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Tectonic Faults

Agents of Change on a Dynamic Earth

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WHAT ARE FAULTS AND WHY SHOULD WE STUDY THEM?

Movements within the Earth and at its surface are accommodated in domains of localized displacement referred to as faults or shear zones. Since the advent of the plate tectonic paradigm, faults have been recognized as primary agents of change at the Earth's surface. Faults delimit tectonic plate boundaries, accommodate plate motion, and guide stress and strain to plate interiors. In extending and contracting lithosphere, faults are the locus of burial and exhumation of large rock bodies.

Active faults are zones of enhanced seismicity with associated surface rupture, ground shaking, and mass wasting. The risk associated with seismic hazard is particularly high in densely populated areas with complex infrastructure. Because faults create morphologies that are in many ways favorable for human settlement (e.g., valleys, harbors), many large population centers are situated near active faults. Prediction of the magnitude, timing, and location of earthquakes is important to the safety and development of these centers.

Faults are also channels for the advection of fluids within the lithosphere. As such, they link the biosphere and atmosphere with the asthenosphere. In particular, faults are conduits for water, which is essential for maintaining life.

They are sites of enhanced dissolution and precipitation, and therefore often contain hydrothermal deposits rich in metal oxides, sulfides, and other minerals of value to industrial society. In addition, faults bound sedimentary basins that contain hydrocarbon resources.

Faults affect the composition of the hydrosphere and atmosphere by exposing fresh rock to weathering. In this sense, faults are a potential factor in long-term climate change. The topography created by faulting provides ecological niches that favor the evolution and migration of mammals, notably hominids. Human evolution has been facilitated by faulting.

Faults are high-permeability pathways for molten rock that ascends from source regions at depth to sinks higher in the lithosphere. Faults are also sites of melt extraction, magma–wall rock interaction, and differentiation. These processes modify both the thermal structure and composition of the Earth's crust and mantle.

Clearly, understanding faults and their underlying processes is a scientific challenge with lasting social and economic relevance. Driven by extensive research in all of these areas, our understanding of faults and faulting has developed rapidly over the past thirty years. Yet many of the factors and feedback mechanisms involved in faulting have still to be constrained. Other notions of fault evolution that have long been accepted are now being called into question. Traditional avenues of research have lost their potential to yield surprising insights. New concepts and initiatives are necessary if we are to augment our knowledge of faulting and harness this knowledge to develop models with predictive capability. This book reports on the findings of the 95th Dahlem Workshop that was devoted to this endeavor.

THE WORKSHOP

The week-long Dahlem Workshop brought together 41 scientists with backgrounds in the natural and engineering sciences, all engaged in various aspects of basic and applied research on fault systems. Prior to the meeting, the program advisory committee had agreed on three main goals for advancing fault research:

- to assess the intrinsic and extrinsic factors controlling fault evolution, from nucleation through growth to maturity and termination;
- to evaluate processes and feedback mechanisms of faulting on different time and length scales, from the surface down to the asthenosphere;
- to advance strategies for predicting fault behavior, for understanding the interaction of faulting with topography and climate, and for interpreting its impact on the rock record.

In accordance with the Dahlem Workshop format, participants were divided into four discussion groups charged with developing the following themes:

1. Nucleation and growth of fault systems
2. Rheology of fault rocks and their surroundings
3. Climatic and surficial controls on and of faulting
4. Fluids, geochemical cycles and mass transport in fault zones.

These themes encompass numerous challenges for basic research in the Earth Sciences, many of them with implications for assessing hazard and mitigating fault-induced risk. To be met, these challenges demand a broad approach in which specialized research is combined with cross-disciplinary studies to develop a new generation of models with predictive capability. The groups' deliberations were facilitated by background papers that had been written on selected aspects of these themes in the months leading up to the meeting. These papers were made available to all participants before the meeting and constitute the bulk of this book. They are complemented by the reports of the four workshop groups, which were drafted by designated rapporteurs by the end of the meeting. In the ensuing months, the authors and other participants were able to revise their papers and reports in light of the discussions and reviews of colleagues who are acknowledged below. This book is therefore the result of a week of well-informed, intensive debate and learning.

WHAT WAS LEARNED?

To answer this question, it helps to begin with some general, long-standing observations. The structure of faults in the Earth's lithosphere varies with depth and displacement: In shallow levels, initial displacement over short times (10^{-2}–10^{0} s) on a complex system of fault segments (10^{-2}–10^{3} m) eventually concentrates or localizes on one or more long faults (10^{3}–10^{6} m), which remain active intermittently over extended periods of time (10^{5}–10^{7} yr). Superposed on this long-term evolution is short-term transient behavior, exemplified by the recurrence of earthquakes (10^{2}–10^{5} yr). The dynamic range of length and timescales of fault-related processes far exceeds the human dimension (see Figure 4.1 in Furlong et al., Chapter 4). The localization of motion on faults implies a weakening of faulted rock with respect to its surrounding host rocks. Accordingly, motion on fault surfaces and systems can be partitioned in different directions relative to the trend of a fault system. Taken together, these general characteristics reflect the interaction of fault motion history (kinematics) with fault mechanics (rheology), the ambient physical conditions of faulting (e.g., temperature, pressure, fluid properties), the physical and chemical properties of rock (mineralogy, porosity, permeability), and the rates and amounts of denudation at Earth's surface. Understanding the processes and feedbacks that govern the impact of faults at Earth's surface is destined to advance along many parallel and intertwined lines of investigation.

The geometry and internal structure of fault zones has been imaged from the surface down to the base of the lithosphere with a variety of geological and geophysical methods, as reviewed by Mooney et al. (Chapter 2). At shallow levels in the Earth's crust, active faults are discrete features, with microseismicity (M_L 1–3) concentrated on strands no more than several tens of meters wide. Damage zones on either side of this core show time-dependent changes in seismic velocity, presumably due to mineral dissolution–precipitation on the grain scale in the fractured rock. The role of fluids in healing and sealing upper crustal fault systems is considered in the context of the earthquake cycle by Gratier and Gueydan (Chapter 12). The lower depth limit of the damage zone is not well known, and reflects the need to develop imaging methods with better resolution at depth (see Furlong et al., Chapter 4, and Tullis et al., Chapter 7).

Inroads in understanding the full three-dimensional evolution of upper crustal fault systems have come from the study of rifted margins with fault activity documented by sediments in fault-bounded basins (Cowie et al., Chapter 3). The temporal resolution of fault motion at Earth's surface is obviously limited by gaps in the stratigraphic record and the inherent difficulty of discerning all length and timescales of fault activity in a large faulted domain (Buck et al., Chapter 10). Fortunately, recent advances in geochronology (e.g., surface exposure dating with cosmogenic nuclides) already allow us to constrain more precisely not only the age of sediments, but also time- and area-integrated rates of denudation (Hovius and von Blanckenburg, Chapter 9). This has facilitated the calculation of short-term slip rates on faults active over the last ca. 10^5 yr. Many of these new techniques await application, especially in regions where numerical modeling predicts that surface mass flux can perturb the mechanical stability of rocks at depth (Koons and Kirby, Chapter 8). Erosion potentially triggers a positive feedback between rock uplift (exhumation), further denudation, and the generation of topography on timescales of the earthquake cycle.

Much knowledge of fault processes at depths beneath 5 km comes from inactive (fossil), exhumed fault systems, for example, in mountain belts. Marked changes in structure are noted at the transition from brittle, frictional sliding and frictional granular flow (cataclasis) to thermally activated, viscous creep (mylonitization), as reviewed by Handy et al. in Chapter 6. The authors illustrate the dynamic nature of this transition and emphasize its significance for decoupling within the lithosphere as well as for short-term, episodic changes in fluid flux and strength. These changes are triggered by frictional or viscous instabilities and may be measurable as transient motion of the Earth's surface, especially after large earthquakes. Geophysical images and geo-electric studies support the idea of high pore-fluid pressures along thrusts and low-angle normal faults; they also indicate that faults can act as fluid conduits, barriers or both depending on the evolving properties of the fault rocks (see Mooney et al., Chapter 2). Yardley and Baumgarter (Chapter 11) underscore the impact of fluid and fluid composition, both on the structural style and on rheology of the crust. This pertains especially to the escape of volatiles during burial and prograde metamorphism, which is expected to dry out and strengthen the crust. On the other hand, the presence of fluids can weaken fault rocks in several ways; in the case of melt, even modest quantities (<5–7 vol.-%) can reduce viscosity by an order of magnitude, possibly more (Rosenberg et al., Chapter 13). Melt-induced weakening within the base of the continental crust can induce lateral crustal flow, a key process for supporting broad topographic loads like the orogenic plateaus of Tibet and the Andean Altiplano. Faults in the Earth's upper mantle, imaged by measurements of seismic anisotropy, are interpreted to be planar zones of distributed shear some 20–100 km wide (Mooney et al., Chapter 2), although more localized shearing is likely based on rare observations in exhumed mantle shear zones. Looking even deeper, the lithosphere–asthenosphere boundary is also a major shear zone that accommodates tectonic plate motion with respect to the convecting asthenosphere. The future ability to image fault structure at these depths is contingent on improving spatial resolution even beyond that achieved by recently developed seismic receiver function methods (Furlong et al., Chapter 4).

The mechanical behavior of fault rocks is considered from different perspectives, depending on the depth interval and conditions of faulting. Regarding the seismic response of upper crustal fault zones, Rice and Cocco (Chapter 5) point out that while rate and state friction laws are adequate descriptions of fault rock behavior at earthquake nucleation and at slow, interseismic rates, new concepts are needed to understand why faults weaken so rapidly during the rupture (growth) stage of large earthquakes. Together with these authors, Tullis et al. (Chapter 7) and Person et al. (Chapter 14) propose several testable hypotheses for fault weakening that call for a new generation of seismic and laboratory experiments, as well as observations of natural fault rocks. In particular, Person et al. (Chapter 14) examine the role of metamorphic reactions and reaction rates in the context of upwardly and downwardly mobile fluids as a possible key for the rheology of upper crustal faults during the earthquake cycle. Osmotic effects of clay minerals in faults are expected to affect pore fluid pressure and frictional properties of fault zones. In contrast, the viscous lower crust contains mechanical anisotropies (e.g., foliations, minerals), which play a principal role in localizing strain within shear zones on all length scales (Handy et al., Chapter 6). Scaling these inherited structures is a necessary step toward incorporating the effect of mechanical anisotropy into constitutive rheological models. This may help to constrain the response time of fault geometry and structure to changes in regional deformation rate associated with changing plate-scale kinematics.

The Earth's dynamic surface, especially in faulted areas, is the product of coupled climatic, erosional, and tectonic processes. Progress in understanding this coupling has been made, but quantitative, predictive models for the environmental effects on and of faulting are still far from mature. The models of Koons and Kirby (Chapter 8) demonstrate the viability of feedbacks between dynamic topography, stress distribution, and uplift rates. However, identifying limits on the time and length scales at which different surface processes can influence faulting (and vice versa) remains a principal challenge, as discussed by Buck et al. (Chapter 10). These limits are expected to depend on a host of climatic factors, as well as on the erodibility of rocks in the faulted area. Hovius and von Blanckenburg (Chapter 9) review the available geomorphological and geochemical techniques for measuring erosion and weathering on timescales relevant to faulting. These are shown to be key to understanding feedbacks between tectonics and climate, especially isostatic effects related to shifting topographic loads and climatic effects associated with CO_2 drawdown in freshly eroded areas of active faulting. The authors argue that although climatic variability and change are evident in the pattern of erosion and weathering, this pattern almost always reflects a stronger tectonic signal.

RECOMMENDATIONS FOR FUTURE RESEARCH

Rather than summarize the wealth of ideas generated by the four group reports, we end this introduction with an attempt to formulate the participants' consensus opinion on recommendations for future work in fault studies.

There was broad agreement that research should develop along both interdisciplinary and multidisciplinary lines. Faults have immediate impacts on society, but understanding them to the point where we can improve predictions of fault behavior is only possible if the underlying processes can be studied on all relevant time and length scales.

Studies should focus on *natural laboratories* and on *interacting processes*. Natural laboratories are regions of the Earth where geological and climatic processes can be characterized and quantified in a geo-historical context. For fault studies, ideal natural laboratories contain both active and fossil (exhumed) fault systems in a well-defined plate tectonic setting (orogenesis, continental transform faulting, back-arc spreading, intraplate faulting). The fault images—whether mapped from space by satellite, at the surface by eye, or resolved at great depth by geophysical methods—can yield insight into coupled processes during prolonged periods of faulting. Several natural laboratories were mentioned at the conference (e.g., Furlong et al., Chapter 4): the European Alps, the Southern Alps of New Zealand, the Aegean trench-backarc system, the North Anatolian and San Andreas faults, the Cordilleran orogens, and the Himalayan–Tibetan orogen–plateau system. The laboratory chosen obviously depends on the nature of the process(es) studied, so comparing the role of a specific process in more than one setting yields better insight into feedbacks. The best natural laboratories would have an in-depth geological, geophysical, and climatological information base. New natural laboratories can only be developed if funding agencies are willing to support prolonged campaigns whose primary objective is to collect, interpret, and assimilate large and diverse datasets. Much of this basic work is perforce interdisciplinary. Some of the technologies applied are new.

Experimental laboratory studies are needed to understand processes under controlled conditions. Specific examples of experiments pertain to fault weakening and the role of gels and fluids, as outlined, respectively, by Tullis et al. (Chapter 7) and Person et al. (Chapter 14). In some cases, these studies will require the development of new deformation apparati to better approach natural conditions in the laboratory. *Improved data acquisition and processing techniques* are needed to augment the resolution of structures and material flux in Earth and at its surface. The improvement of seismic imaging methods remains a high-priority goal of the geophysical community. Advances are also desirable in geochemical techniques, for example, to improve the precision of surface exposure ages obtained by analyzing trace amounts of cosmogenic nuclides.

Modeling is necessary to test hypotheses and to make predictions in coupled Earth systems that are too complex to understand intuitively. This effort includes both physical modeling (i.e., scaled models using analogue, Earth-like materials) and numerical/analytical modeling. Although both forms of modeling are not new to the Earth Science community, the solid Earth community should take more advantage of recent advances in computing technology to study coupled, fault-related processes. For example, fault studies should employ high-power computing facilities (supercomputing, massive parallel arrays) to test theoretical concepts on the nucleation and growth of slip surfaces at the onset of large earthquakes (Tullis et al., Chapter 7). Likewise, climate models could be adapted to test the long-term effects of faulting and weathering on atmospheric and oceanic CO_2 budgets, and therefore on climate. As in any study of complex phenomena, true progress will come from a pragmatic combination of new and existing approaches and technologies.

Outreach, i.e., public information, is not a form of research, but sharing specialized knowledge is a public duty of the scientific community. Under the fresh impression of the devastating M_W 9.3 Sumatra-Andaman earthquake and tsunami of December 26, 2004, the members of Group 3 formulated a strategy of how Earth scientists could better prepare the public for such events and how public officials might be informed of the risks associated with active faulting (*Buck* et al., Chapter 10). The mechanisms by which information flows in societies under existential stress and duress of time (e.g., in advance of short-term predictions of natural calamities, like large earthquakes) may be a field of interdisciplinary research with potential for another Dahlem Workshop.

In this Introduction, we are only able to provide a glimpse of the wealth of new ideas generated at the workshop. It is left to readers to engage each contribution in this book on its own terms.

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