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Introduction

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Article submitted to journal

Subject Areas:

Earth Science, Geology, Geophysics

Keywords:

Earthquakes, Faulting, Rheology, Lithosphere

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Understanding Earthquakes Using The Geological Record: An Introduction

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Synthesising geological and geophysical approaches to investigate the deformation of the lithosphere offers the potential for important new insights because of the range of timescales and lengthscales sampled by the different techniques, although successfully spanning this range represents one of the main challenges to be overcome when conducting such work. Nonetheless, significant progress has been made in linking such diverse observations and models. For example, the recognition of transient and mostly aseismic slip in some parts of subduction zones being coupled to field-based analysis of mixed-lithology fault zones has resulted in a new understanding of the mechanisms for generating transient fault slip at velocities intermediate between earthquakes and plate motions [1–5]. Similarly, observations of earthquake faulting in the lower continental crust made both petrologically (preserved as pseudotachylytes) and seismologically has resulted in a new appreciation of the diversity of rheology in the continental crust, and the importance of trace amounts of water in controlling the deformation [6–10]. In February 2020 the Royal Society hosted a Hooke Discussion Meeting to further explore links between geological and geophysical methods of studying faulting, titled 'Understanding Earthquakes Using the Geological Record'. This introduction highlights some of the common themes of the meeting, relating to the factors that govern fault behaviour, and the feedbacks between faulting and the geological evolution of the Earth's crust and upper mantle.

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A clear pattern that emerges from the articles in this volume, and the wider research topic, is the great diversity of deformation mechanisms and rates active within the lithosphere, and their geological pre-requisites and consequences. It would make no more sense to refer to 'the rheology of the lithosphere' as a single spatially or temporally invariant concept, than it would to refer to 'the weather' as something that never changes. The task of the Earth Scientist is therefore to establish the underlying causes of the variability in lithosphere properties and deformation, and develop a physical and chemical understanding of the governing principles.

The role of water in controlling lithosphere deformation is dramatic. Within the earthquake-producing seismogenic layer, the pressure of pore fluids in a fault zone controls the shear stress that is required to cause the fault to slip, and whether the fault contains hydrous phyllosilicates, and the extent to which they form an interconnected network, has a strong influence on fault strength and slip style [11–15]. Beneath the seismogenic layer, water at the levels of tens to hundreds of parts per million is known to have a dramatic effect on the creep strength of minerals, changing their viscosity by orders of magnitude between 'anhydrous' and 'hydrous' states [16–18].

In this volume, Dunkel et al [8], Jackson et al [9], and Menegon et al [10] investigate the links between hydration state, temperature, deformation mechanism, and rheology in the continental crust. At the present day, most regions where continental earthquakes occur in the mid to lower crust (e.g. deeper than 25 km) are spatially associated with regions of thick lithosphere. However, the effect of the lithosphere thickness on the temperature structure is insufficient on its own to explain the depth of the earthquakes, and implies (by comparison to the oceanic lithosphere) that the continental lower crust in these regions is anhydrous [9]. This inference is consistent with observations from the geological record, where evidence of earthquake slip in the mid to lower crust recorded by the presence of pseudotachylytes is commonly associated with anhydrous metamorphic rocks [8,10], which have had melt (and therefore volatiles) extracted from them. The resulting lateral variations in lithosphere hydration state, and therefore strength, can be seen to have had an important influence on the geological history of the continents [9].

Understanding the rheological implications of the deep earthquake faulting that indicates the presence of anhydrous assemblages is a topic of considerable interest. In some situations, fluid influx associated with earthquake ruptures results in metamorphic reactions to form hydrous assemblages that then deform by ductile creep [9]. In other examples, no fluid input is recorded by the anhydrous rocks but the pseudotachylytes undergo ductile deformation, thought to be by efficient diffusion creep because of their extremely small grain size [10]. Later generations of pseudotachylyte cutting the ductile fabrics implies transient (and maybe cyclical) deformation. In other examples, pristine pseudotachylyte glass is able to persist for hundreds of millions of years, and undergo no subsequent strain [8]. These contrasting observations point towards a spatial and temporal variability to lower crustal deformation that highlights some of the challenges to be addressed in this subject area. There are significant differences between the deviatoric stresses implied by the presence and displacement patterns of pseudotachylyte-bearing ruptures in anhydrous lower crust compared to the (much lower) stress drops in modern-day earthquakes [19,20] and estimates for the integrated strength of the seismogenic crust [15,21,22]. Possible explanations include spatial variability in stress drops along faults, and the effects of stress concentration by ductile creep in the surrounding rocks [10]. Resolving this apparent discrepancy of views, which may be related to the extremely different length-scales of observation, will be crucial for understanding how to scale the field observations of exhumed faults up to an understanding of the evolution of the bulk strength of the lower crust during faulting and metamorphism.

Also in this volume, Behr & Bürgmann [3] and Fagereng & Beall [4] discuss a second prominent theme of the meeting, which was the link between observations of transient fault motion and the behaviour of mixed-rheology fault zones. The continuing development of geodetic and seismological monitoring systems and analysis methods is revealing an increasingly rich diversity of rates, lengthscales, and timescales of fault motion, some of it occurring transiently at rates that are intermediate between earthquake slip and plate motion rates [23–25]. Because much of the transient motion is aseismic, and because the spatial resolving power of seismological and geodetic methods decreases with the depth of the deformation or structure to be imaged, field observations of exhumed fault zones have proved crucial in understanding the mechanisms of transient fault slip. Prominent amongst the proposed mechanisms is motion in lithologically-heterogeneous fault zones, with strong clasts embedded in a weaker shear zone giving rise to mixed frictional-viscous behaviour, possibly also requiring the presence of transient fluctuations in fluid pressure (as described, modelled, and reviewed elsewhere in this volume [3,4]). Considerable attention is now focussed on exploring the link between the different types of transient fault motions and how they are generated and expressed geologically, and their implications for the large-scale strength and behaviour of major fault systems. As with the research regarding the behaviour of the continental lower crust, a key component of this work revolves around establishing how to connect large-scale geophysical observations to the limited sizes of available outcrops, and distinguishing between the importance of processes occurring on a range of scales from individual grains to entire fault systems.

The resolutions to the questions presented above will be important for understanding the spatial and temporal release of strain. In this volume, Lamb [26] analyses GPS data from New Zealand and the Andes, and demonstrates that the velocity field in intersiesmic periods can be fit by distributed elastic strain driven by motion on the deep ductile extension of a subduction zone megathrust. This strain must eventually be expressed as permanent deformation, once the elastic limit of the rocks is surpassed. Lamb argues that the relationship between how this strain is distributed and the characteristics of the decadal GPS-based velocity field is non-unique, and that the (possibly temporally variable) dynamics of the individual candidate fault systems control the location in which rupture occurs. When combined with the studies discussed above, these results show that improving our understanding of the dynamics of fault zone processes has an important role to play in understanding the long-term distribution of strain in response to a given geometry of driving stresses.

The great diversity of timescales and lengthscales that are relevant to understanding the deformation of the lithosphere ensure that geological and geophysical approaches will continue to be used in conjunction to answer tectonic questions. The influence of water on lithosphere deformation, in both its free form and bound into mineral crystal lattices, presents one of the major challenges in understanding active and ancient tectonics. The inability to directly observe the hydration state at depth at the present day, and the difficulties in inferring past pore pressure, and (in the presence of retrogression) mineral hydration state in exhumed rocks accessible to fieldwork, presents a major challenge to understanding the rheological role of fluids. It is in this context that combining present-day geophysical observations with geological observations of past deformation provides a vital link, as demonstrated by the articles in this volume. A clear focus for future work will be the further quantification of the sources, pathways, fluxes, and fates of fluids in the lithosphere.

An additional important avenue for further work will be continued efforts to understand how to reconcile geological observations on small spatial scales, and that represent the integrated effects of now-inactive processes, with larger-spatial scale but shorter timescale geophysical observations. The relationships in a given region between the number of faults, their spatial sizes, and their total offsets, mean that it is the largest faults in a region that accommodate the majority of the strain [29], and these are the faults that break in the largest earthquakes. Where the seismogenic layer is as thin as commonly observed on the continents (e.g. 10–15 km [28]), the largest faults commonly produce magnitude 6 earthquakes, and where the seismogenic layer is thicker the maximum earthquake magnitude in a region correspondingly increases. Magnitude 6 earthquakes commonly have fault dimensions of tens of kilometres [27], and transient slip episodes in subduction zones often occur on similarly-sized or larger fault patches [3]. The spatial size of such faults is larger than is readily accessible in most of the geological record, particularly if specific depth, temperature, or lithological conditions are sought. However, as discussed above and elsewhere in this volume, whether a fault breaks in earthquakes or aseismically creeps (either transiently or at steady state) can depend upon small-scale characteristics of the geology, such as the history of past dehydration or hydration events, the presence or alteration of pseudotachylytes, and the strain distribution within a fault zone that results in the production of lithologically-diverse melanges. The necessity to understand this wide range of lengthscales is one of the reasons why we expect geological and geophysical studies of tectonics to remain inextricably linked.

Acknowledgements. The convenors wish to thank all of the participants in the meeting for an intellectually stimulating series of talks, posters, and discussions. We are particularly thankful to the authors who were able to produce manuscripts under the constraints imposed by the Coronavirus pandemic, whose efforts are greatly appreciated. We also thank the Royal Society for hosting the meeting, and Alice Power and the staff at the Philosophical Transactions for producing this volume.

Data Accessibility. This article has no additional data.

Authors’ Contributions. All convenors contributed to writing the Hooke meeting proposal, chairing the meeting, and writing this introduction.

Competing Interests. We declare we have no competing interests.

Funding. We received no funding for this article.

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