A Unified Forearc Subsidence Model

Based on the Three-Arc Unjoined Structure of the Honshu Arc

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Date 6 August 2026

This submission is a preprint and has not undergone peer review.

Abstract

This study reinterprets the subsidence, uplift, fault activity, and geomorphic development observed in the Nōbi Plain, Ise Bay, Lake Biwa, Wakasa Bay, and Osaka Bay through a new structural framework in which the Honshu Arc is understood as an incompletely joined system of three arcs. The Southwest Japan Arc (narrow sense), the Hida–Tamba Terrane, and the Northeast Japan Arc approached each other during the opening of the Japan Sea but never fully sutured. Their unjoined boundaries are exposed on the forearc side, forming Forearc Weak Suture Zones, where the weakness of accretionary complexes and the overlap of major fault zones concentrate subsidence, seismic shaking, and geomorphic reorganization. The Nōbi Plain lies within a Dual Weak Surface Structure, defined by the Yōrō Fault (inner weak surface) and the Biwa Western Margin–Rokko Fault Zone (outer weak surface), and is therefore interpreted not as a depositional basin but as a subsidence-dominated forearc basin. Ise Bay represents its southern continuation, forming a single forearc subsidence system. Lake Biwa occupies the northwestern end of the unjoined arc structure, while uplift along the Wakasa Bay coast is explained by three-sided tectonic confinement imposed by rigid crustal blocks. The continuous subsidence belt from Lake Biwa through the former Ogura Lake and Funo Basin to Osaka Bay defines the Kinki Subsidence Line, a western counterpart to the South Fossa Magna, effectively a "Second Fossa Magna." This study demonstrates that the South Fossa Magna–Kanto Basin system and the Nōbi–Biwa–Osaka system are governed by the same forearc weak suture zone processes, thereby establishing a unified tectonic model for forearc subsidence in the Japanese Islands.

Keywords

Three-Arc Unjoined Model, Forearc Weak Suture Zone, Dual Subsidence Structure, Kinki Subsidence Line, Nōbi Basin, Lake Biwa Structural Basin, Wakasa Bay Uplift, Three-Sided Tectonic Confinement, Accretionary Complex Crust, Japan Sea Opening, South Fossa Magna, Kanto Basin Subsidence Structure

Chapter 0: Introduction

This study originates from an observation made from the window of the Kintetsu Urban Liner: the unusually flat surfaces of the Nōbi Plain and the Ise Plain. This prompted the idea that the same mechanism operating in the Kantō Plain might also be acting upon the Nōbi Plain.

For many years, the tectonics of the Japanese Islands have been understood under the assumption that a “single island arc deformed in response to plate motion.” Although the Southwest Japan Arc, the Northeast Japan Arc, and the Kuril Arc of Hokkaidō have been treated as independent arcs, the interior of the Honshu Arc has implicitly been regarded as a unified arc. However, this assumption is inconsistent with numerous observations of subsidence, uplift, fault activity, and landform development across the archipelago.

The Nōbi Plain has long been interpreted as a forearc depositional basin with a large alluvial fan, yet in reality natural levees scarcely develop, micro-topography is almost absent, and the surface is extraordinarily flat. The three rivers—the Kiso, Nagara, and Ibi—converge toward the subsidence axis, forming a densely packed drainage system, and a vast flat expanse extends from Nagoya to Nagashima. These phenomena cannot be explained by conventional depositional models.

Lake Biwa has been interpreted as a fault-bounded basin or a rift basin formed by extensional tectonics, but its scale, shape, northward-advancing subsidence axis, and relationship with uplift along the Wakasa Bay coast exceed the explanatory capacity of existing models. Although Wakasa Bay is a subsiding marine basin, Lake Biwa does not open into it; instead, the bay coast is uplifted like a “barrier wall,” a fact that is difficult to explain.

These observations require a new conceptual framework: not a single island arc, but a composite of multiple arcs whose junctions remain incompletely sutured to the present day.

This study introduces three new concepts—the Three-Arc Unjoined Model, the Forearc Weak Suture Zone Model, and the Dual Subsidence Structure Model—to redefine the internal structure of the Honshu Arc.

First, the Honshu Arc is interpreted as a structural assemblage of three arcs: the Southwest Japan Arc (Cretaceous igneous arc), the Hida–Tamba Terrane (Jurassic accretionary arc), and the Northeast Japan Arc (older arc). These arcs approached one another during the fan-shaped extrusion associated with the opening of the Japan Sea, but portions remained unjoined.

Second, the unjoined arc boundaries host Forearc Weak Suture Zones, formed by the weakness of accretionary complexes and the overlap of major fault zones. These zones become centers of subsidence, seismic motion, and landform development.

Third, the subsidence observed in the Nōbi Plain, the Ise Plain, and Lake Biwa is interpreted as a Dual Subsidence Structure, governed by an inner weak surface (the Yorō Fault) and an outer weak surface (the Biwa western margin–Arima-Takatsuki Fault Zone–Rokko/Awaji Fault Zone).

By integrating these three concepts, this study presents a new tectonic model that explains subsidence, uplift, fault activity, and landform development across the Japanese Islands as structural inevitabilities.

The Introduction organizes the limitations of existing models and clarifies the necessity of the new framework proposed here. The following chapters reinterpret the unjoined arc structure, the mechanics of forearc weak suture zones, examples of dual subsidence structures, and the geomorphic and geological phenomena of the Nōbi Plain, Lake Biwa, Osaka Bay, the South Fossa Magna, and the Kantō Basin, ultimately presenting a new tectonic model for the Japanese Islands.

Chapter 1. Background of Previous Research

This study is positioned as an extension of the following existing research.

1.1 Dynamic Leveling of the Kanto Basin, Japan

The Kanto Basin in central Japan has maintained an anomalously flat surface for over one million years, despite being situated within an intensely compressional tectonic environment of the Japanese island arc. Conventional static models based on sedimentation or sea-level fluctuations cannot adequately explain this long-term planar stability.

This research proposed a dynamic leveling mechanism driven by two interacting deep tectonic processes:

(1) the stress-shielding effect of the rigid "Kanto Fragment," an isolated slab of the Pacific Plate buried beneath the basin, and

(2) intermittent Mw 8-class deep earthquakes occurring along its boundary.

By integrating GNSS-derived rigid-block motions of the basin with geotechnical principles such as liquefaction, lateral spreading, and differential consolidation, the study constructed a unified conceptual model for basin-scale dynamic reorganization.

Large deep earthquakes periodically induce forced fluidization within the 3–4 km-thick sequence of unconsolidated sediments, generating three-dimensional lateral flow governed by gravitational potential gradients and differential consolidation driven by sediment load contrasts. These processes act synergistically to reset irregularities formed by static sedimentation and function as the long-term driver of natural surface flattening.

This model provides a coherent explanation for the preservation of terrace surfaces as remnants of formerly flattened landscapes and redefines the geomorphic evolution of the Kanto Basin as a dynamically earthquake-driven system.

(Hiraoka, 2026)

This study is hereafter referred to as "Paper 1."

1.2 Tectonic Controls on the Subsidence of the Kanto Basin

Despite being located within a strong compressional stress field, the Kanto Basin has undergone 1–3 km of subsidence throughout the Quaternary—an exceptionally rare crustal deformation on a global scale. Building upon the dynamic leveling model presented in Paper 1, this study proposed an integrated tectonic model explaining the subsidence structure itself.

The Kanto forearc upper plate is constrained from the south, north, and west, severely limiting horizontal shortening and lateral flow. Under this mechanically isolated condition, rapid subduction of the Pacific Plate induces forearc pull-down, tilting the upper plate obliquely downward. The subsidence axis is geometrically fixed by the Miocene half-graben structure formed during the opening of the Japan Sea.

This model provides a coherent conceptual framework for understanding features previously difficult to explain, including the eccentric subsidence axis, east–west asymmetry, biased fault development, persistence of Tokyo Bay, and the absence of alluvial fans or raised-bed rivers.

(Hiraoka, 2026)

This study is hereafter referred to as "Paper 2."

1.3 The Unjoined Arc Structure Governing the Anomalous Forearc Response of the Kanto Basin

The Kanto Basin exhibits anomalous forearc responses—1–3 km of subsidence, west-shifted subsidence axis, asymmetric fault distribution, persistence of Tokyo Bay, and formation of the Kanto Fragment—that cannot be explained by existing forearc models.

This study hypothesized that the Southwest Japan Arc and Northeast Japan Arc are not fully joined in the South Fossa Magna–Kanto region, leaving an unjoined arc structure. This structure was redefined as a Forearc Weak Suture Zone. Furthermore, the region may contain an upper plate retaining accretionary-complex characteristics, producing a dual-weakness model in which structural weak surfaces (unclosed sutures) overlap with material weak surfaces (accretionary upper plate).

This dual weakness creates a mechanical environment where horizontal shortening is easily converted into vertical deformation due to three-sided confinement and wedge-shaped geometry, amplifying forearc pull-down. As a result, numerous previously unexplained observations—including Kanto Basin subsidence, asymmetry, disappearance of the Median Tectonic Line, bending of the Japanese Islands, and deep crustal intrusion beneath the Koma and Misaka Mountains following the collision of the Izu Arc—can be understood coherently.

This study presented a new tectonic framework explaining the anomalous forearc response of the Kanto Basin and South Fossa Magna, leaving numerical modeling for future work.

(Hiraoka, 2026)

This study is hereafter referred to as “Paper 3.”

Chapter 2. Internal Structure of the Honshu Arc: Proposal of the Three-Arc Unjoined Model

In this study, the crustal unit extending from the western margin of the Fossa Magna to the Tamba Highlands—composed primarily of Jurassic accretionary complexes—is referred to as the Hida–Tamba Terrane.

The Hida–Tamba Terrane has traditionally been treated as part of the “Southwest Japan Arc (broad sense).” However, when integrating the AIST 1:200,000 Seamless Geological Map of Japan®, crustal structure, fault distribution, and geomorphic development, it becomes evident that the interior of the Southwest Japan Arc (broad sense) contains discontinuities that cannot be explained by a single-arc model. These discontinuities are not merely local geological boundaries but structural evidence that the arc itself is a composite of multiple arcs.

This chapter presents a new framework in which the Honshu Arc consists of three arcs—the Southwest Japan Arc (sensu stricto), the Hida–Tamba Terrane, and the Northeast Japan Arc—and in which their junctions remain incompletely sutured to the present day. This “Three-Arc Unjoined Model” forms the conceptual foundation for the Forearc Weak Suture Zone and Dual Subsidence Structure discussed in subsequent chapters.

To avoid confusion, the following terminology is used:

(1) The traditional Southwest Japan Arc including the Hida–Tamba Terrane is referred to as the Southwest Japan Arc (broad sense).

(2) The Southwest Japan Arc excluding the Hida–Tamba Terrane is referred to as the Southwest Japan Arc (sensu stricto).

2.1 Southwest Japan Arc (sensu stricto): Rigid Arc Composed of Cretaceous Igneous Rocks

The Southwest Japan Arc is a high-strength arc composed mainly of Cretaceous igneous rocks, characterized by thick crust and strong resistance to deformation. The igneous arc extending from the Chugoku Mountains through western Kinki to northern Shikoku represents the “original arc” that existed prior to the opening of the Japan Sea, and its rigidity is still expressed today in the structural stability of the Chugoku Mountains.

This arc differs fundamentally from the Hida–Tamba Terrane described later. Their boundary appears clearly on geological maps as the Takatsuki–Miyazu Line, which is interpreted not merely as a lithological boundary but as a suture—an arc–arc boundary.

2.2 Hida–Tamba Terrane: Jurassic Accretionary Arc with Structural Weakness

The terrane composed mainly of Jurassic accretionary complexes, extending across central Kinki, Tokai, and Hokuriku, has traditionally been treated as part of the Southwest Japan Arc (broad sense). However, its geological characteristics—dense fault zones, high degree of fragmentation, and mechanical weakness—differ fundamentally from those of the Southwest Japan Arc (sensu stricto).

This terrane represents an independent arc structure that was trapped during the opening of the Japan Sea and plays a decisive role in forming the unjoined arc structure and the Forearc Weak Suture Zone within the Honshu Arc.

During the rotation and migration of the Honshu Arc associated with Japan Sea opening, the terrane did not fully join with the Southwest Japan Arc (sensu stricto). The unjoined portion remains today as a structural weak zone underlying the Nōbi Plain, Ise Plain, Lake Biwa region, and Osaka Bay.

2.3 Northeast Japan Arc: Independent Arc of Older Geological Origin

The Northeast Japan Arc is an older arc adjacent to the Kuril Arc in Hokkaido and has no geological continuity with the Hida–Tamba Terrane. Their boundary appears as the western margin of the Northern Fossa Magna, and the boundary between the Northeast Japan Arc and the Kuril Arc is exposed geomorphologically as the Tsugaru Strait.

The Tsugaru Strait is considered important evidence of an unjoined arc boundary, as numerous fractured zones were encountered during the excavation of the Seikan Tunnel, indicating that the boundary between the Northeast Japan Arc and the Kuril Arc remains a structural weak zone today.

2.4 Fan-Shaped Extrusion of the Three Arcs During Japan Sea Opening

The opening of the Japan Sea, approximately 15–20 Ma, generated a tectonic environment in which the Honshu Arc rotated clockwise and multiple arcs were extruded in a fan-shaped pattern.

During this process, the Southwest Japan Arc (sensu stricto), the Hida–Tamba Terrane, and the Northeast Japan Arc approached one another but did not fully join. As a result, multiple sutures remain between the arcs, forming the structural basis of the Forearc Weak Suture Zone.

2.5 Formalization of the Three-Arc Unjoined Model

Integrating the above observations, the Honshu Arc is composed of the following three arcs:

Southwest Japan Arc (sensu stricto) — Cretaceous igneous arc (rigid)

Hida–Tamba Terrane — Jurassic accretionary arc (weak)

Northeast Japan Arc — Older independent arc

These three arcs approached each other during the opening of the Japan Sea but never fully sutured, leaving multiple unjoined zones that persist to the present.

This "Three-Arc Unjoined Structure" provides the structural foundation for explaining the subsidence and uplift phenomena observed in the Nōbi Plain, Ise Plain, Lake Biwa, Wakasa Bay, and the Kanto Basin.

Figure 1. Conceptual map showing the locations of the arcs, crustal terranes, and forearc weak suture zones discussed in this study.

This figure illustrates the positions of each arc, terrane, and forearc weak suture zone appearing in the present paper, plotted on a geological map. The treatment of accretionary complexes on the Pacific side of the Median Tectonic Line may be subject to further debate.

Based on the 1:200,000 Seamless Geological Map of Japan® published by the Geological Survey of Japan (AIST), with additional annotations by the author.

Chapter 3. Position of This Study within the Existing Research Framework

Paper 3 demonstrated the theory of "unjoined arc structure + forearc weak suture zone" in the Kanto Basin.

The present study applies that same theoretical framework to the region extending from the Nōbi Plain and Ise Plain through Lake Biwa and the Tamba Highlands to Osaka Bay, and systematizes the structural characteristics of forearc weak suture zones within the Honshu Arc.

In other words:

- Paper 3: Empirical demonstration of the weak suture zone in the Kanto–Kōshin region
- This paper: Empirical demonstration of the weak suture zone in the Nōbi–Biwa region

The two papers form a pair of "twin studies," and by integrating them, the Three-Arc Unjoined Model of the Honshu Arc is completed.
In this study, the following terminology is used:

- The unjoined structure inferred to exist in the South Fossa Magna–Kanto Basin region, as discussed up to Paper 3, is referred to as the South Fossa Magna–Kanto Forearc Weak Suture Zone.
- The unjoined structure inferred to exist from the Nōbi Plain to the Tamba Highlands, as discussed in the present study, is referred to as the Kinki–Nōbi Forearc Weak Suture Zone.

Chapter 4. Subsidence Structure and Landform Development of the Nōbi Plain

The Nōbi Plain is a large lowland situated in the forearc of the Japanese Islands. Its geomorphic characteristics are highly distinctive, comparable to those of the Kanto Plain and unlike other forearc plains. Although traditionally interpreted as a depositional plain with a large alluvial fan, natural levees and raised-bed rivers are scarcely developed, micro-topography is almost absent, and the surface is extraordinarily flat. The three major rivers—the Kiso, Nagara, and Ibi—are densely concentrated and converge toward the subsidence axis on the western side of the plain.
These features are difficult to explain using conventional depositional models. However, when considered within the structural framework of the forearc weak suture zone described in Paper 3, they can be understood for the first time.
This chapter reinterprets the subsidence structure, landform development, and river configuration of the Nōbi Plain from the perspective of the Forearc Weak Suture Zone Model.

4.1 Geological Basement of the Nōbi Plain: Overlap of Accretionary Complex and Dual Weak Surfaces

The basement of the Nōbi Plain consists of Jurassic accretionary complexes overlain by thick Neogene–Quaternary sediments forming a half-graben basin structure (Yamaguchi et al., 2006; Baba et al., 2000). This origin is similar to that of the Kanto Basin.
The Nōbi Plain also contains structural weak lines such as the Yorō Fault Zone and the Suzuka Eastern Margin Fault Zone. These elements together form the structural framework within which subsidence progresses. For this reason, the present study refers to the Nōbi Plain as the Nōbi Basin.
Furthermore, Ise Bay, the Ise Plain, and the Suzuka Fault Zone located to the south are considered extensions of the same structural system. Thus, this study treats them as a single integrated forearc subsidence domain.

4.2 Why Natural Levees and Raised-Bed Rivers Do Not Develop: Influence of Dynamic Leveling

The most distinctive feature of the Nōbi Basin is the near absence of natural levees.
In typical alluvial fans or floodplains, natural levees and raised-bed rivers form through sediment deposition during floods. However, such micro-topography is scarcely observed in the Nōbi Basin. Particularly in the southeastern part of the basin—from Nagoya to Yatomi—extensive flatlands exist despite the absence of rivers supplying sediment from nearby mountains.

This phenomenon is interpreted as dynamic leveling, caused by deep earthquakes characteristic of forearc weak suture zones—specifically, strong seismic shaking generated intermittently along the boundary between the Philippine Sea Plate and the overriding plate. These earthquakes periodically fluidize the thick sedimentary layers, as described in Paper 1.

As a result, natural levees and raised-bed rivers fail to develop, alluvial fans do not form, and the plain becomes extraordinarily flat. The flatness of the Nōbi Basin is therefore interpreted not as a product of sedimentation but as the combined result of dynamic leveling and ongoing subsidence.

4.3 Dense Concentration of the Three Rivers: Convergence Toward the Subsidence Axis

The dense convergence of the Kiso, Nagara, and Ibi Rivers toward the western part of the Nōbi Basin—particularly the fact that the Kiso River detours westward from Inuyama instead of flowing directly south—is a notable geomorphic anomaly.

According to the Forearc Weak Suture Zone Model, as described in Paper 2, three-sided confinement converts compressional stress from plate subduction into predominantly downward vectors, enhancing subsidence and shifting the subsidence axis toward the direction of plate subduction.

In the case of the Nōbi Basin, the three-sided confinement is likely produced by relatively rigid crustal blocks:

North: Hida Mountains
West: Tamba Highlands
South: Kii Peninsula

This configuration is consistent with the westward tilt of the basin.

Consequently, rivers continually adjust their courses toward the subsidence axis, natural levees fail to form, and river channels change frequently—producing the observed dense river convergence.

4.4 The Nōbi Basin Is a “Subsidence Basin,” Not a “Depositional Basin”

Integrating the above observations, the Nōbi Plain should not be understood as a conventional depositional basin. Rather, it is a subsidence basin in which subsidence exceeds sedimentation. Sedimentation is better interpreted as a result of subsidence, not its cause.

Chapter 5. The Lake Biwa Structural Basin and the Southwest-Extending Subsidence Belt: The “Kinki Subsidence Line”

Lake Biwa is the largest freshwater lake in the Japanese Islands, and its scale, shape, and location are highly distinctive compared with other lakes. Although it has traditionally been interpreted as a fault-bounded basin or a rift basin formed by extensional tectonics, its origin, growth direction, and relationship with Wakasa Bay have not been adequately explained by existing models.

Lake Biwa is not merely a fault basin; rather, it is a focal point of subsidence formed at the northwestern end of the Kinki–Nōbi Forearc Weak Suture Zone, and it has grown through interaction with uplift along the Wakasa Bay coast, produced by the rigid Hida–Tamba Terrane acting as a structural barrier.

5.1 The Location of Lake Biwa Corresponds to the Northwestern End of the Unjoined Arc Structure

Lake Biwa formed at the northwestern extension of the subsidence axis originating in the Nōbi Plain. If the Yorō Fault is considered the inner subsidence axis, the outer axis may be defined by the Biwa Western Margin Fault Zone, the Arima–Takatsuki Fault Zone, and the Rokko–Awaji Fault Zone. Lake Biwa lies at the northwestern end of this structural trend.

To the west of Lake Biwa lies the Tamba Highlands, and further west the Takatsuki–Miyazu Line marks the geological boundary between accretionary complexes and igneous rocks—interpreted as a suture between arcs.

Thus, the position of Lake Biwa is not accidental; it is a structurally inevitable feature formed at the northwestern end of the weak surface of the Kinki–Nōbi Forearc Weak Suture Zone, where the unjoined arc structure is exposed on the forearc side.

5.2 Uplift Along the Wakasa Bay Coast as a "Barrier Effect" of the Hida–Tamba Terrane

North of Lake Biwa lies the Wakasa Bay coast, which is uplifted despite the fact that Wakasa Bay itself is a subsiding marine basin. This uplift is difficult to explain using conventional models.

Under the Forearc Weak Suture Zone Model, the Wakasa Bay coast corresponds to the rigid portion of the Hida–Tamba Terrane, which structurally resists deformation of the accretionary complex attempting to subside.

As a result, Lake Biwa grows northward but does not open into Wakasa Bay. The reason Lake Biwa does not "overflow" into Wakasa Bay is explained by this barrier effect.

5.3 The Southwest-Extending Subsidence Belt from Lake Biwa: The "Kinki Subsidence Line"

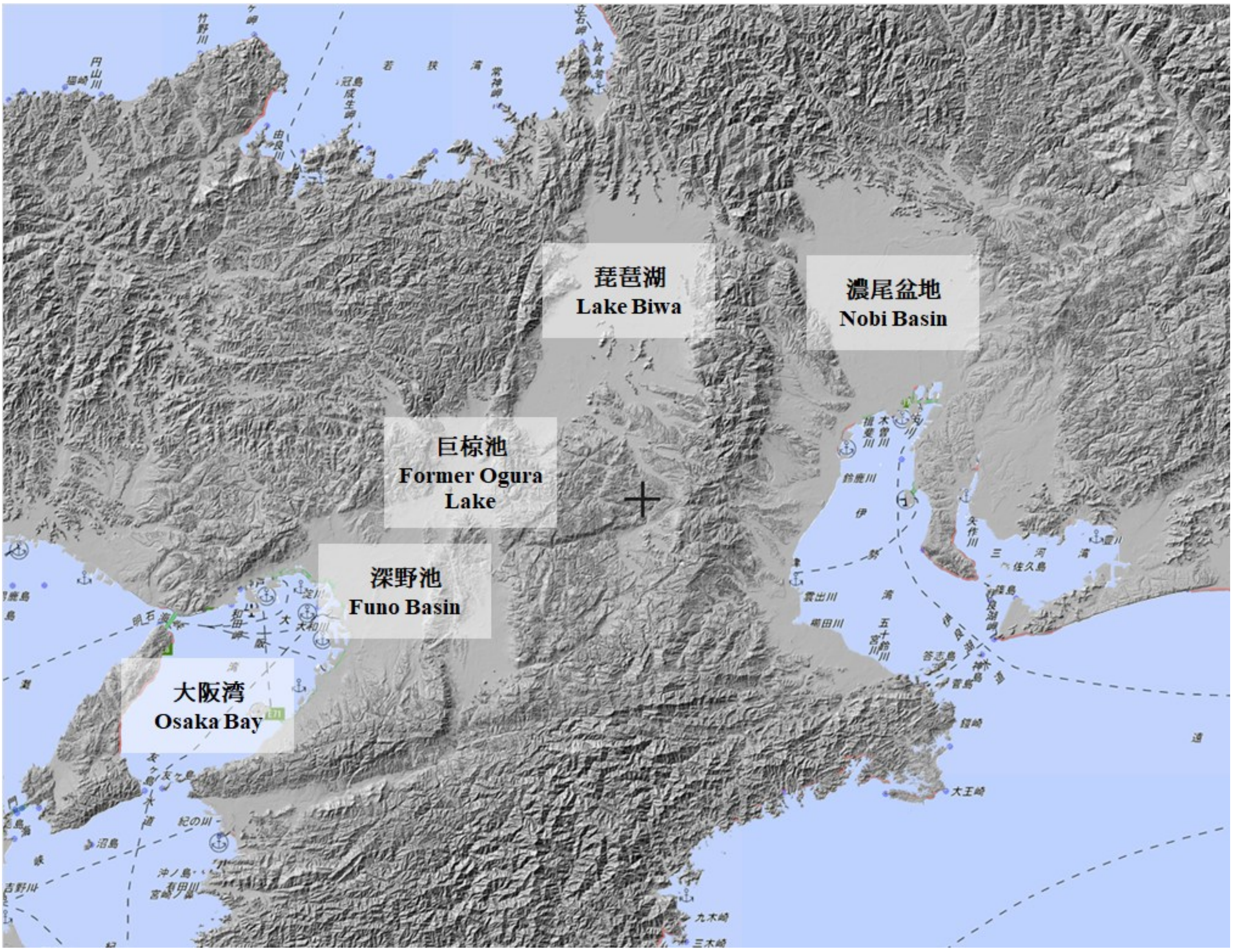
From the western margin of the Lake Biwa structural basin, the Biwa Western Margin Fault Zone extends southwestward, connecting to the Rokko and Awaji Island Fault Zones. Along this line, a series of subsiding landforms—Lake Biwa, the former Ogura Lake, the Funo Basin, and Osaka Bay—are distributed discontinuously.

This southwest-trending subsidence belt may represent the western counterpart of the Fossa Magna within the South Fossa Magna–Kanto Weak Suture Zone, forming the western subsidence axis of the Kinki–Nōbi Weak Suture Zone. In this study, this belt is provisionally termed the Kinki Subsidence Line.

If this subsidence belt lies near the boundary between the Hida–Tamba Terrane and the Southwest Japan Arc (sensu stricto), then the abrupt drop of more than 3,000 m in basement rock on the Osaka Bay side of the Rokko Mountains (Yokokura et al., 1998) can be interpreted as subsidence of the forearc weak suture zone relative to the rigid Southwest Japan Arc.

Thus, the Kinki Subsidence Line is a subsidence structure analogous to the Fossa Magna located at the boundary between the Hida–Tamba Terrane and the Northeast Japan Arc. It may reasonably be described as a "Second Fossa Magna" or "Western Fossa Magna."

Figure 2. Relationship Between the Kinki Subsidence Line and the Nōbi Basin



A continuous chain of subsiding landforms extends from Lake Biwa to Osaka Bay.
Based on the shaded relief map of the Geospatial Information Authority of Japan (GSI, "GSI Maps / Digital Japan"), with additional annotations by the author.

Chapter 6. Nationwide Applicability of the Forearc Weak Suture Zone Model

In the preceding chapters, it was shown that the South Fossa Magna–Kanto Forearc Weak Suture Zone and the Kinki–Nōbi Forearc Weak Suture Zone can be explained coherently by the same structural model. These regions share the following structural characteristics:

- unjoined arc structures
- mechanical weakness of accretionary complexes
- amplification of long-period ground motion from deep earthquakes
- ongoing subsidence

This chapter examines how far the model can be applied to other regions of the Japanese Islands and clarifies both its applicability and its limitations.

6.1 Conditions Required for the Formation of a Forearc Weak Suture Zone

For a forearc weak suture zone to form, the following four conditions must be satisfied:

(1) Persistence of unjoined arc boundaries
(2) Presence of thin and mechanically weak accretionary complexes
(3) Existence of major fault zones acting as structural weak lines
(4) Thick sedimentary sequences capable of amplifying long-period ground motion from deep earthquakes

Regions where all four conditions are met are extremely limited within the Japanese Islands.

6.2 Regions Where Forearc Weak Suture Zones Are Established

(1) Nōbi–Ise–Biwa–Osaka Region

This is the central focus of the present study and represents the most typical example of a forearc weak suture zone.

(2) South Fossa Magna–Kanto Basin Region

This region subsides under the same mechanical principles as the Nōbi–Biwa system.

6.3 Regions Where Forearc Weak Suture Zones May Potentially Exist

(1) Ishikari Plain

The Ishikari Plain exhibits several characteristics similar to forearc weak suture zones:

- thick accretionary complexes
- long-term subsidence
- multiple fault zones

However, the following points remain uncertain:

- whether an unjoined arc boundary is clearly present
- whether a dual-weakness structure exists
- whether subsidence progresses as a broad, planar phenomenon

At present, these conditions have not been sufficiently confirmed.

6.4 The Tsugaru Strait: An Unjoined Arc Structure, but Not a Forearc Weak Suture Zone

The Tsugaru Strait represents an unjoined arc boundary between the Northeast Japan Arc and the Kuril Arc, exposed as a geomorphic feature. The frequent occurrence of fractured zones during excavation of the Seikan Tunnel provides evidence of this unjoined structure.

However, the region does not qualify as a forearc weak suture zone because:

- it is not located in the forearc
- accretionary complexes are not the dominant crustal material
- a dual-weakness structure is absent

Nevertheless, the Tsugaru Strait is valuable within the conceptual framework of this study as the northern symmetric counterpart of the unjoined arc structures discussed earlier.

Chapter 7. A New Tectonic Model for the Japanese Islands

This study begins with the Kinki–Nōbi Forearc Weak Suture Zone and, together with the South Fossa Magna–Kanto Forearc Weak Suture Zone discussed in previous work, integrates the subsidence, uplift, fault activity, and geomorphic development observed in the forearc, arc boundaries, and arc interiors of the Japanese Islands. These phenomena are unified under three structural concepts:

(1) The Three-Arc Unjoined Model

(2) The Forearc Weak Suture Zone Model

(3) The Dual Subsidence Structure Model

By synthesizing these concepts, this study presents a new tectonic model for the Japanese Islands—one that explains a wide range of geological and geomorphic phenomena as structurally inevitable consequences of the incomplete suturing of arcs and the mechanical weakness of forearc crust.

The Three-Arc Unjoined Model provides the fundamental structural framework: the Southwest Japan Arc (sensu stricto), the Hida–Tamba Terrane, and the Northeast Japan Arc approached one another during the opening of the Japan Sea but never fully joined. Their unjoined boundaries remain as weak zones that strongly influence present-day forearc behavior.

The Forearc Weak Suture Zone Model explains how these unjoined boundaries, combined with the mechanical weakness of accretionary complexes and the overlap of major fault zones, create regions where subsidence, long-period seismic motion, and geomorphic reorganization are concentrated.

The Dual Subsidence Structure Model clarifies why forearc basins such as the Nōbi Basin, Ise Bay, Lake Biwa, Osaka Bay, and the Kanto Basin exhibit extreme flatness, persistent subsidence, and asymmetric geomorphic development. These basins are governed by inner and outer weak surfaces that define subsidence axes and constrain crustal deformation.

Together, these three models provide a unified explanation for:

(1) long-term subsidence in forearc basins

(2) asymmetric fault development

(3) anomalous geomorphic features such as the persistence of Tokyo Bay

(4) uplift along rigid arc boundaries (e.g., Wakasa Bay coast)

(5) deep crustal intrusion and arc bending associated with arc–arc collision

(6) the existence of multiple “Fossa Magna–like” structures across Honshu

This integrated framework redefines the tectonics of the Japanese Islands as a system governed not by a single arc, but by the interactions of multiple incompletely joined arcs and their forearc weak suture zones.

Conclusion

This study has demonstrated that the subsidence, uplift, fault activity, and geomorphic development observed across the Japanese Islands—particularly in the Nōbi Plain, Ise Bay, Lake Biwa, Wakasa Bay, Osaka Bay, and the South Fossa Magna–Kanto Basin—can be coherently explained through a unified tectonic framework grounded in three structural concepts:

(1) the Three-Arc Unjoined Model,

(2) the Forearc Weak Suture Zone Model, and

(3) the Dual Subsidence Structure Model.

The Three-Arc Unjoined Model establishes that the Honshu Arc is not a single, continuous arc but a composite of three arcs—the Southwest Japan Arc (sensu stricto), the Hida–Tamba Terrane, and the Northeast Japan Arc—that approached one another during the opening of the Japan Sea but never fully sutured. Their unjoined boundaries remain as structural weak zones that continue to govern present-day forearc behavior.

The Forearc Weak Suture Zone Model explains how these unjoined boundaries, combined with the inherent weakness of accretionary complexes and the overlap of major fault zones, create regions where subsidence, long-period seismic motion, and geomorphic reorganization are concentrated. These zones represent the structural cores of forearc deformation.

The Dual Subsidence Structure Model clarifies why forearc basins such as the Nōbi Basin, Ise Bay, Lake Biwa, Osaka Bay, and the Kanto Basin exhibit extreme flatness, persistent subsidence, and asymmetric geomorphic development. These basins are controlled by inner and outer weak surfaces that define subsidence axes and constrain crustal deformation.

By integrating these three concepts, this study provides a unified tectonic model capable of explaining:

(1) long-term subsidence in forearc basins,
(2) asymmetric fault development,
(3) anomalous geomorphic features such as the persistence of Tokyo Bay,
(4) uplift along rigid arc boundaries (e.g., the Wakasa Bay coast),
(5) deep crustal intrusion and arc bending associated with arc–arc collision,
(6) and the existence of multiple Fossa Magna–like structures across Honshu.

This framework redefines the tectonics of the Japanese Islands as a system governed not by a single arc, but by the interactions of multiple incompletely joined arcs and their forearc weak suture zones. It offers a structural inevitability behind phenomena that have long resisted explanation within conventional models.

Future work should incorporate numerical modeling to quantify the mechanical behavior of dual weak surfaces, evaluate the temporal evolution of subsidence axes, and test the applicability of the model to other regions such as the Ishikari Plain. Nevertheless, the conceptual foundation presented here establishes a new unified perspective on forearc tectonics in the Japanese Islands.

9. Future Directions

This study has established a unified tectonic framework for forearc subsidence in the Japanese Islands based on the Three-Arc Unjoined Model, the Forearc Weak Suture Zone Model, and the Dual Subsidence Structure Model. While the conceptual structure is now in place, several important challenges remain for future research.

First, the mechanical behavior of dual weak surfaces—comprising both structural weak zones (unjoined arc boundaries) and material weak zones (accretionary-complex upper plate)—must be quantified through numerical modeling. Although this study has demonstrated the conceptual necessity of dual weak surfaces, their stress distribution, deformation modes, and temporal evolution require rigorous simulation.

Second, the geometry and migration of subsidence axes should be examined using three-dimensional crustal models. The westward-tilting subsidence axis of the Nōbi Basin, the northward growth of Lake Biwa, and the southwest-trending Kinki Subsidence Line all suggest systematic control by arc boundaries. Clarifying these geometric constraints will be essential for validating the unified model.

Third, the amplification of long-period ground motion in forearc weak suture zones must be investigated using strong-motion records and sedimentary basin models. The dynamic leveling mechanism proposed in Paper 1 and applied here to the Nōbi Basin requires further empirical testing, particularly regarding the recurrence intervals and energy thresholds of deep earthquakes.

Fourth, the nationwide applicability of the model should be evaluated through comparative studies of other basins, including the Ishikari Plain, the Toyama Trough, and the Beppu–Shimabara region. Determining whether these areas possess unjoined arc boundaries, dual weak surfaces, or forearc pull-down signatures will help refine the limits of the model.

Finally, the relationship between arc–arc collision processes and forearc weak suture zones should be explored. The bending of the Japanese Islands, deep crustal intrusion beneath the Koma and Misaka Mountains, and uplift along rigid arc boundaries (such as Wakasa Bay) may represent broader manifestations of the same structural principles identified in this study.

In summary, while this research provides a conceptual foundation for a unified tectonic model of forearc subsidence in the Japanese Islands, future work must integrate numerical modeling, seismic analysis, and comparative regional studies to fully establish the model's quantitative validity and geographic extent.

Data Availability Statement

All data referenced in this study are available from the sources listed in the References. No new data or code were generated for this research.

Conflict of Interest Statement

The author declares no conflicts of interest related to this study.

Funding Statement

This research received no external funding.

Author Contributions

The author conceived the study, conducted the analysis, and wrote the manuscript.

AI Usage Statement

AI tools were used to assist in literature search and stylistic adjustments for academic writing. Machine translation tools were used in a supplementary manner for translation, but all conceptual content is original to the author, who assumes full responsibility for its accuracy.

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