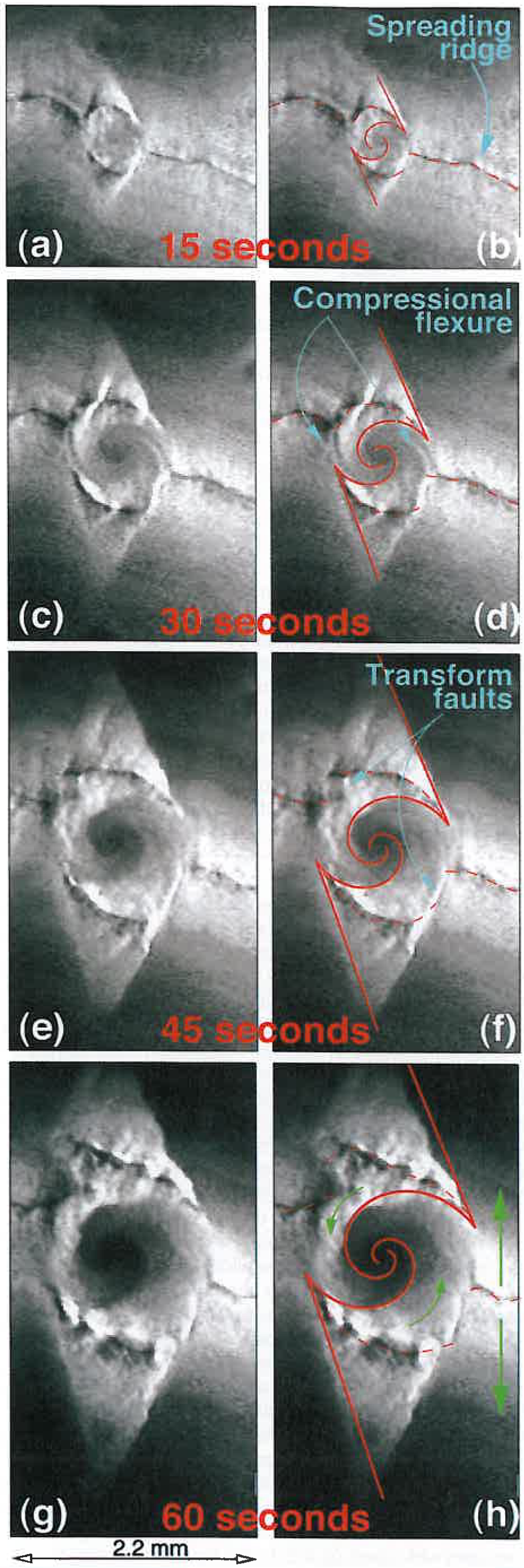
Taking wax for a spin: microplates in an analog model of plate tectonics

Richard F. Katz [1] and Eberhard Bodenschatz [2,3]
[1] Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, USA,
[2] Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, NY, USA,
[3] Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany.

Watching the divergence of tectonic plates at a mid-ocean ridge is about as riveting as watching the grass grow; if you had the patience to stare for a year straight, you'd only see movement of a few centimeters. And, incidentally, with about four kilometers of water between the sea-floor and the closest ship, you'd have to be clever to figure out just how to get a view. Now consider the excitement of watching millions of years of geologic time unfold in seconds, in the comfort of your own laboratory. It's like one of those high-speed movies of clouds skittering across the sky – except that the clock is ticking about 10^{15} times faster than usual and you're watching dynamic processes that are impossible to observe in their natural setting. We've been whiling away geologic time just so, and not merely for entertainment.

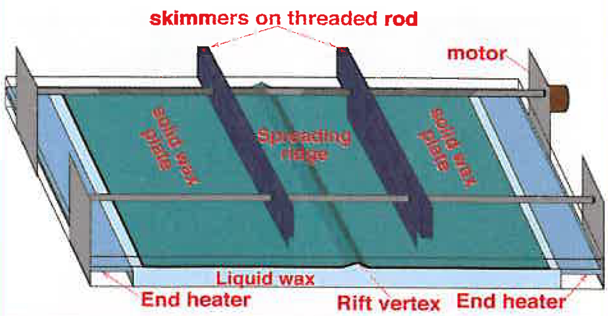
In a paper recently published in the New Journal of Physics [1] we describe a wax analog model that simulates the divergence of two brittle lithospheric plates above a ductile mantle, exactly as it occurs beneath the sea at a mid-ocean ridge over millions of years (the lithosphere is the mechanical boundary layer at the surface of the Earth where the strength of rock increases dramatically). This work breaks new ground in quantifying the kinematic evolution of a curious tectonic feature of mid-ocean ridges, the microplate. Here we give a summary of that work.

In a world where tectonic plates glide slowly from their origin at mid-ocean ridges to where they founder at subduction zones, microplates remain trapped between major plates on a mid-ocean ridge and spin (geologically speaking) about a vertical axis. They grow as they rotate by accreting lithosphere at their edges, leading to a characteristic spiral pattern of pseudofaults, visible to the trained eye through sonar surveys of sea-floor topography. This was geologic theory anyway, derived from the creative minds of marine geophysicists who had never actually watched the sea-floor in motion [2]. We quantified this theory, applied it to detailed

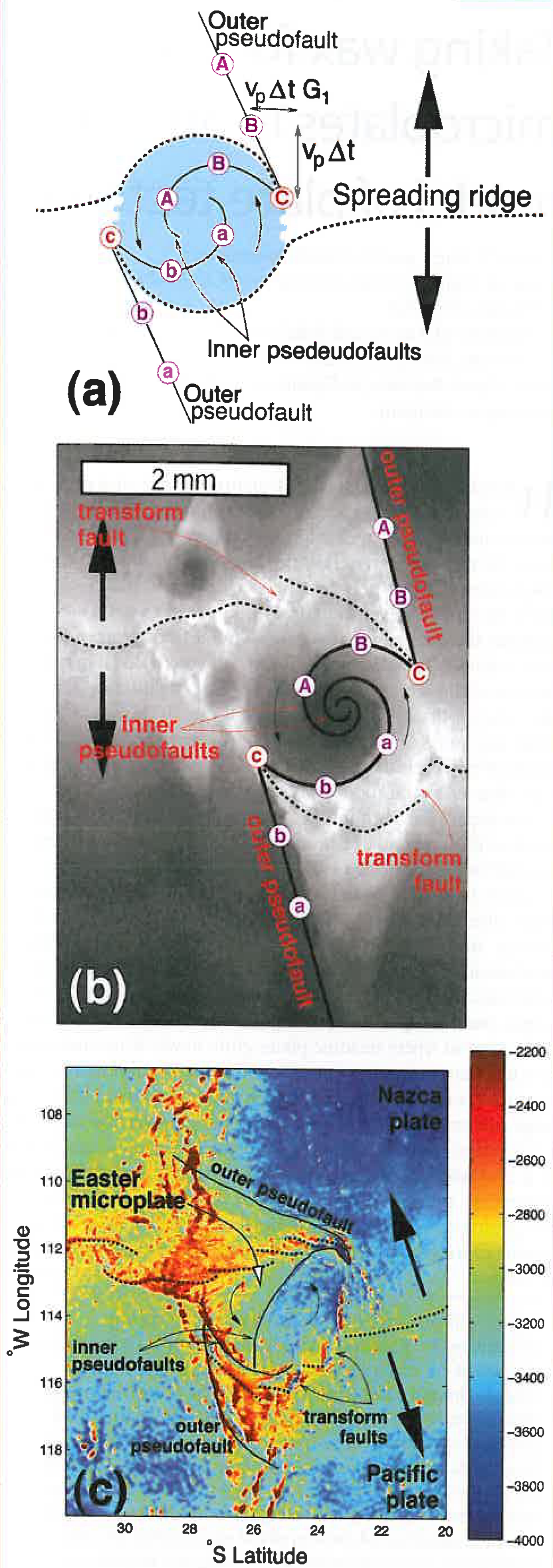


▶ **Fig. 1:** Time series of images showing a growing microplate at 15 second intervals. Spreading is to the top and bottom of each image at a half-rate of 35 μm/sec. **(Left column)** Images of the microplate. **(Right column)** Images identical to those in the left column but with pseudofault pairs and spreading ridge traces overlayed in red. The inner pseudofaults were generated using equations described in the appendix of [1]. Ridge traces were drawn by hand. Blue annotations indicate morphological features. Green arrows show the direction of motion of the main plates and the direction of microplate rotation. The figure is from Ref. [1]

Article available at http://www.europhysicsnews.org or http://dx.doi.org/10.1051/epn:2005503



▲ **Fig. 2:** Schematic diagram of the experimental setup. A rectangular tank of size 114 x 36 x 10 cm³ is filled with Shell Callista 158 wax which melts at about 72° C. The mechanical properties of micro-crystaline wax are brittle at room temperature and paste-like close to the melting point. No detailed mechanical measurements are performed. The tank is heated from below to (80.0 ± 0.05)°C and cooled from above by a constant flow of air at (12.0 ± 2.0)°C. The weakly turbulent refrigerated air flow is directed vertically downward. Before each run the wax is brought to temperature equilibrium at which a layer of solid wax is present on the surface. Skimmers embedded in the solid wax are attached to a threaded rod that is driven by a micro-stepping motor. A detailed description of this setup has been previously published [11]. The rift is initiated with a straight cut through the wax, perpendicular to the spreading direction. Divergence at this cut causes liquid wax to rise into the rift and solidify. Illumination from below permits us to image the plate thickness at the rift from above using a video camera. As the wax plate thickens it scatters more of the transmitted light and appears darker. In images of wax microplates shown here, spreading is toward the top and bottom of the image and the rift appears as a dark line. The figure is from Ref. [1]



► **Fig. 3:** Three microplates: schematic, wax and Earth. Dashed lines show the position of the spreading rift. Solid lines mark the inner and outer pseudofaults. Large black arrows show the spreading direction. Small black arrows show the sense of microplate rotation. **(a)** Schematic diagram illustrating the kinematics of microplates according to the Schouten model. The letters indicate points on the pseudofaults that were formerly at the rift tips, showing how the microplate grows with time. The current positions of the rift tips are marked as (c) and (C). The linear outer pseudofaults indicate a constant radial growth rate, which in turn implies a logarithmic spiral inner pseudofault. **(b)** Image of a wax microplate with model fit and rift tip markers overlayed as in (a). Transform faults are labeled on the image. They are located laterally across the microplate from the rift tips. Note the brighter, thinner wax triangles above and below "south" and "north" of the microplate. The width of the thin-plate triangular region at any distance from the ridge shows the approximate diameter of the microplate at a time in the past. **(c)** Bathymetry of the Easter microplate [12]. Colors denote elevation with respect to sea level; the color scale saturates at a minimum depth of 2200 m and a maximum depth of 4000 m. The Easter microplate is about 400 km across and is currently rotating clockwise at about 15°/Ma; over its lifetime of 5 Ma it has rotated about 95° [2]. Rift and pseudofault locations by D. Naar, modified from Naar and Hey (1991) [13]. Note that this image has been rotated counterclockwise and reflected across the *y*-axis so that the orientation and sense of rotation of the microplate is consistent with panels (a) and (b). The figure is from Ref. [1]

observations of their kinematic model and found excellent agreement, proving a connection between the observed morphology of microplates and their tectonic evolution. In Figure 1 we show that wax microplates obey the same relation between spreading rate, growth rate and spiral pseudofault geometry as their oceanic cousins. Our wax-to-Earth scaling relations indicate that the dimensions of wax microplates are consistent with estimates for oceanic microplates [2, 3]. Through close observation (e.g. Figure 4), we have developed a theory for the nucleation of overlapping spreading centers, known to be the precursors of microplates in wax and on Earth.

Microplates were discovered on the ocean floor in the early 1970s through surveys of their magnetic anomalies, seismicity and topography [4, 5, 6]. An explanation of their peculiar geometry and possible modes of formation were proposed shortly afterward [7]. During the 1980s microplates were recognized as an important tectonic feature of mid-ocean ridges, particularly the East Pacific Rise (EPR) [8] and much work was done to comprehensively map their structure (e.g. [9]). At least 12 paleo- and active microplates are known to exist in the Pacific Basin and additional ones are suspected to exist based on patterns observed in altimetry data [D. Naar, pers. comm., 2004]. The Easter microplate, shown in Figure 3c, sits on the EPR near 25°S between the Pacific and Nazca plates. High-resolution maps enabled the development of kinematic models [2] but due to the difficulty of interpreting sea-floor data, these models have not been conclusively verified. Furthermore, important questions regarding the origin of microplates and their eventual death have not been answered. Current numerical simulations cannot reproduce the coupled fluid-solid deformation processes responsible for microplate nucleation and growth at mid-ocean ridges. On the other hand, published results from a wax analog model yielded the first observations of overlapping spreading centres (OSCs), morphological precursors to microplates, before their discovery on the sea-floor [10]. We demonstrate that wax models still possess significant potential to provide insight into this long-standing problem.

Experiments

Our experimental setup is shown in Figure 2. The experiment is initiated with a cut with a sharp knife to divide the wax surface into two plates. Activating the motor caused the skimmers to diverge, dragging with them the two wax plates and causing fluid wax from below to upwell into the rift between the plates, just as ductile mantle rock upwells from beneath a mid-ocean ridge. The rift remains frozen over as long as the spreading of the plates is slow enough to accomodate the rise and solidification of molten wax from below.

Although the wax rift is initiated with a straight cut, it evolves and changes its morphology, closely mirroring the morphological signature observed in sonar images of the mid-ocean ridge. Three distinct morphological regimes were observed for ranges in spreading rate of an initially orthogonal rift. At slow half-spreading rates (~ 10–30 μm/sec) the straight rift is stable and forms a topographic low. At moderate rates (~ 30–60 μm/sec) the straight rift becomes unstable and overlapping spreading centres (OSCs) and microplates form, evolve and die on the ridge. In this regime the ridge has little or no relief. At higher half spreading rates still, the microplates lose their internal rigidity and become, in an intermediate stage, fault gouge zones and finally (> 70 μm/sec) transform faults at a ridge that forms a topographic high. In the work published in NJP we focused on the microplate regime. Movies and further information on the other regimes can be found at http://milou.msc.cornell.edu/ waxtectonics.html. There it is shown that experiments using other waxes can capture the dynamics of freezing lava lakes.

Tectonics in miniature and warp speed

To interpret the wax tectonics experiments we must consider how experimental distance and time scale from experiment to Earth. A time scaling can be determined by comparing rotation rates: a mature oceanic microplate rotates 20° in about 1 Ma while a wax microplate completes this rotation in about 5 seconds. This means that the experiment is sped up by a factor of approximately one billion. In the NJP article we have also shown that 1 mm in the wax experiment scales to about 50 km on Earth. This corresponds to shrinkage by a factor of 50 million. Indeed, the scales in the wax experiment are almost too small and too fast.

Microplate model confirmed

We have shown [1] that a kinematic model of microplate evolution proposed and applied to the Easter microplate by Schouten *et al.* [2] can explain the data. The Schouten model states that the rigid motion of a microplate is like that of a ball rotating between two parallel, moving plates. Unlike the ball, however, a microplate grows by accreting young lithosphere, as shown schematically in Figure 3a. In Ref. [1] we derived a mathematical formulation of the Schouten model that we used to calculate the predicted shape of the inner pseudofaults for an image of a mature wax microplate. The fit depended only on a single free parameter, the diameter of the microplate when it began to rotate rigidly. All other parameter were determined by the experiment. Once one image had been fitted it was possible to use the formulae to calculate back in time. This way it was possible to to test also the dynamical predictions of the Schouten model. Figure 3 shows an example of predicted and observed morphological time-evolution. Clearly, a similar time-series comparison for Earth is impossible as we would need to wait 500,000 years to acquire the data. Studies, however, have compared the predictions with the current shape of oceanic microplates and found reasonable agreement [2, 3].

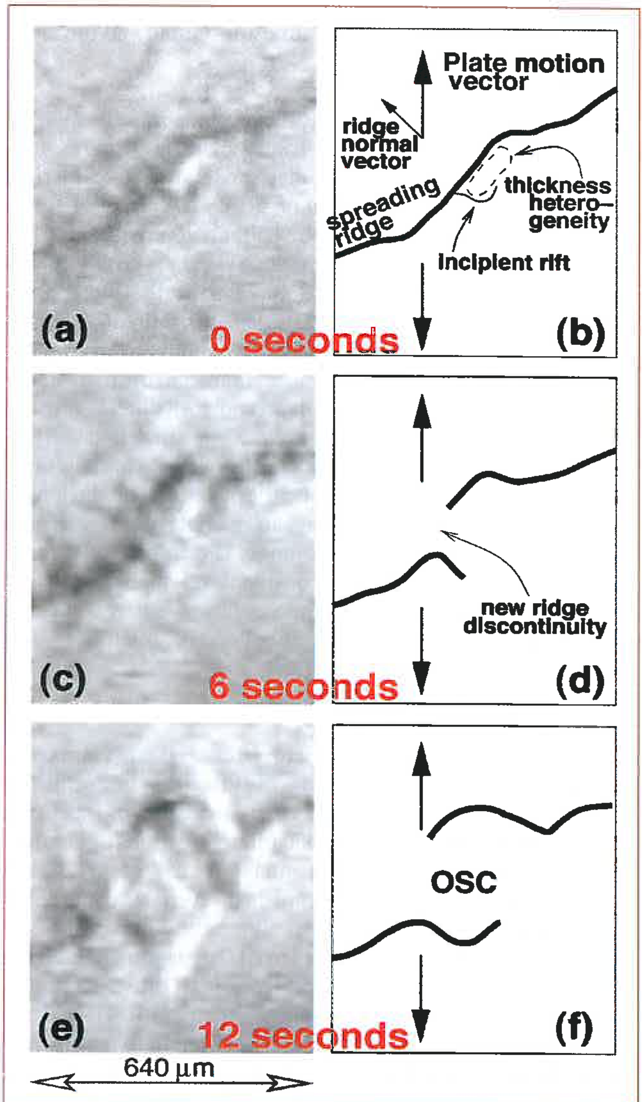
How are microplates born?

Like oceanic microplates, wax microplates originate from overlapping spreading centers (OSCs) which nucleate frequently on the spreading rift. We observed [1] that nucleation of wax OSCs occurs predominantly on ~200-300 micron sections of obliquely spreading rift, where the rift normal is about 45 degrees from the spreading direction. The diminished divergent component of spreading across these segments allows the rift axis to freeze across, introducing a discontinuity in the rift as shown in Figure 4. This results in a local stress field tending to cause the propagation of rift tips into an overlapping geometry [14]. The rift tips will only propagate in this manner if the strength to tensile fracture of the adjacent lithosphere is small relative the the strength of the frozen rift. If, on the other hand, the adjacent lithosphere is too strong to be fractured by rift tip propagation, deformation and faulting will remain localized on the rift centre. A muted strength contrast might be expected at fast spreading ridges where the adjacent lithosphere is thinner and weaker than at slow spreading ridges, consistent with the distribution of microplates on Earth. Furthermore, if applicable to Earth, this freezing-over mechanism of nucleation might explain the formation of OSCs on transform faults that have gained a component of divergence after a plate-motion change or plate-boundary reorganization [15]. This reasoning equally applies to the wax, although we have not experimented with changes in spreading direction.

Conclusion and outlook

In Ref. [1] we have shown that a wax model of sea-floor spreading, under the right conditions, produces tectonic microplates that evolve in time according to a kinematic model designed for oceanic microplates. This finding suggests that wax microplates are a good analog formicroplates on the ocean floor and reinforces the validity of the kinematics prescribed by the Schouten model [2]. Futhermore, the presence of microplates in our analog model indicates that on Earth, microplates are a lithospheric phenomenon not dependent on special conditions or processes in the underlying mantle. Other similarities between wax and Earth suggest that these models have potential to advance our understanding of microplates and other sea-floor spreading phenomena. For example, inferences drawn from repeated observation of the nucleation of wax microplates may apply to the birth of their oceanic counterparts.

Clearly the work so far is only the beginning. The wax tectonics experiments have the advantage that they are much simpler than Earth and that they can be made quantitative in terms of material properties, the measurement of the thermal and flow fields, and possibly the stress field. They can be used to quantitatively test numerical models that later, in a refined form, can be applied to Earth or other planets. ■



▲ Fig. 4: Nucleation of an OSC, precursor of a wax microplate. (Left column) Time series of images at high magnification. (Right column) Interpretive drawings mapping the evolution of the rift into an overlapping geometry. Note that interpretation is based on the movie from which these images were drawn. (a-b) Time $t = 0$. A section of rift with normal vector oriented 45 degrees from the spreading direction. The OSC nucleates around a thickness heterogeneity at the rift which appears as an elongate white blob. (c-d) Time $t = 6$ seconds (~ 1.2 Ma). A rift discontinuity appears and the disconnected rifts begin to overlap. (e-f) Time $t = 12$ seconds (~ 2.4Ma). Rifts are overlapping around an enclosed region with a diameter of about 300 μm. This OSC subsequently develops into a rotating microplate. The figure is from Ref. [1]

About the Authors

Richard Katz is currently a PhD candidate at the Lamont-Doherty Earth Observatory of Columbia University in New York City where he builds mathematical models of the deep roots of volcanoes. The research described here was a part of Rich's senior thesis at Cornell. **Eberhard Bodenschatz** is a professor of physics and mechanical and aerospace engineering at Cornell University and the scientific director of the department for Hydrodynamics, Pattern Formation and Nanobiocomplexity at the Max Planck Institute for Dynamics and Self-Organization in Göttingen, Germany.

References

[1] R.F. Katz, R. Ragnarsson, and E. Bodenschatz. Tectonic microplates in a wax model of sea-floor spreading. New Journal of Physics, 7(37), 2004. http://stacks.iop.org/1367-2630/7/37.

[2] H. Schouten, K.D. Klitgord, and D.G. Gallow. Edge-driven microplate kinematics. J. Geophys. Res., 98 B4:6689–6701, 1993.

[3] R.L. Larson, R.C. Searle, M.C. Kleinrock, H. Schouten, R.T. Bird, D.F. Naar, R.I. Rusby, E.E. Hooft, and H. Lathiotakis. Roller-bearing tectonic evolution of the Juan Fernandez microplate. Nature, 356:571–576, 1992.

[4] E.M. Herron. Two small crustal plates in the South Pacific near Easter Island. Nature Phys. Sci., 240:35–37, 1972.

[5] D.W. Forsyth. Mechanisms of earthquakes and plate motions in east pacific. Earth Plan. Sci. Lett., 17:189–193, 1972.

[6] R.N. Anderson, D.W. Forsyth, P. Molnar, and J. Mammeric. Fault plane solutions of earthquakes on nazca plate boundaries and easter plate. Earth Plan. Sci. Lett., 24:188–202, 1974.

[7] R.N. Hey. A new class of pseudofaults and their bearing on plate tectonics. Earth Plan. Sci. Lett., 37:321–325, 1977.

[8] K.C.Macdonald, D.S. Scheirem, and S.M. Carbotte. Mid-ocean ridges: Discontinuities, segments and giant cracks. Science, 253:986–994, 1991.

[9] R.C. Searle, R.I. Rusby, J. Engeln, R.N. Hey, J. Zukin, P.M. Hunter, T.P. LeBas, H.J. Hoffman, and R. Livermore. Comprehensive sonar imaging of the easter microplate. Nature, 341:701–705, 1989.

[10] D.W. Oldenburg and J.N. Brune. Ridge transform fault spreading patterns in freezing wax. Science, 178:301–304, 1972.

[11] R. Ragnarsson, J.L. Ford, C.D. Santangelo, and E. Bodenschatz. Rifts in spreading wax layers. Phys. Rev. Lett., 76:3456–3459, 1996.

[12] W.H.F. Smith and D.T. Sandwell. Global seafloor topography from satellite altimetry and ship depth soundings. Science, 277:1957–1962, 1997.

[13] D.F. Naar and R.N. Hey. Tectonic evolution of the Easter microplate. J. Geophys. Res., 96:7961–7993, 1991.

[14] N.R. Grindley and P.J. Fox. Lithospheric stresses associated with nontransform offsets of the Mid-Atlantic ridge: implications from a finite element analysis. Tectonics, 12:982–1003, 1993.

[15] R.T. Bird and D.F. Naar. Intratransform origins of mid-ocean ridge microplates. Geology, 22:987–990, 1994.