

# The Formation of Forearc Seismic Belt

## A Potential Explanation of Seismogenesis in a Weakly Coupled Subduction Zone

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The enigmatic occurrence of seismic activity in forearc regions, particularly within weakly coupled subduction zones, continues to perplex geoscientists. While traditional models of plate interface coupling explain many megathrust earthquakes, they fall short in accounting for the spatial distribution and mechanism of intermediate-magnitude earthquakes within the forearc crust. This opinion article explores the formation of the forearc seismic belt (FSB) as a plausible and coherent framework for understanding seismogenesis in such settings. Drawing from geophysical observations, recent advances in subduction zone modeling, and tectonic analogs, the article argues that the FSB emerges as a structural and stress-response feature linked to lower plate geometry, fluid fluxing, and crustal heterogeneities in the overriding plate. This perspective challenges the narrow view that only strongly coupled megathrust interfaces are responsible for major seismicity and proposes that crustal adaptation to slab dynamics plays a more active role. Recognizing the FSB's role could refine seismic hazard assessments in subduction zones previously thought to be relatively quiescent.

**Keywords:** Forearc Seismic Belt; Seismogenesis; Forearc Crust; Subduction Zone; Earthquakes

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THE CLASSIC paradigm of subduction zone seismogenesis has been dominated by the conceptual division of tectonic regimes into well-coupled and weakly coupled interfaces, correlating with the likelihood of great megathrust earthquakes. In this framework, highly coupled subduction zones such as the Chilean or Japanese trenches are deemed

seismically dangerous due to the accumulation of elastic strain, whereas weakly coupled margins—like parts of the Cascadia or Mariana arcs—are perceived as largely aseismic (Cruikshank & Peterson, 2019). However, this dichotomy fails to account for the existence of persistent, moderate seismicity belts observed in forearc regions that overlie seemingly weakly coupled segments.

The formation and persistence of the so-called forearc seismic belt (FSB) in such settings raise critical questions about the mechanisms driving intraplate seismicity and the need to reconsider the relationship between interface coupling and earthquake generation.

At the heart of this opinion lies the contention that the FSB represents a structural and dynamic expression of long-term interactions between the downgoing slab and the overriding plate—particularly in weakly coupled zones where plate interface locking is insufficient to generate classic megathrust earthquakes. Unlike locked interfaces that accumulate strain across the entire megathrust, weakly coupled zones allow a portion of the tectonic stress to be redistributed into the overriding crust (Oryan et al., 2024). This redirection may manifest as distributed faulting and seismicity within the upper plate, especially along zones of structural weakness or inherited rheological contrasts. Thus, the forearc seismic belt may not be an incidental feature, but rather a necessary expression of the stress-transfer processes inherent to such tectonic settings.

Recent geophysical observations lend credibility to this view. Studies from the Hikurangi margin in New Zealand and the northern segment of the Cascadia subduction zone indicate the presence of active faulting and seismic clusters within the forearc crust (Plata - Martínez et al., 2024). Notably, these areas coincide with regions of low interface coupling, deep-seated fluids, and complex slab morphology. Seismic tomography and magnetotelluric imaging further suggest that the forearc region is characterized by high pore fluid pressures, fractured crustal domains, and elevated heat flow—all of which may reduce effective normal stress and facilitate fault slip. The spatial correlation between forearc seismicity and zones of fluid-saturated crust underscores the role of hydrological processes in modulating crustal strength and promoting brittle failure (Umeda et al., 2024).

From a mechanical standpoint, the formation of an FSB can be understood as a response to strain partitioning in a tectonic regime where interface slip is predominantly aseismic. Instead of accumulating strain on the megathrust, tectonic convergence in these regions may induce flexure and bending of the upper plate, promoting the development of reverse and strike-slip fault systems that accommodate strain laterally (Nuyen & Schmidt, 2024). The location of the FSB—typically tens of kilometers landward of the trench—suggests it is structurally aligned with crustal domains that are either rheologically weaker or geometrically predisposed to fail under compressive loading. The recurring seismicity in such belts may therefore reflect the progressive deformation of the overriding crust rather than episodic failure of the plate interface.

Moreover, the role of fluids expelled from the subducting slab should not be understated. As oceanic lithosphere descends into the mantle, it undergoes dehydration reactions that liberate water and other volatiles. These fluids migrate upwards through the mantle wedge and into the forearc crust, reducing the effective normal stress on faults and facilitating brittle failure. In weakly coupled settings, where megathrust earthquakes are less efficient at releasing strain energy, the fluid-induced weakening of upper plate structures may become a dominant mechanism of seismogenesis (Gardonio et al., 2024). The FSB, in this context,

acts as a pressure valve that accommodates localized deformation and stress release without requiring catastrophic rupture of the plate boundary.

Critically, the presence of an FSB in a weakly coupled subduction zone should not be interpreted as a benign phenomenon. On the contrary, persistent moderate-magnitude earthquakes in forearc regions can pose significant hazards, especially in areas with dense population centers or critical infrastructure. Furthermore, the seismicity associated with the FSB may not be entirely decoupled from deeper megathrust processes. Episodic tremor and slip (ETS) events, often observed in weakly coupled zones, have been shown to modulate stress in the overriding crust and may even trigger upper plate earthquakes (Bombardier et al., 2024). The dynamic interplay between slow slip, fluid migration, and crustal faulting suggests a more integrated model of subduction zone behavior—one that includes the FSB as a core component of the seismotectonic system.

The FSB hypothesis also bears implications for seismic hazard assessment and modeling. Traditional seismic hazard maps often underestimate the risk in forearc regions of weakly coupled zones due to the assumption of low plate interface locking and hence, minimal earthquake potential. However, if the FSB represents an alternative locus of strain release, then these regions may face a different but no less significant seismic threat. Current probabilistic models, heavily reliant on interface coupling metrics derived from GPS and InSAR data, may need to be recalibrated to include crustal fault systems activated by long-term subduction dynamics (Zaccagnino et al., 2023). In regions like Cascadia, where dense urban development overlaps with mapped forearc fault systems, such reassessment is not merely academic—it is vital for public safety.

Moreover, viewing the FSB as an outcome of long-term subduction and crustal interaction invites a reevaluation of the tectonic lifecycle of subduction zones. Weak coupling may not be a permanent condition but could represent one stage in a broader evolution involving fluid redistribution, thermal maturation, and eventual transition to stronger coupling. In this light, the FSB could be seen as a transient feature—a structural response that precedes or accompanies the evolution of the plate interface (Fisher et al., 2021). Geodynamic simulations support this idea, suggesting that hydration of the mantle wedge and overriding crust can influence the development of interface shear zones, eventually transforming weakly coupled segments into strongly coupled ones capable of generating great earthquakes (Menant et al., 2019). If true, then tracking the evolution of the FSB over geological timescales might offer a predictive window into future seismic behavior.

The interdisciplinary nature of this hypothesis—linking structural geology, geophysics, petrology, and fluid dynamics—underscores the complexity of subduction systems. It also highlights the limitations of simplistic binary models that classify subduction zones solely by their megathrust coupling status. In practice, seismogenesis is a multi-scalar, multi-mechanism phenomenon, and the FSB serves as a reminder of the diverse pathways through which tectonic stress can be accommodated. As new observational technologies emerge—such as ocean-bottom seismometers, high-resolution crustal imaging, and machine learning analysis of seismic catalogs—the oppor-

tunity arises to test the FSB model more rigorously across different global subduction systems (Dobretsov et al., 2013).

Nevertheless, skepticism is warranted. Not all forearc seismicity can be neatly attributed to the FSB model, and some critics may argue that the belt represents a coincidental clustering of events rather than a coherent structural feature. Additionally, the challenge of mapping crustal faults beneath sedimentary cover and offshore regions introduces uncertainties into the interpretation of seismicity patterns. Furthermore, distinguishing between intraslab, upper plate, and interface earthquakes can be difficult, especially in regions with sparse instrumentation or complex slab geometry. Thus, while the FSB presents a compelling explanatory framework, it should be approached with cautious empiricism and tested against alternative models.

In sum, the forearc seismic belt offers a novel lens through which to view the puzzle of seismicity in weakly coupled subduction zones. Rather than an anomaly, the FSB may represent an integral component of the tectonic system—one that reflects the redistribution of stress, the influence of fluids, and the internal dynamics of the overriding plate. Recognizing and understanding the FSB is not merely an academic exercise; it has direct implications for assessing seismic hazards, modeling tectonic processes, and interpreting the long-term evolution of subduction systems. As our tools and datasets continue to improve, embracing a more nuanced model of subduction zone behavior—one that includes the forearc as a dynamic participant in seismic processes—will be essential for advancing both science and public resilience. ■

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## References

- Bombardier, M., Cassidy, J. F., Dosso, S. E., & Kao, H. (2024). Spatial distribution of tremor episodes from Long - Term Monitoring in the Northern Cascadia subduction Zone. *Journal of Geophysical Research Solid Earth*, 129(8). DOI: <https://doi.org/10.1029/2024jb029159>
- Cruikshank, K. M., & Peterson, C. D. (2019). Cascadia Convergent Zone: An example of primary convergent seismogenic structure. *Open Journal of Earthquake Research*, 08(02), 132–164. DOI: <https://doi.org/10.4236/ojer.2019.82009>
- Dobretsov, N., Koulakov, I., & Polyansky, O. (2013). Geodynamics and stress–strain patterns in different tectonic settings. *Russian Geology and Geophysics*, 54(4), 357–380. DOI: <https://doi.org/10.1016/j.rgg.2013.03.001>
- Fisher, D. M., Hooker, J. N., Smye, A. J., & Chen, T. (2021). Insights from the geological record of deformation along the subduction interface at depths of seismogenesis. *Geosphere*, 17(6), 1686–1703. DOI: <https://doi.org/10.1130/ges02389.1>
- Gardonio, B., Marsan, D., Bodin, T., Socquet, A., Durand, S., Radiguet, M., Ricard, Y., & Schubnel, A. (2024). Change of deep subduction seismicity after a large megathrust earthquake. *Nature Communications*, 15(1). DOI: <https://doi.org/10.1038/s41467-023-43935-3>
- Menant, A., Angiboust, S., & Gerya, T. (2019). Stress-driven fluid flow controls long-term megathrust strength and deep accretionary dynamics. *Scientific Reports*, 9(1). DOI: <https://doi.org/10.1038/s41598-019-46191-y>
- Nuyen, C., & Schmidt, D. (2024). Along-strike changes in ETS behavior near the slab edge of Southern Cascadia. *Seismica*, 2(4). DOI: <https://doi.org/10.26443/seismica.v2i4.1097>
- Oryan, B., Olive, J., Jolivet, R., Malatesta, L. C., Gailleton, B., & Bruhat, L. (2024). Megathrust locking encoded in subduction landscapes. *Science Advances*, 10(17). DOI: <https://doi.org/10.1126/sciadv.adl4286>
- Plata - Martinez, R., Iinuma, T., Tomita, F., Nakamura, Y., Nishimura, T., & Hori, T. (2024). Revisiting slip deficit rates and its insights into large and slow earthquakes at the Nankai subduction zone. *Journal of Geophysical Research Solid Earth*, 129(12). DOI: <https://doi.org/10.1029/2023jb027942>
- Umeda, K., Yamazaki, Y., & Sumino, H. (2024). Geochemical signature of deep fluids triggering earthquake swarm in the Noto peninsula, central Japan. *Geophysical Research Letters*, 51(13). DOI: <https://doi.org/10.1029/2024gl108581>
- Zaccagnino, D., Telesca, L., Tan, O., & Doglioni, C. (2023). Clustering Analysis of Seismicity in the Anatolian Region with Implications for Seismic Hazard. *Entropy*, 25(6), 835. DOI: <https://doi.org/10.3390/e25060835>