RHEOLOGY AND DEFORMATION OF THE LITHOSPHERE AT CONTINENTAL MARGINS

Edited by
Garry D. Karner, Brian Taylor, Neal W. Driscoll, and David L. Kohlstedt
Rheology and Deformation of the Lithosphere at Continental Margins
MARGINS Theoretical and Experimental Earth Science Series

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Continental margins are the Earth’s principle loci for producing hydrocarbon and metal resources, for earthquake, landslide, volcanic, and climatic hazards, and for the greatest population density. Despite the societal and economic importance of margins, many of the mechanical, fluid, chemical, and biological processes that shape them are poorly understood. Progress is hindered by the sheer scope of the problems and by the spatial-temporal scale and complexities of the processes.

The MARGINS Program (a research initiative supported by the U.S. National Science Foundation) seeks to understand the complex interplay of processes that govern continental margin evolution. The objective is to develop a self-consistent understanding of the processes that are fundamental to margin formation and evolution. The books in the MARGINS series investigate aspects of these active systems as a whole, viewing a margin not so much as a geological entity of divergent, translational, or convergent types but more in terms of a complex physical, chemical, and biological system subject to a variety of influences.
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This volume is a collection of papers resulting from presentations made during a four-day short course at the first U.S. MARGINS Theoretical and Experimental Institute (TEI) held January 23–26, 2000. The institute was funded by the National Science Foundation and examined field, laboratory, and modeling constraints on how lithosphere rheology and deformation evolve throughout continental margin evolution. Traditionally, investigations of the rheology and deformation of the lithosphere have taken place at one scale in the laboratory and at entirely different scale in the field; development of an understanding of large-scale processes requires an integrated approach. The long-term objective of the short course and its ensuing publication is to stimulate cross-disciplinary inquiry into the rheology and deformation of the lithosphere. The first day of the short course provided an overview of the setting and nature of deformation at extensional and compressional continental margins. Day two concentrated on: (1) observations supporting, and models explaining, strain partitioning within the crust and lithosphere and (2) numerical and analogue modeling experiments that address the scaling problem of comparing physical experiments with natural systems. Day three focused on laboratory observations related to frictional sliding and crack healing along fault surfaces. Day four was centered on experimental studies of the rheology of crustal and mantle rocks.

The institute significantly influenced the subsequent research objectives and directions of the MARGINS Rupturing Continental Lithosphere (RCL) initiative, which were examined during a two-day workshop that followed the short course. The RCL initiative had as its basic tenet that the mechanisms allowing continental lithosphere to be deformed by weak tectonic forces were not understood, and neither was the manner in which strain was partitioned and magma distributed. These problems were encapsulated by the following themes: (1) the low-stress paradox of lithospheric deformation and (2) strain partitioning of the lithosphere during deformation. A series of papers verified the existence and complexities of the spatial and temporal distribution of strain within deforming lithosphere (chapters 1, 4, and 7: Buck, Davis and Kusznir, and Willett and Pope).
However, the low-stress paradox of lithospheric deformation that figured so prominently in all MARGINS planning documents prior to the TEI was significantly challenged. This paradox relates to the fact that large fault structures (subduction thrusts, major transforms, and perhaps normal detachments) accommodate a major component of strain but move at resolved shear stresses far smaller than those expected to cause failure. In turn, this apparent low-strength property of large faults may be corollary to an even more fundamental issue; namely, the tectonic forces available are insufficient to rupture the continental lithosphere as defined by the integrated yield-stress envelope of the continental lithosphere. Buck (chapter 1) elegantly showed that dike intrusion could reduce the amount of tectonic force required to rift normal continental lithosphere by an order of magnitude below that needed to stretch lithosphere in the absence of dykes.

Active low-angle normal detachments are the extreme case of the weak fault/low-strength paradox. The present debate revolves around whether low-angle faults mapped in such regions as the Whipple and Mormon Mountains of the western United States actually moved at low fault dip angles or moved on high-dipping faults whose footwalls were rotated into the observed field relationships, either in a domino style or by a rolling hinge mechanism. Continental intraplate earthquake focal mechanisms are predominantly related to high-dipping faults. Nevertheless, the megamullion structures of seafloor spreading centers and the geological reconstructions summarized by Axen (chapter 3) for the fault systems of southeastern Nevada, southwestern Utah, and southeastern California appear to require an active period of low-angle normal faulting. The controversy continues.

This same weak fault/low-strength paradox issue was the rationale behind the Ocean Drilling Program drilling (Leg 180) of the Moresby detachment zone in Papua New Guinea, one of the few examples of an active, low-angle (\(\sim 30^\circ\)) normal fault (Taylor and Huchon 2002). Studies there showed the existence of many meters of talc-chlorite-serpentinite gouge with low coefficients of friction (0.21–0.3; Kopf et al. 2003) within a permeable, porous, and anisotropic fault zone at greater than hydrostatic fluid pressures. Scholz and Hanks (chapter 9) effectively dismiss the paradox of the Moresby Detachment in demonstrating that its lock-up angle is consistent with Andersonian failure theory.

The weak fault/low-strength paradox has become entwined with the elastic thickness controversy in which earthquakes in midplate settings rarely occur below 40 km depth, indicating that the physical and chemical conditions prevailing in deeper rocks do not permit them to deform by brittle failure. In support of this observation, the elastic thickness of the continents inferred from free-air gravity, Bouguer gravity, and topography data is typically less than 40 km and less than the local depth to the Moho. In contrast, estimates of flexural loading of the lithosphere require elastic conditions to prevail to depths of 40 to 100 km over time periods of many millions of years. Hence the controversy: how is it possible for the Earth to support loads elastically at great depth and over long periods when the crust fails seismically at shallow depth and at short periods? Directly linked to this controversy is the viability of the yield-stress envelope for continental lithosphere. For many years, laboratory measurements of high-temperature creep
of rock-forming minerals has been used to infer that crustal minerals should deform more readily than olivine at the same temperature. This led to the “jelly sandwich” image of a brittle upper crust, a potentially weak ductile lower crust, and a stronger upper mantle. Topography and the distribution of deformation near the Earth’s surface concur with this image, at least for regions like the Basin and Range Province and Tibet. To what extent does a jelly sandwich simulate the rheology of continental lithosphere? Jackson (chapter 2) introduces a contentious idea suggesting that the strength of the continental lithosphere resides in its seismogenic layer, which is contained wholly within the crust, and that the continental lithospheric mantle is characterized by a wet rheology and thus is relatively weak. Willett and Pope (chapter 7), via a series of finite-element modeling experiments for the regional and intensive compressional deformation of continental lithosphere (bivergent orogenic edges and orogenic plateaus), offer important insights into the actual rheological behavior of the lithosphere.

In a set of related papers, Ruff and Hyndman (chapters 5 and 6, respectively) characterize the rheology of the zone between interacting converging plates, the seismogenic zone, which is defined by the spatial extent of earthquakes. Their intent is to define the processes controlling the updip and downdip rupture limits of the seismogenic zone. In this environment, the updip fault rheology appears to be dominated by temperature, which in turn controls the onset of seismic behavior via the dehydration of stable sliding smectite clay to stick-slip chlorite/illite, either in overlying sediments or within the fault zone gouge. The downdip limit of the seismogenic zone appears to be a function of the temperature dependence of the slip characteristics, for example, from stick-slip to stable sliding, in the fault zone material and the composition and thus rheology of the material in the overriding plate. Ruff (chapter 5) also attempts to define the controls on the various depths to the seismogenic limit within continental interiors, which seems to require more than just a temperature control.

Having a weak lithospheric mantle appears to be consistent with the laboratory studies reported by Xu et al. (chapter 10) and Evans et al. (chapter 11). Xu et al. investigated the role of melt on the anelastic and plastic properties of partially molten rocks as well as the effect of deformation on the distribution of the melt phase. The melt phase provides short-circuit diffusion paths or melt-rich bands, which aid in the relaxation of stress concentrations. The melt-rich bands are zones of low viscosity and high permeability, which act on a geologic scale to produce a marked anisotropy in seismic properties in addition to profoundly influencing the style of deformation. The link between magmatic processes and lithospheric strength is further explored by Evans et al., who show that rock strength decreases significantly when even a small amount of melt is present. In contrast, Chester et al. (chapter 8) describe the details of the porosity and permeability structure of large-displacement, strike-slip fault zones of the San Andreas system. The damaged zone and fault core are composed of very fine-grained, altered fault rocks in which the relatively permeable damage zone acts as a conduit for fluid flow along the fault and the low-permeability fault core serves as a barrier for cross-fault flow; the fault zone at least within the upper crust is conducive to fluid flow.
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