text{core},q} + \mathbf{L}_{\text{surface},q} + \mathbf{L}_{\text{escape},q}. \tag{485}$$

Its evolution satisfies

$$\frac{d\mathbf{L}_{\text{tot},q}}{dt} = \boldsymbol{\tau}_{\text{external},q}. \tag{486}$$

Internal exchanges must cancel globally.

37.8 Net Plate-Rotation State

The area- or mass-weighted net plate rotation is

$$\boldsymbol{\omega}_{\text{net},q} = \frac{\sum_i w_i \boldsymbol{\omega}_{i,q}}{\sum_i w_i}. \tag{487}$$

Its interpretation depends on the chosen reference frame and coupling architecture.

37.9 Closure Composite Score

$$\mathcal{J}_{\text{closure},q} = w_c \chi^2_{\text{circ},q} + w_J \chi^2_{J,q} + w_A \chi^2_{A,q} + w_L \chi^2_{L,q} + w_R \chi^2_{\text{net rot},q}. \tag{488}$$

37.10 Global-Closure Falsifier

Global-closure falsifier V-C4.
A model fails the global motion comparison if its predicted plate velocities violate closed plate circuits, triple-junction compatibility, surface-area accounting, shared-boundary action–reaction, or total angular-momentum accounting.

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38 Present-Day and Deep-Time Motion Evidence

38.1 Motion-Evidence Classes

The shared motion evidence includes:

Direct present-day velocity
Instrumental site velocities and strain rates.

Recent geological velocity
Displacements averaged over longer recent intervals.

Finite rotations
Plate and block rotation between reconstructed time slices.

Paleomagnetic constraints
Orientation, rotation, and latitude-related evidence.

Boundary age and production
Material-age patterns linked to opening, creation, or removal.

Terrane trajectories
Displacement, rotation, and transfer of material domains.

Structural offsets
Dated displacement across faults, sutures, or shear zones.

38.2 Present-Day Dataset

The present-day motion dataset is

$$\mathbf{D}_V^{\text{present}} = \{\mathbf{x}_j, \mathbf{v}_j, \dot{\boldsymbol{\epsilon}}_j, \boldsymbol{\Sigma}_j, \mathcal{R}_{f,j}, t_j\}\,. \tag{489}$$

38.3 Deep-Time Dataset

The deep-time dataset is

$$\mathbf{D}_V^{\text{deep}} = (\mathbf{R}_i(t_2, t_1), \mathbf{x}_T(t), \mathbf{M}_{\text{PM}}, a(\mathbf{x}), \mathbf{T}_{\text{boundary}}, \mathbf{D}_{\text{offset}})\,. \tag{490}$$

38.4 Temporal Averaging

An observation over interval Δt represents

$$\overline{\mathbf{v}}_{\Delta t} = \frac{1}{\Delta t}\int_{t_1}^{t_2} \mathbf{v}(t)\,dt. \tag{491}$$

Each model must be averaged over the same interval before comparison.

38.5 Present-Day Likelihood

$$\mathcal{L}_{V,\text{present},q} = p\left(\mathbf{D}_V^{\text{present}} \mid \widehat{\mathbf{D}}_{V,q}^{\text{present}}, \boldsymbol{\Sigma}_{V,\text{present}}\right). \tag{492}$$

38.6 Deep-Time Likelihood

$$\mathcal{L}_{V,\text{deep},q} = p\left(\mathbf{D}_V^{\text{deep}} \mid \widehat{\mathbf{D}}_{V,q}^{\text{deep}}, \boldsymbol{\Sigma}_{V,\text{deep}}\right). \tag{493}$$

38.7 Timescale Coherence

Define present and deep-time parameter posteriors

$$p_{\text{present}}\left(\boldsymbol{\Theta}_q\right) \tag{494}$$

and

$$p_{\text{deep}}\left(\boldsymbol{\Theta}_q\right). \tag{495}$$

Their overlap is

$$\mathcal{O}_{V,q} = \int \min\left[p_{\text{present}}\left(\boldsymbol{\Theta}_q\right), p_{\text{deep}}\left(\boldsymbol{\Theta}_q\right)\right]\, d\boldsymbol{\Theta}_q. \tag{496}$$

Low overlap indicates that present and deep-time motion require incompatible parameter states.

38.8 Motion-History Reconstruction

For time slices

$$t_0, t_1, \ldots, t_n, \tag{497}$$

the model predicts

$$\widehat{\mathbf{V}}_q(t_0), \widehat{\mathbf{V}}_q(t_1), \ldots, \widehat{\mathbf{V}}_q(t_n). \tag{498}$$

38.9 Chronological Motion Residual

$$\chi^2_{V,T,q} = \sum_n \left(\mathbf{D}_V^{\text{obs}}(t_n) - \widehat{\mathbf{D}}_{V,q}(t_n)\right)^{\mathsf{T}} \boldsymbol{\Sigma}_{V,n}^{-1} \left(\mathbf{D}_V^{\text{obs}}(t_n) - \widehat{\mathbf{D}}_{V,q}(t_n)\right). \tag{499}$$

38.10 No Double Counting

If finite rotations, paleomagnetic constraints, and reconstructed velocities derive from the same underlying data, their covariance must be included.

The likelihood cannot multiply dependent reconstructions as if they were independent confirmations.

38.11 Data-Type Holdout

Possible holdouts include:

- present-day direct velocities;
- one plate's finite rotations;
- one time interval;

- paleomagnetic constraints;
- one boundary-age field;
- or one terrane trajectory.

38.12 Timescale Falsifier

Motion-timescale falsifier V-C5.
A model fails temporal coherence if it fits present-day motion with parameters incompatible with finite rotations, paleomagnetic evidence, boundary ages, terrane trajectories, or other deep-time constraints.

39 Force, Torque, Power, and Dissipation

39.1 Force-Balance Residual

For plate i,

$$\mathbf{R}_{F,i,q} = M_i \dot{\mathbf{V}}_{i,q} - \mathbf{F}^{\mathrm{net}}_{i,q}. \tag{500}$$

The normalized residual is

$$r_{F,i,q} = \frac{\|\mathbf{R}_{F,i,q}\|}{F_{i,\mathrm{ref}}}. \tag{501}$$

39.2 Torque-Balance Residual

$$\mathbf{R}_{\tau,i,q} = \frac{d\mathbf{L}_{i,q}}{dt} - \boldsymbol{\tau}^{\mathrm{net}}_{i,q}. \tag{502}$$

The normalized residual is

$$r_{\tau,i,q} = \frac{\|\mathbf{R}_{\tau,i,q}\|}{\tau_{i,\mathrm{ref}}}. \tag{503}$$

39.3 Mechanical Power

For force component a,

$$\dot{W}^{\mathrm{trans}}_{i,a,q} = \mathbf{F}_{i,a,q} \cdot \mathbf{V}_{i,q}. \tag{504}$$

For torque component a,

$$\dot{W}^{\mathrm{rot}}_{i,a,q} = \boldsymbol{\tau}_{i,a,q} \cdot \boldsymbol{\omega}_{i,q}. \tag{505}$$

39.4 Total Power

$$\dot{W}_{i,q}^{\mathrm{net}} = \sum_a \left(\dot{W}_{i,a,q}^{\mathrm{trans}} + \dot{W}_{i,a,q}^{\mathrm{rot}} \right). \tag{506}$$

39.5 Kinetic-Energy Evolution

$$\frac{dE_{K,i,q}}{dt} = \dot{W}_{i,q}^{\mathrm{drive}} - \dot{E}_{i,q}^{\mathrm{diss}}. \tag{507}$$

39.6 Dissipation Components

The dissipation rate may include

$$\dot{E}_{i,q}^{\mathrm{diss}} = \dot{E}_{i,q}^{\mathrm{boundary}} + \dot{E}_{i,q}^{\mathrm{mantle}} + \dot{E}_{i,q}^{\mathrm{internal}} + \dot{E}_{i,q}^{\mathrm{bending}} + \dot{E}_{i,q}^{\mathrm{fracture}} + \dot{E}_{i,q}^{\mathrm{thermal}}. \tag{508}$$

39.7 Nonnegative Dissipation

For passive dissipative components,

$$\dot{E}_{i,q}^{\mathrm{diss}} \geq 0. \tag{509}$$

A model requiring persistent negative dissipation from a passive resistance law is physically invalid.

39.8 Power Sufficiency

Define

$$\Pi_{W,i,q} = \frac{\dot{W}_{i,q}^{\mathrm{drive}}}{\dot{E}_{i,q}^{\mathrm{diss}} + dE_{K,i,q}/dt + \epsilon}. \tag{510}$$

A consistent solution requires a ratio compatible with unity under the declared sign conventions and uncertainties.

39.9 Global Power

The global plate power is

$$\dot{W}_{P,q}^{\mathrm{global}} = \sum_i \dot{W}_{i,q}^{\mathrm{net}}. \tag{511}$$

The complete Earth-system power must include transfers with:

- mantle;
- core;
- atmosphere;
- oceans;

- gravitational potential;
- and event-derived reservoirs.

39.10 Energy-Reservoir Depletion

For energy reservoir a,

$$\frac{dE_{a,q}}{dt} = \dot{E}_{a,q}^{\text{source}} - \dot{E}_{a,q}^{\text{transfer}} - \dot{E}_{a,q}^{\text{loss}}. \tag{512}$$

The model must not draw indefinitely from a finite event-created reservoir without depletion.

39.11 Power-Direction Consistency

Positive power requires

$$\mathbf{F}_{i,a,q} \cdot \mathbf{V}_{i,q} > 0. \tag{513}$$

A force approximately orthogonal to motion may redirect the plate without materially increasing speed.

A force opposed to motion is resistive.

39.12 Physical-Budget Score

Define

$$\mathcal{J}_{\text{budget},q} = w_F \sum_i r_{F,i,q}^2 + w_\tau \sum_i r_{\tau,i,q}^2 + w_W \chi_{W,q}^2 + w_D \mathcal{P}_{\text{negative diss},q} + w_E \mathcal{P}_{\text{reservoir},q}. \tag{514}$$

39.13 Physical-Budget Falsifier

Motion-budget falsifier V-C6.
A model fails the physical motion comparison if its predicted velocities require unbalanced force, unbalanced torque, unavailable power, persistent negative dissipation, or energy extraction exceeding the capacity of its declared reservoirs.

40 Motion Counterfactuals and Causal Necessity

40.1 Purpose

Motion agreement does not establish the causal necessity of the mechanism used to describe it.

Each defining motion component must be removed in a controlled counterfactual.

40.2 Astro-Ballistic No-Event Counterfactual

For the astro-ballistic or hybrid model,

$$\mathcal{E} \to \varnothing, \qquad \mathbf{Q}_{\text{inherit}}^{\text{ABC}} \to \mathbf{0}. \tag{515}$$

The event-motion necessity score is

$$N_{V,E,q} = \mathcal{J}_{V,q,-E} - \mathcal{J}_{V,q}^{+}. \tag{516}$$

40.3 Impulse Ablation

Remove direct impulse while retaining other event-created states:

$$\mathbf{I}_E \to \mathbf{0}, \qquad \Delta\mathbf{L}_E \to \mathbf{0}. \tag{517}$$

The necessity is

$$N_{V,I} = \mathcal{J}_{V,-I} - \mathcal{J}_{V}^{+}. \tag{518}$$

40.4 Boundary-Memory Ablation

Replace event-created boundary mobility with background mobility:

$$\mathbf{K}_B^{\text{event}} \to \mathbf{K}_B^{0}. \tag{519}$$

40.5 Directional-Anisotropy Ablation

$$\mathbf{D}_{\text{event}} \to \operatorname{Iso}\left(\mathbf{D}_{\text{event}}\right). \tag{520}$$

40.6 Density and Buoyancy Ablation

$$\Delta\rho_{\text{event}} \to 0, \qquad \mathbf{F}_B^{\text{event}} \to \mathbf{0}. \tag{521}$$

40.7 Thermal and Phase Ablation

$$\Delta T_{\text{event}} \to 0, \qquad \Delta\phi_{\text{event}} \to 0. \tag{522}$$

40.8 Event-Modified Mantle-Flow Ablation

$$\Delta\mathbf{V}_m^{\text{event}} \to \mathbf{0}. \tag{523}$$

40.9 Plate-Tectonic Gravity Ablation

Where physically interpretable,

$$\mathbf{F}_g \to \mathbf{0}. \tag{524}$$

40.10 Plate-Tectonic Buoyancy Ablation

$$\mathbf{F}_B \to \mathbf{0}. \tag{525}$$

40.11 Mantle-Traction Ablation

$$\mathbf{F}_m \to \mathbf{0}, \qquad \boldsymbol{\tau}_m \to \mathbf{0}. \tag{526}$$

40.12 Boundary-Traction Ablation

$$\mathbf{F}_{\partial P} \to \mathbf{0}, \qquad \boldsymbol{\tau}_{\partial P} \to \mathbf{0}. \tag{527}$$

40.13 Inherited-Weakness Ablation

For either model family,

$$\mathbf{D}_0 \to \mathrm{Iso}\left(\mathbf{D}_0\right), \qquad \eta_0 \to \eta_{\mathrm{uniform}}. \tag{528}$$

40.14 Leave-One-Event-Out Motion Test

For event k,

$$\mathcal{E}_{-k} = \mathcal{E} \setminus \{\mathcal{E}_k\}. \tag{529}$$

The marginal contribution is

$$N_{V,k} = \mathcal{J}_{V,-k} - \mathcal{J}_{V,\mathrm{full}}. \tag{530}$$

40.15 Leave-One-Force-Class-Out Test

For force class a,

$$\mathcal{M}_{q,-F_a} \tag{531}$$

removes that class globally rather than only for plates where it performs poorly.

40.16 Hybrid Interaction Ablation

For the hybrid model,

$$\mathbf{Q}_{\mathrm{interaction}} \to \mathbf{0}. \tag{532}$$

The interaction necessity is

$$N_{V,\mathrm{int}} = \mathcal{J}_{V,\mathrm{HYB},-\mathrm{int}} - \mathcal{J}_{V,\mathrm{HYB}}. \tag{533}$$

40.17 Component Interaction

For components a and b,

$$N_{V,a\times b} = \mathcal{J}_{V,-a} + \mathcal{J}_{V,-b} - \mathcal{J}_{V,-a,-b} - \mathcal{J}_V^{+}. \tag{534}$$

40.18 Causal Contribution Fraction

For component c,

$$f_{V,c,q} = \frac{\mathcal{J}_{V,q,-c} - \mathcal{J}_{V,q}^{+}}{\mathcal{J}_{V,q,-\mathrm{all}} - \mathcal{J}_{V,q}^{+} + \epsilon}. \tag{535}$$

40.19 Motion Causal-Necessity Rule

A defining causal component is necessary only if:

$$N_{V,c,q} > N_{V,\mathrm{crit}} \tag{536}$$

across:

- plate directions;
- plate speeds;
- Euler poles;
- relative boundary motion;
- deep-time rotations;
- and held-out motion observations.

40.20 Motion-Necessity Falsifier

Motion causal-necessity falsifier V-C7.
If removal, isotropization, or randomization of a model's defining motion-generating component leaves the global velocity and rotation field materially unchanged, that component is not established as the primary cause of plate motion.

41 Motion Complexity and Predictive Tests

41.1 Motion-Specific Complexity Vector

For model q,

$$\mathbf{k}_{V,q} = (k_{\mathrm{IC}}, k_{\mathrm{event}}, k_{\mathrm{force}}, k_{\mathrm{torque}}, k_{\mathrm{resist}}, k_{\mathrm{coupling}}, k_{\mathrm{memory}}, k_{\mathrm{frame}}, k_{\mathrm{plate}}, k_{\mathrm{revision}}) . \tag{537}$$

41.2 Force-Field Complexity

For force field parameterization

$$\mathbf{F}_q = \mathbf{F}_q \left(\boldsymbol{\Theta}_{F,q} \right) , \tag{538}$$

define

$$k_{F,q} = \dim \left(\boldsymbol{\Theta}_{F,q} \right)_{\mathrm{effective}} . \tag{539}$$

41.3 Coupling Complexity

For mantle and boundary coupling tensors,

$$k_{K,q} = \mathrm{rank} \left(\mathbf{K}_{m,q}, \mathbf{K}_{B,q} \right)_{\mathrm{adjustable}} . \tag{540}$$

41.4 Memory Complexity

For velocity-memory kernel

$$\mathbf{K}_{V,q}(t, t_0), \tag{541}$$

define

$$k_{\mathrm{mem},q} = \text{number of independently adjustable amplitudes, timescales, directions, and exponents.} \tag{542}$$

41.5 Reference-Frame Complexity

If frame parameters are fitted,

$$k_{\mathcal{R},q} = \dim\left(\boldsymbol{\Theta}_{\mathcal{R},q}\right). \tag{543}$$

A frame chosen after inspection to optimize one model counts as selection flexibility.

41.6 Plate-Specific Parameter Penalty

Let

$$N_{\mathrm{plate,param},q} \tag{544}$$

be the number of independently plate-specific parameters.

Define

$$\mathcal{P}_{V,\mathrm{plate},q} = \lambda_{V,\mathrm{plate}} N_{\mathrm{plate,param},q}. \tag{545}$$

41.7 Motion Information Criterion

$$\begin{aligned}\mathrm{IC}_{V,q} = & -2\ln\mathcal{L}_{V,q} + \kappa k_{V,\mathrm{eff},q} + \mathcal{P}_{V,\mathrm{plate},q} \\ & + \mathcal{P}_{V,\mathrm{assign},q} + \mathcal{P}_{V,\mathrm{switch},q} + \mathcal{P}_{V,\mathrm{frame},q} + \mathcal{P}_{V,\mathrm{revision},q}.\end{aligned} \tag{546}$$

41.8 Motion Holdouts

The comparison should include:

VH1. withheld plates;

VH2. withheld present-day velocity sites;

VH3. withheld boundaries;

VH4. withheld Euler poles;

VH5. withheld time intervals;

VH6. withheld finite rotations;

VH7. withheld paleomagnetic constraints;

VH8. withheld terrane paths;

VH9. and withheld acceleration or direction-change episodes.

41.9 Site-Velocity Predictive Score

For held-out site j,

$$S^{\text{site}}_{V,j,q} = -\frac{1}{2}\left(\mathbf{v}^{\text{obs}}_j - \widehat{\mathbf{v}}_{j,q}\right)^{\mathsf{T}} \boldsymbol{\Sigma}_j^{-1}\left(\mathbf{v}^{\text{obs}}_j - \widehat{\mathbf{v}}_{j,q}\right). \tag{547}$$

41.10 Euler-Pole Predictive Score

$$S^{\text{test}}_{\omega,i,q} = -\frac{1}{2}\left(\boldsymbol{\omega}^{\text{obs}}_i - \widehat{\boldsymbol{\omega}}_{i,q}\right)^{\mathsf{T}} \boldsymbol{\Sigma}_{\omega,i}^{-1}\left(\boldsymbol{\omega}^{\text{obs}}_i - \widehat{\boldsymbol{\omega}}_{i,q}\right). \tag{548}$$

41.11 Finite-Rotation Predictive Score

$$S^{\text{test}}_{R,i,q} = -\frac{1}{2}\frac{\left(\Delta\theta_{R,i,q}\right)^2}{\sigma^2_{R,i}}. \tag{549}$$

41.12 Direction-Change Predictive Score

$$S^{\text{test}}_{\Delta\theta,i,q} = -\frac{1}{2}\frac{\left(\Delta\theta^{\text{obs}}_i - \Delta\theta^{\text{pred}}_{i,q}\right)^2}{\sigma^2_{\Delta\theta,i}}. \tag{550}$$

41.13 Negative Motion Predictions

Each model must identify:

- plates predicted not to accelerate after a proposed event;
- boundaries predicted not to reverse;
- regions predicted to remain internally rigid;
- plates predicted to lack event-direction inheritance;
- and time intervals predicted to lack major motion changes.

False positive changes count against the model.

41.14 Randomized Motion Nulls

For the astro-ballistic family, randomize:

- event positions;
- event directions;
- event ages;
- plate-event assignments;
- or inheritance orientations.

For inherited-state models, shuffle initial anisotropy or boundary mobility while preserving global distributions.

41.15 Motion Null Probability

$$p_{V,q,\text{null}} = \frac{1 + \sum_{r=1}^{N_R} \mathbf{1}\left[\mathcal{J}_{V,q}^{(r)} \leq \mathcal{J}_{V,q}^{\text{obs}}\right]}{N_R + 1}. \tag{551}$$

41.16 Predictive Superiority

Model i exceeds model j in held-out motion prediction when

$$S_{V,\text{test},i} - S_{V,\text{test},j} > \Delta S_{V,\text{crit}} \tag{552}$$

with declared uncertainty.

42 Plate-Motion Replacement Viability and Falsification

42.1 Motion-Comparison Parameter Set

For model q,

$$\boldsymbol{\Theta}_{V,q}^{\text{IV}} = \left(\mathbf{Q}_{0,q}, \mathcal{E}_q, \mathcal{B}_q, \mathbf{I}_P, \mathbf{F}_q, \boldsymbol{\tau}_q, \mathbf{K}_{m,q}, \mathbf{K}_{B,q}, \mathbf{K}_{V,q}, \mathbf{R}_q, \boldsymbol{\Theta}_{\mathcal{R},q}\right). \tag{553}$$

42.2 Motion-Model Viable Set

Define

$$\mathcal{V}_{V,q}^{\text{IV}} = \left\{ \boldsymbol{\Theta}_{V,q}^{\text{IV}} : \begin{array}{l} \text{mechanical eligibility satisfied,} \\ \text{mass and inertia compatible,} \\ \text{force balance satisfied,} \\ \text{torque balance satisfied,} \\ \text{power budget satisfied,} \\ \text{dissipation admissible,} \\ \text{Euler poles compatible,} \\ \text{absolute velocities compatible,} \\ \text{relative velocities compatible,} \\ \text{speed hierarchy compatible,} \\ \text{acceleration history compatible,} \\ \text{plate circuits close,} \\ \text{junctions compatible,} \\ \text{present-day evidence compatible,} \\ \text{deep-time evidence compatible,} \\ \text{defining cause necessary,} \\ \text{complexity controlled,} \\ \text{held-out prediction successful} \end{array} \right\}. \tag{554}$$

42.3 Astro-Ballistic Motion-Replacement Condition

The astro-ballistic motion model is a replacement candidate only if

$$\mathcal{V}_{V,\mathrm{ABC}}^{\mathrm{IV}} \neq \varnothing \tag{555}$$

and

$$\mathrm{Score}_V\left(\mathcal{M}_{\mathrm{ABC}}\right) < \mathrm{Score}_V\left(\mathcal{M}_{\mathrm{PT}}\right) - \delta_V \tag{556}$$

after physical, predictive, and complexity corrections.

42.4 Hybrid Motion Preference

The hybrid is preferred when

$$\mathrm{Score}_V\left(\mathcal{M}_{\mathrm{HYB}}\right) < \min\left[\mathrm{Score}_V\left(\mathcal{M}_{\mathrm{PT}}\right), \mathrm{Score}_V\left(\mathcal{M}_{\mathrm{ABC}}\right)\right] - \delta_V \tag{557}$$

and event-derived inheritance, later geodynamic forcing, and their interaction remain necessary.

42.5 Motion Equivalence

Models are motion-equivalent when

$$\left|\mathrm{Score}_{V,i} - \mathrm{Score}_{V,j}\right| \leq \delta_{V,\mathrm{equiv}}. \tag{558}$$

42.6 Motion-Replacement Falsification Matrix

Table 3: Paper-IV plate-motion replacement falsification matrix.

ID	Comparison claim	Falsifying result	Consequence
IV-V01	Motion eligibility	The astro-ballistic model requires Paper-II or Paper-III states already excluded.	Astro-ballistic motion model is ineligible.
IV-V02	Ancient material mapping	Event momentum is assigned using modern plate outlines without valid lineage reconstruction.	Reject event-to-plate motion attribution.
IV-V03	Impulse partition	Event momentum and angular momentum do not close across plates, mantle, deformation, and escape.	Reject event motion handoff.

ID	Comparison claim	Falsifying result	Consequence
IV-V04	Impulse persistence	Present speeds require an unattenuated ancient impulse without later power.	Reject sustained-motion mechanism.
IV-V05	Plate mass and inertia	Required translations or rotations are incompatible with reconstructed plate mass and inertia.	Reject motion response.
IV-V06	Force balance	Predicted acceleration does not match modeled net force.	Reject plate dynamics.
IV-V07	Torque balance	Predicted angular evolution does not match modeled net torque.	Reject plate rotation.
IV-V08	Power supply	Available driving power is insufficient to balance motion and dissipation.	Reject motion maintenance.
IV-V09	Dissipation	The model requires persistent negative dissipation or an unmodeled energy source.	Reject physical motion solution.
IV-V10	Euler-pole generation	Observed Euler poles must be inserted independently rather than generated.	Reject causal pole prediction.
IV-V11	Euler-pole direction	Predicted Euler-pole directions systematically fail.	Reject rotational-direction prediction.
IV-V12	Angular speed	Predicted angular speeds systematically fail.	Reject rotational-magnitude prediction.
IV-V13	Euler-pole drift	Predicted pole migration conflicts with finite-rotation history.	Reject rotational chronology.
IV-V14	Absolute velocity	Predicted site velocities fail independent present-day observations.	Reject present-day absolute-motion prediction.
IV-V15	Relative velocity	Predicted shared-boundary motion fails.	Reject relative plate-motion prediction.
IV-V16	Motion direction	Predicted plate directions systematically disagree with observations.	Reject directional motion claim.
IV-V17	Plate speed	Predicted plate-speed magnitudes systematically fail.	Reject speed prediction.

ID	Comparison claim	Falsifying result	Consequence
IV-V18	Speed hierarchy	Observed speed ordering requires independent plate-specific tuning.	Reject shared speed law.
IV-V19	Acceleration history	The model fails independently constrained acceleration or deceleration.	Reject motion-history prediction.
IV-V20	Direction changes	The model fails the timing or magnitude of plate-direction changes.	Reject redirection mechanism.
IV-V21	Event-linked changes	Proposed events do not produce their predicted plate-specific motion responses.	Reject event-motion assignment.
IV-V22	Plate circuits	Relative Euler vectors fail closed-circuit consistency.	Reject global velocity field.
IV-V23	Triple junctions	Predicted relative velocities are incompatible at junctions.	Reject junction kinematics.
IV-V24	Surface-area balance	Creation, removal, storage, and deformation fail global area accounting.	Reject global motion reconstruction.
IV-V25	Angular-momentum balance	Internal exchanges do not close or require unaccounted external torque.	Reject global rotational solution.
IV-V26	Present versus deep time	Present-day and deep-time motion require incompatible parameter states.	Reject temporal coherence.
IV-V27	Finite rotations	Predicted plate and block rotations fail.	Reject deep-time kinematics.
IV-V28	Paleomagnetic evidence	Predicted rotations or latitude histories conflict with independent constraints.	Reject paleogeographic motion history.
IV-V29	Terrane trajectories	Predicted terrane displacement and rotation fail material continuity.	Reject regional motion history.
IV-V30	Reference-frame robustness	Model preference disappears under defensible reference-frame changes.	Reject frame-robust superiority.
IV-V31	Astro-ballistic necessity	Removing event inheritance leaves the global motion field unchanged.	Reject primary event causation.

ID	Comparison claim	Falsifying result	Consequence
IV-V32	Plate-Tectonic necessity	Removing the comparison model's defining force architecture leaves motion unchanged.	Reject claimed primary role of those components.
IV-V33	Hybrid necessity	The hybrid wins while one parent contribution or interaction is unnecessary.	Reject joint causal attribution.
IV-V34	Leave-one-event-out	Claimed major events have negligible marginal motion contribution.	Reject those events as motion organizers.
IV-V35	Randomized-event null	Randomized event catalogs reproduce the motion field equally well.	Reject special event-sequence significance.
IV-V36	Initial-state null	Shuffled inherited structures reproduce the motion field equally well.	Reject specific inherited-direction significance.
IV-V37	Motion complexity	The apparent advantage disappears after force, coupling, memory, plate-specific, frame, and revision costs are counted.	Reject motion replacement preference.
IV-V38	Held-out plates	The model cannot predict plates omitted from calibration.	Reject shared global motion law.
IV-V39	Held-out time intervals	The model fails motion evolution outside the calibration period.	Reject temporal predictive generality.
IV-V40	Held-out data types	The model fails independent motion evidence not used in fitting.	Reject cross-observational prediction.
IV-V41	Replication	Independent teams cannot reproduce the comparative result.	Reject confirmatory motion preference.
IV-V42	Motion equivalence	Model scores remain within the equivalence interval.	Report motion causal non-resolution.
IV-V43	Plate-Tectonic superiority	The strongest Plate-Tectonic model predicts motion better after penalties.	Reject astro-ballistic motion replacement.
IV-V44	Astro-ballistic superiority	The astro-ballistic model does not achieve a clear penalized advantage.	Primary motion replacement is unsupported.

ID	Comparison claim	Falsifying result	Consequence
IV-V45	Hybrid superiority	The hybrid does not outperform both parents with all defining components necessary.	Hybrid motion preference is unsupported.
IV-V46	Complete motion viability	The astro-ballistic motion viable set is empty.	Motion component of replacement thesis fails.

42.7 Motion Outcome Classes

The motion comparison permits:

Motion Outcome A: Plate-Tectonic preference
The Plate-Tectonic family provides the strongest penalized motion prediction.

Motion Outcome B: Astro-ballistic preference
The event-derived family provides the strongest penalized motion prediction.

Motion Outcome C: Hybrid preference
Event-derived inheritance and later geodynamic forcing are jointly necessary.

Motion Outcome D: Directional event contribution
Events materially redirect or guide selected plates but do not explain the global speed-and-force system.

Motion Outcome E: Regional event contribution
Selected plates or boundaries retain event-derived support without global replacement.

Motion Outcome F: Equivalence
Available motion evidence does not distinguish the model families.

Motion Outcome G: Shared failure
None of the tested models adequately predicts the complete motion domain.

42.8 Motion-Replacement Decision Rule

Plate-motion replacement decision rule.
Astro-Ballistic Chronostratigraphic Sequencing can replace Plate Tectonics as the primary explanation of global plate motion only if one mechanically admissible and chronologically ordered event sequence generates the observed Euler poles, plate directions, relative speeds, acceleration histories, boundary motions, plate circuits, finite rotations, and deep-time displacements from conserved impulse, force, torque, power, and material-state evolution.
The comparison must distinguish an initiating impulse from the persistent work required to maintain motion.
Observed Euler poles and plate velocities may evaluate the model; they may not be inserted as the causal solution.

43 Motion-Comparison Synthesis

This motion-comparison synthesis records:

1. the shared plate-motion observation state;
2. Plate-Tectonic, astro-ballistic, and hybrid motion-mechanism classes;
3. complete motion-origin records;
4. the prohibition against independent plate-by-plate force fitting;
5. the distinction between impulse and sustained force;
6. linear and angular impulse response;
7. post-impulse relaxation and maintenance equations;
8. impulse-memory and directional-memory fractions;
9. impulse and maintenance sufficiency ratios;
10. the prohibition against treating ancient impulse as perpetual power;
11. complete gravitational, buoyant, mantle, boundary, topographic, flexural, and resistive force decomposition;
12. action–reaction and force-direction tests;
13. event-modified force fractions;
14. plate inertia and Euler-vector dynamics;
15. Euler-pole direction, angular-speed, drift, and finite-rotation residuals;
16. rigid-motion adequacy tests;
17. the prohibition against fitted Euler poles receiving causal credit;
18. absolute and relative velocity comparison;
19. common reference-frame transformation and frame-robust scores;
20. plate direction and speed residuals;
21. acceleration, deceleration, turning, and change-point tests;
22. event-linked speed and direction-change predictions;
23. observed and predicted plate-speed rankings;
24. shared force-to-speed laws;
25. plate-specific flexibility penalties;
26. leave-one-plate-out prediction;
27. plate-circuit and triple-junction closure;
28. global surface-area and angular-momentum accounting;

29. present-day and deep-time motion likelihoods;
30. temporal averaging and timescale coherence;
31. force, torque, power, dissipation, and energy-reservoir accounting;
32. event, impulse, boundary-memory, anisotropy, density, thermal, mantle-flow, gravity, buoyancy, and traction ablations;
33. leave-one-event-out and leave-one-force-class-out tests;
34. hybrid interaction necessity;
35. motion-specific effective complexity;
36. held-out site, plate, Euler-pole, finite-rotation, and direction-change predictions;
37. randomized event and inherited-state motion nulls;
38. the complete Paper-IV motion viable set;
39. the plate-motion replacement falsification matrix; and
40. explicit Plate-Tectonic, astro-ballistic, hybrid, directional, regional, equivalence, and shared-failure outcomes.

The following sections compare the major surface and deep-Earth explanatory domains directly:

- competing mountain-building mechanisms;
- trench, descent, bending, and underthrusting mechanisms;
- ridge, rift, and new-material-production mechanisms;
- basin formation, subsidence, and inversion;
- plateau uplift and crustal-thickening mechanisms;
- volcanic-province and melt-path mechanisms;
- terrane transfer, sutures, and continental assembly;
- gravity and geoid predictions;
- seismic-velocity, attenuation, and anisotropy predictions;
- magnetic and heat-flow predictions;
- surface and deep-structure counterfactuals;
- structure-specific complexity and predictive tests;
- and the complete structural-and-geophysical replacement matrix.

44 Competing Mountain-Building Mechanisms

44.1 Mountains as Shared Observations

Mountain systems are shared evidence.

For orogen m, define the observed state

$$\mathbf{D}^{\text{obs}}_{O,m} = (\mathcal{O}_m, z_m, H_{c,m}, H_{\ell,m}, \boldsymbol{\epsilon}_m, \boldsymbol{\sigma}_m, \mathbf{A}_m, \mathcal{C}_m, \mathbf{T}_{O,m}) \,, \tag{559}$$

where:

$$\mathcal{O}_m = \text{mapped orogenic domain,} \tag{560}$$
$$z_m = \text{elevation and relief,} \tag{561}$$
$$H_{c,m} = \text{crustal thickness,} \tag{562}$$
$$H_{\ell,m} = \text{lithospheric thickness,} \tag{563}$$
$$\boldsymbol{\epsilon}_m = \text{deformation history,} \tag{564}$$
$$\boldsymbol{\sigma}_m = \text{stress history,} \tag{565}$$
$$\mathbf{A}_m = \text{anisotropy and orientation,} \tag{566}$$
$$\mathcal{C}_m = \text{composition and terrane structure,} \tag{567}$$
$$\mathbf{T}_{O,m} = \text{orogenic chronology.} \tag{568}$$

44.2 Plate-Tectonic Mountain-Building Classes

The Plate-Tectonic comparison family may generate mountains through:

PT-O1. plate convergence;

PT-O2. continental collision;

PT-O3. underthrusting;

PT-O4. crustal shortening;

PT-O5. lithospheric thickening;

PT-O6. terrane accretion;

PT-O7. magmatic addition;

PT-O8. dynamic support;

PT-O9. flexural response;

PT-O10. lower-crustal flow;

PT-O11. isostatic rebound;

PT-O12. and reactivation of inherited structures.

44.3 Astro-Ballistic Mountain-Building Classes

The astro-ballistic family may contribute through:

ABC-O1. event-derived compression;

ABC-O2. event-created displacement;

ABC-O3. residual-stress localization;

ABC-O4. damage-guided later convergence;

ABC-O5. event-created density anomalies;

ABC-O6. event-created thermal or phase anomalies;

ABC-O7. midpoint or off-axis pressure localization;

ABC-O8. event-generated terrane displacement;

ABC-O9. later-event reinforcement;

ABC-O10. and inherited boundary amplification.

44.4 Hybrid Orogenic Model

The hybrid orogen model is

$$\widehat{\mathbf{Q}}_{O,\mathrm{HYB}} = \mathcal{U}_O \left[\mathbf{Q}_{O,0}^{\mathrm{event}}, \mathbf{F}_{\mathrm{conv}}, \mathbf{F}_g, \mathbf{F}_m, \mathbf{Q}_{\mathrm{eros}}, t \right]. \tag{569}$$

The hybrid gains causal support only if the event-created initial state and later geodynamic amplification are both necessary.

44.5 Mountain-Location Comparison

For model q, define predicted orogenic domain

$$\widehat{\mathcal{O}}_{m,q}. \tag{570}$$

The intersection-over-union score is

$$\mathrm{IoU}_{O,m,q} = \frac{\mathrm{Area}\left(\widehat{\mathcal{O}}_{m,q} \cap \mathcal{O}_m^{\mathrm{obs}}\right)}{\mathrm{Area}\left(\widehat{\mathcal{O}}_{m,q} \cup \mathcal{O}_m^{\mathrm{obs}}\right)}. \tag{571}$$

The centroid residual is

$$d_{O,m,q} = d_{\mathcal{S}} \left(\mathbf{x}_{O,m,q}^{\mathrm{pred}}, \mathbf{x}_{O,m}^{\mathrm{obs}} \right). \tag{572}$$

44.6 Mountain-Orientation Comparison

For observed and predicted mountain-axis tangents,

$$A_{\gamma,O,m,q} = \left| \widehat{\mathbf{t}}^{\text{obs}}_{O,m} \cdot \widehat{\mathbf{t}}^{\text{pred}}_{O,m,q} \right|. \tag{573}$$

44.7 Shortening Comparison

The predicted cumulative shortening is

$$\widehat{\mathcal{S}}_{\text{short},m,q} = \int \dot{\epsilon}_{\text{comp},m,q}\, dt. \tag{574}$$

The residual is

$$\epsilon_{\text{short},m,q} = \mathcal{S}^{\text{obs}}_{\text{short},m} - \widehat{\mathcal{S}}_{\text{short},m,q}. \tag{575}$$

44.8 Crustal-Thickness Comparison

$$\epsilon_{H_c,m,q} = H^{\text{obs}}_{c,m} - H^{\text{pred}}_{c,m,q}. \tag{576}$$

44.9 Elevation and Relief Comparison

For elevation field,

$$\chi^2_{z,O,q} = \sum_m \left(\mathbf{z}^{\text{obs}}_m - \mathbf{z}^{\text{pred}}_{m,q} \right)^{\mathsf{T}} \mathbf{\Sigma}^{-1}_{z,m} \left(\mathbf{z}^{\text{obs}}_m - \mathbf{z}^{\text{pred}}_{m,q} \right). \tag{577}$$

44.10 Orogenic Chronology

Each model predicts

$$\widehat{\mathbf{T}}_{O,m,q} = (t_{\text{init}}, t_{\text{short}}, t_{\text{met}}, t_{\text{uplift}}, t_{\text{exhum}}, t_{\text{react}})_{m,q}. \tag{578}$$

The chronology residual is

$$\chi^2_{T,O,m,q} = \left(\mathbf{T}^{\text{obs}}_{O,m} - \widehat{\mathbf{T}}_{O,m,q} \right)^{\mathsf{T}} \mathbf{\Sigma}^{-1}_{T,O,m} \left(\mathbf{T}^{\text{obs}}_{O,m} - \widehat{\mathbf{T}}_{O,m,q} \right). \tag{579}$$

44.11 Orogenic Power and Work

The work contributing to mountain growth is

$$W_{O,m,q} = \int_{t_1}^{t_2} \int_{\mathcal{O}_m} \boldsymbol{\sigma}_q : \dot{\boldsymbol{\epsilon}}_q \, dV\, dt. \tag{580}$$

The model must account for partition into:

- elastic storage;
- permanent deformation;
- crustal thickening;
- gravitational-potential increase;
- metamorphism;
- heating;
- fracture;
- and erosion.

44.12 Mountain Counterfactual

For model q, define

$$N_{O,c,q} = \mathcal{J}_{O,q,-c} - \mathcal{J}^{+}_{O,q}, \tag{581}$$

where component c may be:

- event inheritance;
- convergence;
- collision;
- underthrusting;
- dynamic support;
- inherited weakness;
- or mantle coupling.

44.13 Mountain Comparison Score

Define

$$\begin{aligned}\mathcal{J}_{O,q} = w_{\mathrm{loc}} \sum_{m} (1 - \mathrm{IoU}_{O,m,q}) + w_d \sum_{m} \widetilde{d}_{O,m,q} \\ + w_\gamma \sum_{m} (1 - A_{\gamma,O,m,q}) + w_s \chi^2_{\mathrm{short},q} + w_H \chi^2_{H_c,O,q} \\ + w_z \chi^2_{z,O,q} + w_T \chi^2_{T,O,q} + w_W \mathcal{P}_{W,O,q}.\end{aligned} \tag{582}$$

44.14 Mountain-Building Falsifier

Mountain-building comparison falsifier S-C1.
A model fails the mountain comparison if it cannot jointly predict orogenic location, orientation, shortening, crustal thickness, elevation, chronology, and mechanical work from its declared boundary and motion system.

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45 Trench, Descent, Bending, and Underthrusting Comparison

45.1 Observed Trench State

For trench r, define

$$\mathbf{D}_{T,r}^{\text{obs}} = \left(\Gamma_r, z_r, W_r, \kappa_r, \gamma_r, \mathbf{v}_r^{\text{rel}}, \mathbf{Q}_r^{\text{deep}}, \mathbf{T}_r\right), \tag{583}$$

where:

$$\Gamma_r = \text{trench axis}, \tag{584}$$

$$z_r = \text{depth}, \tag{585}$$

$$W_r = \text{width}, \tag{586}$$

$$\kappa_r = \text{curvature}, \tag{587}$$

$$\mathbf{Q}_r^{\text{deep}} = \text{deep material and seismic state}. \tag{588}$$

45.2 Plate-Tectonic Trench Classes

The Plate-Tectonic family may generate trenches through:

PT-T1. lithospheric descent;

PT-T2. underthrusting;

PT-T3. plate bending;

PT-T4. flexural response;

PT-T5. negative buoyancy;

PT-T6. boundary convergence;

PT-T7. rollback or retreat;

PT-T8. sediment loading;

PT-T9. and inherited-margin reactivation.

45.3 Astro-Ballistic Trench Classes

The astro-ballistic family may contribute through:

ABC-T1. terminal excavation;

ABC-T2. terminal collapse;

ABC-T3. terminal damage;

ABC-T4. event-created density anomalies;

ABC-T5. event-created descent corridors;

ABC-T6. impact-generated displacement;

ABC-T7. event-guided later underthrusting;

ABC-T8. later-event reactivation;

ABC-T9. and inherited curvature or segmentation.

45.4 Complete Trench Decomposition

For model q,

$$z_{T,q} = z_{\text{exc},q} + z_{\text{bend},q} + z_{\text{desc},q} + z_{\text{under},q} + z_{\text{dyn},q} + z_{\text{load},q} + z_{\text{other},q}. \tag{589}$$

45.5 Trench-Axis Comparison

For predicted axis $\widehat{\Gamma}_{r,q}$,

$$d_{\Gamma,r,q} = d_{\text{ASD}}\left(\Gamma_r^{\text{obs}}, \widehat{\Gamma}_{r,q}\right). \tag{590}$$

45.6 Depth and Width Residuals

$$\epsilon_{z,T,r,q} = z_r^{\text{obs}} - z_{r,q}^{\text{pred}}, \tag{591}$$

$$\epsilon_{W,T,r,q} = W_r^{\text{obs}} - W_{r,q}^{\text{pred}}. \tag{592}$$

45.7 Curvature Comparison

$$\epsilon_{\kappa,T,r,q} = \kappa_r^{\text{obs}} - \kappa_{r,q}^{\text{pred}}. \tag{593}$$

45.8 Deep-Descent Comparison

For deep structure field $\mathbf{Q}_r^{\text{deep}}$,

$$\chi^2_{T,\text{deep},q} = \sum_r \left(\mathbf{Q}_r^{\text{deep,obs}} - \mathbf{Q}_{r,q}^{\text{deep,pred}}\right)^{\mathsf{T}} \mathbf{\Sigma}_{T,r}^{-1} \left(\mathbf{Q}_r^{\text{deep,obs}} - \mathbf{Q}_{r,q}^{\text{deep,pred}}\right). \tag{594}$$

45.9 Descent Mass Flux

For model q,

$$\dot{M}_{\mathrm{desc},r,q} = \int_{\mathcal{S}_{r,q}} \rho_q v_{n,q}^{+} \, dA. \tag{595}$$

45.10 Bending Energy

$$E_{\mathrm{bend},r,q} = \frac{1}{2} \int_{\mathcal{A}_r} D_{f,q} \kappa_{b,q}^2 \, dA. \tag{596}$$

45.11 Underthrust Distance

$$D_{\mathrm{under},r,q} = \int v_{\mathrm{under},r,q} \, dt. \tag{597}$$

45.12 Trench Chronology

Each model predicts

$$\widehat{\mathbf{T}}_{T,r,q} = (t_{\mathrm{precursor}}, t_{\mathrm{init}}, t_{\mathrm{deep}}, t_{\mathrm{bend}}, t_{\mathrm{react}}, t_{\mathrm{modern}}) \, . \tag{598}$$

45.13 Mechanism Attribution

Define contribution fractions

$$f_{\mathrm{exc},r,q} + f_{\mathrm{bend},r,q} + f_{\mathrm{desc},r,q} + f_{\mathrm{under},r,q} + f_{\mathrm{dyn},r,q} = 1. \tag{599}$$

The fractions must derive from forward-model ablation.

45.14 Trench Comparison Score

$$\begin{aligned} \mathcal{J}_{T,q} = {} & w_\Gamma \chi^2_{\Gamma,T,q} + w_z \chi^2_{z,T,q} + w_W \chi^2_{W,T,q} + w_\kappa \chi^2_{\kappa,T,q} \\ & + w_v \chi^2_{v,T,q} + w_D \chi^2_{T,\mathrm{deep},q} + w_M \chi^2_{\dot{M},T,q} + w_T \chi^2_{T,\mathrm{chron},q} \\ & + w_E \mathcal{P}_{E,T,q}. \end{aligned} \tag{600}$$

45.15 Trench Falsifier

Trench comparison falsifier S-C2.
A model fails the trench comparison if it reproduces surface trench geometry but cannot predict the required descent, underthrusting, bending, mass flux, energy, chronology, and deep geophysical structure.

46 Ridge, Rift, and New-Material-Production Comparison

46.1 Observed Ridge and Rift State

For ridge or rift s, define

$$\mathbf{D}_{R,s}^{\text{obs}} = (\Gamma_s, \gamma_s, W_s, v_{\text{open},s}, H_{\ell,s}, \chi_{m,s}, a_s(\mathbf{x}), \mathcal{S}_s, \mathbf{T}_{R,s}) , \tag{601}$$

where:

$$\Gamma_s = \text{axis geometry}, \tag{602}$$

$$v_{\text{open},s} = \text{opening rate}, \tag{603}$$

$$\chi_{m,s} = \text{melt fraction or production state}, \tag{604}$$

$$a_s(\mathbf{x}) = \text{material-age field}, \tag{605}$$

$$\mathcal{S}_s = \text{segmentation and offset structure}. \tag{606}$$

46.2 Plate-Tectonic Ridge Classes

The Plate-Tectonic family may generate ridges and rifts through:

PT-R1. plate separation;

PT-R2. lithospheric extension;

PT-R3. decompression melting;

PT-R4. mantle upwelling;

PT-R5. thermal thinning;

PT-R6. inherited weakness;

PT-R7. propagating rifts;

PT-R8. transform segmentation;

PT-R9. and interaction with regional stress.

46.3 Astro-Ballistic Ridge Classes

The astro-ballistic family may contribute through:

ABC-R1. event-created extensional fractures;

ABC-R2. event-created damaged corridors;

ABC-R3. event-derived displacement;

ABC-R4. thermal weakening;

ABC-R5. decompression along event paths;

ABC-R6. event-guided mantle upwelling;

ABC-R7. event-created segmentation;

ABC-R8. and later reactivation of inherited corridors.

46.4 Ridge-Axis Comparison

For predicted axis $\widehat{\Gamma}_{s,q}$,

$$d_{\Gamma,R,s,q} = d_{\mathrm{ASD}}\left(\Gamma_s^{\mathrm{obs}}, \widehat{\Gamma}_{s,q}\right). \tag{607}$$

46.5 Opening-Rate Comparison

$$\epsilon_{\mathrm{open},s,q} = v_{\mathrm{open},s}^{\mathrm{obs}} - v_{\mathrm{open},s,q}^{\mathrm{pred}}. \tag{608}$$

46.6 New-Area Production

$$\dot{A}_{\mathrm{new},s,q} = \int_{\Gamma_{s,q}} v_{\mathrm{open},s,q}\, d\ell. \tag{609}$$

The global production rate is

$$\dot{A}_{\mathrm{new},q}^{\mathrm{global}} = \sum_s \dot{A}_{\mathrm{new},s,q}. \tag{610}$$

46.7 Material-Age Field

The predicted material age is

$$\widehat{a}_{s,q}(\mathbf{x}) = t_{\mathrm{now}} - t_{\mathrm{form},s,q}(\mathbf{x}). \tag{611}$$

The age-field residual is

$$\chi^2_{a,R,q} = \sum_s \left(\mathbf{a}_s^{\mathrm{obs}} - \widehat{\mathbf{a}}_{s,q}\right)^{\mathsf{T}} \mathbf{\Sigma}_{a,s}^{-1} \left(\mathbf{a}_s^{\mathrm{obs}} - \widehat{\mathbf{a}}_{s,q}\right). \tag{612}$$

46.8 Ridge-Flank Symmetry

For opposite flanks,

$$\Delta a_{s,q}(x) = a_{+,s,q}(x) - a_{-,s,q}(x). \tag{613}$$

The model must predict whether the ridge is:

- symmetric;
- asymmetric;

- migrating;
- propagating;
- segmented;
- offset;
- or terminating.

46.9 Melt-Production Comparison

$$\dot{M}_{m,s,q} = \int_{\mathcal{V}_{m,s}} \rho_q \frac{D\chi_{m,q}}{Dt}\, dV. \tag{614}$$

46.10 Ridge Heat and Composition

Each model predicts:

- thermal anomaly;
- melt volume;
- melt depth;
- composition;
- crustal addition;
- and heat-flow expression.

46.11 Ridge Comparison Score

$$\begin{aligned}\mathcal{J}_{R,q} = {} & w_\Gamma \chi^2_{\Gamma,R,q} + w_\gamma \chi^2_{\gamma,R,q} + w_v \chi^2_{\text{open},q} + w_A \chi^2_{\dot{A},q} \\ & + w_a \chi^2_{a,R,q} + w_m \chi^2_{\dot{M},R,q} + w_S \chi^2_{\text{seg},R,q} + w_T \chi^2_{T,R,q}.\end{aligned} \tag{615}$$

46.12 Ridge Falsifier

Ridge-and-rift comparison falsifier S-C3.
A model fails the ridge comparison if it cannot predict axis location, opening rate, age-distance structure, segmentation, melt production, new-material creation, and chronology from its boundary and motion solution.

47 Basin Formation, Subsidence, and Inversion Comparison

47.1 Observed Basin State

For basin b, define

$$\mathbf{D}^{\text{obs}}_{BA,b} = (\mathcal{B}_b, A_b, V_b, H_{s,b}, H_{c,b}, S_b(t), T_b(t), \mathbf{A}_b, \mathbf{T}_{BA,b})\,. \tag{616}$$

47.2 Plate-Tectonic Basin Classes

The Plate-Tectonic family may generate basins through:

PT-BA1. lithospheric extension;

PT-BA2. thermal subsidence;

PT-BA3. flexure;

PT-BA4. sediment loading;

PT-BA5. strike-slip deformation;

PT-BA6. foreland loading;

PT-BA7. dynamic subsidence;

PT-BA8. crustal thinning;

PT-BA9. and later inversion.

47.3 Astro-Ballistic Basin Classes

The astro-ballistic family may contribute through:

ABC-BA1. excavation;

ABC-BA2. collapse;

ABC-BA3. event-created extension;

ABC-BA4. damaged crust;

ABC-BA5. density anomalies;

ABC-BA6. thermal anomalies;

ABC-BA7. displacement discontinuities;

ABC-BA8. path-guided subsidence;

ABC-BA9. and later-event inversion.

47.4 Complete Subsidence Decomposition

For model q,

$$\begin{aligned} S_{b,q}(t) = {} & S_{\text{event},b,q} + S_{\text{ext},b,q} + S_{\text{thermal},b,q} + S_{\text{flex},b,q} \\ & + S_{\text{load},b,q} + S_{\text{dynamic},b,q} + S_{\text{comp},b,q} + S_{\text{boundary},b,q}. \end{aligned} \tag{617}$$

47.5 Basin Geometry Comparison

For predicted basin domain $\widehat{\mathcal{B}}_{b,q}$,

$$\mathrm{IoU}_{BA,b,q} = \frac{\mathrm{Area}\left(\widehat{\mathcal{B}}_{b,q} \cap \mathcal{B}_b^{\mathrm{obs}}\right)}{\mathrm{Area}\left(\widehat{\mathcal{B}}_{b,q} \cup \mathcal{B}_b^{\mathrm{obs}}\right)}. \tag{618}$$

47.6 Subsidence-History Comparison

$$\chi^2_{S,BA,b,q} = \left(\mathbf{S}_b^{\mathrm{obs}} - \mathbf{S}_{b,q}^{\mathrm{pred}}\right)^{\mathsf{T}} \mathbf{\Sigma}_{S,b}^{-1} \left(\mathbf{S}_b^{\mathrm{obs}} - \mathbf{S}_{b,q}^{\mathrm{pred}}\right). \tag{619}$$

47.7 Sediment-Accommodation Comparison

For accommodation volume,

$$\epsilon_{V_c,b,q} = V_{c,b}^{\mathrm{obs}} - V_{c,b,q}^{\mathrm{pred}}. \tag{620}$$

47.8 Thermal-History Comparison

$$\chi^2_{T,BA,b,q} = \left(\mathbf{T}_b^{\mathrm{obs}} - \mathbf{T}_{b,q}^{\mathrm{pred}}\right)^{\mathsf{T}} \mathbf{\Sigma}_{T,b}^{-1} \left(\mathbf{T}_b^{\mathrm{obs}} - \mathbf{T}_{b,q}^{\mathrm{pred}}\right). \tag{621}$$

47.9 Basin Inversion

The predicted inversion time is

$$t_{\mathrm{inv},b,q} = \inf\left\{t : \dot{S}_{b,q}(t) < 0 \text{ or } \dot{\epsilon}_{\mathrm{comp},b,q} > \dot{\epsilon}_{\mathrm{inv,crit}}\right\}. \tag{622}$$

The inversion residual is

$$\epsilon_{t,\mathrm{inv},b,q} = t_{\mathrm{inv},b}^{\mathrm{obs}} - t_{\mathrm{inv},b,q}^{\mathrm{pred}}. \tag{623}$$

47.10 Basin Comparison Score

$$\begin{aligned}\mathcal{J}_{BA,q} = w_{\mathrm{loc}} \sum_b (1 - \mathrm{IoU}_{BA,b,q}) + w_S \chi^2_{S,BA,q} + w_V \chi^2_{V_c,q} \\ + w_T \chi^2_{T,BA,q} + w_H \chi^2_{H_s,q} + w_I \chi^2_{\mathrm{inv},q} + w_C \chi^2_{\mathrm{chron},BA,q}.\end{aligned} \tag{624}$$

47.11 Basin Falsifier

Basin comparison falsifier S-C4.
A model fails the basin comparison if it cannot jointly predict basin location, geometry, subsidence, thermal history, sediment accommodation, crustal structure, and inversion chronology.

48 Plateau Uplift and Crustal-Thickening Comparison

48.1 Observed Plateau State

For plateau p, define

$$\mathbf{D}^{\text{obs}}_{PL,p} = (\mathcal{P}_p, z_p, A_p, H_{c,p}, H_{\ell,p}, \rho_p, T_p, \mathbf{v}_{m,p}, \mathbf{T}_{P,p})\,. \tag{625}$$

48.2 Plate-Tectonic Plateau Classes

The Plate-Tectonic family may generate plateaus through:

PT-P1. crustal shortening;

PT-P2. lithospheric thickening;

PT-P3. underthrusting;

PT-P4. magmatic addition;

PT-P5. thermal support;

PT-P6. mantle dynamic support;

PT-P7. phase buoyancy;

PT-P8. lower-crustal flow;

PT-P9. and erosion-driven rebound.

48.3 Astro-Ballistic Plateau Classes

The astro-ballistic family may contribute through:

ABC-P1. event-created uplift;

ABC-P2. event-created buoyancy;

ABC-P3. event-derived density reduction;

ABC-P4. event-created phase anomalies;

ABC-P5. event-localized later compression;

ABC-P6. event-guided magmatism;

ABC-P7. event-created resistant blocks;

ABC-P8. and repeated event amplification.

48.4 Plateau Elevation Decomposition

For model q,

$$z_{p,q} = z_{\text{crust},q} + z_{\text{thermal},q} + z_{\text{dynamic},q} + z_{\text{phase},q} + z_{\text{event},q} + z_{\text{eros},q}. \tag{626}$$

48.5 Plateau-Domain Comparison

$$\mathrm{IoU}_{P,p,q} = \frac{\mathrm{Area}\left(\widehat{\mathcal{P}}_{p,q} \cap \mathcal{P}_p^{\mathrm{obs}}\right)}{\mathrm{Area}\left(\widehat{\mathcal{P}}_{p,q} \cup \mathcal{P}_p^{\mathrm{obs}}\right)}. \tag{627}$$

48.6 Elevation and Root Residuals

$$\epsilon_{z,P,p,q} = z_p^{\mathrm{obs}} - z_{p,q}^{\mathrm{pred}}, \tag{628}$$
$$\epsilon_{H_c,P,p,q} = H_{c,p}^{\mathrm{obs}} - H_{c,p,q}^{\mathrm{pred}}. \tag{629}$$

48.7 Dynamic-Support Prediction

For model q,

$$z_{\mathrm{dynamic},p,q} = \mathcal{D}_{z,q}\left[\mathbf{v}_{m,q}, \eta_q, \Delta\rho_q, \boldsymbol{\sigma}_{m,q}\right]. \tag{630}$$

48.8 Persistence Comparison

Define plateau amplitude

$$A_{P,p,q}(t) = \int_{\widehat{\mathcal{P}}_{p,q}} \max\left[z_q(\mathbf{x},t) - z_{\mathrm{ref}}, 0\right]\, dA. \tag{631}$$

The persistence fraction is

$$P_{p,q}(t) = \frac{A_{P,p,q}(t)}{A_{P,p,q}(t_{\mathrm{form}})}. \tag{632}$$

48.9 Plateau Comparison Score

$$\begin{aligned}\mathcal{J}_{P,q} = w_{\mathrm{loc}} \sum_p \left(1 - \mathrm{IoU}_{P,p,q}\right) + w_z \chi^2_{z,P,q} + w_H \chi^2_{H_c,P,q} \\ + w_D \chi^2_{\mathrm{dyn},P,q} + w_\rho \chi^2_{\rho,P,q} + w_T \chi^2_{T,P,q} + w_{\mathrm{pers}} \chi^2_{\mathrm{pers},P,q}.\end{aligned} \tag{633}$$

48.10 Plateau Falsifier

Plateau comparison falsifier S-C5.
A model fails the plateau comparison if it cannot account for plateau location, elevation, crustal root, lithospheric state, buoyancy, dynamic support, chronology, and persistence.

49 Volcanic Provinces and Melt-Path Comparison

49.1 Observed Volcanic State

For volcanic province v, define

$$\mathbf{D}^{\mathrm{obs}}_{VO,v} = \left(\mathcal{D}_v, V_{m,v}, \dot{V}_{m,v}, \mathcal{C}_v, \mathbf{T}_v, \Gamma_{m,v}, \mathbf{Q}^{\mathrm{deep}}_v\right). \tag{634}$$

49.2 Plate-Tectonic Volcanic Classes

The Plate-Tectonic family may generate volcanism through:

PT-VO1. decompression melting;

PT-VO2. volatile-assisted melting;

PT-VO3. lithospheric extension;

PT-VO4. mantle upwelling;

PT-VO5. boundary-related fluid transfer;

PT-VO6. crustal assimilation;

PT-VO7. plume-like thermal anomalies;

PT-VO8. and inherited fracture pathways.

49.3 Astro-Ballistic Volcanic Classes

The astro-ballistic family may contribute through:

ABC-VO1. impact or event heating;

ABC-VO2. pressure release;

ABC-VO3. damage-guided permeability;

ABC-VO4. melt generation along event corridors;

ABC-VO5. event-created density and phase anomalies;

ABC-VO6. event-modified mantle flow;

ABC-VO7. terminal or entrance decompression;

ABC-VO8. and later-event reactivation.

49.4 Melt-Generation Comparison

For model q,

$$\dot{M}_{m,v,q} = \int_{\mathcal{V}_{m,v}} \rho_q \frac{D\chi_{m,q}}{Dt}\, dV. \tag{635}$$

49.5 Melt-Path Comparison

The predicted melt-path network is

$$\widehat{\Gamma}_{m,v,q} = \mathrm{Stream}\left[\mathbf{v}_{m\ell,q}\right]. \tag{636}$$

The path-distance residual is

$$d_{m,v,q} = d_{\mathrm{net}}\left(\Gamma^{\mathrm{obs}}_{m,v}, \widehat{\Gamma}_{m,v,q}\right). \tag{637}$$

49.6 Volcanic-Domain Comparison

$$\mathrm{IoU}_{V,v,q} = \frac{\mathrm{Area}\left(\widehat{\mathcal{D}}_{v,q} \cap \mathcal{D}^{\mathrm{obs}}_{v}\right)}{\mathrm{Area}\left(\widehat{\mathcal{D}}_{v,q} \cup \mathcal{D}^{\mathrm{obs}}_{v}\right)}. \tag{638}$$

49.7 Volume and Rate Residuals

$$\epsilon_{V_m,v,q} = V^{\mathrm{obs}}_{m,v} - V^{\mathrm{pred}}_{m,v,q}, \tag{639}$$

$$\epsilon_{\dot{V}_m,v,q} = \dot{V}^{\mathrm{obs}}_{m,v} - \dot{V}^{\mathrm{pred}}_{m,v,q}. \tag{640}$$

49.8 Composition Comparison

For compositional observation vector $\mathbf{C}^{\mathrm{obs}}_{v}$,

$$\chi^2_{C,V,v,q} = \left(\mathbf{C}^{\mathrm{obs}}_{v} - \mathbf{C}^{\mathrm{pred}}_{v,q}\right)^{\mathsf{T}} \mathbf{\Sigma}^{-1}_{C,v} \left(\mathbf{C}^{\mathrm{obs}}_{v} - \mathbf{C}^{\mathrm{pred}}_{v,q}\right). \tag{641}$$

49.9 Volcanic Chronology

The predicted chronology is

$$\widehat{\mathbf{T}}_{V,v,q} = \left(t_{\mathrm{init}}, t_{\mathrm{peak}}, t_{\mathrm{pulse},1}, \ldots, t_{\mathrm{end}}\right). \tag{642}$$

49.10 Event-to-Volcanism Lag

For event k,

$$\Delta t_{v,k,q} = t_{v,\mathrm{init},q} - t_{k,q} \tag{643}$$

in forward-time coordinates.

The lag must follow from modeled heating, decompression, melt generation, transport, and boundary response.

49.11 Volcanic Comparison Score

$$\begin{aligned} \mathcal{J}_{VO,q} = {} & w_{\mathrm{loc}} \sum_{v} \left(1 - \mathrm{IoU}_{V,v,q}\right) + w_m \chi^2_{\dot{M},V,q} + w_{\Gamma} \chi^2_{\Gamma_m,q} \\ & + w_V \chi^2_{V_m,q} + w_C \chi^2_{C,V,q} + w_T \chi^2_{T,V,q} + w_D \chi^2_{\mathrm{deep},V,q}. \end{aligned} \tag{644}$$

49.12 Volcanic Falsifier

Volcanic comparison falsifier S-C6.
A model fails the volcanic comparison if it cannot jointly predict province location, melt volume, eruption rate, composition, chronology, subsurface source, and melt-transport pathways.

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50 Terrane Transfer, Sutures, and Continental Assembly

50.1 Observed Terrane State

For terrane u, define

$$\mathbf{D}_{TE,u}^{\text{obs}} = (\mathcal{C}_u, \mathbf{A}_u, \mathbf{M}_u, \mathbf{S}_u, \mathbf{x}_u(t), \mathbf{R}_u(t), \mathbf{T}_u)\,, \tag{645}$$

where the entries represent composition, age, magnetization, structure, trajectory, rotation, and chronology.

50.2 Plate-Tectonic Assembly Classes

The Plate-Tectonic family may assemble terranes through:

PT-TE1. relative plate motion;

PT-TE2. collision;

PT-TE3. accretion;

PT-TE4. underthrusting;

PT-TE5. transform transfer;

PT-TE6. continental convergence;

PT-TE7. ocean-basin closure;

PT-TE8. and reactivation of inherited sutures.

50.3 Astro-Ballistic Assembly Classes

The astro-ballistic family may contribute through:

ABC-TE1. event-created terrane displacement;

ABC-TE2. event-created fragmentation;

ABC-TE3. event-generated rotation;

ABC-TE4. event-derived convergence directions;

ABC-TE5. event-created boundary localization;

ABC-TE6. event-sequenced collision;

ABC-TE7. and later event-guided reassembly.

50.4 Terrane Trajectory Comparison

For model q,

$$\widehat{\mathbf{x}}_{u,q}(t) = \mathcal{U}_{TE,q}\left[\mathbf{x}_u(t_0), \mathbf{V}_q, \mathcal{B}_q, \mathcal{E}_q\right]. \tag{646}$$

The trajectory residual is

$$\chi^2_{x,TE,u,q} = \sum_a \frac{d^2_{\mathcal{S}}\left[\mathbf{x}^{\mathrm{obs}}_u(t_a), \widehat{\mathbf{x}}_{u,q}(t_a)\right]}{\sigma^2_{x,u,a}}. \tag{647}$$

50.5 Terrane-Rotation Comparison

For finite rotations,

$$\Delta\theta_{R,TE,u,q} = \arccos\left[\frac{\mathrm{tr}\left(\left[\mathbf{R}^{\mathrm{pred}}_{u,q}\right]^{-1}\mathbf{R}^{\mathrm{obs}}_u\right) - 1}{2}\right]. \tag{648}$$

50.6 Material-Identity Comparison

$$\chi^2_{\mathrm{id},u,q} = \left(\mathbf{Q}^{\mathrm{id,obs}}_u - \mathbf{Q}^{\mathrm{id,pred}}_{u,q}\right)^{\mathsf{T}} \mathbf{\Sigma}^{-1}_{u,\mathrm{id}} \left(\mathbf{Q}^{\mathrm{id,obs}}_u - \mathbf{Q}^{\mathrm{id,pred}}_{u,q}\right). \tag{649}$$

50.7 Suture Prediction

For observed suture $\mathcal{S}^{\mathrm{obs}}_u$ and predicted suture $\widehat{\mathcal{S}}_{u,q}$,

$$d_{S,u,q} = d_{\mathrm{ASD}}\left(\mathcal{S}^{\mathrm{obs}}_u, \widehat{\mathcal{S}}_{u,q}\right). \tag{650}$$

50.8 Assembly Graph

For model q,

$$\widehat{\mathcal{G}}_{\mathrm{asm},q} = \left(\widehat{\mathcal{N}}_{TE,q}, \widehat{\mathcal{E}}_{\mathrm{contact},q}\right). \tag{651}$$

The observed graph is

$$\mathcal{G}^{\mathrm{obs}}_{\mathrm{asm}}. \tag{652}$$

The adjacency residual is

$$D_{A,TE,q} = \frac{\left\|\mathbf{A}^{\mathrm{obs}}_A - \mathbf{A}^{\mathrm{pred}}_{A,q}\right\|_F}{\left\|\mathbf{A}^{\mathrm{obs}}_A\right\|_F}. \tag{653}$$

50.9 Assembly Chronology

Each model predicts

$$\widehat{\mathbf{T}}_{A,u,q} = (t_{\text{approach}}, t_{\text{contact}}, t_{\text{closure}}, t_{\text{met}}, t_{\text{exhum}}) . \tag{654}$$

50.10 Terrane Comparison Score

$$\begin{aligned}\mathcal{J}_{TE,q} = w_x \chi^2_{x,TE,q} + w_R \chi^2_{R,TE,q} + w_{\text{id}} \chi^2_{\text{id},q} + w_S \chi^2_{S,q} \\ + w_A D_{A,TE,q} + w_T \chi^2_{T,A,q} + w_M \mathcal{P}_{\text{material viol},q}.\end{aligned} \tag{655}$$

50.11 Terrane-Assembly Falsifier

Terrane-and-assembly comparison falsifier S-C7.
A model fails the assembly comparison if it cannot reproduce terrane trajectories, rotations, material identities, suture locations, contact order, and assembly chronology without violating material continuity.

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51 Gravity and Geoid Comparison

51.1 Observed Gravity State

Define observed gravity dataset

$$\mathbf{D}_g^{\text{obs}} = \left(\mathbf{g}^{\text{obs}}, \Phi^{\text{obs}}, N^{\text{obs}}, \mathbf{\Sigma}_g, \mathcal{R}_g\right), \tag{656}$$

where $\mathcal{R}_g$ contains spatial resolution and processing information.

51.2 Model Density Field

For model q,

$$\rho_q = \rho_0 + \Delta\rho_{T,q} + \Delta\rho_{C,q} + \Delta\rho_{\phi,q} + \Delta\rho_{m,q} + \Delta\rho_{D,q}. \tag{657}$$

51.3 Gravity Prediction

$$\widehat{\Phi}_q(\mathbf{x}) = -G \int \frac{\rho_q(\mathbf{r})}{\|\mathbf{x} - \mathbf{r}\|} \, dV. \tag{658}$$

$$\widehat{\mathbf{g}}_q = -\nabla \widehat{\Phi}_q. \tag{659}$$

51.4 Geoid Prediction

$$\widehat{N}_q = \mathcal{G}_N \left[\widehat{\Phi}_q, \Phi_{\text{ref}}, \mathbf{Q}_\oplus\right]. \tag{660}$$

51.5 Resolution-Matched Prediction

Before comparison,

$$\widehat{\mathbf{D}}_{g,q}^{\text{res}} = \mathcal{R}_g \left[\widehat{\mathbf{D}}_{g,q} \right]. \tag{661}$$

51.6 Gravity Residual

$$\boldsymbol{\epsilon}_{g,q} = \mathbf{D}_g^{\text{obs}} - \widehat{\mathbf{D}}_{g,q}^{\text{res}}. \tag{662}$$

51.7 Gravity Misfit

$$\chi_{g,q}^2 = \boldsymbol{\epsilon}_{g,q}^{\mathsf{T}} \boldsymbol{\Sigma}_g^{-1} \boldsymbol{\epsilon}_{g,q}. \tag{663}$$

51.8 Anomaly-Sign Prediction

For target region r,

$$A_{\text{sign},g,r,q} = \mathbf{1} \left[\text{sign} \left(\Delta g_r^{\text{obs}} \right) = \text{sign} \left(\Delta g_{r,q}^{\text{pred}} \right) \right]. \tag{664}$$

51.9 Depth-Sensitivity Comparison

For density perturbation at depth z, define model sensitivity

$$K_{g,q}(\mathbf{x}, z) = \frac{\partial \widehat{g}_q(\mathbf{x})}{\partial \rho_q(z)}. \tag{665}$$

A surface fit does not uniquely identify depth.

The model must compare gravity jointly with seismic and material constraints.

51.10 Gravity Counterfactuals

Remove:

- event-derived density anomalies;
- thermal density anomalies;
- compositional anomalies;
- phase anomalies;
- crustal-thickness anomalies;
- and mantle-flow-associated density structure.

For component c,

$$N_{g,c,q} = \mathcal{J}_{g,q,-c} - \mathcal{J}_{g,q}^{+}. \tag{666}$$

51.11 Gravity Falsifier

Gravity comparison falsifier G-C1.
A model fails the gravity comparison if the density field required by its boundaries, mountains, trenches, mantle state, or event corridors predicts gravity or geoid anomalies incompatible with observation.

52 Seismic Velocity, Attenuation, and Anisotropy

52.1 Observed Seismic State

Define

$$\mathbf{D}_{SE}^{\text{obs}} = \left(V_P^{\text{obs}}, V_S^{\text{obs}}, Q^{-1,\text{obs}}, \mathbf{A}_{\text{seis}}^{\text{obs}}, \mathbf{T}_{\text{travel}}^{\text{obs}}, \mathcal{R}_{SE}\right), \tag{667}$$

where $\mathcal{R}_{SE}$ contains resolution and inversion information.

52.2 Elastic Prediction

For model q,

$$V_{P,q} = \sqrt{\frac{K_q + \frac{4}{3}G_q}{\rho_q}}, \tag{668}$$

$$V_{S,q} = \sqrt{\frac{G_q}{\rho_q}}. \tag{669}$$

52.3 Constitutive Dependence

$$K_q, G_q = \mathcal{F}_{K,G}\left(P_q, T_q, C_q, \phi_q, \chi_{m,q}, D_q, \mathbf{A}_q\right). \tag{670}$$

52.4 Attenuation Prediction

$$Q_q^{-1} = \mathcal{F}_Q\left(P_q, T_q, \chi_{m,q}, D_q, \phi_q, C_q, \omega\right). \tag{671}$$

52.5 Anisotropy Tensor

$$\mathbf{C}_q = \mathbf{C}_{\text{iso},q} + \Delta\mathbf{C}_{\text{strain},q} + \Delta\mathbf{C}_{\text{damage},q} + \Delta\mathbf{C}_{\text{phase},q}. \tag{672}$$

52.6 Forward Observation Operator

$$\widehat{\mathbf{d}}_{SE,q} = \mathcal{O}_{SE}\left[V_{P,q}, V_{S,q}, Q_q^{-1}, \mathbf{A}_q\right]. \tag{673}$$

52.7 Resolution Matching

$$\widehat{\mathbf{D}}_{SE,q}^{\text{res}} = \mathcal{R}_{SE}\left[\widehat{\mathbf{D}}_{SE,q}\right]. \tag{674}$$

52.8 Seismic Misfit

$$\chi^2_{SE,q} = \left(\mathbf{D}^{\mathrm{obs}}_{SE} - \widehat{\mathbf{D}}^{\mathrm{res}}_{SE,q}\right)^{\mathsf{T}} \mathbf{\Sigma}^{-1}_{SE} \left(\mathbf{D}^{\mathrm{obs}}_{SE} - \widehat{\mathbf{D}}^{\mathrm{res}}_{SE,q}\right). \tag{675}$$

52.9 Corridor-Detection Comparison

For predicted corridor $\mathcal{T}_q$ and observed seismic residual field $\mathcal{D}^{\mathrm{resid}}_{SE}$, define

$$C_{\mathrm{corr},q} = \frac{\int \mathcal{T}_q \mathcal{D}^{\mathrm{resid}}_{SE}\, dV}{\sqrt{\int \mathcal{T}_q^2\, dV}\sqrt{\int \left(\mathcal{D}^{\mathrm{resid}}_{SE}\right)^2\, dV}}. \tag{676}$$

52.10 Anisotropy-Direction Residual

For observed and predicted fast axes,

$$A_{\mathrm{fast},q} = \left|\widehat{\mathbf{a}}^{\mathrm{obs}}_{\mathrm{fast}} \cdot \widehat{\mathbf{a}}^{\mathrm{pred}}_{\mathrm{fast},q}\right|. \tag{677}$$

52.11 Seismic Counterfactuals

Remove:

- event damage;
- event thermal anomalies;
- event phase anomalies;
- event melt;
- plate-driven strain;
- mantle-flow anisotropy;
- and inherited compositional structure.

52.12 Seismic Falsifier

Seismic comparison falsifier G-C2.
A model fails the seismic comparison if its required material, temperature, phase, damage, melt, and strain fields predict incompatible wave speeds, attenuation, anisotropy, travel times, or deep continuity.

53 Magnetic and Heat-Flow Comparison

53.1 Observed Magnetic and Thermal State

Define

$$\mathbf{D}_{MH}^{\mathrm{obs}} = \left(\mathbf{B}^{\mathrm{obs}}, \mathbf{M}^{\mathrm{obs}}, q_H^{\mathrm{obs}}, T^{\mathrm{obs}}, \mathbf{T}_{MH}, \mathcal{R}_{MH}\right). \tag{678}$$

53.2 Magnetization Prediction

For model q,

$$\mathbf{M}_q = \mathcal{F}_M \left[\mathbf{M}_0, T_{\max,q}, P_{\max,q}, D_q, \chi_{m,q}, \phi_q, \mathbf{B}(t), t\right]. \tag{679}$$

53.3 Magnetic Observation Prediction

$$\widehat{\mathbf{B}}_q = \mathcal{O}_B \left[\mathbf{M}_q, \mathbf{Q}_{\mathrm{crust},q}, \mathbf{Q}_{\mathrm{mantle},q}\right]. \tag{680}$$

53.4 Magnetic Residual

$$\boldsymbol{\epsilon}_{B,q} = \mathbf{B}^{\mathrm{obs}} - \widehat{\mathbf{B}}_q^{\mathrm{res}}. \tag{681}$$

$$\chi^2_{B,q} = \boldsymbol{\epsilon}_{B,q}^{\mathsf{T}} \boldsymbol{\Sigma}_B^{-1} \boldsymbol{\epsilon}_{B,q}. \tag{682}$$

53.5 Magnetic Resetting Test

For predicted reset domain

$$\mathcal{D}_{M,q}^{\mathrm{reset}} = \left\{\mathbf{x} : T_{\max,q} \geq T_{\mathrm{reset}} \text{ or } D_q \geq D_{\mathrm{reset}}\right\}, \tag{683}$$

compare with independently observed reset or remanence patterns.

53.6 Thermal Evolution

For model q,

$$\rho_q c_{P,q} \frac{DT_q}{Dt} = \nabla \cdot (k_q \nabla T_q) + Q_{\mathrm{int},q} + Q_{\mathrm{event},q} + Q_{\mathrm{phase},q} + Q_{\mathrm{visc},q}. \tag{684}$$

53.7 Heat-Flow Prediction

$$\mathbf{q}_{H,q} = -k_q \nabla T_q. \tag{685}$$

The surface-normal heat flow is

$$q_{H,n,q} = -\mathbf{q}_{H,q} \cdot \widehat{\mathbf{n}}_{\mathcal{S}}. \tag{686}$$

53.8 Heat-Flow Residual

$$\epsilon_{q_H,q} = q_H^{\mathrm{obs}} - q_{H,q}^{\mathrm{pred}}. \tag{687}$$

$$\chi^2_{q_H,q} = \boldsymbol{\epsilon}_{q_H,q}^{\mathsf{T}} \boldsymbol{\Sigma}_{q_H}^{-1} \boldsymbol{\epsilon}_{q_H,q}. \tag{688}$$

53.9 Thermal-Memory Test

For event-derived thermal anomaly

$$\Delta T_{\mathrm{event},q}(t), \tag{689}$$

define thermal-memory fraction

$$f_{T,q}(t) = \frac{\|\Delta T_{\mathrm{event},q}(t)\|}{\|\Delta T_{\mathrm{event},q}(t_0)\|}. \tag{690}$$

The model must demonstrate whether present thermal effects remain detectable after diffusion, advection, phase change, and later deformation.

53.10 Magnetic and Thermal Counterfactuals

Remove:

- event heating;
- event pressure;
- event damage;
- event melt;
- background thermal anomalies;
- mantle advection;
- and crustal heat production.

53.11 Magnetic-Heat Comparison Score

$$\mathcal{J}_{MH,q} = w_B \chi^2_{B,q} + w_R \chi^2_{\mathrm{reset},q} + w_H \chi^2_{q_H,q} + w_T \chi^2_{T,q} + w_C \chi^2_{\mathrm{chron},MH,q}. \tag{691}$$

53.12 Magnetic and Heat-Flow Falsifier

Magnetic-and-thermal comparison falsifier G-C3.
A model fails the magnetic and thermal comparison if its required pressure, temperature, melting, phase, and damage histories predict magnetic resetting, remanence, subsurface temperature, or surface heat flow incompatible with observation.

54 Structural and Geophysical Counterfactuals

54.1 Unified Structural State

Define

$$\mathbf{Q}_{SG,q} = (\mathbf{Q}_{O,q}, \mathbf{Q}_{T,q}, \mathbf{Q}_{R,q}, \mathbf{Q}_{BA,q}, \mathbf{Q}_{P,q}, \mathbf{Q}_{VO,q}, \mathbf{Q}_{TE,q}, \mathbf{Q}_{G,q}) \,. \tag{692}$$

54.2 No-Event Counterfactual

For astro-ballistic and hybrid models,

$$\mathcal{E} \to \varnothing, \qquad \mathbf{Q}^{\mathrm{ABC}}_{\mathrm{inherit}} \to \mathbf{0}. \tag{693}$$

The global structural necessity is

$$N_{SG,E,q} = \mathcal{J}_{SG,q,-E} - \mathcal{J}^{+}_{SG,q}. \tag{694}$$

54.3 Boundary Counterfactual

Replace the model-generated boundary network with a reduced or randomized network:

$$\mathcal{B}_q \to \mathcal{B}^{(r)}_q. \tag{695}$$

54.4 Motion Counterfactual

Replace predicted motion with:

$$\mathbf{V}_q \to \mathbf{V}^0_q \tag{696}$$

or remove a declared force component.

54.5 Convergence Ablation

$$v_{\mathrm{conv}} \to 0 \tag{697}$$

tests mountain, trench, plateau, and suture dependence on convergence.

54.6 Extension Ablation

$$v_{\mathrm{open}} \to 0 \tag{698}$$

tests ridge, rift, basin, and melt dependence on extension.

54.7 Mantle-Flow Ablation

$$\mathbf{v}_m \to \mathbf{0} \tag{699}$$

where physically interpretable.

54.8 Damage Ablation

$$D_q \to D_0. \tag{700}$$

54.9 Density Ablation

$$\Delta\rho_q \to 0. \tag{701}$$

54.10 Thermal Ablation

$$\Delta T_q \to 0. \tag{702}$$

54.11 Phase Ablation

$$\Delta\phi_q \to 0. \tag{703}$$

54.12 Melt and Permeability Ablation

$$\chi_m \to 0, \qquad \mathbf{k}_{\text{perm}} \to \mathbf{k}_0. \tag{704}$$

54.13 Inheritance Isotropization

$$\mathbf{Q}_{\text{inherit}} \to \text{Iso}\left(\mathbf{Q}_{\text{inherit}}\right). \tag{705}$$

This tests whether directional inheritance is necessary.

54.14 Leave-One-Structure-Class-Out Test

For structure class g,

$$\mathcal{J}_{SG,q}^{(-g)} \tag{706}$$

fits the model without that class and predicts it as held-out evidence.

54.15 Leave-One-Event-Out Structural Test

For event k,

$$N_{SG,k} = \mathcal{J}_{SG,-k} - \mathcal{J}_{SG,\text{full}}. \tag{707}$$

54.16 Component Interaction

For components a and b,

$$N_{SG,a\times b} = \mathcal{J}_{SG,-a} + \mathcal{J}_{SG,-b} - \mathcal{J}_{SG,-a,-b} - \mathcal{J}_{SG}^{+}. \tag{708}$$

54.17 Counterfactual Consistency

A counterfactual must remain physically interpretable.

Removing gravity from a gravitational system may test dependence but does not create a realistic alternate Earth.

Such tests must be labeled:

- physical ablation;
- mathematical sensitivity;
- causal intervention;
- or randomized null.

54.18 Structural Causal-Necessity Rule

A defining component is necessary only when its removal degrades:

- surface structure;
- chronology;
- deep geophysics;
- and held-out predictions

without being replaced by an unconstrained compensating parameter.

54.19 Structural-Necessity Falsifier

Structural causal-necessity falsifier S-C8.
If removing or randomizing a model's defining structural component leaves mountains, trenches, ridges, basins, plateaus, volcanism, terrane assembly, and deep geophysical predictions materially unchanged, that component is not established as the primary cause.

55 Structural Complexity and Predictive Tests

55.1 Structural Complexity Vector

For model q, define

$$\mathbf{k}_{SG,q} = (k_O, k_T, k_R, k_{BA}, k_P, k_{VO}, k_{TE}, k_G, k_{\text{assign}}, k_{\text{lag}}, k_{\text{pres}}, k_{\text{switch}}, k_{\text{revision}}) . \tag{709}$$

55.2 Structure-Specific Parameter Count

Let

$$k_{g,q}^{\text{local}} \tag{710}$$

be the number of parameters fitted only to structure g.

The total is

$$k_{S,\text{local},q} = \sum_g k_{g,q}^{\text{local}}. \tag{711}$$

55.3 Event-to-Structure Assignment Penalty

Let

$$N_{E\to S,q} \tag{712}$$

be the number of manually assigned event-to-structure links.

Define

$$\mathcal{P}_{E\to S,q} = \lambda_{E\to S} N_{E\to S,q}. \tag{713}$$

55.4 Lag Complexity

For independently fitted response lags,

$$k_{\text{lag},q} = N_{\text{lag,global}} + N_{\text{lag,regional}} + N_{\text{lag,local}}. \tag{714}$$

55.5 Preservation Complexity

If each structure receives an independent preservation function,

$$k_{\text{pres},q} = \sum_g k_{\text{pres},g,q}. \tag{715}$$

Preservation cannot be invoked only where predicted evidence is absent.

55.6 Mechanism-Switching Penalty

$$\mathcal{P}_{S,\text{switch},q} = \lambda_{S,\text{switch}} N_{S,\text{switch},q}. \tag{716}$$

55.7 Structural Information Criterion

$$\begin{aligned}\mathrm{IC}_{SG,q} = &-2\ln\mathcal{L}_{SG,q} + \kappa k_{SG,\mathrm{eff},q} + \mathcal{P}_{E\to S,q}\\ &+ \mathcal{P}_{S,\mathrm{switch},q} + \mathcal{P}_{S,\mathrm{pres},q} + \mathcal{P}_{S,\mathrm{revision},q}.\end{aligned} \tag{717}$$

55.8 Held-Out Structure Classes

The predictive program should include:

SH1. withheld mountain systems;

SH2. withheld trenches;

SH3. withheld ridges or rifts;

SH4. withheld basins;

SH5. withheld plateaus;

SH6. withheld volcanic provinces;

SH7. withheld terranes or sutures;

SH8. withheld gravity regions;

SH9. withheld seismic volumes;

SH10. withheld magnetic regions;

SH11. and withheld heat-flow observations.

55.9 Spatial Holdout

For withheld region $\mathcal{D}_h$, each model predicts

$$p_q\left(\mathbf{D}_{SG,h} \mid \mathbf{D}_{SG,-h}\right). \tag{718}$$

55.10 Depth Holdout

Where surface structures are known but deep data are withheld, each model predicts:

- anomaly depth;
- anomaly sign;
- thickness;
- continuity;
- orientation;
- and material state.

55.11 Chronology Holdout

Fit structure location and geometry while withholding age information.

Then predict

$$\widehat{\mathbf{T}}_{g,q}^{\text{test}}. \tag{719}$$

55.12 Observation-Type Holdout

Examples include:

- fit gravity and predict seismic structure;
- fit seismic structure and predict gravity;
- fit mountain geometry and predict crustal thickness;
- fit basin geometry and predict thermal history;
- fit volcanic location and predict composition;
- fit terrane identity and predict trajectory.

55.13 Negative Structural Predictions

Each model must identify control regions where it predicts:

- no major mountain system;
- no trench continuation;
- no rift or ridge;
- no deep corridor;
- no significant volcanic pathway;
- no gravity anomaly of the claimed sign;
- and no magnetic or heat-flow response.

55.14 Structural Predictive Score

$$S_{SG,q}^{\text{test}} = \sum_h \log p\left(\mathbf{D}_{SG,h}^{\text{obs}} \mid \mathbf{D}_{SG,\text{train}}, \mathcal{M}_q\right). \tag{720}$$

55.15 Randomized Structural Nulls

For event-based models, randomize:

- event coordinates;
- event ages;
- event directions;

- event-to-structure assignments;
- and event response kernels.

For inherited-state models, randomize:

- initial weakness;
- density anomalies;
- thermal anomalies;
- anisotropy;
- and boundary mobility.

55.16 Structural Null Probability

$$p_{SG,q,\mathrm{null}} = \frac{1 + \sum_{r=1}^{N_R} \mathbf{1}\left[\mathcal{J}_{SG,q}^{(r)} \le \mathcal{J}_{SG,q}^{\mathrm{obs}}\right]}{N_R + 1}. \tag{721}$$

55.17 Predictive Superiority

Model i predictively outperforms model j when

$$S_{SG,i}^{\mathrm{test}} - S_{SG,j}^{\mathrm{test}} > \Delta S_{SG,\mathrm{crit}} \tag{722}$$

with predeclared uncertainty.

56 Structural-and-Geophysical Replacement Viability

56.1 Structural Comparison Parameter Set

For model q,

$$\mathbf{\Theta}_{SG,q}^{\mathrm{IV}} = (\mathbf{Q}_{0,q}, \mathcal{E}_q, \mathcal{B}_q, \mathbf{V}_q, \mathbf{F}_q, \mathbf{R}_q, \mathbf{\Theta}_{O,q}, \mathbf{\Theta}_{T,q}, \mathbf{\Theta}_{R,q}, \mathbf{\Theta}_{BA,q}, \mathbf{\Theta}_{P,q}, \mathbf{\Theta}_{VO,q}, \mathbf{\Theta}_{TE,q}, \mathbf{\Theta}_{G,q}). \tag{723}$$

56.2 Structural-and-Geophysical Viable Set

Define

$$\mathcal{V}_{SG,q}^{\mathrm{IV}} = \left\{ \boldsymbol{\Theta}_{SG,q}^{\mathrm{IV}} : \begin{array}{l} \text{boundary solution admissible,} \\ \text{motion solution admissible,} \\ \text{mountains compatible,} \\ \text{trenches compatible,} \\ \text{ridges and rifts compatible,} \\ \text{basins compatible,} \\ \text{plateaus compatible,} \\ \text{volcanic provinces compatible,} \\ \text{terranes and sutures compatible,} \\ \text{gravity and geoid compatible,} \\ \text{seismic structure compatible,} \\ \text{magnetics compatible,} \\ \text{heat flow compatible,} \\ \text{chronology compatible,} \\ \text{energy and material budgets satisfied,} \\ \text{defining causes necessary,} \\ \text{complexity controlled,} \\ \text{held-out prediction successful} \end{array} \right\}. \tag{724}$$

56.3 Astro-Ballistic Structural Replacement Condition

The astro-ballistic structural model remains a replacement candidate only if

$$\mathcal{V}_{SG,\mathrm{ABC}}^{\mathrm{IV}} \neq \varnothing \tag{725}$$

and

$$\mathrm{Score}_{SG}(\mathcal{M}_{\mathrm{ABC}}) < \mathrm{Score}_{SG}(\mathcal{M}_{\mathrm{PT}}) - \delta_{SG}. \tag{726}$$

56.4 Hybrid Structural Preference

The hybrid is preferred when

$$\mathrm{Score}_{SG}(\mathcal{M}_{\mathrm{HYB}}) < \min\left[\mathrm{Score}_{SG}(\mathcal{M}_{\mathrm{PT}}), \mathrm{Score}_{SG}(\mathcal{M}_{\mathrm{ABC}})\right] - \delta_{SG} \tag{727}$$

and event-derived inheritance, later geodynamics, and interaction terms remain necessary.

56.5 Structural Equivalence

Models are structurally equivalent when

$$|\text{Score}_{SG,i} - \text{Score}_{SG,j}| \leq \delta_{SG,\text{equiv}}. \tag{728}$$

56.6 Structural-and-Geophysical Falsification Matrix

Table 4: Paper-IV structural-and-geophysical replacement falsification matrix.

ID	Comparison claim	Falsifying result	Consequence
IV-SG01	Structural eligibility	Required structures depend on excluded boundary, motion, or Paper-II states.	Structural model is ineligible.
IV-SG02	Mountain localization	Predicted orogenic domains systematically miss observed systems.	Reject mountain-location explanation.
IV-SG03	Mountain orientation	Predicted axes systematically fail.	Reject directional orogenic explanation.
IV-SG04	Mountain shortening	Predicted shortening and strain are incompatible.	Reject orogenic deformation model.
IV-SG05	Mountain crustal root	Predicted crustal thickness is incompatible.	Reject mountain-support model.
IV-SG06	Mountain chronology	Initiation, uplift, metamorphism, or exhumation timing fails.	Reject mountain-history explanation.
IV-SG07	Trench geometry	Predicted trench axis, depth, width, curvature, or segmentation fails.	Reject trench geometry.
IV-SG08	Trench deep structure	Required descent or underthrusting structure is absent.	Reject deep trench mechanism.
IV-SG09	Trench energy	Bending, descent, or excavation energy is unavailable.	Reject trench dynamics.
IV-SG10	Ridge localization	Predicted ridge and rift axes fail.	Reject extensional localization.
IV-SG11	Ridge opening	Predicted opening rates fail.	Reject ridge kinematics.
IV-SG12	Material-age field	Predicted age-distance structure is incompatible.	Reject material-production history.
IV-SG13	Melt production	Predicted ridge melt volume or depth fails.	Reject ridge thermal model.
IV-SG14	Basin geometry	Predicted basin domains or orientations fail.	Reject basin localization.

ID	Comparison claim	Falsifying result	Consequence
IV-SG15	Basin subsidence	Predicted subsidence and accommodation histories fail.	Reject basin evolution.
IV-SG16	Basin inversion	Predicted inversion timing or direction fails.	Reject sequenced basin history.
IV-SG17	Plateau location	Predicted uplift domains fail.	Reject plateau localization.
IV-SG18	Plateau support	Crustal, thermal, phase, or dynamic support is insufficient.	Reject plateau mechanism.
IV-SG19	Volcanic localization	Predicted volcanic domains and melt paths fail.	Reject volcanic localization.
IV-SG20	Volcanic volume	Predicted melt or eruption volume fails.	Reject volcanic production model.
IV-SG21	Volcanic composition	Predicted source and transport history conflicts with composition.	Reject melt-source model.
IV-SG22	Volcanic chronology	Predicted event-to-volcanism lag or pulse history fails.	Reject volcanic chronology.
IV-SG23	Terrane trajectories	Predicted terrane paths or rotations fail.	Reject displacement history.
IV-SG24	Material identity	Predicted terrane lineage conflicts with composition or age.	Reject terrane assignment.
IV-SG25	Suture assembly	Predicted sutures, contacts, or closure order fail.	Reject assembly history.
IV-SG26	Gravity	Required density structure predicts incompatible gravity.	Reject density architecture.
IV-SG27	Geoid	Predicted geoid response is incompatible.	Reject long-wavelength mass distribution.
IV-SG28	Seismic velocity	Predicted wave speeds fail.	Reject material or thermal state.
IV-SG29	Attenuation	Predicted attenuation fails.	Reject melt, thermal, or damage state.
IV-SG30	Anisotropy	Predicted fast-axis direction or magnitude fails.	Reject directional strain or damage history.
IV-SG31	Deep corridor	Predicted event corridor is absent at adequate resolution.	Reject preserved-corridor claim.
IV-SG32	Magnetics	Predicted resetting or remanence fails.	Reject pressure-temperature history.

ID	Comparison claim	Falsifying result	Consequence
IV-SG33	Heat flow	Predicted thermal inheritance conflicts with observation.	Reject thermal history.
IV-SG34	Cross-observation consistency	Gravity, seismic, and thermal fields require incompatible structures.	Reject integrated geophysical model.
IV-SG35	Event necessity	Removing event inheritance leaves structures and geophysics unchanged.	Reject primary astro-ballistic causation.
IV-SG36	Plate-Tectonic necessity	Removing defining comparison-model components leaves the solution unchanged.	Reject their claimed primary role.
IV-SG37	Hybrid necessity	Hybrid performance remains after one parent component is removed.	Reject joint causal attribution.
IV-SG38	Leave-one-event-out	Claimed major events have negligible structural contribution.	Reject those event assignments.
IV-SG39	Leave-one-class-out	The model cannot predict a withheld structure class.	Reject cross-structural generality.
IV-SG40	Spatial holdout	The model fails withheld regions.	Reject geographic predictive generality.
IV-SG41	Depth holdout	The model fails withheld deep structure.	Reject subsurface prediction.
IV-SG42	Chronology holdout	The model cannot predict structure ages without fitting them.	Reject temporal prediction.
IV-SG43	Negative prediction	The model predicts major structures or anomalies in declared control regions.	Reject specificity.
IV-SG44	Randomized-event null	Randomized event catalogs perform equally well.	Reject special event-sequence significance.
IV-SG45	Inherited-state null	Randomized initial heterogeneity performs equally well.	Reject specific inherited-state significance.
IV-SG46	Complexity	The apparent advantage disappears after local parameters, assignments, lags, preservation, and switching are counted.	Reject structural replacement preference.

ID	Comparison claim	Falsifying result	Consequence
IV-SG47	Replication	Independent teams cannot reproduce the result.	Reject confirmatory preference.
IV-SG48	Structural equivalence	Model scores remain inside the equivalence interval.	Report structural causal non-resolution.
IV-SG49	Plate-Tectonic superiority	The strongest Plate-Tectonic model performs better after penalties.	Reject astro-ballistic structural replacement.
IV-SG50	Astro-ballistic superiority	The astro-ballistic model lacks a clear penalized advantage.	Primary structural replacement is unsupported.
IV-SG51	Hybrid superiority	The hybrid fails to outperform both parents with all components necessary.	Hybrid structural preference is unsupported.
IV-SG52	Complete viability	The astro-ballistic structural-and-geophysical viable set is empty.	Structural component of replacement thesis fails.

56.7 Structural Outcome Classes

The structural and geophysical comparison permits:

Structural Outcome A: Plate-Tectonic preference
The Plate-Tectonic model provides the strongest penalized structural and geophysical explanation.

Structural Outcome B: Astro-ballistic preference
Event-derived inheritance provides the strongest penalized explanation.

Structural Outcome C: Hybrid preference
Event-created states and later geodynamic evolution are jointly necessary.

Structural Outcome D: Regional event contribution
Selected mountains, basins, volcanic provinces, trenches, or deep structures retain event-derived support without global replacement.

Structural Outcome E: Geometric fit without causal support
Surface structures align, but chronology, deep geophysics, energy, or necessity fails.

Structural Outcome F: Equivalence
Available evidence does not distinguish the models.

Structural Outcome G: Shared failure
None of the tested models adequately predicts the complete structural and geophysical domain.

56.8 Structural Replacement Decision Rule

Structural-and-geophysical replacement decision rule.
Astro-Ballistic Chronostratigraphic Sequencing can replace Plate Tectonics as the primary explanation of global crustal and lithospheric structure only if the same mechanically admissible event sequence that generates the boundary and motion system also predicts mountains, trenches, ridges, basins, plateaus, volcanic provinces, terrane assemblies, gravity, seismic structure, magnetics, and heat flow more accurately and predictively after physical, chronological, and complexity penalties.
Surface resemblance alone is insufficient.
The predicted subsurface material state, chronology, work, mass transfer, and geophysical expression must also survive.

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57 Structural and Geophysical Comparison Synthesis

This structural-and-geophysical synthesis records:

1. mountains as shared observational and causal targets;
2. Plate-Tectonic, astro-ballistic, and hybrid mountain-building classes;
3. mountain-domain, orientation, shortening, crustal-thickness, elevation, chronology, and work comparisons;
4. trench excavation, bending, descent, underthrusting, and hybrid decomposition;
5. trench-axis, depth, width, curvature, deep-structure, mass-flux, energy, and chronology tests;
6. ridge and rift mechanism comparison;
7. ridge-axis, opening-rate, material-age, segmentation, melt-production, and new-area-production tests;
8. basin-location, subsidence, sediment-accommodation, thermal-history, and inversion comparisons;
9. plateau-location, elevation, crustal-root, dynamic-support, buoyancy, chronology, and persistence tests;
10. volcanic-domain, melt-volume, eruption-rate, composition, chronology, and melt-path comparison;
11. terrane-trajectory, rotation, material-identity, suture, contact-order, and assembly comparisons;
12. gravity, geoid, density-field, anomaly-sign, and depth-sensitivity comparisons;
13. seismic velocity, attenuation, anisotropy, travel-time, resolution, and corridor-detection comparisons;
14. magnetic-resetting, remanence, thermal-evolution, and heat-flow comparisons;
15. unified structural and geophysical counterfactuals;

16. no-event, convergence, extension, mantle-flow, damage, density, thermal, phase, melt, permeability, and anisotropy ablations;
17. leave-one-event-out and leave-one-structure-class-out tests;
18. structural-component interaction analysis;
19. structural effective-complexity accounting;
20. event-to-structure assignment, lag, preservation, switching, and revision penalties;
21. spatial, depth, chronology, and observation-type holdouts;
22. negative structural and geophysical predictions;
23. randomized-event and inherited-state null models;
24. the complete structural-and-geophysical viable set;
25. the structural-and-geophysical replacement falsification matrix; and
26. explicit Plate-Tectonic, astro-ballistic, hybrid, regional, geometric-only, equivalence, and shared-failure outcomes.

The following final Paper-IV sections integrate the full adjudication:

- chronology-wide comparison;
- paleogeographic and continental-reconstruction comparison;
- causal coverage and explanatory scope;
- model evidence and posterior ranking;
- effective degrees of freedom and description length;
- sequence-wide null models;
- multiple-testing and selection-bias controls;
- global advance-prediction comparison;
- hybrid causal decomposition;
- regional versus global outcome classification;
- the complete Paper-IV viable set;
- the formal replacement decision tree;
- Paper-IV claim ledger;
- complete falsification matrix;
- independent replication protocol;
- integrated discussion;
- limitations;

- conclusions;
- appendices;
- and the formal handoff to Paper V.

58 Chronology-Wide Model Comparison

58.1 Chronology Is a Shared Causal Constraint

A model may reproduce modern geometry while assigning incorrect ages to the processes that created it.

Paper IV therefore compares the complete chronology of:

- event initiation;
- boundary formation;
- plate fragmentation;
- plate acceleration and redirection;
- continental displacement;
- mountain building;
- trench development;
- ridge and rift initiation;
- basin subsidence and inversion;
- plateau uplift;
- volcanism;
- terrane transfer;
- suture formation;
- geophysical anomaly development;
- reactivation;
- and termination.

58.2 Global Chronology Vector

Define the shared chronology vector

$$\mathbf{D}_T^{\text{obs}} = (\mathbf{T}_E, \mathbf{T}_B, \mathbf{T}_V, \mathbf{T}_C, \mathbf{T}_O, \mathbf{T}_{TR}, \mathbf{T}_R, \mathbf{T}_{BA}, \mathbf{T}_P, \mathbf{T}_{VO}, \mathbf{T}_{TE}, \mathbf{T}_G)\,. \tag{729}$$

For model q,

$$\widehat{\mathbf{D}}_{T,q} = \mathcal{F}_{T,q}\left[\mathbf{Q}_{q,0}, \mathcal{E}_q, \mathcal{B}_q, \mathbf{V}_q, \mathbf{F}_q, t\right]. \tag{730}$$

58.3 Forward-Time Convention

Let $a \geq 0$ denote age before present, so older states have larger a. Define forward time

$$\tau = a_{\text{start}} - a. \tag{731}$$

Thus a cause preceding an effect satisfies $a_c \geq a_e$ and equivalently $\tau_c \leq \tau_e$. All causal-order tests must state which convention is used.

58.4 Causal Dependency Graph

For model q, define

$$\mathcal{G}_{T,q} = \left(\mathcal{N}_{T,q}, \mathcal{E}_{T,q}\right), \tag{732}$$

where nodes represent dated processes and edges represent required causal precedence.

An edge

$$a \to b \tag{733}$$

states that process a must occur before or condition process b.

58.5 Chronological Violation Indicator

For edge $a \to b$,

$$I^T_{ab,q} = \begin{cases} 1, & \tau^{\text{pred}}_{a,q} > \tau^{\text{pred}}_{b,q} \text{ when } a \text{ must precede } b, \\ 0, & \text{otherwise.} \end{cases} \tag{734}$$

The violation count is

$$N^T_{\text{viol},q} = \sum_{a \to b} I^T_{ab,q}. \tag{735}$$

58.6 Age Residual

For dated observation j,

$$\epsilon_{T,j,q} = \frac{t^{\text{obs}}_j - t^{\text{pred}}_{j,q}}{\sigma_{T,j}}. \tag{736}$$

58.7 Correlated Chronology Misfit

$$\chi^2_{T,q} = \left(\mathbf{D}_T^{\text{obs}} - \widehat{\mathbf{D}}_{T,q}\right)^{\mathsf{T}} \mathbf{\Sigma}_T^{-1} \left(\mathbf{D}_T^{\text{obs}} - \widehat{\mathbf{D}}_{T,q}\right). \tag{737}$$

58.8 Response-Lag Prediction

For causal process a and response b,

$$\Delta t_{a\to b,q} = t_{b,q}^{\text{pred}} - t_{a,q}^{\text{pred}}. \tag{738}$$

The lag must follow from a declared response kernel

$$K_{a\to b,q}\left(t - t_a\right) \tag{739}$$

rather than being independently fitted for each favorable association.

58.9 Change-Point Comparison

Let observed system change points be

$$\mathcal{T}_{\text{change}}^{\text{obs}} = \left\{t_1^*, t_2^*, \ldots, t_{N_*}^*\right\}. \tag{740}$$

For model q,

$$\widehat{\mathcal{T}}_{\text{change},q} = \mathcal{F}_{\text{change},q}\left[\mathbf{Q}_q(t)\right]. \tag{741}$$

The change-point score must include:

- timing;
- affected regions;
- affected plates;
- sign of motion change;
- structural response;
- and duration.

58.10 Chronological Causal Coverage

Define

$$f_{T,q}^{\text{covered}} = \frac{N_{T,q}^{\text{predicted}}}{N_T^{\text{required}}}. \tag{742}$$

A dated observation counts as predicted only when its causal precursor and response interval were declared before the age was used for calibration.

58.11 Temporal Holdout

Fit model q using chronology before cutoff τ_c.

Predict the younger state:

$$\widehat{\mathbf{D}}_{T,q}^{\text{test}} = \mathcal{F}_{T,q}\left[\mathbf{D}_T^{\text{train}}, \tau > \tau_c\right]. \tag{743}$$

58.12 Chronology-Permutation Null

Retain model geometry while permuting event or process ages:

$$\left\{t_k^{(r)}\right\} = \text{Permute}\left[\{t_k\}\right]. \tag{744}$$

The null determines whether chronology contributes information beyond spatial matching.

58.13 Chronology Comparison Score

$$\begin{aligned}\mathcal{J}_{T,q} = {} & w_\chi \widetilde{\chi}_{T,q}^2 + w_{\text{viol}} N_{\text{viol},q}^T + w_{\text{lag}} \chi_{\text{lag},q}^2 \\ & + w_{\text{change}} \chi_{\text{change},q}^2 + w_{\text{cover}}\left(1 - f_{T,q}^{\text{covered}}\right) + w_{\text{pred}} \mathcal{J}_{T,\text{test},q}.\end{aligned} \tag{745}$$

58.14 Chronology-Wide Falsifier

Chronology-wide comparison falsifier T-C1.
A model fails the chronology-wide comparison if it reproduces modern geometry only by assigning causal events after their proposed consequences, fitting independent response lags, or violating independently constrained initiation, reactivation, motion, deformation, or termination ages.

---

59 Paleogeographic and Continental-Reconstruction Comparison

59.1 Present Geography Is Not the Event-Time State

Every model must reconstruct the material domains relevant to each event and process at the applicable time.

For material point $\mathbf{x}_0$ at the present,

$$\mathbf{x}_q(t) = \mathcal{R}_q^{-1}\left[\mathbf{x}_0, t, t_{\text{now}}\right]. \tag{746}$$

59.2 Shared Paleogeographic Dataset

Define

$$\mathbf{D}_C^{\mathrm{obs}}(t) = (\mathcal{P}(t), \mathcal{C}(t), \Gamma_C(t), \mathbf{x}_C(t), \mathbf{R}_C(t), \mathbf{A}_C(t), \mathbf{M}_C(t), \mathbf{X}_C(t), \mathcal{N}_C(t)) . \tag{747}$$

59.3 Model Reconstruction

For model q,

$$\widehat{\mathbf{D}}_{C,q}(t) = \mathcal{F}_{C,q}\left[\mathbf{Q}_{q,0}, \mathcal{B}_q, \mathbf{V}_q, \mathcal{E}_q, t\right]. \tag{748}$$

59.4 Centroid Distance

For continental or terrane domain i,

$$d_{C,i,q}(t) = d_{\mathcal{S}}\left[\mathbf{x}_{C,i}^{\mathrm{obs}}(t), \mathbf{x}_{C,i,q}^{\mathrm{pred}}(t)\right]. \tag{749}$$

59.5 Shape Overlap

$$\mathrm{IoU}_{C,i,q}(t) = \frac{\mathrm{Area}\left[\mathcal{C}_i^{\mathrm{obs}}(t) \cap \mathcal{C}_{i,q}^{\mathrm{pred}}(t)\right]}{\mathrm{Area}\left[\mathcal{C}_i^{\mathrm{obs}}(t) \cup \mathcal{C}_{i,q}^{\mathrm{pred}}(t)\right]}. \tag{750}$$

59.6 Boundary Distance

$$d_{C,\mathrm{ASD},i,q} = d_{\mathrm{ASD}}\left[\Gamma_{C,i}^{\mathrm{obs}}, \Gamma_{C,i,q}^{\mathrm{pred}}\right]. \tag{751}$$

59.7 Rotation Residual

$$\mathbf{R}_{C,i,q}^{\mathrm{res}} = \left[\mathbf{R}_{C,i,q}^{\mathrm{pred}}\right]^{-1} \mathbf{R}_{C,i}^{\mathrm{obs}}. \tag{752}$$

$$\Delta\theta_{C,i,q} = \arccos\left[\frac{\mathrm{tr}\left(\mathbf{R}_{C,i,q}^{\mathrm{res}}\right) - 1}{2}\right]. \tag{753}$$

59.8 Adjacency Comparison

Let

$$\mathbf{A}_C^{\mathrm{obs}}(t) \tag{754}$$

and

$$\mathbf{A}_{C,q}^{\mathrm{pred}}(t) \tag{755}$$

be observed and predicted adjacency matrices.

Define

$$D_{A,C,q} = \frac{\left\| \mathbf{A}_C^{\text{obs}} - \mathbf{A}_{C,q}^{\text{pred}} \right\|_F}{\left\| \mathbf{A}_C^{\text{obs}} \right\|_F}. \tag{756}$$

59.9 Material-Identity Residual

$$\chi^2_{C,\text{mat},q} = \left(\mathbf{X}_C^{\text{obs}} - \mathbf{X}_{C,q}^{\text{pred}} \right)^\top \mathbf{\Sigma}_{C,\text{mat}}^{-1} \left(\mathbf{X}_C^{\text{obs}} - \mathbf{X}_{C,q}^{\text{pred}} \right). \tag{757}$$

59.10 Paleomagnetic Comparison

$$\chi^2_{C,\text{PM},q} = \left(\mathbf{M}_C^{\text{obs}} - \mathbf{M}_{C,q}^{\text{pred}} \right)^\top \mathbf{\Sigma}_{C,\text{PM}}^{-1} \left(\mathbf{M}_C^{\text{obs}} - \mathbf{M}_{C,q}^{\text{pred}} \right). \tag{758}$$

59.11 Fragmentation and Merger Accounting

For continent or block i, define lineage graph

$$\mathcal{G}_{C,i,q}^{\text{lineage}} = \left(\mathcal{V}_{C,i,q}, \mathcal{E}_{C,i,q} \right). \tag{759}$$

The graph must record:

- fragmentation;
- transfer;
- accretion;
- merger;
- internal deformation;
- erosion;
- burial;
- and destruction.

59.12 Material Continuity

For tracked material mass $M_{C,i}$,

$$\frac{dM_{C,i}}{dt} = \dot{M}_{\text{in},i} - \dot{M}_{\text{out},i} + \dot{M}_{\text{create},i} - \dot{M}_{\text{destroy},i}. \tag{760}$$

A reconstruction cannot move a present landmass backward as a rigid polygon when its material identity changed through time without recording that change.

59.13 Event-Time Path Test

For event path $\mathcal{P}_{k,q}(t_k)$ and reconstructed target domain $\mathcal{D}_{k,q}(t_k)$,

$$d_{P,k,q} = \min_{\mathbf{x}\in\mathcal{D}_{k,q}(t_k)} d\left[\mathcal{P}_{k,q}(t_k), \mathbf{x}\right]. \tag{761}$$

A present-coordinate alignment receives no causal credit if it fails in event-time material coordinates.

59.14 Reconstruction Ensemble

For model q, evaluate

$$\left\{\widehat{\mathbf{D}}_{C,q}^{(r)}\right\}_{r=1}^{N_R} \tag{762}$$

across defensible:

- reference frames;
- plate lineages;
- internal deformation models;
- paleomagnetic interpretations;
- boundary uncertainties;
- and missing-material assumptions.

59.15 Paleogeographic Comparison Score

$$\begin{aligned}\mathcal{J}_{C,q} = {} & w_x \widetilde{d}_{C,q} + w_S \sum_i \left(1 - \mathrm{IoU}_{C,i,q}\right) + w_B \widetilde{d}_{C,\mathrm{ASD},q} \\ & + w_R \chi^2_{C,R,q} + w_A D_{A,C,q} + w_M \chi^2_{C,\mathrm{mat},q} \\ & + w_{\mathrm{PM}} \chi^2_{C,\mathrm{PM},q} + w_L \mathcal{P}_{C,\mathrm{lineage},q} + w_P \chi^2_{C,\mathrm{path},q}.\end{aligned} \tag{763}$$

59.16 Paleogeographic Falsifier

Paleogeographic comparison falsifier C-C1.
A model fails the paleogeographic comparison if its proposed causal relationships exist only in modern coordinates, require incompatible plate or terrane lineages, violate material continuity, or fail continental position, rotation, shape, adjacency, and paleomagnetic constraints at the relevant times.

---

60 Causal Coverage and Explanatory Scope

60.1 Coverage Is Not Binary

A model may explain:

- one regional feature;
- one structural class;
- one period of motion;
- selected boundaries;
- or the integrated global system.

Paper IV therefore records both depth and breadth of causal coverage.

60.2 Observation-Class Registry

Let required classes be

$$\mathfrak{D} = \{B, V, C, T, O, TR, R, BA, P, VO, TE, G, P_{\text{adv}}\}. \tag{764}$$

60.3 Coverage Indicator

For class g and model q,

$$I^{\text{cov}}_{g,q} = \begin{cases} 1, & \text{class } g \text{ satisfies its admissibility threshold,} \\ 0, & \text{otherwise.} \end{cases} \tag{765}$$

60.4 Weighted Coverage Fraction

$$f_{\text{cov},q} = \frac{\sum_g w_g I^{\text{cov}}_{g,q}}{\sum_g w_g}. \tag{766}$$

Weights must be frozen before model ranking.

60.5 Causal-Depth Levels

For class g, define causal depth

$$L^C_{g,q} \in \{0, 1, 2, 3, 4, 5, 6\}, \tag{767}$$

corresponding to:

0: No account
The model does not address the observation.

1: Compatibility
The model does not contradict it.

2: Representation
The model encodes or reconstructs it.

3: Kinematic prediction
The model predicts motion or geometric evolution.

4: Dynamic explanation
The model predicts the relevant force, work, or material process.

5: Historical causal organization
The model predicts the process within the complete sequence.

6: Advance prediction
The model predicts withheld or future evidence.

60.6 Mean Causal Depth

$$\overline{L}_q^C = \frac{\sum_g w_g L_{g,q}^C}{\sum_g w_g}. \tag{768}$$

60.7 Causal Chain Completion

For required causal chain

$$\mathcal{C}_{g,q} = (c_1, c_2, \ldots, c_{N_c}), \tag{769}$$

define completion

$$f_{\mathrm{chain},g,q} = \frac{N_{c,g,q}^{\mathrm{supported}}}{N_{c,g}^{\mathrm{required}}}. \tag{770}$$

For the replacement thesis, a representative chain is

$$\text{event} \rightarrow \text{mechanical state} \rightarrow \text{boundary} \rightarrow \text{plate partition} \rightarrow \text{motion} \rightarrow \text{surface and deep structure}. \tag{771}$$

60.8 Unsupported-Link Penalty

Let

$$N_{\mathrm{gap},q} \tag{772}$$

be the number of required causal links represented only by assertion or unconstrained handoff.

Define

$$\mathcal{P}_{\mathrm{gap},q} = \lambda_{\mathrm{gap}} N_{\mathrm{gap},q}. \tag{773}$$

60.9 Regional-Tuning Penalty

Let

$$N_{\mathrm{regional},q} \tag{774}$$

be the number of regional parameter sets not derived from shared physical variation.

Define

$$\mathcal{P}_{\mathrm{regional},q} = \lambda_{\mathrm{regional}} N_{\mathrm{regional},q}. \tag{775}$$

60.10 Explanatory-Scope Score

$$\mathcal{J}_{\mathrm{scope},q} = w_f \left(1 - f_{\mathrm{cov},q}\right) + w_L \left(1 - \frac{\overline{L}_q^C}{6}\right) + w_C \left(1 - \overline{f}_{\mathrm{chain},q}\right) + \mathcal{P}_{\mathrm{gap},q} + \mathcal{P}_{\mathrm{regional},q}. \tag{776}$$

60.11 Scope Falsifier

Causal-scope falsifier COV-C1.
A model does not establish global replacement if its apparent success depends on regional case-by-case explanations, incomplete causal handoffs, or omission of mandatory boundary, motion, chronology, structural, or geophysical domains.

---

61 Model Evidence, Posterior Ranking, and Equivalence

The adjudication distinguishes likelihood fit, information criteria, description length, Bayesian evidence, and out-of-sample prediction [6, 7, 8, 10]. These quantities are not interchangeable and are not averaged merely because they all concern model comparison. Every comparison must preserve a common data domain, observation model, uncertainty convention, and score direction.

61.1 Model Families

The compared family set is

$$\mathfrak{M} = \left\{\mathfrak{M}_{\mathrm{PT}}, \mathfrak{M}_{\mathrm{ABC}}, \mathfrak{M}_{\mathrm{HYB}}, \mathfrak{M}_{\mathrm{REG}}, \mathfrak{M}_0, \mathfrak{M}_{\mathrm{RAND}}\right\}. \tag{777}$$

61.2 Common Comparison Contract

Before any model ranking, freeze

$$\mathbf{C}_{\mathrm{cmp}} = \left(\mathbf{D}_{\mathrm{shared}}, \mathcal{P}_{\mathrm{train/val/test}}, \mathcal{L}_{\mathrm{obs}}, \mathbf{\Sigma}_{\mathrm{obs}}, \Pi_q, \mathcal{S}_{\mathrm{score}}, \mathcal{R}_{\mathrm{missing}}, \mathcal{R}_{\mathrm{direction}}\right), \tag{778}$$

where the record identifies the shared observations, partitioning, likelihood or observation model, uncertainty representation, model priors, scoring rules, missing-data treatment, and whether larger or smaller values are favorable. A Bayes factor is interpretable only when both models address the same registered data under commensurable likelihoods and proper priors. An information criterion is compared only within the data and likelihood domain for which it was computed.

61.3 Marginal Model Evidence

For model $\mathcal{M}_q$,

$$\mathcal{Z}_q = \int p\left(\mathbf{D}_{\text{shared}} \mid \mathbf{\Theta}_q, \mathcal{M}_q\right) p\left(\mathbf{\Theta}_q \mid \mathcal{M}_q\right) \, d\mathbf{\Theta}_q. \tag{779}$$

61.4 Bayes Factor

$$K_{ij} = \frac{\mathcal{Z}_i}{\mathcal{Z}_j}. \tag{780}$$

The interpretation threshold must be declared before inspecting the final evidence ratio.

61.5 Posterior Model Probability

$$p\left(\mathcal{M}_q \mid \mathbf{D}\right) = \frac{\mathcal{Z}_q p(\mathcal{M}_q)}{\sum_j \mathcal{Z}_j p(\mathcal{M}_j)}. \tag{781}$$

The model prior $p(\mathcal{M}_q)$ must be explicit.

61.6 Prior-Sensitivity Analysis

For prior family $\Pi_q^{(r)}$, compute

$$\mathcal{Z}_q^{(r)} = \int \mathcal{L}_q \Pi_q^{(r)} \, d\mathbf{\Theta}_q. \tag{782}$$

The model preference must be reported across defensible prior choices.

61.7 Posterior Predictive Score

$$S_{\text{PP},q} = \log p\left(\mathbf{D}_{\text{test}} \mid \mathbf{D}_{\text{train}}, \mathcal{M}_q\right). \tag{783}$$

61.8 Cross-Validated Model Ranking

For folds $r = 1, \ldots, N_F$,

$$S_{\text{CV},q} = \sum_{r=1}^{N_F} \log p\left(\mathbf{D}_r \mid \mathbf{D}_{-r}, \mathcal{M}_q\right). \tag{784}$$

61.9 Integrated Ranking Vector

Define

$$\mathbf{R}_q = \left(\log \mathcal{Z}_q, S_{\mathrm{PP},q}, S_{\mathrm{CV},q}, -\mathrm{IC}_q, -\mathcal{J}_{IV,q}\right). \tag{785}$$

A final preference should not depend on one unstable statistic.

61.10 No Unregistered Scalar Rank Averaging

The components of $\mathbf{R}_q$ have different scales, assumptions, and uncertainty structures. They must not be arithmetically averaged or converted into a single rank by an unregistered transformation. A scalar summary is admissible only when every component is made dimensionless, its direction and weight are frozen, and sensitivity to those choices is reported.

Absent such a frozen scalarization, comparison proceeds through hard eligibility gates, paired score differences, predictive checks, and the registered vector of results. A model is not declared superior merely because it wins a majority of correlated metrics.

61.11 Equivalence Interval

Define paired differences

$$\Delta\mathcal{J}_{ij} = \mathcal{J}_{IV,i} - \mathcal{J}_{IV,j}, \tag{786}$$

$$\Delta S_{ij} = S_{\mathrm{test},i} - S_{\mathrm{test},j}. \tag{787}$$

Models i and j are operationally equivalent only when the frozen uncertainty interval for the paired loss difference is contained within

$$-\delta_{J,\mathrm{equiv}} \leq \Delta\mathcal{J}_{ij} \leq \delta_{J,\mathrm{equiv}} \tag{788}$$

and the corresponding predictive interval is contained within

$$-\delta_{S,\mathrm{equiv}} \leq \Delta S_{ij} \leq \delta_{S,\mathrm{equiv}}. \tag{789}$$

The margins, interval type, confidence or posterior level, and paired resampling unit must be frozen before final comparison. A small observed point difference alone does not establish equivalence.

61.12 Ranking Probability

$$P_{i<j} = \Pr\left(\mathcal{J}_{IV,i} < \mathcal{J}_{IV,j}\right). \tag{790}$$

61.13 Posterior-Ranking Falsifier

Model-ranking falsifier M-C1.
A replacement preference is not established when the result is unstable across defensible priors, data partitions, reconstruction ensembles, or scoring methods, or when the competing models remain inside the declared equivalence interval.

62 Effective Degrees of Freedom and Description Length

62.1 Raw Parameter Count Is Incomplete

For model q,

$$k_q = \dim\left(\boldsymbol{\Theta}_q\right) \tag{791}$$

does not include all flexibility.

62.2 Effective-Complexity Ledger

Define the registered flexibility vector

$$\begin{aligned}\mathbf{k}_{\text{flex},q} = \big(&k_{\text{numeric},q}, k_{\text{initial},q}, k_{\text{boundary},q}, k_{\text{event},q}, k_{\text{history},q}, k_{\text{regional},q}, k_{\text{assignment},q},\\ &k_{\text{threshold},q}, k_{\text{lag},q}, k_{\text{preservation},q}, k_{\text{branch},q}, k_{\text{frame},q}, k_{\text{revision},q}, k_{\text{selection},q}\big).\end{aligned} \tag{792}$$

This ledger is not automatically an additive estimate of statistical effective degrees of freedom. Categories may overlap, differ in units, or represent discrete search decisions rather than fitted numeric parameters. Any scalar effective-complexity estimate must name its estimator, data domain, and double-counting controls. Description-length penalties provide a separate common unit only when the encoding is frozen and nonoverlapping.

62.3 Event-Catalog Complexity

$$k_{\mathcal{E}} = k_{N_E} + \sum_{j=1}^{N_E}\left(k_{t,j} + k_{x,j} + k_{d,j} + k_{E,j} + k_{M,j} + k_{Q,j} + k_{\text{assign},j}\right). \tag{793}$$

62.4 Initial-State Complexity

$$L_{\text{IC},q} = -\log p\left(\mathbf{Q}_{q,0} \mid \mathcal{M}_q\right). \tag{794}$$

62.5 Boundary-State Complexity

$$L_{B,0,q} = -\log p\left(\mathcal{B}_{q,0} \mid \mathcal{M}_q\right). \tag{795}$$

62.6 Search-Space Complexity

A logarithm cannot be applied meaningfully to a dimensional search volume without a reference measure. For registered resolution or prior cells $\mathcal{V}_{c,q}^{\text{ref}}$, define the dimensionless search multiplicity

$$\widetilde{\mathcal{V}}_{\mathrm{search},q} = \prod_{c\in\{x,t,d,M,S,R\}} \frac{\mathcal{V}_{c,q}}{\mathcal{V}_{c,q}^{\mathrm{ref}}}. \tag{796}$$

The search-description penalty is then

$$L_{\mathrm{search},q} = \log \widetilde{\mathcal{V}}_{\mathrm{search},q}. \tag{797}$$

An equivalent prior-mass formulation may be used, but the reference measure, coordinate transformation, and resolution must be frozen so that reparameterization cannot change the penalty arbitrarily.

62.7 Revision Description Length

For model versions

$$\mathcal{M}_q^{(1)}, \mathcal{M}_q^{(2)}, \ldots, \mathcal{M}_q^{(N_v)}, \tag{798}$$

define

$$L_{\mathrm{rev},q} = \sum_{v=2}^{N_v} L\left(\mathcal{M}_q^{(v)} \mid \mathcal{M}_q^{(v-1)}\right). \tag{799}$$

62.8 Data Description Length

For residual encoding,

$$L\left(\mathbf{D} \mid \mathcal{M}_q\right) = -\log p\left(\mathbf{D} \mid \widehat{\mathbf{\Theta}}_q, \mathcal{M}_q\right). \tag{800}$$

62.9 Total Description Length

$$\begin{aligned} L_{\mathrm{tot},q} = L\left(\mathcal{M}_q\right) &+ L_{\mathrm{IC},q} + L_{B,0,q} + L_{\mathcal{E},q} \\ &+ L_{\mathrm{search},q} + L_{\mathrm{rev},q} + L\left(\mathbf{D} \mid \mathcal{M}_q\right). \end{aligned} \tag{801}$$

62.10 Causal Compression Ratio

Let $I_{\mathbf{D}}$ be the information represented by the shared observation domain.

Define

$$C_q = \frac{I_{\mathbf{D}}}{L_{\mathrm{tot},q}}. \tag{802}$$

62.11 Encoding and Logarithm Convention

All description lengths and information quantities must use the same log base and a declared coding convention. The causal-compression ratio is interpretable only when $I_{\mathbf{D}}$ and $L_{\mathrm{tot},q}$ refer to the same observation domain and compatible encoding. It is a comparative bookkeeping statistic, not an independently measured physical quantity.

62.12 Effective-Flexibility Falsifier

Effective-complexity falsifier M-C2.
A model does not establish causal superiority if its apparent fit advantage disappears after counting initial-state information, event selection, regional tuning, mechanism switching, response lags, preservation functions, reference-frame selection, and post-outcome revision.

63 Sequence-Wide Null Models

63.1 Purpose

The complete replacement claim must outperform null models that preserve relevant geological, chronological, observational, and computational opportunity.

63.2 Null Family

Define

$$\mathfrak{N}_{\mathrm{IV}} = \{\mathcal{N}_0, \mathcal{N}_1, \ldots, \mathcal{N}_{N_N}\}. \tag{803}$$

63.3 Uniform Spatial Null

$$\mathbf{x}_{E,k}^{(r)} \sim p_{\mathrm{uniform}}\left(\mathcal{S}_{\oplus}\right). \tag{804}$$

63.4 Geological-Opportunity Null

$$\mathbf{x}_{E,k}^{(r)} \sim p\left(\mathbf{x} \mid \mathcal{O}_{\mathrm{geological}}\right), \tag{805}$$

where $\mathcal{O}_{\mathrm{geological}}$ preserves comparable exposure, preservation, structural density, and data availability.

63.5 Boundary-Conditioned Null

$$\mathbf{x}_{E,k}^{(r)} \sim p\left(\mathbf{x} \mid d\left[\mathbf{x}, \mathcal{B}^{\mathrm{obs}}\right] \le d_{B,\max}\right). \tag{806}$$

This tests whether apparent success results simply from selecting geologically complex boundary regions.

63.6 Plate-Preserving Null

$$\mathbf{x}_{E,k}^{(r)} \sim p\left(\mathbf{x} \mid \mathcal{P}_{i(k)}(t_k)\right). \tag{807}$$

63.7 Chronology-Permutation Null

$$\left\{t_k^{(r)}\right\} = \text{Permute}\left[\{t_k\}\right]. \tag{808}$$

63.8 Direction-Randomization Null

$$\widehat{\mathbf{d}}_{E,k}^{(r)} \sim p_{\text{orient}}\left(\widehat{\mathbf{d}}\right). \tag{809}$$

63.9 Event-to-Structure Assignment Null

Retain events and structures but randomize their assignments:

$$\pi^{(r)} : \mathcal{E} \to \mathcal{S}. \tag{810}$$

63.10 Inherited-State Randomization Null

$$\mathbf{Q}_0^{(r)} = \text{Shuffle}\left[\mathbf{Q}_0\right] \tag{811}$$

while preserving the global distributions of:

- weakness;
- density;
- temperature;
- damage;
- anisotropy;
- and boundary mobility.

63.11 Topology-Preserving Null

Retain network node degree and edge count while randomizing geographic embedding:

$$\mathcal{G}_B^{(r)} \sim p\left(\mathcal{G} \mid p_{\text{degree}}, N_E, N_V\right). \tag{812}$$

63.12 Reference-Frame Null

Test whether model preference results from a selected frame by sampling

$$\mathcal{R}_f^{(r)} \sim p\left(\mathfrak{R}_{\text{defensible}}\right). \tag{813}$$

63.13 Complete Null Score

For null realization r,

$$\mathcal{J}_{IV,q}^{(r)} = \mathcal{J}_{\text{IV}}\left[\mathcal{N}^{(r)}, \mathcal{M}_q\right]. \tag{814}$$

63.14 Empirical Null Probability

$$p_{IV,q,\mathrm{null}} = \frac{1 + \sum_{r=1}^{N_R} \mathbf{1}\left[\mathcal{J}_{IV,q}^{(r)} \le \mathcal{J}_{IV,q}^{\mathrm{obs}}\right]}{N_R + 1}. \tag{815}$$

63.15 Full-Pipeline Null Exchangeability

The plus-one empirical probability is valid only when the observed and null realizations are exchangeable under the declared null. Each null realization must therefore rerun every search, assignment, threshold, reference-frame choice, and model-selection step that was available to the observed analysis. Randomizing only the final coordinates while retaining an outcome-informed selected pipeline understates the null opportunity space.

63.16 Class-Specific Nulls

For observation class g,

$$p_{g,q,\mathrm{null}} = \frac{1 + \sum_{r} \mathbf{1}\left[\mathcal{J}_{g,q}^{(r)} \le \mathcal{J}_{g,q}^{\mathrm{obs}}\right]}{N_R + 1}. \tag{816}$$

63.17 Null-Model Falsifier

Sequence-wide null falsifier N-C1.
The proposed sequence does not establish special causal organization if randomized, opportunity-matched, boundary-conditioned, plate-preserving, chronology-permuted, or assignment-shuffled models reproduce the integrated result with comparable frequency.

64 Multiple Testing, Selection Bias, and Revision Accounting

64.1 Complete Search Ledger

The search ledger must report:

- all candidate events;
- all tested entrance points;
- all tested terminal points;
- all tested midpoint or response targets;
- all tested ages;
- all tested path widths;
- all tested mechanism branches;
- all tested plate assignments;
- all tested boundary thresholds;
- all tested structure assignments;

- all reconstruction models;
- all reference frames;
- all score definitions;
- all excluded regions;
- and all major revisions.

64.2 Selection Record

For decision s,

$$\mathbf{L}_s = (\text{candidate}, \text{decision time}, \text{data visible}, \text{selection rule}, \text{alternatives}, \text{result}) . \tag{817}$$

64.3 Confirmatory Family Definition

Before correction, register the confirmatory hypothesis family, its unit of multiplicity, and the level at which error is controlled. Exploratory maps, branch screening, component diagnostics, and the final replacement decision are not silently pooled into one convenient denominator or split into many smaller families after results are visible. Hard physical admissibility checks are reported as physical constraints, not converted into significance tests merely to enter a multiple-testing procedure.

64.4 Family-Wise Error

For m independent tests with per-test error α_{ind},

$$\alpha_{\text{FWER}} = 1 - (1 - \alpha_{\text{ind}})^m . \tag{818}$$

A conservative threshold is

$$\alpha_{\text{ind}} = \frac{\alpha_{\text{family}}}{m}. \tag{819}$$

The independence expression is illustrative rather than universal. Dependence-aware permutation, max-statistic, or other resampling control is preferred for spatially and chronologically correlated tests.

64.5 False-Discovery Control

False-discovery control is reported with its dependence assumptions and is supplemented by resampling where the tests are correlated [9].

For ordered probabilities

$$p_{(1)} \leq p_{(2)} \leq \cdots \leq p_{(m)}, \tag{820}$$

retain the largest k satisfying

$$p_{(k)} \leq \frac{k}{m} q_{\text{FDR}} \tag{821}$$

when the assumptions of the chosen procedure are satisfied.

64.6 Selection-Adjusted Probability

Define

$$p_{\text{sel}} = \Pr\left(T_{\max} \geq T_{\text{obs}} \mid \mathcal{N}, \mathcal{S}_{\text{search}}\right), \tag{822}$$

where $T_{\max}$ is the best score obtained over the complete declared search.

64.7 Holdout Depletion

Let original independent test data be

$$\mathbf{D}_{\text{test}}^{(0)}. \tag{823}$$

After revision v, data previously examined are removed:

$$\mathbf{D}_{\text{test}}^{(v)} = \mathbf{D}_{\text{test}}^{(v-1)} \setminus \mathbf{D}_{\text{viewed}}^{(v)}. \tag{824}$$

A repeatedly inspected holdout set becomes calibration data.

64.8 Model-Version Registry

$$\mathcal{M}_q^{(1)}, \mathcal{M}_q^{(2)}, \ldots, \mathcal{M}_q^{(N_v)}. \tag{825}$$

Each version must record:

- modification;
- reason;
- data viewed;
- affected claims;
- affected parameters;
- and new validation requirement.

64.9 Stopping Rule

The analysis must state whether model development stopped because:

- a preregistered endpoint was reached;
- all planned tests were completed;
- computational resources ended;
- a model was falsified;
- or a favorable result appeared.

64.10 Selection-Bias Falsifier

Selection-and-revision falsifier N-C2.
A confirmatory replacement result is invalid if the event catalog, target structures, chronology, comparison model, score, or decision threshold was selected after outcome inspection without correction and new independent validation.

---

65 Global Advance-Prediction Comparison

65.1 Prediction Registry

Every advance prediction must be frozen as

$$\mathbf{P}_{j,q} = (\text{model}, \text{claim}, \text{location}, \text{depth}, \text{orientation}, \text{magnitude}, \text{age}, \text{uncertainty}, \text{control}, \text{falsifier}) \,. \tag{826}$$

65.2 Required Prediction Classes

The final comparison should include predictions of:

AP1. unknown or concealed boundary continuations;

AP2. boundary type and motion;

AP3. plate or block velocity;

AP4. Euler-pole direction;

AP5. subsurface damage corridors;

AP6. crustal-thickness structure;

AP7. mountain roots;

AP8. deep trench continuity;

AP9. ridge or rift segmentation;

AP10. basin subsidence;

AP11. volcanic pathways;

AP12. terrane ancestry;

AP13. gravity anomalies;

AP14. seismic velocity;

AP15. seismic anisotropy;

AP16. magnetic resetting;

AP17. heat-flow anomalies;

AP18. and explicit negative-control regions.

65.3 Predictive Distribution

$$p\left(\mathbf{D}_{\text{new}} \mid \mathbf{D}_{\text{train}}, \mathcal{M}_q\right) = \int p\left(\mathbf{D}_{\text{new}} \mid \boldsymbol{\Theta}_q, \mathcal{M}_q\right) p\left(\boldsymbol{\Theta}_q \mid \mathbf{D}_{\text{train}}, \mathcal{M}_q\right)\, d\boldsymbol{\Theta}_q. \tag{827}$$

65.4 Continuous Predictive Score

For a registered multivariate Gaussian predictive distribution of dimension d_j, use the complete log score

$$\begin{aligned} S^{\text{cont}}_{j,q} = -\frac{1}{2}\Big[&\left(\mathbf{y}^{\text{obs}}_j - \mathbf{y}^{\text{pred}}_{j,q}\right)^{\mathsf{T}} \boldsymbol{\Sigma}^{-1}_{j,q} \left(\mathbf{y}^{\text{obs}}_j - \mathbf{y}^{\text{pred}}_{j,q}\right) \\ &+ \log\det\left(2\pi \boldsymbol{\Sigma}_{j,q}\right)\Big]. \end{aligned} \tag{828}$$

The determinant term is required when models predict different uncertainties; otherwise an overdispersed model can be rewarded without paying for its lack of resolution. Non-Gaussian predictions must use a proper score for their declared predictive distribution.

65.5 Binary Predictive Score

$$S^{\text{bin}}_{j,q} = y_j \log p_{j,q} + (1 - y_j)\log\left(1 - p_{j,q}\right). \tag{829}$$

65.6 Spatial Prediction Score

For predicted probability field $p_q(\mathbf{x})$,

$$S_{\text{spatial},q} = \sum_j \log p_q\left(\mathbf{x}^{\text{obs}}_j\right) - \lambda_A A^{\text{pred}}_q. \tag{830}$$

The area penalty prevents uninformative prediction of broad regions.

65.7 Proper-Score Requirement

The spatial area penalty, binary score, and continuous score must be frozen as proper or demonstrably calibrated scoring rules for the registered observation process. Any tuning constant such as λ_A must be selected without test-data leakage and subjected to sensitivity analysis. A score that can be improved by deliberately misstating predictive uncertainty is ineligible for replacement ranking.

65.8 Calibration

The area penalty prevents uninformative prediction of broad regions.

65.9 Calibration

For probability level p,

$$\Pr(Y = 1 \mid p_q = p) \approx p. \tag{831}$$

65.10 Resolution

A model must state prediction width or uncertainty.

A prediction covering most of the globe is less informative than a narrow prediction with the same hit outcome.

65.11 Negative Predictions

Each model must publish domains

$$\mathcal{D}_q^0 \tag{832}$$

where the claimed structure or anomaly should not occur.

False positives in those domains count against the model.

65.12 Prospective Validation

The strongest validation uses data acquired or released after the prediction freeze.

Examples include:

- new seismic surveys;
- new gravity products;
- new drilling;
- new geochronology;
- new structural mapping;
- new paleomagnetic results;
- and new exploration outcomes.

65.13 Prediction Comparison

Model i predictively outperforms model j when

$$S_{\mathrm{adv},i} - S_{\mathrm{adv},j} > \Delta S_{\mathrm{adv,crit}} \tag{833}$$

with a predeclared uncertainty threshold.

65.14 Advance-Prediction Falsifier

Advance-prediction falsifier P-C1.
A model does not establish replacement if it reconstructs known observations but fails registered spatial, chronological, structural, or geophysical predictions, performs no better than comparison models, or obtains success only through excessively broad prediction domains.

66 Hybrid Causal Decomposition

66.1 Hybrid Models Require Explicit Attribution

The hybrid state is

$$\mathbf{Q}_{\mathrm{HYB}} = \mathcal{F}_H \left[\mathbf{Q}_{\mathrm{PT}}, \mathbf{Q}_{\mathrm{ABC}}, \mathbf{Q}_{\mathrm{int}}\right]. \tag{834}$$

The combination is not assumed to be linear.

66.2 Parent Ablations

Define:

$$\mathcal{M}_{H,-\mathrm{ABC}} = \text{hybrid without astro-ballistic inheritance,} \tag{835}$$

$$\mathcal{M}_{H,-\mathrm{PT}} = \text{hybrid without the declared Plate-Tectonic component,} \tag{836}$$

$$\mathcal{M}_{H,-\mathrm{int}} = \text{hybrid without interaction terms.} \tag{837}$$

66.3 Parent Necessity

$$N_{\mathrm{ABC}|H} = \mathcal{J}_{H,-\mathrm{ABC}} - \mathcal{J}_H, \tag{838}$$

$$N_{\mathrm{PT}|H} = \mathcal{J}_{H,-\mathrm{PT}} - \mathcal{J}_H, \tag{839}$$

$$N_{\mathrm{int}|H} = \mathcal{J}_{H,-\mathrm{int}} - \mathcal{J}_H. \tag{840}$$

Because lower $\mathcal{J}$ is better, positive values indicate that removing the named component worsens the hybrid. Hybrid necessity is a conjunctive criterion rather than a sum:

$$N_H^{\min} = \min\left(N_{\mathrm{ABC}|H}, N_{\mathrm{PT}|H}, N_{\mathrm{int}|H}\right), \tag{841}$$

with each component compared against its own preregistered threshold. One very large contribution cannot compensate for an unnecessary parent or interaction term.

66.4 Interaction Difference-in-Differences Diagnostic

$$N_{\mathrm{ABC}\times\mathrm{PT}} = \mathcal{J}_{H,-\mathrm{ABC}} + \mathcal{J}_{H,-\mathrm{PT}} - \mathcal{J}_{H,-\mathrm{ABC},-\mathrm{PT}} - \mathcal{J}_{H}. \tag{842}$$

This difference-in-differences quantity is scale- and parameterization- dependent. Its sign is descriptive only unless the loss scale, refitting rule, and ablation estimand are frozen. The primary test of interaction necessity remains $N_{\mathrm{int}|H} = \mathcal{J}_{H,-\mathrm{int}} - \mathcal{J}_{H}$ under a matched refit; the diagnostic above cannot by itself establish joint causation.

66.5 Observation-Class Attribution

For class g,

$$\Delta\mathcal{J}_{g,\mathrm{ABC}|H} = \mathcal{J}_{g,H,-\mathrm{ABC}} - \mathcal{J}_{g,H}, \tag{843}$$

and

$$\Delta\mathcal{J}_{g,\mathrm{PT}|H} = \mathcal{J}_{g,H,-\mathrm{PT}} - \mathcal{J}_{g,H}. \tag{844}$$

66.6 Dominance Fraction

Let $[x]_+ = \max(x, 0)$. When at least one parent has a positive registered necessity contribution for observation class g, define

$$f^{H}_{\mathrm{ABC},g} = \frac{[\Delta\mathcal{J}_{g,\mathrm{ABC}|H}]_+}{[\Delta\mathcal{J}_{g,\mathrm{ABC}|H}]_+ + [\Delta\mathcal{J}_{g,\mathrm{PT}|H}]_+}. \tag{845}$$

If both positive parts are zero, the dominance fraction is undefined and no parent dominance is claimed. This restriction prevents negative or negligible ablation contributions from producing fractions outside the unit interval.

66.7 Hybrid Outcome Classes

The hybrid may be classified as:

Event initiated
: Events generate the architecture and later geodynamics maintain it.

Event localized
: Events determine where later geodynamic processes concentrate.

Event redirected
: Events materially change an existing boundary or motion system.

Event amplified
: Events strengthen a process already operating.

Event regional
: Event effects are necessary only in selected regions.

Event incidental
: Removing event inheritance produces negligible degradation.

Event incompatible
: Event inheritance worsens the physically admissible solution.

66.8 Hybrid Complexity Requirement

The hybrid must outperform both parents after including:

$$k_{\mathrm{eff},H} = k_{\mathrm{shared}} + k_{\mathrm{ABC,unique}} + k_{\mathrm{PT,unique}} + k_{\mathrm{interaction}}. \tag{846}$$

66.9 Hybrid Search and Revision Parity

The hybrid complexity ledger must include not only its fitted parameters but also parent selection, interaction-form search, branch switching, regional allocation, reference-frame choice, threshold tuning, and all post-outcome revisions. A hybrid is not favored by comparing its best searched version against frozen untuned parent versions.

66.10 Hybrid Falsifier

Hybrid causal-decomposition falsifier H-C1.
A hybrid result does not establish joint causation when one parent component is unnecessary under global ablation, when interaction terms are not predictive, or when the hybrid advantage disappears after its combined flexibility is counted.

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67 Regional Versus Global Classification

67.1 Regional Domains

Partition the globe into regions

$$\mathfrak{R}_G = \{\mathcal{R}_1, \mathcal{R}_2, \ldots, \mathcal{R}_{N_R}\}. \tag{847}$$

For region r and model q, define

$$\mathcal{J}_{r,q}. \tag{848}$$

67.2 Regional Viability

$$\mathcal{V}_{r,q} = \{\boldsymbol{\Theta}_q : \mathcal{J}_{r,q} \le \mathcal{J}_{r,\mathrm{crit}}\}. \tag{849}$$

67.3 Global Viability

Global viability requires

$$\mathcal{V}_{\text{global},q} = \bigcap_{r=1}^{N_R} \mathcal{V}_{r,q} \neq \varnothing \tag{850}$$

for mandatory regions and observation classes.

67.4 Transferability Score

Fit parameters in region r and test region s:

$$S_{r\to s,q} = \log p\left(\mathbf{D}_s \mid \widehat{\boldsymbol{\Theta}}_{q,r}, \mathcal{M}_q\right). \tag{851}$$

67.5 Parameter Heterogeneity

For region-specific posterior mean $\boldsymbol{\mu}_{r,q}$,

$$H_{\Theta,q} = \frac{1}{N_R}\sum_r \left(\boldsymbol{\mu}_{r,q} - \boldsymbol{\mu}_q^{\text{global}}\right)^{\mathsf{T}} \boldsymbol{\Sigma}_{\Theta,q}^{-1} \left(\boldsymbol{\mu}_{r,q} - \boldsymbol{\mu}_q^{\text{global}}\right). \tag{852}$$

67.6 Regional Contribution Fraction

$$f_{\text{regional},q} = \frac{\sum_r w_r I_{r,q}^{\text{supported}}}{\sum_r w_r}. \tag{853}$$

67.7 Global Classification Rules

A model is:

Global
: One common parameter architecture succeeds across mandatory regions.

Multi-regional
: The model succeeds in multiple regions with limited shared parameter variation.

Regional
: The model succeeds in one or a few regions but fails global transfer.

Local
: The model explains one structure or locality.

Geometric only
: Spatial agreement survives, but physical, chronological, or predictive tests fail.

Unsupported
: The viable regional set is empty.

67.8 Regional-to-Global Falsifier

Regional-to-global falsifier R-C1.
Regional event support does not establish global replacement when the same parameter architecture fails transfer to other regions, requires independent regional tuning, or produces an empty intersection across the mandatory global observation domain.

68 Complete Paper-IV Viability

68.1 Eligibility Sets and Qualification Gates

Define the physical and historical eligibility sets

$$\mathcal{V}^{\mathrm{IV}}_{B,q} = \text{boundary viable set,} \tag{854}$$
$$\mathcal{V}^{\mathrm{IV}}_{V,q} = \text{motion viable set,} \tag{855}$$
$$\mathcal{V}^{\mathrm{IV}}_{SG,q} = \text{structural and geophysical viable set,} \tag{856}$$
$$\mathcal{V}^{\mathrm{IV}}_{T,q} = \text{chronology viable set,} \tag{857}$$
$$\mathcal{V}^{\mathrm{IV}}_{C,q} = \text{paleogeographic viable set.} \tag{858}$$

Null control, advance prediction, complexity-adjusted preference, causal necessity, and replication are qualification gates rather than parameter sets. Register

$$\mathbf{G}_{IV,q} = \left(G_{N,q}, G_{P,q}, G_{K,q}, G_{C,q}, G_{R,q}\right), \tag{859}$$

where each gate has status `PASS`, `FAIL`, or `UNRESOLVED` under its frozen T3 or T4 rule.

68.2 Complete Model Eligibility Set

For model q,

$$\mathcal{V}^{\mathrm{elig}}_{IV,q} = \mathcal{V}^{\mathrm{IV}}_{B,q} \cap \mathcal{V}^{\mathrm{IV}}_{V,q} \cap \mathcal{V}^{\mathrm{IV}}_{SG,q} \cap \mathcal{V}^{\mathrm{IV}}_{T,q} \cap \mathcal{V}^{\mathrm{IV}}_{C,q}. \tag{860}$$

A failed or unresolved qualification gate can prevent replacement qualification without emptying a physically nonempty eligibility set.

68.3 Astro-Ballistic Eligibility

For one preregistered candidate sequence $\mathcal{S}$, define $\mathcal{V}^{\mathrm{elig}}_{IV,\mathcal{S},\mathrm{ABC}}$ as the complete Paper-IV viable set for the astro-ballistic model member built from that sequence. Eligibility requires

$$\left[\bigcap_{k\in\mathcal{S}} \left(\mathcal{V}_{I,k} \cap \mathcal{V}_{II,k}\right)\right] \cap \mathcal{V}_{III,\mathcal{S}} \cap \mathcal{V}^{\mathrm{elig}}_{IV,\mathcal{S},\mathrm{ABC}} \neq \varnothing. \tag{861}$$

The astro-ballistic Paper-IV model-family viable set is

$$\mathcal{V}_{IV,\mathrm{ABC}}^{\mathrm{elig}} = \bigcup_{\mathcal{S}\in\mathfrak{S}_{\mathrm{elig}}} \mathcal{V}_{IV,\mathcal{S},\mathrm{ABC}}^{\mathrm{elig}}. \tag{862}$$

68.4 Shared Parameter Intersection

For required parameter θ_j, define class-specific intervals

$$\Theta_j^B, \Theta_j^V, \Theta_j^{SG}, \Theta_j^T, \Theta_j^C, \Theta_j^P. \tag{863}$$

The common interval is

$$\Theta_j^* = \Theta_j^B \cap \Theta_j^V \cap \Theta_j^{SG} \cap \Theta_j^T \cap \Theta_j^C \cap \Theta_j^P. \tag{864}$$

If

$$\Theta_j^* = \varnothing, \tag{865}$$

the integrated model fails for parameter j.

68.5 Posterior Overlap

For component posteriors $p_g(\mathbf{\Theta})$,

$$\mathcal{O}_{IV,q} = \int \min_g \left[p_g\left(\mathbf{\Theta}_q\right)\right] \, d\mathbf{\Theta}_q. \tag{866}$$

Near-zero overlap indicates that different observation classes require incompatible model states.

68.6 Complete Adjudication Score

$$\begin{aligned}
\mathcal{J}_{IV,q} = {} & w_B \mathcal{J}_{B,q} + w_V \mathcal{J}_{V,q} + w_{SG} \mathcal{J}_{SG,q} + w_T \mathcal{J}_{T,q} \\
& + w_C \mathcal{J}_{C,q} + w_{\mathrm{scope}} \mathcal{J}_{\mathrm{scope},q} + \mathcal{P}_{\mathrm{phys},q} \\
& + \mathcal{P}_{\mathrm{complex},q} + \mathcal{P}_{\mathrm{null},q} + \mathcal{P}_{\mathrm{selection},q} \\
& + \mathcal{P}_{\mathrm{causal},q} + \mathcal{P}_{\mathrm{prediction},q} + \mathcal{P}_{\mathrm{replication},q}.
\end{aligned} \tag{867}$$

68.7 Primary Replacement Condition

After the comparative threshold-freeze record is complete, the astro-ballistic model qualifies as a primary replacement candidate only if

$$\mathcal{V}_{IV,\mathrm{ABC}}^{\mathrm{elig}} \neq \varnothing \tag{868}$$

and

$$\mathcal{J}_{IV,\mathrm{ABC}} < \mathcal{J}_{IV,\mathrm{PT}} - \delta_{\mathrm{IV}} \tag{869}$$

and

$$S_{\mathrm{adv,ABC}} > S_{\mathrm{adv,PT}} + \Delta S_{\mathrm{adv,crit}} \tag{870}$$

and

$$N_{\mathrm{ABC}} > N_{\mathrm{ABC,crit}}. \tag{871}$$

If the viable set is nonempty but one or more comparative inequalities are not met, replacement is not established or is disfavored; the nonempty model is not thereby converted into a physically falsified model.

68.8 Qualification-Gate Conjunction

In addition to nonempty eligibility and the frozen comparative inequalities, primary replacement qualification requires

$$G_{N,\mathrm{ABC}} = G_{P,\mathrm{ABC}} = G_{K,\mathrm{ABC}} = G_{C,\mathrm{ABC}} = G_{R,\mathrm{ABC}} = \mathtt{PASS}. \tag{872}$$

A `FAIL` gate yields scoped non-qualification or `DISFAVORED` status according to its registered consequence. An `UNRESOLVED` gate yields `NOT-ESTABLISHED` or `UNRESOLVED`, not model falsification.

68.9 Hybrid Preference Condition

The hybrid is preferred only if

$$\mathcal{J}_{IV,\mathrm{HYB}} < \min\left[\mathcal{J}_{IV,\mathrm{PT}}, \mathcal{J}_{IV,\mathrm{ABC}}\right] - \delta_H \tag{873}$$

under a frozen T4 margin, after effective complexity is counted, and both parent contributions and their interaction are necessary under predeclared ablations. Otherwise hybrid preference is not established.

68.10 Complete-Viability Decision

Complete Paper-IV viability and replacement decision.
A frozen global astro-ballistic model version is rejected when a completed valid test yields an empty eligibility set, or when mandatory observation classes require incompatible parameter states or hard physical or chronological violations.
If the eligibility set is nonempty but a qualification gate fails or remains unresolved, primary replacement is disfavored, not established, or unresolved according to the frozen gate consequence. That outcome does not convert a physically admissible model into a physically falsified model and does not erase independently surviving claims.

69 Formal Replacement Decision Tree

69.1 Decision Step 1: Mechanical Eligibility

Evaluate:

$$\mathcal{V}_{II} \neq \varnothing. \tag{874}$$

If false:

$$\text{Global astro-ballistic replacement rejected.} \tag{875}$$

69.2 Decision Step 2: Global Reconstruction Eligibility

Evaluate:

$$\mathcal{V}_{\mathrm{III}} \neq \varnothing. \tag{876}$$

If false:

$$\text{Global replacement rejected; regional claims remain separable.} \tag{877}$$

69.3 Decision Step 3: Boundary Viability

Evaluate:

$$\mathcal{V}^{\mathrm{IV}}_{B,\mathrm{ABC}} \neq \varnothing. \tag{878}$$

If false:

$$\text{Boundary-origin replacement rejected.} \tag{879}$$

69.4 Decision Step 4: Motion Viability

Evaluate:

$$\mathcal{V}^{\mathrm{IV}}_{V,\mathrm{ABC}} \neq \varnothing. \tag{880}$$

If false:

$$\text{Plate-motion replacement rejected.} \tag{881}$$

69.5 Decision Step 5: Structural and Geophysical Viability

Evaluate:

$$\mathcal{V}^{\mathrm{IV}}_{SG,\mathrm{ABC}} \neq \varnothing. \tag{882}$$

If false:

$$\text{Global structural replacement rejected.} \tag{883}$$

69.6 Decision Step 6: Chronology and Paleogeography

Evaluate:

$$\mathcal{V}^{\mathrm{IV}}_{T,\mathrm{ABC}} \cap \mathcal{V}^{\mathrm{IV}}_{C,\mathrm{ABC}} \neq \varnothing. \tag{884}$$

If false:

$$\text{Historical causal sequence rejected.} \tag{885}$$

69.7 Decision Step 7: Null and Selection Control

Evaluate:

$$p_{IV,\mathrm{ABC},\mathrm{null}} < \alpha_{\mathrm{crit}} \tag{886}$$

after complete search-space correction.

If false:

$$\text{Special event-sequence significance unsupported.} \tag{887}$$

69.8 Decision Step 8: Causal Necessity

Evaluate:

$$N_{\text{ABC}} > N_{\text{ABC,crit}}. \tag{888}$$

If false:

$$\text{Astro-ballistic inheritance is not primary.} \tag{889}$$

69.9 Decision Step 9: Predictive Performance

Evaluate:

$$S_{\text{adv,ABC}} > S_{\text{adv,PT}} + \Delta S_{\text{adv,crit}}. \tag{890}$$

If false:

$$\text{Replacement prediction standard not met.} \tag{891}$$

69.10 Decision Step 10: Complexity-Adjusted Preference

Evaluate:

$$\mathcal{J}_{IV,\text{ABC}} < \mathcal{J}_{IV,\text{PT}} - \delta_{\text{IV}}. \tag{892}$$

If false and models are equivalent:

$$\text{Causal non-resolution.} \tag{893}$$

If the Plate-Tectonic model performs better:

$$\text{Plate-Tectonic preference.} \tag{894}$$

69.11 Decision Step 11: Hybrid Comparison

Evaluate:

$$\mathcal{J}_{IV,\text{HYB}} < \min\left[\mathcal{J}_{IV,\text{ABC}}, \mathcal{J}_{IV,\text{PT}}\right] - \delta_H. \tag{895}$$

Then evaluate parent and interaction necessity.

69.12 Decision Step 12: Replication

Evaluate whether independent teams reproduce:

- the model ranking;
- the viable parameter intersection;
- the causal ablations;
- the null-model result;
- and the advance-prediction score.

69.13 Final Outcome Classification

The final result must be one of:

IV-A: Model-version rejected
A completed valid test produces an empty eligibility set or a hard physical, chronological, or shared-parameter contradiction.

IV-B: Local or regional
Selected event-derived hypotheses survive without global replacement.

IV-C: Complementary
Event inheritance improves selected classes while Plate Tectonics remains the primary framework.

IV-D: Hybrid preferred
Both causal architectures and their interaction are necessary after matched ablation and complexity control.

IV-E: Causal equivalence
Frozen uncertainty intervals remain inside the equivalence margins.

IV-F: Replacement not established or disfavored
Eligibility survives, but one or more comparative qualification gates are unresolved or fail.

IV-G: Astro-ballistic replacement candidate
The candidate achieves nonempty eligibility, passes every mandatory qualification gate, and shows clear adjusted superiority.

IV-H: Shared failure
None of the tested models adequately explains the complete evidence domain.

69.14 Formal Decision Rule

Formal replacement decision rule.
Astro-Ballistic Chronostratigraphic Sequencing qualifies as a primary causal-replacement candidate only if one mechanically admissible, chronologically ordered, and paleogeographically valid event sequence generates the boundary network, plate-motion field, continental reconstruction, surface structures, and deep geophysical state from a shared parameter architecture; remains necessary under ablation; outperforms realistic null models; predicts withheld evidence; survives effective-complexity penalties; and achieves a clear, independently replicated advantage over the strongest defensible Plate-Tectonic comparison model.
Any weaker result must be classified as not established, disfavored, regional, complementary, hybrid, equivalent, unresolved, or rejected according to the exact failed or unresolved gate.

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70 Paper-IV Claim Ledger

Table 5: Paper-IV claim ledger.

ID	Class	Claim	Current status
P4-C01	Shared evidence	Observed continental and plate motion is accepted by all compared model families.	Framework position
P4-C02	Comparison burden	The disputed question is primary causal organization rather than the existence of motion.	Framework position
P4-C03	Eligibility	The replacement model must survive Papers I through III before direct comparison.	Requirement defined
P4-C04	Fair comparison	All model families must predict the same frozen observation domain.	Requirement defined
P4-C05	Comparison strength	The candidate must be compared with strong defensible Plate-Tectonic implementations rather than a weakened caricature.	Requirement defined
P4-C06	Boundary origin	Boundary generation must be distinguished from boundary-conditioned motion prediction.	Requirement defined
P4-C07	Initial conditions	Information inserted through initial boundaries and heterogeneity must count as model complexity.	Requirement defined

ID	Class	Claim	Current status
P4-C08	Motion generation	Euler poles and plate velocities must be generated rather than inserted as free causal solutions.	Requirement defined
P4-C09	Impulse	An ancient impulse cannot be treated as perpetual unattenuated power.	Physical requirement
P4-C10	Motion maintenance	Present motion requires explicit force, torque, power, resistance, and dissipation accounting.	Requirement defined
P4-C11	Boundary viability	The astro-ballistic model is hypothesized to generate a globally adequate boundary network.	Untested
P4-C12	Motion viability	The astro-ballistic model is hypothesized to generate the global plate-motion field.	Untested
P4-C13	Structural viability	The same event model is hypothesized to predict mountains, trenches, ridges, basins, plateaus, volcanism, and terrane assembly.	Untested
P4-C14	Geophysical viability	The model can predict compatible gravity, seismic, magnetic, and heat-flow fields.	Untested
P4-C15	Chronology	The event sequence can predict the temporal order of the global geological system.	Untested
P4-C16	Paleogeography	The candidate relationships survive reconstruction into event-time material coordinates.	Untested
P4-C17	Material continuity	The reconstruction preserves plate, terrane, and continental material lineage.	Untested
P4-C18	Causal coverage	One shared event model explains the mandatory global observation classes.	Untested
P4-C19	Causal necessity	Removing astro-ballistic inheritance materially degrades the successful model.	Untested
P4-C20	Plate-Tectonic necessity	The defining comparison-model components are necessary for its successful outputs.	Untested
P4-C21	Hybrid necessity	A preferred hybrid requires both parent components and their interaction.	Untested

ID	Class	Claim	Current status
P4-C22	Statistical significance	The proposed sequence outperforms realistic opportunity-matched null models.	Untested
P4-C23	Selection control	The comparative result survives complete search-space and revision accounting.	Untested
P4-C24	Complexity	The astro-ballistic model retains its advantage after effective flexibility is counted.	Untested
P4-C25	Prediction	The candidate is hypothesized to predict withheld observations better than comparison models.	Untested
P4-C26	Regional classification	Regional success is separable from global replacement.	Architecture defined
P4-C27	Equivalence	The framework permits an explicit causal non-resolution result.	Architecture defined
P4-C28	Replication	Independent teams can reproduce the principal comparative result.	Untested
P4-C29	Replacement	The complete astro-ballistic viable set is nonempty and superior.	Unknown
P4-C30	Paper-V dependency	The complete claim, equation, data, and falsification dependencies can be represented in the companion atlas.	Reserved for Paper V

71 Complete Paper-IV Falsification Matrix

Table 6: Complete integrated Paper-IV falsification matrix.

ID	Replacement claim	Falsifying result	Consequence
P4-F01	Event-mechanics eligibility	One required event lies outside its mechanically viable set.	Reject every candidate sequence requiring that event; reject global replacement only if no eligible sequence remains.

ID	Replacement claim	Falsifying result	Consequence
P4-F02	Paper-III global eligibility	Every preregistered eligible global reconstruction has an empty viable set.	Reject the global replacement model family while retaining separately viable regional or complementary claims.
P4-F03	Boundary generation	The candidate cannot generate persistent connected boundaries.	Reject boundary-origin replacement.
P4-F04	Boundary geometry	Boundary location, orientation, curvature, or segmentation fails.	Reject boundary architecture.
P4-F05	Boundary type	The model predicts incorrect opening, closing, shear, collision, or descent behavior.	Reject boundary dynamics.
P4-F06	Boundary chronology	Boundary initiation, reactivation, inversion, or termination ages fail.	Reject historical boundary sequence.
P4-F07	Plate partition	The network does not enclose realistic plate and block domains.	Reject global plate architecture.
P4-F08	Initial-state independence	The observed network is inserted as an unconstrained initial condition.	No independent boundary-origin credit.
P4-F09	Euler-pole generation	Observed Euler vectors must be fitted independently.	Reject causal plate-rotation claim.
P4-F10	Plate direction	Predicted plate-motion directions systematically fail.	Reject directional inheritance.
P4-F11	Plate speed	Predicted speed magnitudes or hierarchy fail.	Reject global motion law.
P4-F12	Relative motion	Shared-boundary normal or tangential velocities fail.	Reject relative kinematics.
P4-F13	Acceleration history	Predicted acceleration, deceleration, or redirection fails.	Reject motion-history claim.
P4-F14	Motion closure	Plate circuits, junctions, area balance, or angular momentum fail.	Reject global velocity field.
P4-F15	Force and torque	The model requires unbalanced force or torque.	Reject physical motion solution.
P4-F16	Power and dissipation	Available work is insufficient or dissipation becomes unphysical.	Reject motion maintenance.
P4-F17	Impulse persistence	Present motion requires an unattenuated ancient impulse.	Reject primary impulse maintenance.

ID	Replacement claim	Falsifying result	Consequence
P4-F18	Mountain systems	Location, orientation, shortening, crustal root, chronology, or work fails.	Reject global orogenic explanation.
P4-F19	Trench systems	Surface geometry or required deep descent, bending, or mass flux fails.	Reject trench explanation.
P4-F20	Ridge and rift systems	Axis, opening rate, age field, segmentation, or melt production fails.	Reject extensional explanation.
P4-F21	Basins	Geometry, subsidence, thermal history, accommodation, or inversion fails.	Reject basin explanation.
P4-F22	Plateaus	Location, elevation, root, buoyancy, dynamic support, or persistence fails.	Reject plateau explanation.
P4-F23	Volcanism	Location, melt volume, pathways, composition, or chronology fails.	Reject volcanic explanation.
P4-F24	Terrane assembly	Trajectories, rotations, identities, sutures, or contact order fail.	Reject assembly explanation.
P4-F25	Gravity and geoid	Required density architecture predicts incompatible anomalies.	Reject density model.
P4-F26	Seismic structure	Required material state predicts incompatible wave speed, attenuation, anisotropy, or continuity.	Reject deep-state model.
P4-F27	Magnetics	Predicted resetting or remanence conflicts with observations.	Reject pressure-temperature history.
P4-F28	Heat flow	Predicted thermal state conflicts with subsurface temperature or surface heat flow.	Reject thermal history.
P4-F29	Cross-geophysical consistency	Gravity, seismic, magnetic, and thermal observations require incompatible structures.	Reject integrated geophysical state.
P4-F30	Chronology	Proposed consequences precede their assigned causes.	Reject causal sequence.
P4-F31	Response lags	Successful chronology requires independently fitted post hoc delays.	Reject temporal causal compression.

ID	Replacement claim	Falsifying result	Consequence
P4-F32	Paleogeography	Key alignments fail in reconstructed event-time coordinates.	Reject event assignment.
P4-F33	Material continuity	Plate, continent, or terrane lineage cannot be reconstructed.	Reject historical reconstruction.
P4-F34	Causal coverage	Mandatory observation classes are omitted or require disconnected models.	Reject global explanatory scope.
P4-F35	Shared parameters	Different observation classes require incompatible parameter states.	Reject integrated model.
P4-F36	Astro-ballistic necessity	Removing event inheritance leaves the successful model unchanged.	Reject primary astro-ballistic causation.
P4-F37	Plate-Tectonic necessity	Removing defining comparison components leaves its solution unchanged.	Reject their claimed primary role.
P4-F38	Hybrid necessity	The hybrid wins while one parent or the interaction is unnecessary.	Reject joint causal attribution.
P4-F39	Randomized-event null	Randomized event catalogs perform equally well.	Reject sequence specificity.
P4-F40	Opportunity-matched null	Comparable geological opportunities reproduce the result.	Reject special spatial significance.
P4-F41	Chronology null	Permuted ages reproduce the result.	Reject chronological specificity.
P4-F42	Assignment null	Random event-to-structure assignments perform equally well.	Reject assignment significance.
P4-F43	Selection correction	Significance disappears after the full search space is counted.	Reject confirmatory statistical support.
P4-F44	Revision accounting	The result depends on repeatedly inspected validation data.	Classify as exploratory.
P4-F45	Effective complexity	The apparent advantage disappears after all flexibility is counted.	Reject causal preference.
P4-F46	Advance prediction	The candidate fails registered withheld observations.	Reject predictive replacement.
P4-F47	Negative prediction	The model predicts structures or anomalies in declared control regions.	Reject predictive specificity.

ID	Replacement claim	Falsifying result	Consequence
P4-F48	Regional transfer	The model succeeds only through independent regional parameter sets.	Reject global generality.
P4-F49	Model evidence	The strongest comparison model has greater marginal evidence.	Reject astro-ballistic preference.
P4-F50	Predictive ranking	The comparison model has stronger held-out predictive performance.	Reject astro-ballistic replacement.
P4-F51	Equivalence	Model differences remain inside the equivalence interval.	Report causal non-resolution.
P4-F52	Independent replication	Independent teams cannot reproduce model ranking or viable intersections.	Reject confirmatory preference.
P4-F53	Complete viability	The complete astro-ballistic Paper-IV viable set is empty.	Reject formal replacement thesis.
P4-F54	Hybrid superiority	The hybrid does not outperform both parent models after penalties.	Hybrid preference unsupported.
P4-F55	Astro-ballistic superiority	The candidate lacks a clear adjusted and predictive advantage.	Primary replacement unsupported.
P4-F56	Shared failure	No tested model adequately predicts the complete evidence domain.	Report unresolved global causation.

71.1 No Cross-Compensation

A favorable geometric alignment cannot compensate for mechanical failure.

A successful boundary fit cannot compensate for failed motion.

A successful regional model cannot compensate for failed global transfer.

A favorable statistical score cannot compensate for conservation failure.

A successful reconstruction cannot compensate for failed advance prediction.

71.2 Compartmentalized Failure

Failure of the global replacement thesis does not automatically reject every regional event hypothesis.

Failure of one event does not automatically reject every candidate event.

Each surviving regional claim must retain its own mechanics, chronology, evidence, and falsifier.

72 Independent Replication Protocol

72.1 Replication Level R1: Source and Selection Audit

The replicating team reproduces:

- source ledger;
- event catalog;
- target selection;
- search-space inventory;
- model-version history;
- and rejected alternatives.

72.2 Replication Level R2: Papers I Through III Handoff

The replicating team confirms:

- geometry;
- mechanical eligibility;
- event states;
- boundary predictions;
- motion predictions;
- structural predictions;
- chronology;
- and falsification status.

72.3 Replication Level R3: Comparison Models

The team independently implements:

- the selected Plate-Tectonic comparison family;
- the astro-ballistic family;
- the hybrid family;
- the regional models;
- and the declared baselines.

72.4 Replication Level R4: Shared Data Freeze

The team reproduces:

- observation vectors;

- uncertainty models;
- spatial masks;
- chronology;
- reference frames;
- reconstruction ensembles;
- and train-validation-test partitions.

72.5 Replication Level R5: Component Comparisons

The team reproduces:

- boundary scores;
- motion scores;
- structural scores;
- geophysical scores;
- chronology scores;
- paleogeographic scores;
- and causal coverage.

72.6 Replication Level R6: Counterfactuals

The team reproduces:

- no-event ablation;
- no-inheritance ablation;
- force and traction ablations;
- boundary randomization;
- motion ablation;
- structural ablations;
- hybrid parent ablations;
- and interaction tests.

72.7 Replication Level R7: Null and Selection Analysis

The team reproduces:

- randomized event catalogs;
- opportunity-matched catalogs;

- chronology permutation;
- assignment shuffling;
- reference-frame sensitivity;
- multiple-testing correction;
- and revision accounting.

72.8 Replication Level R8: Advance Prediction

The team validates the frozen prediction registry against withheld or new observations.

72.9 Replication Level R9: Final Adjudication

The team reproduces:

- model evidence;
- effective complexity;
- integrated score;
- common viable parameter intersection;
- outcome classification;
- and formal replacement decision.

72.10 Repository Structure

```
abc-paper-iv/
|
|-- manuscript/
|   |-- main.tex
|   `-- figures/
|
|-- handoff/
|   |-- paper-i/
|   |-- paper-ii/
|   `-- paper-iii/
|
|-- sources/
|   |-- source-ledger.csv
|   |-- selection-ledger.csv
|   |-- revision-ledger.csv
|   `-- chronology-ledger.csv
|
|-- data/
|   |-- boundaries/
```

```
|   |-- velocities/
|   |-- paleogeography/
|   |-- structures/
|   |-- chronology/
|   |-- gravity/
|   |-- seismology/
|   |-- magnetics/
|   |-- heat-flow/
|   `-- prediction-holdouts/
|
|-- models/
|   |-- Plate-Tectonic/
|   |-- astro-ballistic/
|   |-- hybrid/
|   |-- regional/
|   `-- nulls/
|
|-- comparison/
|   |-- boundary/
|   |-- motion/
|   |-- structural/
|   |-- chronology/
|   |-- paleogeography/
|   |-- complexity/
|   |-- evidence/
|   `-- prediction/
|
|-- validation/
|   |-- spatial-holdout/
|   |-- temporal-holdout/
|   |-- observation-holdout/
|   |-- leave-one-event-out/
|   |-- leave-one-region-out/
|   |-- cross-solver/
|   `-- independent-replication/
|
|-- ledgers/
|   |-- claim-ledger.csv
|   |-- equation-registry.csv
|   |-- parameter-registry.csv
|   |-- data-registry.csv
|   |-- falsification-matrix.csv
|   |-- model-version-registry.csv
|   `-- prediction-registry.csv
```

```
|
`-- README.md
```

72.11 Required Metadata

Every run must report:

- model family and version;
- code version;
- data version;
- event catalog version;
- reference frame;
- coordinate system;
- chronology convention;
- initial conditions;
- boundary conditions;
- priors;
- parameter bounds;
- mesh and timestep;
- solver;
- random seed;
- convergence tests;
- conservation residuals;
- data partition;
- null-model family;
- decision thresholds;
- and failed runs.

72.12 Replication Statuses

Allowed statuses are:

Reproduced
The principal model ranking and viable set agree within declared tolerances.

Partially reproduced
Some components agree, but the integrated result differs.

Not reproduced
: The declared inputs do not generate the published result.

Model-dependent
: The result depends on one implementation and fails across defensible alternatives.

Reference-frame dependent
: The result changes materially across defensible frames.

Selection-dependent
: The result depends on undisclosed or post hoc choices.

Statistically non-distinct
: The model does not outperform its null family.

Predictively unsupported
: The reconstruction fits, but withheld predictions fail.

Falsified
: A predeclared rejection condition is triggered.

73 Integrated Discussion

73.1 Paper IV Adjudicates Rather Than Presumes

This paper does not assume that Astro-Ballistic Chronostratigraphic Sequencing has established a global replacement.

It defines the conditions under which that conclusion could be reached or rejected.

73.2 Continental Drift Is Shared Evidence

Observed continental and plate motion is not the principal point of dispute.

The comparison concerns the origin and maintenance of the global boundary, motion, structural, and geophysical system.

73.3 Boundary Origin and Motion Maintenance Are Distinct

A model may explain why a boundary exists without explaining the full present velocity field.

A model may predict present motion while receiving the observed boundary architecture as an initial condition.

Paper IV therefore scores boundary origin and motion generation separately before integrating them.

73.4 Astro-Ballistic Replacement Has a Stronger Burden Than Regional Compatibility

A primary replacement must connect:

$$\text{event geometry} \rightarrow \text{mechanical transmission} \rightarrow \text{persistent material inheritance} \\ \rightarrow \text{boundary network} \rightarrow \text{plate motion} \rightarrow \text{global structure.} \tag{896}$$

A failure in any mandatory link prevents the affected frozen replacement model version from surviving. It does not reject neighboring regional claims or alternate event sequences that do not depend on the failed link.

73.5 Plate-Tectonic Models Also Require Explicit Specification

The comparison model cannot receive automatic explanatory credit through general association.

It must specify:

- initial state;
- boundary state;
- force architecture;
- rheology;
- mantle coupling;
- material evolution;
- and predicted observations.

73.6 Initial Conditions Are Explanatory Inputs

Both model families may rely on inherited structure.

The comparison must count the information inserted through those structures.

A model that begins with a near-modern boundary network has not derived that network merely because it evolves it forward.

73.7 Ancient Events May Initiate Without Maintaining

An astro-ballistic event may:

- fragment a material domain;
- initiate displacement;
- redirect motion;
- create weakness;
- modify density;
- modify mantle flow;
- or localize later deformation.

Present motion still requires adequate long-time force and power.

73.8 Hybrid Outcomes Are Scientifically Substantive

A hybrid result is not a rhetorical compromise.

It may indicate that astro-ballistic events created or redirected structures later maintained by internally organized geodynamics.

It may also reveal that event inheritance is unnecessary.

The parent ablations determine which interpretation survives.

73.9 Chronology and Paleogeography Are Decisive

Modern spatial correspondence can be attractive while historically impossible.

Every causal assignment must survive reconstruction of:

- material positions;
- plate identities;
- terrane lineages;
- event ages;
- response lags;
- and structural chronology.

73.10 Deep Geophysics Restricts Surface Narratives

Mountains, trenches, basins, ridges, and volcanic provinces imply subsurface material states.

Those states predict:

- gravity;
- seismic velocity;
- attenuation;
- anisotropy;
- magnetics;
- and heat flow.

A surface-only success cannot compensate for incompatible deep predictions.

73.11 Prediction Distinguishes Reconstruction From Replacement

A sufficiently flexible model can often reconstruct known patterns.

A replacement claim requires accurate prediction of evidence not used to build the model.

73.12 Regional Failure and Global Failure Must Remain Compartmentalized

A global replacement may fail while a regional event hypothesis remains viable.

A regional event hypothesis may fail without rejecting every other event.

The final reporting must preserve that compartmentalization.

73.13 Paper IV Is a Decision Architecture

This manuscript establishes:

- matched model families;
- shared observations;
- causal levels;
- component scores;
- physical constraints;
- complexity penalties;
- null models;
- counterfactuals;
- prediction standards;
- and formal decision rules.

It does not claim that the required full numerical adjudication has already been completed.

74 Limitations

74.1 Conditional Inputs

Paper IV depends on the accuracy and completeness of Papers I through III.

Errors in geometry, mechanics, event states, chronology, or reconstruction propagate into the comparison.

74.2 No Completed Global Simulation

The manuscript defines the comparison architecture but does not present a completed end-to-end numerical solution of either model family.

74.3 Comparison-Model Breadth

Plate Tectonics is represented by a family of models rather than one universally fixed implementation.

The selected comparison set must be broad enough to avoid false preference caused by a weak implementation.

74.4 Astro-Ballistic Catalog Uncertainty

The event catalog, event ages, event coordinates, mechanism branches, and event-to-structure assignments remain provisional.

74.5 Initial-Condition Uncertainty

Both model families may require uncertain ancient thermal, compositional, rheological, and boundary states.

74.6 Paleogeographic Uncertainty

Ancient plate identities, terrane locations, internal deformation, and reference frames remain uncertain.

74.7 Constitutive Uncertainty

Damage, healing, viscosity, friction, phase transformation, melting, permeability, anisotropy, and long-time memory are incompletely constrained.

74.8 Computational Scale

A full comparison spans:

- short transient event times;
- long geological evolution;
- changing plate topology;
- nonlinear rheology;
- coupled mantle and lithosphere dynamics;
- and global observation operators.

74.9 Observation Dependence

Several geological datasets share measurements, reconstruction assumptions, and processing pipelines.

Their covariance may be difficult to estimate.

74.10 Preservation Bias

Ancient structures may be buried, eroded, metamorphosed, displaced, or destroyed.

Preservation models can create substantial flexibility and must be constrained independently.

74.11 Selection Risk

The global abundance of geological features creates a high risk of post hoc matching.

The search ledger and null-model program are therefore essential.

74.12 Model Nonuniqueness

Multiple physical histories may generate similar present observations.

A successful fit does not guarantee unique historical identification.

74.13 Hybrid Nonuniqueness

A hybrid model may improve fit without uniquely determining the relative contribution of its parent models.

74.14 Prediction Availability

Some decisive tests require new data, new surveys, or data withheld from the model-development process.

74.15 Bibliographic Production

All external factual claims, datasets, constitutive models, and comparison-model implementations require source verification and an embedded bibliography before publication. Data and software releases should also satisfy explicit discoverability, access, provenance, and reproducibility requirements [11, 12, 13].

74.16 Declared-Scope Limitation

The current comparison cannot award ABC credit for additional directional or material-displacement hypotheses that remain outside the frozen corpus. It also cannot count their deliberate omission as a failed prediction unless the corresponding evidence class is mandatory for the decision at hand. A future global replacement decision will require a frozen mandatory-coverage vector and a frozen event catalog broad enough to test that claim.

75 Conclusions

75.1 Conclusion 1: The Comparison Concerns Causal Organization

Observed continental and plate motion is shared evidence.

The replacement question concerns the causal origin and organization of the global tectonic system.

75.2 Conclusion 2: Eligibility Is Conditional

The replacement model must survive the geometric, mechanical, and global-reconstruction burdens of Papers I through III.

75.3 Conclusion 3: Boundaries and Motion Must Be Compared Separately

Boundary origin, plate partition, plate direction, Euler poles, relative velocities, and speed hierarchy require distinct tests.

75.4 Conclusion 4: Initial Conditions Count

A model does not independently explain a boundary or structure already encoded through a high-information initial condition.

75.5 Conclusion 5: Ancient Impulse Is Not Permanent Power

Astro-ballistic events may initiate, redirect, fragment, or localize.

Present motion requires explicit later work, force, torque, and dissipation accounting.

75.6 Conclusion 6: Surface and Deep Predictions Must Agree

Mountains, trenches, ridges, basins, plateaus, volcanism, and terrane assembly must be compatible with gravity, seismic, magnetic, and thermal observations.

75.7 Conclusion 7: Chronology and Paleogeography Can Reject Modern Alignments

A causal assignment fails when the relevant material domains were not in the required positions or when the proposed consequence predates its cause.

75.8 Conclusion 8: Causal Necessity Is Required

A defining mechanism must materially improve the successful model under controlled ablation.

75.9 Conclusion 9: Complexity Must Include Hidden Flexibility

Event selection, initial conditions, regional tuning, mechanism switching, response lags, preservation, reference frames, and model revision all contribute to effective complexity.

75.10 Conclusion 10: Null Models Must Preserve Geological Opportunity

The proposed sequence must outperform randomized and opportunity-matched alternatives.

75.11 Conclusion 11: Advance Prediction Is Decisive

A replacement model must predict withheld observations more accurately than its comparison models.

75.12 Conclusion 12: Regional Success Is Not Global Replacement

Regional event hypotheses may remain scientifically valuable even when the global viable-set intersection is empty.

75.13 Conclusion 13: Hybrid Preference Requires Joint Necessity

A hybrid model is preferred only when both parent causal components and their interaction survive ablation and complexity correction.

75.14 Conclusion 14: Equivalence Is an Allowed Result

Paper IV permits a formal conclusion that available evidence does not distinguish the model families.

75.15 Conclusion 15: Replacement Requires One Shared Model

For a single sequence $\mathcal{S}$, the decisive object is

$$\begin{aligned}\mathcal{V}^{\text{elig}}_{IV,\mathcal{S},\text{ABC}} = \mathcal{V}^{\text{IV}}_{B,\text{ABC}} &\cap \mathcal{V}^{\text{IV}}_{V,\text{ABC}} \cap \mathcal{V}^{\text{IV}}_{SG,\text{ABC}} \\ &\cap \mathcal{V}^{\text{IV}}_{T,\text{ABC}} \cap \mathcal{V}^{\text{IV}}_{C,\text{ABC}} \cap \mathcal{V}^{\text{IV}}_{N,\text{ABC}} \\ &\cap \mathcal{V}^{\text{IV}}_{P,\text{ABC}} \cap \mathcal{V}^{\text{IV}}_{R,\text{ABC}}.\end{aligned} \tag{897}$$

The model-family result is the union of these sequence-specific sets over the preregistered eligible sequence family.

75.16 Final Paper-IV Statement

Astro-Ballistic Chronostratigraphic Sequencing can replace Plate Tectonics as the primary causal framework of global crustal organization only if one shared and mechanically admissible event sequence generates the observed boundary architecture, plate-motion field, continental history, structural systems, and deep geophysical state; survives chronological and paleogeographic reconstruction; remains necessary under counterfactual removal; outperforms realistic null models; predicts withheld evidence; survives complete complexity accounting; and is independently reproduced.

If those conditions are not jointly satisfied, the formal replacement claim must be classified as rejected, regional, complementary, hybrid, or causally unresolved.

AI-Assisted Research Disclosure

Artificial-intelligence systems were used as analytical, organizational, equation-formatting, and editorial-assistance tools during manuscript development.

Justin B Fine is the sole human author and is responsible for the scientific framing, claim selection, interpretation, source verification, revisions, model decisions, and final publication.

Artificial-intelligence systems are not authors and do not assume scientific responsibility.

Paper V is an AI-supported companion atlas designed to improve claim tracking, equation auditing, source verification, reproducibility, and falsification access.

A Shared Model-Comparison Data Registry

Table 7: Minimum shared-data registry for Paper IV.

Class	**Symbol**	**Required content**
Boundaries	$\mathbf{D}_B$	Location, type, age, orientation, curvature, width, motion, topology
Motion	$\mathbf{D}_V$	Site velocities, Euler poles, relative motion, finite rotations, acceleration
Continents	$\mathbf{D}_C$	Positions, shapes, rotations, adjacencies, lineages, material identity
Chronology	$\mathbf{D}_T$	Event, boundary, motion, deformation, uplift, descent, volcanism ages
Surface structures	$\mathbf{D}_S$	Mountains, trenches, ridges, basins, plateaus, volcanism, sutures
Gravity	$\mathbf{D}_g$	Gravity, potential, geoid, resolution, covariance
Seismology	$\mathbf{D}_{SE}$	Wave speed, attenuation, anisotropy, travel times, resolution
Magnetics	$\mathbf{D}_{\text{mag}}$	Magnetization, anomaly fields, resetting, remanence
Thermal	$\mathbf{D}_H$	Heat flow, subsurface temperature, thermal chronology
Predictions	$\mathbf{D}_P$	Frozen claims, controls, validation results, timestamps

B Integrated Model Scorecard

Table 8: Template for final model comparison.

Comparison class	**Plate Tectonics**	**Astro-ballistic**	**Hybrid**
Mechanical eligibility	NOT-YET-EXECUTED	NOT-YET-EXECUTED	NOT-YET-EXECUTED
Boundary score	NOT-YET-EXECUTED	NOT-YET-EXECUTED	NOT-YET-EXECUTED
Motion score	NOT-YET-EXECUTED	NOT-YET-EXECUTED	NOT-YET-EXECUTED
Structural score	NOT-YET-EXECUTED	NOT-YET-EXECUTED	NOT-YET-EXECUTED

Comparison class	**Plate Tectonics**	**Astro-ballistic**	**Hybrid**
Geophysical score	NOT-YET-EXECUTED	NOT-YET-EXECUTED	NOT-YET-EXECUTED
Chronology score	NOT-YET-EXECUTED	NOT-YET-EXECUTED	NOT-YET-EXECUTED
Paleogeographic score	NOT-YET-EXECUTED	NOT-YET-EXECUTED	NOT-YET-EXECUTED
Causal necessity	NOT-YET-EXECUTED	NOT-YET-EXECUTED	NOT-YET-EXECUTED
Null probability	NOT-YET-EXECUTED	NOT-YET-EXECUTED	NOT-YET-EXECUTED
Effective complexity	NOT-YET-EXECUTED	NOT-YET-EXECUTED	NOT-YET-EXECUTED
Advance prediction	NOT-YET-EXECUTED	NOT-YET-EXECUTED	NOT-YET-EXECUTED
Replication	NOT-YET-EXECUTED	NOT-YET-EXECUTED	NOT-YET-EXECUTED
Integrated score	NOT-YET-EXECUTED	NOT-YET-EXECUTED	NOT-YET-EXECUTED
Final status	NOT-YET-EXECUTED	NOT-YET-EXECUTED	NOT-YET-EXECUTED

C Advance-Prediction Registry Template

Table 9: Minimum advance-prediction registry.

ID	**Model**	**Frozen prediction**	**Validation data**	**Outcome**
Example	ABC, PT, or HYB	Location, depth, sign, magnitude, uncertainty, control	Withheld or newly acquired data	Supported, failed, unresolved

Every prediction must record:

- freeze date;
- model version;
- data cutoff;
- parameter version;
- prediction domain;

- uncertainty;
- negative-control domain;
- validation authority;
- and whether the observation was previously known.

D Model-Version and Selection Audit Template

Table 10: Minimum model-version and selection audit.

Version	Date	Modification	Data visible	Status
Example	YYYY-MM-DD	Event, parameter, score, boundary, comparison, or prior change	Training, validation, test, or prospective data	Exploratory or confirmatory

E Formal Decision Checklist

Before issuing a primary replacement conclusion, confirm:

1. Paper-II mechanical viability is nonempty.
2. Paper-III global viability is nonempty.
3. The event catalog was frozen.
4. The comparison-model family was frozen.
5. The observation domain was shared.
6. The boundary viable set is nonempty.
7. The motion viable set is nonempty.
8. The structural and geophysical viable set is nonempty.
9. The chronology viable set is nonempty.
10. The paleogeographic viable set is nonempty.
11. One common parameter intersection exists.
12. The event component is necessary under ablation.
13. The comparison-model components were also tested by ablation.
14. The result survives realistic null models.
15. The result survives search-space correction.
16. The result survives effective-complexity accounting.

17. The candidate predicts held-out evidence.
18. Negative predictions were evaluated.
19. The result transfers across regions.
20. The result survives reference-frame variation.
21. The result survives reconstruction uncertainty.
22. The result is independently reproduced.
23. The candidate outperforms the comparison model by the frozen threshold.
24. The result is not inside the equivalence interval.
25. The final conclusion matches the decision tree.

F Figure and Table Production Registry

Table 11: Minimum Paper-IV visual-production registry.

ID	Planned visual	Required input
F4-01	Four-paper dependency and adjudication architecture	Frozen handoff states
F4-02	Model-family comparison diagram	PT, ABC, hybrid, regional, and null definitions
F4-03	Boundary-generation comparison	Predicted and observed boundary networks
F4-04	Euler-pole and plate-velocity comparison	Predicted and observed motion fields
F4-05	Force, torque, power, and dissipation budgets	Motion-model outputs
F4-06	Surface-structure comparison maps	Mountain, trench, ridge, basin, plateau outputs
F4-07	Gravity, seismic, magnetic, and heat-flow comparison	Resolution-matched geophysical outputs
F4-08	Chronology and causal dependency graph	Chronology ledger
F4-09	Paleogeographic reconstruction ensemble	Time-slice continental reconstructions
F4-10	Null-score distributions	Sequence-wide null simulations
F4-11	Effective complexity and description length	Complete parameter and selection ledger
F4-12	Advance-prediction results	Frozen predictions and validation data

ID	Planned visual	Required input
F4-13	Complete viable-set intersection	Component posterior and parameter intersections
F4-14	Formal replacement decision tree	Frozen decision thresholds
F4-15	Final model scorecard	Integrated Paper-IV results
F4-16	Paper-V atlas architecture	Claims, equations, data, and falsification registries

G Paper-V Handoff

G.1 Purpose of the Companion Atlas

Paper V is the AI-supported companion to Papers I through IV.

It does not introduce a fifth independent replacement argument.

It organizes the scientific burden into a searchable and reproducible atlas of:

- claims;
- equations;
- variables;
- parameters;
- datasets;
- sources;
- figures;
- model dependencies;
- predictions;
- and falsification conditions.

G.2 Causal Audit Fields for Paper V

The Paper-V handoff must include causal-edge records, alternative-family records, assumption-intervention records, causal-level classifications, valid and invalid ablations, and surviving support paths for every principal decision. Aggregate rankings without those records are not machine-auditable causal conclusions.

G.3 Paper-V Handoff State

Define

$$\mathbf{Q}_{V,0} = (\mathbf{L}_C, \mathbf{L}_E, \mathbf{L}_D, \mathbf{L}_S, \mathbf{L}_P, \mathbf{L}_F, \mathbf{G}_{\text{dep}}, \mathbf{Q}_{\text{status}}), \tag{898}$$

where:

$$\mathbf{L}_C = \text{claim ledger}, \tag{899}$$
$$\mathbf{L}_E = \text{equation registry}, \tag{900}$$
$$\mathbf{L}_D = \text{data registry}, \tag{901}$$
$$\mathbf{L}_S = \text{source registry}, \tag{902}$$
$$\mathbf{L}_P = \text{prediction registry}, \tag{903}$$
$$\mathbf{L}_F = \text{falsification registry}, \tag{904}$$
$$\mathbf{G}_{\text{dep}} = \text{claim-equation-data dependency graph}, \tag{905}$$
$$\mathbf{Q}_{\text{status}} = \text{current support and test status}. \tag{906}$$

G.4 Required Paper-V Relationships

Paper V must map:

$$\text{claim} \rightarrow \text{equation} \rightarrow \text{parameter} \rightarrow \text{data} \rightarrow \text{test} \rightarrow \text{falsifier}. \tag{907}$$

G.5 Paper-V Status Categories

Each claim must be labeled:

- source-derived;
- author-derived;
- model assumption;
- model prediction;
- independently observed;
- conditionally supported;
- unsupported;
- unresolved;
- or falsified.

G.6 AI Companion Limitation

Paper V may assist readers in navigation, comparison, equation checking, and test design.

It cannot replace source verification, independent derivation, numerical reproduction, peer review, or scientific judgment.

H Paper-IV Production Checklist

Before release, Paper IV requires:

1. complete LaTeX compilation;
2. notation audit;
3. equation-reference audit;
4. cross-paper terminology audit;
5. verified Paper-I handoff;
6. verified Paper-II handoff;
7. verified Paper-III handoff;
8. frozen event catalog;
9. frozen comparison-model family;
10. shared data release;
11. complete uncertainty model;
12. complete prior registry;
13. complete parameter registry;
14. complete source ledger;
15. complete selection ledger;
16. complete revision ledger;
17. boundary comparison;
18. motion comparison;
19. structural comparison;
20. geophysical comparison;
21. chronology comparison;
22. paleogeographic comparison;
23. physical-budget audit;
24. effective-complexity audit;
25. sequence-wide null simulations;
26. multiple-testing correction;
27. causal ablation program;
28. spatial holdouts;

29. temporal holdouts;
30. observation-type holdouts;
31. advance-prediction registry;
32. prospective validation;
33. independent replication;
34. final model ranking;
35. final viable-set intersection;
36. final outcome classification;
37. embedded source-verified bibliography;
38. and frozen Paper-V handoff package.

Paper-IV Freeze Status and Handoff

Corpus Freeze 1.0 fixes the Paper-IV comparison architecture. The empirical comparison and replacement adjudication remain unexecuted.

The four-paper scientific core is:

Paper I. *Aegean Entrance, Everest Midpoint, Mariana Exit*

Paper II. *Transmission Through a Differentiated Earth*

Paper III. *From Event Geometry to Continents, Trenches, Mountains, and Basins*

Paper IV. *Astro-Ballistic Chronostratigraphic Sequencing Versus Plate Tectonics*

The companion manuscript in the frozen series is:

Astro-Ballistic Chronostratigraphic Sequencing V

Claims, Equations, Data, and Falsification Atlas

An AI-Supported Companion for Verification, Reproducibility, Dependency Tracking, and Independent Testing

Paper V converts the four-paper scientific core into a navigable technical system in which every principal claim can be traced to its equations, assumptions, parameters, sources, datasets, predictions, and direct falsifiers.

References

The external references below support conventional scientific context, standard methods, and comparison requirements. Their inclusion does not imply endorsement or independent verification of Astro-Ballistic Chronostratigraphic Sequencing.

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