MODEL OF CORTICAL MOSAICS (MMC)

An Auto-Organized Evolutionary Trajectory from the Primitive Crust to Proto-Plates

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Note on Terminology

The acronym MMC (from the original Spanish Modelo de Mosaicos Corticales) is retained to preserve conceptual continuity.

Declaration on the Use of AI Tools

This manuscript was prepared with the assistance of large-language-model tools (ChatGPT, OpenAI) used exclusively for drafting and language clarification. All scientific content is the responsibility of the author.

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Note on terminology. The acronym **MMC** (from the original Spanish *Modelo de Mosaicos Corticales*) is retained throughout this English version to preserve conceptual continuity and avoid ambiguity with existing geological acronyms. In English, the framework is referred to as the **Cortical Mosaic Model**, abbreviated here as **MMC**.

Abstract

The structure and dynamics of Earth's crust during the Hadean–Eoarchean remain one of the central challenges in geodynamics. Traditional models describe early states in terms of discrete regimes—stagnant lid, heat-pipe, episodic tectonics, or proto-plates—but none provides a continuous framework linking primitive fragmentation with the late emergence of plate tectonics.

This work proposes the Model of Cortical Mosaics (MMC), a conceptual framework that interprets the early crust as a self-organized system composed of cortical islets separated by thermally active boundaries and decoupled by an underlying warm matrix. Segmentation, continual reorganization, and hierarchical domain growth emerge from the interaction of initial heterogeneity, strong thermal gradients, local feedbacks, and frequent external forcing.

As Earth cools, the mosaic matures: the number of active boundaries decreases, larger domains consolidate, and coherent lateral mobility develops, setting the stage for localized foundering and plate-like behavior. Under this perspective, modern plate tectonics is not an independent regime but the advanced phase of the natural evolution of the cortical mosaic.

The MMC produces qualitative predictions testable in the Archean record, including persistent isotopic heterogeneity, domain hierarchies within cratons, deep relict discontinuities, marked variability in crustal thickness, and potential rotations or overturning

of cortical islets. These signals allow evaluation of the model through reasonable falsification criteria compatible with the fragmentary nature of the early record.

The MMC thus provides a unified, physically motivated, and evolutionary framework that integrates disparate processes and offers a continuous narrative for interpreting the transition from Earth’s fragmented primitive crust to the establishment of plate tectonics.

TABLE OF CONTENTS

1. Introduction

The dynamics of Earth's crust during the Hadean and Eoarchean represent one of the most complex and unresolved problems in geoscience. Although there is broad consensus that the early Earth experienced extreme conditions—high thermal flux, frequent impacts, intense volcanism, and deep chemical differentiation—significant uncertainty remains regarding how the initial shell evolved into crustal units capable of lateral mobility and, eventually, stable subduction.

Classical models (stagnant lid, heat-pipe, episodic tectonics, and proto-plates) explain partial aspects of early evolution but fail to offer a continuous framework connecting primitive fragmentation with modern plate tectonics. The Archean record—persistent isotopic heterogeneity, independent domains within cratons, deep relict discontinuities, and incomplete lateral mobility—suggests a more complex crustal regime than any of the discrete models proposed so far.

This work introduces the Model of Cortical Mosaics (MMC), interpreting the early crust as a self-organized system composed of cortical islets separated by thermally active boundaries and decoupled by a warm underlying matrix.

The MMC is a conceptual model grounded in physical principles and indirect evidence, offering a continuous evolutionary narrative that links fragmented protocrust to the emergence of proto-plates.

Objective of the Study

The objective of this article is to:

- define the Cortical Mosaic as a self-organized system;
- develop its physical foundations and internal dynamics;
- explain the transition toward plate-like units;
- propose qualitative predictions verifiable in the Archean record;
- establish reasonable criteria for its falsification;
- discuss its implications for Earth and planetary evolution.

The MMC does not aim to replace prior models but to provide a unified framework that integrates them into a physically motivated and logically consistent evolutionary path. This proposal seeks to contribute to our understanding of early lithospheric evolution by illuminating the processes that enabled the emergence of plate tectonics and the stabilization of continental crust.

2. Synthesized State of the Art

Understanding crustal dynamics during the Hadean–Eoarchean has emerged from multiple lines of research which, although robust within their respective domains, provide a fragmented view of the problem. Key contributions stem from studies on magma oceans, early geochemical heterogeneity, proposed tectonic regimes, the role of external forcing, and structural evidence preserved in Archean cratons. This section synthesizes these contributions and highlights the conceptual discontinuities that motivate the formulation of the Model of Cortical Mosaics (MMC).

2.1. Magma Oceans and Heterogeneous Solidification

Following Earth's accretion and the Moon-forming impact, several studies suggest that the planet underwent one or more episodes of global or near-global magma oceans whose solidification produced a thin, thermally unstable, and compositionally heterogeneous crystalline crust (Elkins-Tanton, 2012; Labrosse et al., 2007).

Heat loss from the surface into the interior generated strong thermal gradients and lateral variations in thickness, composition, and viscosity. This early crust was unlikely a continuous shell but rather a patchwork of domains with divergent properties—physical precursors to later segmentation.

2.2. Early Compositional and Geochemical Heterogeneity

Isotopic signals preserved in Hadean zircons and Archean TTG terrains indicate that the early protocontinental crust was marked by persistent heterogeneity, reflecting multiple sources, partial melting events, recycling, and incomplete mixing (Kemp et al., 2010; Valley et al., 2014; Hawkesworth et al., 2020).

No model assuming a continuous and homogeneous crust can explain both the observed isotopic diversity and the coexistence of independent domains within cratons such as Pilbara or Kaapvaal.

This evidence suggests that early crustal domains maintained distinct thermal and compositional identities, implying segmentation from very early stages.

2.3. Early Tectonic Regimes: Proposals and Limitations

The literature proposes several tectonic regimes for the early Earth:

- **Stagnant lid**: a rigid lid with absence of sustained subduction (Bédard, 2018)

- **Heat-pipe**: vertical transport dominated by intense volcanism (Moore & Webb, 2013)
- **Episodic tectonics**: alternation between mobility and rigidity linked to deep mantle reorganizations or impacts (O'Neill et al., 2007)
- **Proto-plates**: discrete units with limited mobility but lacking global coherence (O'Neill & Debaille, 2012; Gerya, 2019)

Although each model captures important aspects of early dynamics, none provides a continuous framework explaining the transition from initial fragmentation to the emergence of mature plates. Furthermore, many of these regimes are formulated as mutually exclusive states, hindering integration into a unified evolutionary trajectory.

2.4. Early External Forcing: Impacts, Volcanism, and Convective Reorganizations

The Hadean was characterized by high impact flux and frequent convective reorganization (Abramov & Mojzsis, 2009; Abramov et al., 2013). These events not only fragmented the crust but also:

- generated localized thermal rejuvenation;
- extended or reactivated existing discontinuities;
- induced partial melting and redistribution of stresses;
- reorganized crustal geometry and topography.

Simultaneously, the young mantle exhibited significantly higher convective vigor than today (Solomatov, 1995; Tackley, 2000), promoting deep reorganizations capable of modifying the surface stress field.

Despite this, most existing models treat these processes as "external perturbations" rather than structural components of the early crustal regime.

2.5. Conceptual Gaps and Discontinuity Among Existing Models

The combination of isotopic heterogeneity, structural segmentation, persistent fragmentation, limited mobility, and absence of global tectonics before ~3.2–3.0 Ga (van Kranendonk et al., 2021) suggests the existence of a crustal regime not adequately represented by classical models.

What is missing is a framework that:

- integrates initial fragmentation;
- explains the persistence of discontinuities;
- incorporates the role of external forcing;
- describes continual reorganization;

- enables maturation toward coherent mobility;
- connects previous regimes within a single evolutionary pathway.

These limitations motivate the development of the Model of Cortical Mosaics, which interprets the protocontinental crust as a self-organized system in which segmentation, boundary selection, and hierarchization emerge from planetary cooling and its interaction with external perturbations.

3. Physical and Conceptual Foundations of the MMC

The formation of the Model of Cortical Mosaics (MMC) is rooted in the extreme conditions that characterized Earth during the Hadean and Eoarchean: a young planet with a steep thermal gradient, a rapidly solidifying surface, and an interior exhibiting vigorous dynamics. These conditions produced a heterogeneous, thermomechanically unstable crust highly sensitive to external perturbations. In this context, the early crust could not have behaved as a continuous and homogeneous layer; instead, it evolved as a system predisposed to fragmentation, spontaneous formation of discontinuities, and recurrent reorganization.

This section establishes the physical principles that make the emergence of a self-organized regime of cortical islets and thermally active boundaries not only plausible but inevitable.

3.1. The Early Crust as a Highly Unstable Brittle–Ductile Interface

During its first several hundred million years, Earth cooled rapidly from the surface while the interior remained extremely hot. The initial crust—crystalline residue of the magma ocean—displayed:

- low thickness;
- high residual temperatures;
- brittle behavior near the surface;
- ductile behavior at depth;
- pronounced lateral variability.

This brittle–ductile combination created a superficial layer prone to mechanical discontinuities, cracks, primary faults, and zones of thermal weakening. This intermediate rheological character—neither fully rigid nor fully viscous—is central to the emergence of a self-organized crustal system.

3.2. Initial Thermal, Compositional, and Rheological Heterogeneity

The solidification of the magma ocean did not produce a monolithic crust. Its initial properties varied widely depending on:

- local cooling rates;
- differentiated crystal accumulation;
- melt segregation;
- volatile content;
- effects of late perturbations.

These variations produced thermal and compositional islets from the outset. Each domain possessed distinct viscosity, density, deformational capacity, and thickness. This heterogeneity acted as a natural "seedbed" for later segmentation.

Under such conditions, even small local differences were sufficient to create brittle zones, hotter and weaker patches, and rigid cores that would become precursors to cortical islets.

3.3. Natural Formation of Discontinuities Through Differential Cooling

As the early crust lost heat to space, cooling occurred unevenly: thinner or volatile-rich regions cooled and contracted more quickly, whereas thicker or hotter areas retained ductility for longer periods. This asymmetry generated:

- surface fracturing;
- differential stresses;
- thermal segmentation;
- incipient faults acting as primary boundaries.

These discontinuities were not isolated events but systematic consequences of a planet cooling under strong lateral contrasts. Their presence from early stages set the foundation for a segmented, self-organizing crust.

3.4. Warm Underlying Matrix and Islet–Asthenosphere Decoupling

Beneath the early crust lay a thermally warm and rheologically weak matrix: the proto-asthenosphere. Its low viscosity allowed the newly formed cortical islets to:

- move laterally;
- undergo independent rotations;
- experience differential foundering;
- respond sensitively to thermal variations;
- maintain active discontinuities between them.

The presence of this underlying matrix was essential for preventing rapid healing of discontinuities and for enabling relative mobility among islets. It is the physical medium that makes the MMC regime dynamically viable.

3.5. Conditions Favoring Cortical Self-Organization

The MMC naturally emerges when four conditions—fully present on early Earth—coexist:

1. **Significant initial heterogeneity**
   → establishes contrasts that promote segmentation.
2. **High thermal flux and steep gradients**
   → allow persistent localization of dissipation along thin boundaries.
3. **Basal decoupling by the warm matrix**
   → grants dynamic independence to individual islets.
4. **Frequent external forcing**
   → impacts, volcanism, and convective reorganizations that renew discontinuities.

The combination of these factors creates a system in which:

- boundaries persist or vanish according to local rules;
- the crust reorganizes without global control;
- stable yet adaptive spatial patterns emerge.

In short, the physics of the early Earth naturally favored a self-organized system, rather than a stable lid or an already mature plate-tectonic regime. The MMC is the conceptual manifestation of that self-regulated state.

4. Definition of the Cortical Mosaic

The Cortical Mosaic (MMC) is defined as an early lithospheric system that is self-organized and composed of a set of discrete cortical islets separated by thermally active boundaries that concentrate deformation, heat dissipation, and structural reorganization. The underlying matrix—a warm, low-viscosity proto-asthenosphere—decouples these islets and enables their relative mobility, rotation, thickening, coalescence, and recurrent reconfiguration.

In contrast to early tectonic models that describe discrete regimes (stagnant lid, heat-pipe, episodic tectonics, proto-plates), the MMC represents a dynamic framework in which these regimes can be understood as partial manifestations of a single continuous system governed by local feedbacks. The MMC is not an event or a transient state; it is a structural regime that naturally emerges under the physical conditions of the early Earth.

Figure 1 summarizes the basic architecture of the cortical mosaic, illustrating the cortical islets, thermally active boundaries, and warm underlying matrix that decouples them.

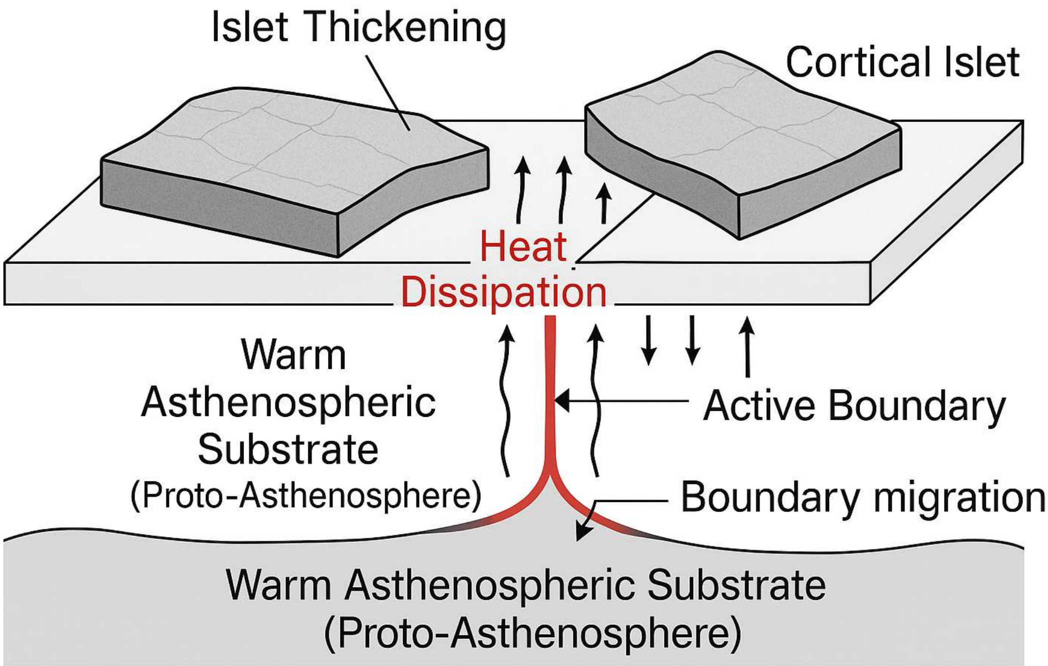

Figure 1. Basic architecture of the Cortical Mosaic (MMC). The figure shows cortical islets of variable thickness, thermally active boundaries that focus heat dissipation, and the warm asthenospheric matrix (proto-asthenosphere) that dynamically decouples the islets.

4.1. Central Concept and Structural Elements

The architecture of the mosaic is defined by the interaction of three essential components:

- **Cortical islets**: discrete, relatively rigid units with coherent thermomechanical behavior.
- **Mosaic boundaries**: active, thinner, and hotter discontinuities where deformation and thermal flow are concentrated.
- **Underlying matrix**: a warm, ductile zone (proto-asthenosphere) that dynamically decouples the islets.

The interplay of these components determines not only the geometry of the mosaic but also its emergent behavior.

4.2. Cortical Islets and Their Properties

Cortical islets represent the "structural pixels" of the mosaic. They are characterized by:

- local mechanical cohesion;
- variable thickness (10–40 km in early stages);
- higher viscosity relative to the underlying matrix;
- their own thermal history;
- the capacity to thicken and stabilize over time;
- limited but independent mobility.

As they cool, islets thicken, increase their rigidity, and become anchors of the system, setting the stage for the formation of larger domains.

4.3. Mosaic Boundaries as Thermal Valves

The boundaries of the mosaic are mechanical and thermal discontinuities that concentrate energy dissipation. They are characterized by:

- reduced thickness;
- relatively elevated temperatures;
- lower viscosity;
- high susceptibility to intrusions and thermal rejuvenation;
- localization of deformation (shear, extension, thinning);
- efficient connectivity with the proto-asthenosphere.

These boundaries act as functional elements—thermal valves—allowing the system to regulate which discontinuities persist, migrate, or heal. Their activity depends on local rules: thermal flux, mechanical gradients, and changes in crustal thickness.

These boundaries are essential: they are the key elements that render the early crust a self-organized system.

4.4. Underlying Matrix and Limited Mobility

The underlying matrix, corresponding to the warm proto-asthenosphere, exhibits:

- low viscosity;
- ductile behavior;
- high sensitivity to thermal gradients;
- capacity to redistribute load and heat.

These properties permit decoupling of the islets and provide a medium in which:

- islets can move partially;
- they can rotate independently;
- they can undergo differential foundering;
- boundaries can migrate.

Without this underlying ductile matrix, the mosaic regime could not be sustained nor reorganize its internal structures.

4.5. The Mosaic as a Self-Organized and Self-Regulated System

The MMC constitutes a self-organized system in which segmentation patterns and structural hierarchy emerge from local interactions without a global controller. Thermal and mechanical feedbacks allow:

- active boundaries to strengthen or weaken depending on heat dissipation;
- recurrent structural reorganization;
- colder, more rigid islets to act as anchors;
- inefficient boundaries to heal;
- stable yet adaptive spatial patterns to arise.

This self-regulation is fundamental to the persistence of the mosaic for hundreds of millions of years, even under intense external forcing and high thermal flux.

In this view, the cortical mosaic is not an intermediate regime but the fundamental organizational structure of the early crust, from which coherent lateral mobility, larger domains, and proto-plates later emerge.

5. System Dynamics: Emergences and Feedbacks

Once cortical islets and their boundaries are established, the Cortical Mosaic (MMC) evolves as a self-organized system in which the geometry, activity, and persistence of discontinuities are not imposed by a global controller but emerge from continuous interaction among thermal gradients, local rheological properties, heat loss, and recurrent external forcing. In this system, surface dynamics are highly sensitive to local variations, and small differences in temperature, thickness, or viscosity can be amplified and come to define crustal-scale structure.

This section describes the mechanisms governing the internal dynamics of the mosaic: deformation localization, thermal feedbacks, boundary selection, externally induced reconfiguration, differential stabilization, and progressive hierarchization.

5.1. Deformation Localization in Active Boundaries

Mosaic boundaries function as brittle–ductile zones where deformation localizes due to three key factors:

- reduced thickness, facilitating stress transmission;
- higher temperatures, which lower local viscosity;
- efficient connectivity with the proto-asthenosphere, enabling thermal and mechanical rejuvenation.

Deformation localization is natural in a system with strong thermal gradients and rheological heterogeneity. These boundaries act as preferred channels for thermal and mechanical flow, controlling where surface reorganization occurs and where rigid, stabilizing protocrustal domains are preserved.

5.2. Thermal Feedbacks and Boundary Selection

The MMC is sustained by a set of positive and negative feedbacks:

Positive feedbacks
These enhance the persistence of a boundary:

- higher thermal flux → local weakening;
- weakening → increased deformation;
- increased deformation → greater heat dissipation;
- more heat → further boundary reinforcement.

This cycle transforms certain discontinuities into long-lived structures capable of channeling activity over millions of years.

Negative feedbacks
These promote boundary disappearance:

- reduced thermal gradients;
- increased viscosity;
- diminished deformation;
- thermal annealing;
- reintegration of the boundary into the adjacent islet.

These feedbacks allow the mosaic to dynamically select which boundaries survive and which vanish, creating coherent spatial patterns without external direction.

5.3. Reconfiguration Induced by External Forcing

Early Earth experienced frequent perturbations: impacts, mantle convective reorganizations, and high-rate volcanism. This external forcing interacted with the mosaic's internal feedbacks, generating:

- new fracturing;
- extension of existing discontinuities;
- localized thermal rejuvenation;
- adjustments in the orientation of islets;
- partial rotations or overturning;
- redistribution of stresses and topographic load.

Rather than destroying the mosaic, these perturbations kept it active, preventing premature collapse into a continuous crust.

The result was a system oscillating between reorganization and stabilization, yet consistently maintaining its segmented structure.

5.4. Thickening, Stabilization, and Coalescence of Islets

As Earth lost heat, cortical islets:

- thickened;
- decreased their internal temperatures;
- increased their viscosity;
- became mechanically more stable.

Cooler islets acted as mechanical anchors around which thinner and hotter islets reorganized.

Simultaneously, many thermally active boundaries lost energy and annealed, leading to coalescence processes in which previously independent islets merged to form larger crustal domains.

This process was neither uniform nor global; it occurred regionally and at different times, generating the characteristic hierarchical structure of the mature mosaic.

5.5. Progressive Hierarchization and Structural Maturation

The natural evolution of the mosaic leads to an organization characterized by:

- fewer active boundaries;
- larger domains;
- less abrupt thermal transitions;

- more coherent lateral mobility;
- persistent thermal and mechanical asymmetries;
- conditions favorable for localized foundering (proto-subduction).

Hierarchization is an emergent property—not the result of global decisions but of the interplay among:

- boundary geometry;
- thermal contrasts;
- mantle convective vigor;
- the thermal structure of the underlying matrix.

With time, the mosaic matures into domains capable of plate-like behavior, establishing the conceptual bridge between Archean crust and modern plate tectonics.

Synthesis
The dynamics of the MMC are defined by the interaction between internal self-organization and stochastic external perturbations. The combination of both produces a segmented, adaptable, and hierarchical system that naturally evolves toward larger, more coherent crustal domains. The regime is sustained by persistent active boundaries, recurrent reorganization, and dynamic boundary selection—mechanisms that explain the complexity of the Archean record and the gradual transition toward organized lateral mobility.

6. Evolution of the Mosaic Toward Plate-Like Units

The transition from a highly segmented and dynamic regime to one capable of coherent lateral mobility does not constitute an abrupt change or a sudden "onset" of modern plate tectonics. From the perspective of the MMC, this transition marks the mature phase of a self-organized system in which the hierarchization of cortical islets and the natural selection of discontinuities lead to the emergence of coherent domains—proto-plate-like units.

This evolution is gradual, internally guided, and regionally variable. Its central elements include the spontaneous reduction of active boundaries, the expansion of laterally coherent domains, the development of thermal and mechanical asymmetries, and the appearance of physical conditions necessary for localized foundering. Figure 2 illustrates this transition in three stages.

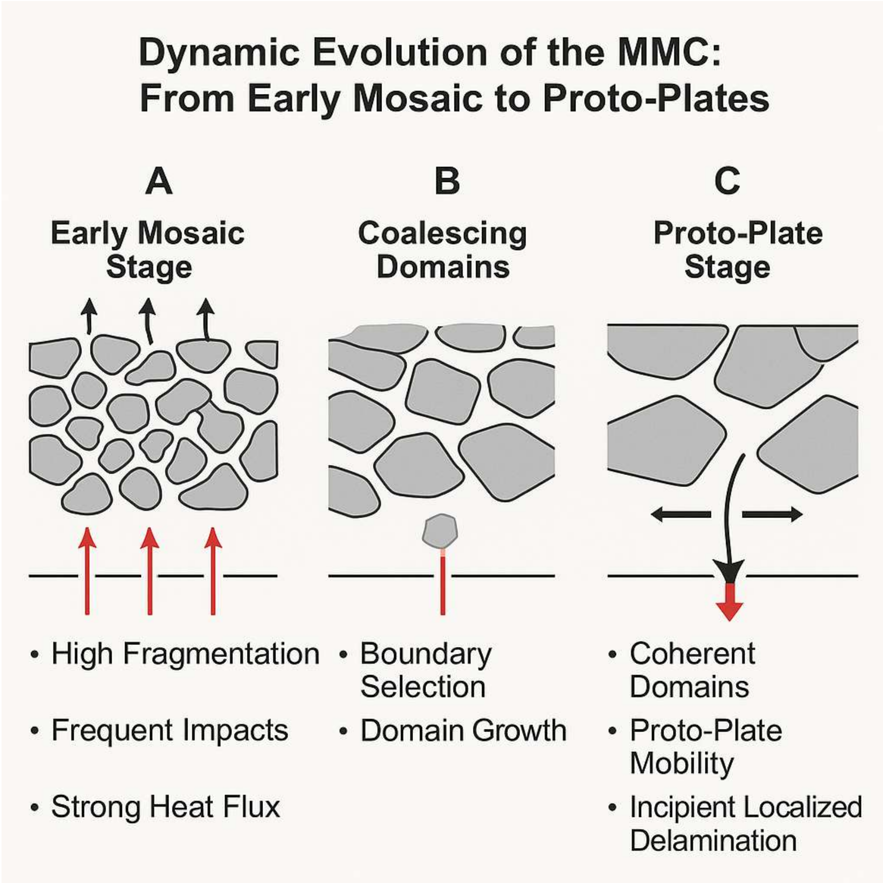

Figure 2. Dynamic evolution of the Cortical Mosaic (MMC) from a highly fragmented regime toward plate-like units. Panel A shows the early mosaic with numerous islets and active boundaries; Panel B illustrates the coalescence stage and boundary selection; Panel C depicts coherent domains with lateral mobility and incipient localized foundering.

6.1. Spontaneous Reduction in the Number of Active Boundaries

As the system loses heat, the thermal feedbacks described earlier promote the deactivation of many mosaic boundaries. This occurs because:

- thermal gradients decrease;
- lateral thermal conductivity increases;
- viscosity increases in formerly hot regions;
- some boundaries lose their capacity to dissipate heat efficiently.

The result is a natural pruning of discontinuities in which only boundaries that:

- remain thermally connected to the underlying matrix;
- sustain localized deformation;

- are reinforced by external perturbations,

are able to persist.

This reduction in boundary density represents the first major step toward a more organized crustal architecture with greater mechanical continuity.

6.2. Formation of Larger Domains and Coherent Mobility

When several islets lose the boundaries that once separated them, coalescence occurs:

- thermal properties partially homogenize;
- the effective viscosity of the composite region increases;
- internal fragmentation decreases;
- a larger crustal domain emerges.

Such domains—ranging from tens to hundreds of kilometers—exhibit:

- enhanced lateral rigidity;
- increased thermal thickness;
- diminished sensitivity to local perturbations;
- the ability to move their edges as integrated units.

With time, this lateral coherence enables these domains to move semi-rigidly, marking the onset of plate-like behavior.

6.3. Thermal and Mechanical Asymmetries Among Domains

As domains consolidate and cool at different rates, asymmetries arise between them:

- colder, thicker domains;
- hotter, thinner domains;
- variations in lithospheric roots;
- differences in density and load-bearing capacity.

These asymmetries are crucial because they:

- generate differential stress fields;
- modulate coupling with the underlying matrix;
- define regions where deformation tends to localize;
- prepare boundaries susceptible to foundering.

In a mature mosaic, these contrasts constitute the primary drivers of lateral dynamics and the seeds of future subduction.

6.4. Conditions for Localized Foundering (Proto-Subduction)

The MMC does not require immediate, sustained subduction. Instead, proto-subduction emerges as a late consequence of:

- significant density contrasts between domains;
- edges that are thinned and thermally weakened;
- compressive stresses generated by emerging lateral mobility;
- reactivation of persistent boundaries;
- the capacity of certain domains to founder partially into the underlying matrix.

Proto-subduction does not imply global or long-lasting geometry. It manifests as:

- localized, episodic foundering events;
- deep shear zones;
- mafic intrusions into weakened margins;
- localized metamorphism under steep gradients.

These behaviors represent the physical precursors of modern subduction and link the mosaic's dynamics to the earliest forms of tectonic behavior.

6.5. Plate Tectonics as the Mature Phase of the Self-Organized System

From the MMC viewpoint, plate tectonics does not arise because mantle dynamics changed abruptly. Instead, it emerges because the cortical mosaic:

- lost sufficient heat;
- deactivated most of its boundaries;
- consolidated large domains;
- established persistent thermal asymmetries;
- developed regions prone to localized foundering;
- created rigid units capable of transmitting stresses at regional scales.

Thus, modern plate tectonics represents:

- the mature expression of the mosaic;
- the final stage of a self-organized process;
- the inevitable evolutionary consequence of early crustal dynamics.

The MMC provides a continuous framework linking the initial fragmentation of the Hadean–Eoarchean crust with the later emergence of plate tectonics, without requiring independent tectonic regimes or abrupt transitions.

Synthesis

The evolution of the mosaic toward plate-like units is an emergent process guided by the system's internal self-organization. Boundary selection, islet coalescence, the development of larger domains, and the appearance of thermal asymmetries collectively enable the primitive crust to acquire the essential characteristics for coherent mobility and localized foundering. In this view, plate tectonics is the natural outcome—not the replacement—of mosaic dynamics.

7. Qualitative Predictions of the MMC

The self-organized nature of the Cortical Mosaic (MMC) implies that early crustal dynamics produced spatial, structural, and geochemical patterns that should be identifiable in the Archean rock record. These predictions do not depend on fine-tuned parameters or complex numerical simulations, but rather on the physical logic of the system: initial heterogeneity, local feedbacks, recurrent reorganization, and strong external forcing.

The presence—partial or integrated—of these signals strengthens the plausibility of the MMC; their systematic absence would weaken it. Figure 3 summarizes the proposed temporal trajectory of the MMC and the intervals in which these signals should manifest.

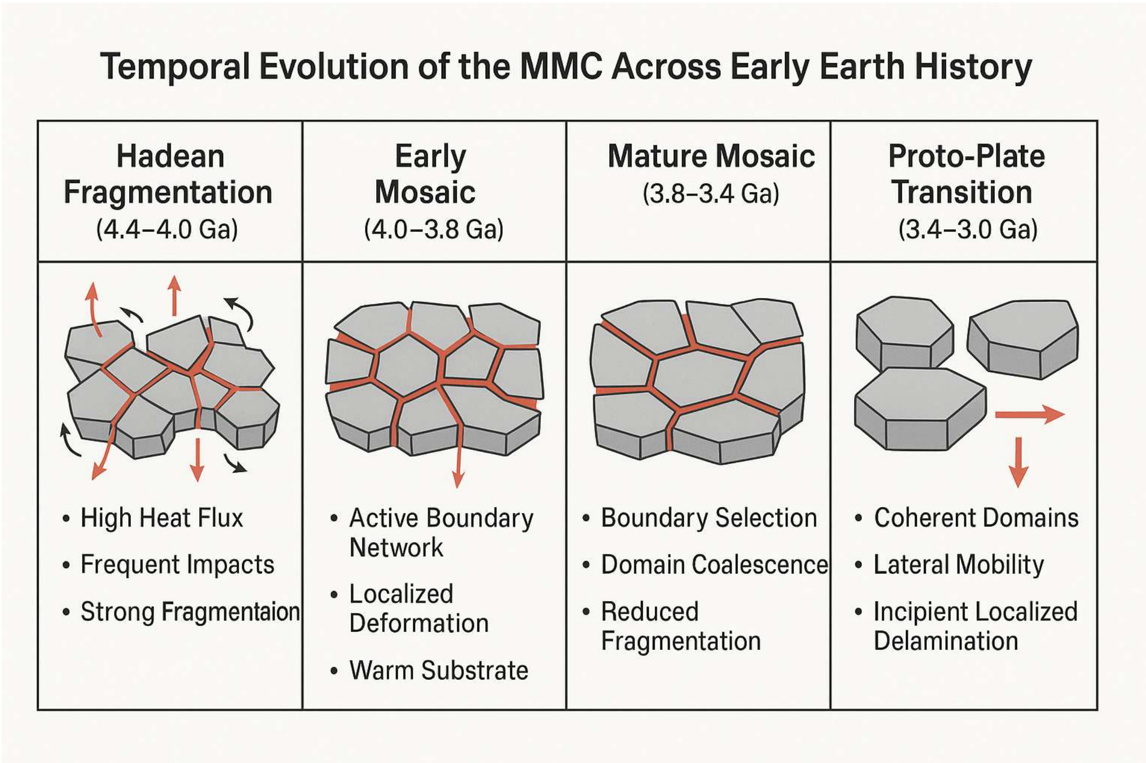

Figure 3. Summary of the proposed temporal trajectory of the MMC, from Hadean fragmentation to the proto-plate transition, indicating windows when different model predictions should be observable.

7.1. Rotated or Partially Overturned Cortical Islets

A distinctive prediction of the MMC is the existence of rigid islets that underwent independent rotations or even partial overturning in response to:

- mechanical reorganization of the mosaic;
- energetic impacts;

- differential foundering events;
- abrupt changes in load or crustal thickness.

Such behavior may expose materials originally at depth—such as very ancient zircon crystals—or produce anomalous crystalline orientations not easily explained by modern tectonic mechanisms or deep exhumation.

Expected signals include:

- crystals exposed without clear exhumation context;
- domains exhibiting extreme tilting or disruptive geometries;
- blocks rotated relative to neighbors without a coherent regional framework.

This phenomenon is natural in a decoupled, segmented, and thermally perturbed system.

7.2. Persistent Isotopic Heterogeneity Between Neighboring Domains

In a self-organized mosaic, islets maintain independent thermal and compositional histories for extended periods. Thus, the MMC predicts:

- coexistence of multiple isotopic populations (Hf, Nd, O, Pb);
- signatures of partial recycling and incomplete mixing;
- domains with overlapping ages but different origins.

The isotopic heterogeneity observed in >4.0 Ga zircons and Archean TTG terrains is consistent with this prediction.

7.3. Structural Hierarchies Within Archean Cratons

As islets evolve and merge, the mosaic acquires hierarchical patterns in which small domains become embedded within larger ones.

The MMC predicts:

- cratons with multiscale architecture;
- internal lithochemical domains better defined than peripheral margins;
- relict boundaries separating ancient subdomains.

This fractal-like or hierarchical structure reflects the progressive selection and coalescence of discontinuities.

7.4. Deep and Narrow Relict Discontinuities

Mosaic boundaries function as zones of intense thermal and mechanical activity. Although many anneal with time, some should leave deep and persistent traces:

- narrow metamorphic belts;
- mafic or ultramafic ribbons;
- internal seismic lineaments;
- abrupt contrasts in seismic velocities.

These relict discontinuities—buried beneath more stable domains—are expected outcomes of a system that continually reorganized its boundaries.

7.5. Marked Variability in Crustal Thickness and Abrupt Transitions

Because islets evolve at different rates, the MMC predicts heterogeneity in:

- crustal thickness;
- density;
- rigidity;
- internal structure.

Archean crust should therefore exhibit:

- pronounced thickness contrasts between adjacent domains;
- heterogeneous cratonic roots;
- abrupt transitions that do not align with a coherent global tectonic geometry.

These features reflect the fragmented and heterogeneous nature of the mosaic.

7.6. Mixed Signals of Lateral Mobility Before 3.0 Ga

In the mature mosaic stage, before the establishment of modern plates, the MMC predicts regional but not global lateral mobility, manifested as:

- local convergence;
- partial foundering events;
- restricted lateral displacements;
- isolated shear zones;
- incomplete or discontinuous tectonic geometries.

These mixed signals should appear between ~3.4 and 3.0 Ga, reflecting a transitional regime where fragmentary behavior coexisted with incipient coherent mobility.

Synthesis
The MMC anticipates an Archean record dominated by heterogeneity, segmentation, hierarchical structures, independent rotations of islets, relict discontinuities, and incomplete lateral mobility. These predictions directly reflect a self-organized system subjected to strong external forcing and provide a coherent set of signals for assessing the model's plausibility in the geologic record.

8. Falsification Criteria

Although the Model of Cortical Mosaics (MMC) is a conceptual framework describing the early evolution of Earth's crust, it generates a set of observable expectations whose systematic absence would critically challenge its validity. These criteria do not aim to refute the model using strict quantitative parameters—unsuitable for a system based on emergent behavior—but rather to provide reasonable empirical conditions under which the MMC would be inconsistent with geological or geophysical evidence.

The falsification criteria derive directly from the operational principles of the mosaic: persistent segmentation, initial heterogeneity, local feedbacks, boundary selection, and progressive hierarchization.

8.1. Absence of Early Isotopic Heterogeneity

The MMC requires that cortical islets maintained distinct thermal and compositional histories while coexisting within a segmented system.

If the Archean record displayed global isotopic homogeneity before ~3.5 Ga—across Hf, Nd, O, Pb, or very ancient zircons—the prolonged maintenance of independent domains would be incompatible with the model.

8.2. Lack of Hierarchies and Internal Domains in Archean Cratons

A crust that evolved under a self-organized mosaic must preserve hierarchical structures, with small domains embedded within larger ones.

If Archean cratons exhibited monolithic, uniform architectures—lacking evidence of ancient subdomains, internal amalgamation, or relict boundaries—then the principle of progressive coalescence would be difficult to sustain.

8.3. Absence of Rotations, Inversions, or Overturning of Islets

The MMC predicts that segmented dynamics and decoupling from the warm matrix allow independent rotations, extreme tilting, and even partial overturning of cortical islets.

If the structural record consistently lacked:

- blocks rotated relative to neighboring domains;
- domains with anomalously inclined or inverted internal geometries;
- exposed crystals lacking a context of deep exhumation,

then one of the model's most distinctive predictions would be undermined.

8.4. Nonexistence of Narrow and Deep Relict Discontinuities

Mosaic boundaries function as zones of high thermal dissipation and localized deformation. Although many are annealed over time, some should leave persistent traces in the form of:

- internal seismic lineaments;
- buried shear zones;
- narrow metamorphic belts;
- abrupt contrasts in seismic velocities.

If seismic and geological studies revealed a complete absence of such relict discontinuities in Archean cratons, the model's core assumption of boundary-driven organization would lose support.

8.5. Evidence of Global Coherent Tectonics Before 3.0 Ga

According to the MMC, coherent lateral mobility emerges late and only locally, as the mosaic matures.

If the rock record between 3.5 and 3.0 Ga showed unequivocal evidence of:

- continuous, global subduction;
- well-defined plate geometries at planetary scale;
- coherent global margins;
- fully developed Wilson cycles,

then a segmented, self-organized mosaic would not be required to explain early crustal evolution.

Synthesis
The falsification criteria for the MMC are based on reasonable indicators of segmented, heterogeneous, and hierarchical early crustal behavior. Their systematic absence would imply that the Archean crust did not operate as a self-organized system, weakening the model's

central premise. Conversely, the presence of these elements reinforces the plausibility of the MMC as a coherent framework bridging early fragmentation with the emergence of modern plate tectonics.

9. Discussion

The Model of Cortical Mosaics (MMC) proposes that the early Earth's crust evolved as a self-organized system in which discontinuities and crustal domains emerged from localized interactions among thermal gradients, compositional heterogeneity, rheological feedbacks, and intense external forcing. This perspective provides an integrative reinterpretation that contrasts with traditional early tectonic models, which typically describe discrete regimes or sequences of partially disconnected states.

The following discussion evaluates the coherence of the MMC relative to the state of the art, its broader conceptual implications, its compatibility with Archean geological observations, and its relevance for understanding lithospheric evolution on other planetary bodies.

9.1. The MMC as a Self-Organized System: Conceptual Implications

A self-organized framework implies that:

- there is no single initial tectonic regime, but rather an emergent trajectory driven by primordial heterogeneity;
- crustal fragmentation is not a failure mode but a natural consequence of differential cooling;
- recurrent reorganization is part of the system's normal behavior, not an exceptional event;
- discontinuities are dynamically selected based on their ability to dissipate energy.

These ideas refine the traditional view of the primitive crust by showing that the transition to plate tectonics does not require a global external shift but arises naturally from the maturation of an internally regulated system.

9.2. Critical Comparison With Previous Models

Major early Earth tectonic models can be reinterpreted as local expressions of the MMC:

- **Fractured stagnant lid**: corresponds to the mosaic's initial fragmentation stage;
- **Heat-pipe dynamics**: reflect episodes of intense volcanism rejuvenating active boundaries;

- **Episodic tectonics**: captures phases of reorganization caused by impacts or mantle rearrangements;
- **Proto-plates**: represent the mature stage of consolidated domains.

The MMC does not compete with these models; it unifies them within a continuous evolutionary framework, supplying the physical narrative that links otherwise separate regimes.

9.3. Indispensable Role of External Forcing

Impacts, intense volcanism, and convective reorganizations played a critical role in maintaining the mosaic. Rather than interrupting self-organization, external forcing:

- reinforced boundary activity;
- generated new discontinuities;
- produced thermal rejuvenation;
- prevented premature homogenization of the crust.

The MMC treats this forcing not as a sporadic disturbance but as a structural component, differing from models in which impacts are viewed as isolated events.

9.4. Why the Crust—Not the Mantle—Develops a Mosaic

The primitive crust occupied a critical rheological zone between rigidity and ductility, where small differences in temperature or thickness produced major changes in:

- fragility;
- viscosity;
- capacity for deformation localization.

This rheological sensitivity favored early formation of shallow discontinuities. The mantle, although vigorous, was more homogeneous and operated on longer timescales; it lacked the spatial heterogeneity and thermal sensitivity needed to sustain a long-lived segmented pattern.

Thus, the mosaic is a surface phenomenon deeply coupled to internal planetary dynamics.

9.5. Model Limitations

The MMC has limitations inherent to conceptual models:

- **Lack of explicit quantification**: it does not impose precise numerical values for viscosity or thickness, limiting fine-grained testing;

- **Dependence on fragmentary Archean records**: available evidence is incomplete and variably preserved;
- **Need for specialized thermomechanical simulations**: required to explore boundary selection, domain hierarchies, and islet overturning dynamics;
- **Complexity of emergent systems**: makes it difficult to distinguish primary from secondary effects.

These limitations do not invalidate the MMC but indicate areas for future refinement.

9.6. Relevance for Planetary Evolution and Analog Bodies

The MMC enables reinterpretation of partially analogous regimes in other Solar System bodies:

- **Venus**: localized fragmentation without sustained subduction;
- **Io**: segmentation driven by extreme volcanism;
- **Early Mars**: preserved crustal heterogeneity without global tectonics;
- **Mercury**: crust too thick to sustain a prolonged mosaic regime.

These parallels suggest that cortical mosaics may be a common phenomenon on planets and moons with high initial thermal flux and relatively thin early crusts.

9.7. Directions for Future Research

Three research avenues are particularly relevant:

1. **3D numerical modeling with realistic initial heterogeneity**: to quantify spatial scales, reorganization rates, and domain hierarchies.
2. High-resolution isotopic and structural studies in Archean cratons: to identify independent domains and relict discontinuities.
3. **Targeted deep seismic investigations**: to detect buried boundaries and abrupt contrasts in lithospheric roots.

These approaches will help evaluate the robustness of the MMC and refine it into a more operational and testable framework.

Synthesis
The MMC offers a coherent narrative integrating previously disconnected regimes, explaining persistent Archean fragmentation, linking surface self-organization with external forcing, and providing a clear conceptual bridge between primitive crust and the emergence of plate tectonics. Its emergent, adaptive nature reflects the inherent complexity of the early Earth and opens new lines of inquiry on early and planetary lithospheric dynamics.

10. Conclusions

The Model of Cortical Mosaics (MMC) proposes that Earth's earliest crust did not operate under a single discrete tectonic regime, but rather as a self-organized system strongly influenced by initial heterogeneity, uneven thermal dissipation, basal decoupling by a warm underlying matrix, and intense external forcing. In this framework, fragmentation, reconfiguration, and domain hierarchization are not isolated events but natural expressions of planetary physics during the Hadean and Eoarchean.

Three central ideas emerge from the analysis:

(1) Crustal segmentation is an inevitable consequence of initial conditions. Rheological heterogeneity, rapid heat loss, and the brittle–ductile character of the primitive crust generated discontinuities and independent domains from very early stages. The early crust could not have behaved as a rigid lid nor as a globally coherent system.

(2) Crustal evolution was regulated by feedbacks and boundary selection. The persistence of mosaic boundaries depended on their capacity to concentrate thermal flux and deformation. Internal feedbacks—combined with impacts, volcanism, and convective reorganizations—kept the mosaic dynamically active, preventing premature homogenization.

(3) Modern plate tectonics is the mature phase of this self-organized system. Islet coalescence, differential thickening, and progressive reduction in active boundaries enabled the formation of extensive domains capable of coherent lateral mobility. Under this view, incipient subduction and proto-plates are not separate regimes but the natural outcome of mosaic maturation.

The MMC therefore integrates key elements from previous models—fragmentation, episodic mobility, heat-pipe behavior, and proto-plate dynamics—into a continuous evolutionary trajectory explaining the complexity of the Archean record and the intermediate steps leading to modern plate tectonics.

Finally, the model opens new opportunities for research through:

isotopic studies aimed at resolving domain hierarchies;

seismic analyses to identify relict discontinuities;

advanced numerical simulations exploring boundary selection and emergent patterns.

The MMC does not seek to replace existing models but to connect them within a coherent, physically motivated narrative of the early Earth's thermal and mechanical evolution. Its strength lies in offering an emergent, self-regulated perspective that illuminates the natural progression from a fragmented protocontinental crust to the plate-tectonic system that shapes the modern Earth.

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12. Declarations

12.1. Conflict of Interest

The author declares no conflicts of interest relevant to the content of this manuscript. The research, interpretation, and conclusions presented here were conducted independently and without financial or institutional pressures that could influence the results.

12.2. Author Contribution

The author is solely responsible for the conception of the model, theoretical development, literature review, manuscript preparation, and all revisions. No external co-authors or contributors participated in the scientific content of this work.

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