Seafloor Tectonics and Accretion at Ridge — Transform Plate Boundaries (START)

Structure and Dynamics of the Mid-Ocean Ridge — Transform Fault System

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In Short

- Understanding seafloor tectonics at ridge — transform intersections and transform — fracture zones transitions.
- Developing the sophisticated tectono-hydrothermal-magmatic models of the ridge — transform system.
- Integrating seafloor morphological, geological, and geophysical data with novel geodynamic models.

The ocean floor exhibits pronounced morphological features, including axial valleys along the mid-ocean ridge (MOR) flanked by normal faults, as well as the oceanic transform fault (OTF) valleys formed by strike-slip faulting, where ridge segments are offset along small circles of plate motion (**Figure 1**). Despite great advancements made throughout the sixty years since the discovery of the MOR — OTF system [1], there are still gaps in our understanding of seafloor tectonics and dynamics at ridge-transform intersections (RTI). This is in part due to an initial focus of many marine surveys on the spreading axis itself rather than RTIs as well as transform-fracture zone transitions. It is also in part due to the three-dimensional nature of RTIs, which requires explicit integration of geodynamic processes such as magma intrusion, seafloor faulting, and hydrothermal circulation that is still beyond the capability of existing geodynamic tools.

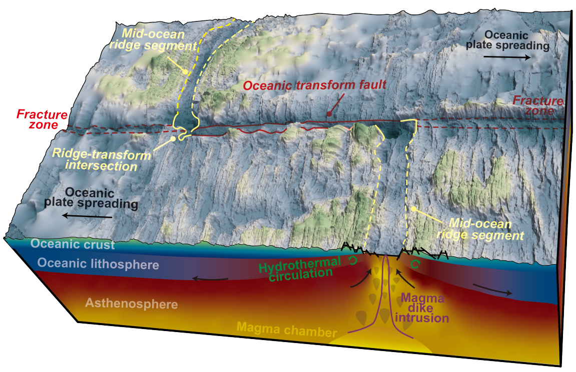

__Figure 1:__ Tectonic schematic of the mid-ocean ridge — transform fault system. The top bathymetric map shows the seafloor morphology of the Kane transform on the Mid-Atlantic Ridge.

This project will address some of these shortcomings with an innovative approach that integrates seafloor observations with novel geodynamic models, thereby exploiting synergies between geodynamics, geophysics, marine geology, and oceanography. In particular, this project builds upon recent advancements made by our team, including two research cruises to the Oceanographer transform in 2021, and two recently published papers highlighting the striking discrepancy in seafloor depth and morphology between transform valleys and fracture zones [2], likely attributable to their disparate crustal thicknesses [3]. We are now poised to take advantage of these previous studies by working on the fundamental processes underlying these observations using our sophisticated tectono-hydrothermal-magmatic modelling approach.

We use a highly scalable parallel code ASPECT (Advanced Solver for Problems in Earth's ConvecTion) [4] to construct these comprehensive multi-scale geodynamic models. This code enables the geodynamic simulation from a few hundred meters to over 3000 km by using an adaptive mesh refinement approach. The scalability performance of ASPECT is determined to be excellent on HLRN.

At the present stage, we have tested the general feasibility of exploring the interrelations between magmatic accretion and tectonic faulting using ASPECT. For this purpose, we have implemented a magma injection term that mimics dike injection.This implementation way is very similar to the way dilational faulting is implemented in other geodynamic codes ([5]).

Figure 2 shows the results of tectono-magmatic models with magma intruding through a narrow dike 400 m wide and 4 km deep below the ridge axis. The dike opening rate is the product of the magmatic fraction M and the half-spreading velocity U_{out}. In this model, the system is driven by prescribed extension (U_{out} = 2 cm/yr) on both sides of the model domain and allows for inflow at the open bottom boundary to achieve mass balance (**Figure 2**a). Evolution of the fault and topography at the surface can be tracked through a free surface boundary condition.

Figure 2 also illustrates the effect of changing M. When there is no magma accretion (M = 0), all extension is taken up by short-lived normal faults (**Figure 2**b-c). These faults alternate in position and dip direction between the two ridge flanks. A long-lived detachment fault forms when M = 0.5 because the fault ceases to migrate as a result of the zero-

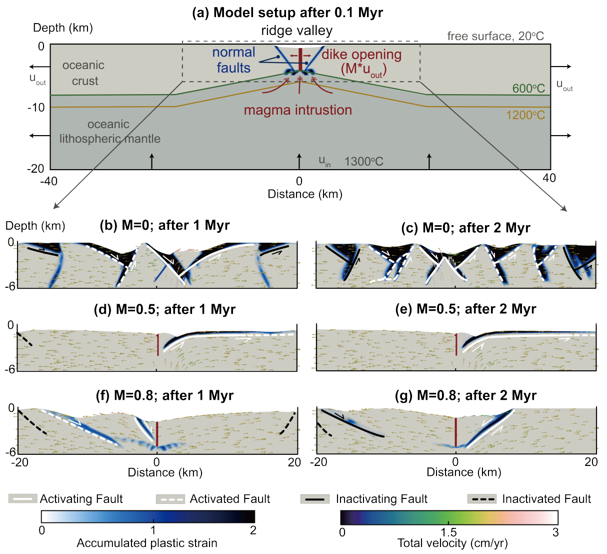

Figure 2: *2D tecono-magmatic models of the MOR.* ***(a)*** *Model setup after the isostatic equilibrium of 0.1 Myr.* U_{out} *is the horizontal outflow velocity and is balanced by the inflow velocity* U_{in}*. The opening rate in the dike (red column) is equal to the product of the fraction M and* U_{out}*. A distinct ridge valley formed and is flanked by normal faults that dip towards the axis.* ***(b-g)*** *Snapshots of modeled fault behavior after 1 Myr and 2 Myr for M values between 0 and 0.8. Interpretation of fault behavior is superimposed on the distribution of accumulated plastic strain.*

migration velocity of its hanging wall (**Figure 2**d-e). At M = 0.8, faults form on both ridge flanks. A fault generated near the ridge axis migrates off axis, becomes inactive due to its strength increase with distance from the axis (**Figure 2**f), and is eventually replaced by a new fault (**Figure 2**g). Results of our 2D injection models reproduced the faulting modes for MORs from previous studies on modes of faulting at MORs([5]).

Furthermore, we have utilized these tectono-magmatic models to investigate the unclear physical mechanisms underlying the intermittent detachment faulting on the Southwest Indian Ridge. By comparing model results with geological and geophysical observations, we propose that intermittent detachment faulting is a function of lithospheric structure rather than variations in magma flux. A thicker axial lithosphere results in a smaller fault heave, while a flatter angle in lithosphere thicken away from the accretion axis stabilizes the active fault. These findings have important implications for discerning mechanical differences between detachment faults at slow- and ultraslow-spreading ridges, highlighting that temporal changes in magmatism are not necessary for the occurrence of intermittent detachment faults.

In our next steps, we will integrate the process of hydrothermal circulation, which plays a crucial role in the initiation of new faults at slow- and ultraslow-spreading MORs, into the tectono-magmatic model. In addition, we will expand our well-established 2D model into a computationally-intensive 3D tectono-hydrothermal-magmatic model. This will enable us to explore the potential relationships between tectonic factors (such as spreading rate and extent of magmatic supply) and seafloor faulting patterns along the ridge axis.

This interdisciplinary collaborative study will ultimately provide the first comprehensive geodynamic view of seafloor evolution and tectonics at ridge-transform intersections and transform-fracture zone transitions and bridge knowledge gaps regarding these regions. We will also integrate our models with new geoscientific datasets from the Oceanographer transform at the Mid-Atlantic Ridge. These insights are crucial for assessing the role of OTFs as potential sites of enhanced biogeochemical exchange, as well as understanding seismicity patterns at strike-slip systems — knowledge that can also be transferred to strike-slip systems on land that often produce hazardous earthquakes.

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https://www.geomar.de/forschen/fb4/fb4-muhs/schwerpunkte/seafloor-modeling-group

More Information

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Section 2.5: Geodynamic Modelling, GFZ

DFG Subject Area

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