# FEniCS-SZ: Two-dimensional modeling of the thermal structure of subduction zones

**Cian R. Wilson** [1]*¶, **Cameron Seebeck**[1]*, **Kidus Teshome**[1]*, **Nathan Sime** [1]*, and **Peter E. van Keken** [1]*

**1** Earth and Planets Laboratory, Carnegie Institution for Science, Washington D.C., United States ROR ¶

Corresponding author * These authors contributed equally.

## Summary

## Statement of need

Plate tectonics on Earth is the surface expression of the slow convective release of heat from its interior. Subduction zones form the location of the return flow of mantle convection and are sites of mountain building and significant natural hazards in the form of earthquakes and explosive volcanism. The depth extent of large and sometimes tsunamogenic earthquakes, intermediate-depth earthquakes, and melt formation are linked to thermal transitions and corresponding thermally activated processes such as metamorphic reactions (including those causing dehydration and release of volatile phases such as water and carbon). To understand the short- and long-term evolution of the tectonic and geological processes it is critically important to understand the thermal structure of subduction zones (van Keken & Wilson, 2023a).
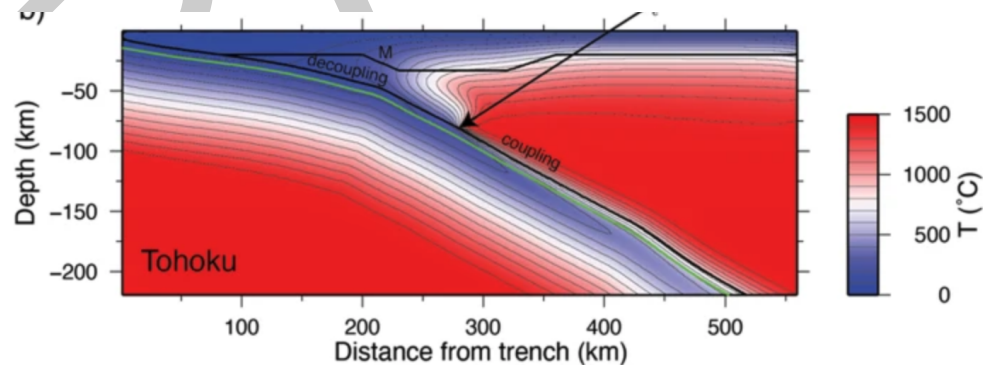
**Figure 1:** Figure of SZ thermal structure with oceanic and continental Moho.

FEniCS-SZ is cool and is based on Wilson & van Keken (2023).

FEniCS-SZ is intended also for classroom use and interactive work via Jupyter notebooks (Wilson et al., 2025) that explore the FEM examples in Wilson & van Keken (2023). The didactic nature of these tutorials (progressing from the stand-alone Poisson and Stokes equations, reproduction of mantle convection benchmarks, to the fully coupledset of time-dependent equations used in the subduction models) augments the FEniCSX Tutorial (Dokken, 2023), which is itself built on the FEniCS Tutorial (Langtangen & Logg, 2016).

## State of the field

Thermal models of subduction zones that are most useful in the prediction of metamorphic dehydration reactions and their role in seismogenesis and seismic structure, slab dehydration, arc volcanism, and the long term chemical evolution of the Earth require high numerical resolution, faithful gridding of material boundaries (such as the slab surface and oceanic Moho), and ability to handle velocity discontinuities along the seismogenic zone and its extension to about 80 km depth. Semi-analytical techniques can be used successfully along the shallow plate interface to limited depth (see discussion and references in van Keken et al. (2019)), but the effects of the cornerflow with realistic mantle rheology requires numerical solution of the Stokes and heat equations. A number of dynamical approaches exist that can be used to trace subduction zone thermal evolution (Holt & Condit (2021), Gerya (2011)) but these provide slab evolution models that are difficult to use when predicting the thermal structure of present-day subduction zones since geometry and convergence parameters such as convergence speed cannot be controlled. Other workers have provided finite element and finite difference approaches to study the thermal structure (e.g. Wada & Wang (2009); Lee & King (2009); Lin et al. (2010); Rees Jones et al. (2018); van Zelst et al. (2023)). These approaches have shown good comparisons with other codes in a code intercomparison (van Keken et al., 2008), by reproduction of benchmark cases therein, or in direct intercomparisons (van Keken & Wilson, 2023b). Many of these subduction implementations, however, are not readily available as open source software even if they are based on general open source finite element software.

## Software design

## Research impact statement

## AI usage disclosure

No information or code was harmed by AI.

## Acknowledgements

## References

Dokken, J. S. (2023). *The FEniCSx Tutorial*. https://jsdokken.com/dolfinx-tutorial/

Gerya, T. (2011). Future directions in subduction modeling. *Journal of Geodynamics*, *52*, 344–378. https://doi.org/10.1016/j.jog.2011.06.005

Holt, A. F., & Condit, C. B. (2021). Slab temperature evolution over the lifetime of a subduction zone. *Geochemistry, Geophysics, Geosystems*, *22*, e2020GC009476. https://doi.org/10.1029/2020GC009476

Langtangen, H. P., & Logg, A. (2016). *Solving PDEs in Python* (p. 146). Springer Open. https://doi.org/10.1007/978-3-319-52462-7

Lee, C., & King, S. D. (2009). Effect of mantle compressibility on the thermal and flow structures of the subduction zones. *Geochemistry, Geophysics, Geosystems*, *10*, Q01006. https://doi.org/10.1029/2008GC002151

66 Lin, S.-C., Kuo, B.-Y., & S-L, C. (2010). Thermomechanical models for the dynamics and
67 melting processes in the Marianas subduction zone. *Journal of Geophysical Research: Solid*
68 *Earth*, *115*, B12403. https://doi.org/10.1029/2010JB007658

69 Rees Jones, D. W., Katz, R. J., Tian, M., & Rudge, J. F. (2018). Thermal impact of
70 magmatism in subduction zones. *Earth and Planetary Science Letters*, *481*, 73–79. https:
71 //doi.org/10.1016/j.espl.2017.10.015

72 van Keken, P. E., Currie, C., King, S. D., Behn, M. D., Cagnioncle, A., He, J., Katz, R.
73 F., Lin, S.-C., Parmentier, E. M., Spiegelman, M., & Wang, K. (2008). A community
74 benchmark for subduction zone modeling. *Phys Earth Planet Int*, *171*, 187–197. https:
75 //doi.org/10.1016/j.pepi.2008.04.015

76 van Keken, P. E., Wada, I., Sime, N., & Abers, G. A. (2019). Thermal structure of the
77 forearc in subduction zones: A comparison of methodologies. *Geochemistry, Geophysics,*
78 *Geosystems*, *20*, 3268–3288. https://doi.org/10.1029/2019GC008334

79 van Keken, P. E., & Wilson, C. R. (2023a). An introductory review of the thermal structure of
80 subduction zones: I—motivation and selected examples. *Progress in Earth and Planetary*
81 *Science*, *10*, 42. https://doi.org/10.1186/s40645-023-00573-z

82 van Keken, P. E., & Wilson, C. R. (2023b). An introductory review of the thermal structure
83 of subduction zones: III—Comparison between models and observations. *Progress in Earth*
84 *and Planetary Science*, *10*, 1–18. https://doi.org/10.1186/s40645-023-00589-5

85 van Zelst, I., Thieulot, C., & Craig, T. J. (2023). The effect of temperature-dependent
86 material properties on simple thermal models of subduction zones. *Solid Earth*, *14*,
87 683–707. https://doi.org/10.5194/se-14-683-2023

88 Wada, I., & Wang, K. (2009). Common depth of slab-mantle decoupling: Reconciling
89 diversity and uniformity of subduction zones. *Geochem Geophys Geosys*, *10*, Q10009.
90 https://doi.org/10.1029/2009GC002570

91 Wilson, C. R., Seebeck, C., Teshome, K., Sime, N., & van Keken, P. E. (2025). *The FEniCS*
92 *Subduction Zone Jupyter Book*. https://github.com/cianwilson/fenics-sz/blob/main/
93 readme.md

94 Wilson, C. R., & van Keken, P. E. (2023). An introductory review of the thermal structure of
95 subduction zones: II—numerical approach and validation. *Progress in Earth and Planetary*
96 *Science*, *10*, 1–29. https://doi.org/10.1186/s40645-023-00588-6