Geological Fingerprints of Slow Earthquakes

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CONVENERS

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INTRODUCTION

This Penrose Conference assembled a multidisciplinary group of scientists to debate how geological evidence can contribute toward understanding why slow earthquakes occur and to explain their characteristics. Slow earthquakes are a family of fault and shear zone slip events that include slow slip events (SSEs), tectonic tremor, and low frequency earthquakes (LFEs). In some systems these different events occur together, and they are known as episodic tremor and slip, or "ETS." Compared to earthquakes, the slip across a fault during a slow earthquake occurs slowly, but significantly faster than plate-rate creep. Slow earthquakes are widely observed where geophysical networks are robust, contribute significantly to the overall slip budget in portions of some plate boundary faults, and may elucidate stress transfer between portions of plate boundaries with different modes of fault slip. Understanding slow earthquakes is therefore critical to better constrain regional seismic hazards and may also constrain the physical conditions and fault-loading rates at depth.

The conference was held on 1–5 April 2022 at the University of Southern California Wrigley Institute for Environmental Studies on Pimu (Santa Catalina Island), California, USA, where the exceptional exposures and structural complexity of the Catalina Schist provided inspiration for the discussions. Forty-seven attendees, including ~45% early-career scientists, traveled from eight different countries, including Canada, Germany, Japan, Italy, the Netherlands, New Zealand, and the UK. The meeting launched with a series of keynote talks presenting cutting-edge perspectives on slow earthquakes from seismological, geodetic, experimental, modeling, and geological communities. The subsequent breakout discussion sessions and poster sessions were devoted to research presentations from the participants, framing relevant hypotheses that explain slow earthquakes and debating how geological evidence can be leveraged to test those hypotheses.

A day-long field trip informed much of the meeting discussions, with participants taking in exposures of the Catalina Schist that were metamorphosed and deformed under conditions similar to where some slow earthquakes occur today. Exposures included a mélange and a sheeted vein complex in the Catalina Blueschist Unit, which focused attention on pore pressure constraints, coupling between metamorphic and structural processes, the importance of mechanical heterogeneity during deformation, and the rates at which veining/fracture and distributed deformation occur. In the Catalina Amphibolite Unit, blocks of mafic and ultramafic rocks in a metasomatized matrix attested to fluid-rock interaction and the accompanying progressive changes in rock rheology leading to mechanical heterogeneity.

The keynote presentations emphasized that the well-resolved source parameters of slow earthquakes (e.g., ~10^{-7} m/s slip rate, km/day rupture propagation rate, and ~10 kPa stress drop for SSEs) are distinct from regular earthquakes. Furthermore, to first order the geodetic and seismic records of slow earthquakes appear to be similar, regardless of tectonic setting or depth of the slip event. A broadly held view was that because the SSEs accommodate substantially more of the plate motion budget and exhibit much larger seismic moments than LFEs, SSEs are the dominant member of the slow earthquake family and should be the focus of future efforts to understand the physics of slow slip. However, some participants argued that the LFE components of SSE were the best-resolved geophysically and should be instrumental in driving more specific comparisons to geologic features. The breakout discussions therefore explored the significance of existing geological observations and the future research needs from geological work in two themes:

1. Is there any process, condition, or structure common to slow earthquakes that could explain their characteristics?

The consistent geodetic and seismological characteristics of slow slip suggest there may be a common process or set of conditions at the sources of SSEs and possibly another for tectonic tremor and LFEs. Attendees debated if and how grain-scale deformation mechanisms, deformation structure geometry, and deformation conditions (e.g., effective pressure, temperature, etc.) could be different across the range of slow earthquake occurrences but combine to yield similar slip phenomena. A combination of deformation mechanisms involving frictional sliding plus some viscous-type mechanism likely promotes slow earthquakes. Further work is needed to determine how the two mechanisms interact and are preserved in the rock record, recognizing that both the interactions and the preservation may vary between different SSE settings. Attendees agreed that geological field observations from slow earthquake source depths indicate the deformation associated with these events likely affects a volume rather than a planar or quasi-planar surface, which is also allowed by the geophysical constraints. Heterogeneity is ubiquitous, but further work is needed to determine what structures or rheological contrasts are relevant to slow slip, and how slow slip can propagate over long distances despite the heterogeneity. Although slow slip phenomena occur over a broad range of metamorphic conditions, attendees noted that low effective stresses promote slow slip by driving slip toward frictionally neutral stability, though low effective stresses alone cannot explain why slow slip occurs rather than regular earthquakes. More detailed analyses of slow earthquake sources in places with well-constrained thermal structures should be undertaken to connect the deformation conditions with slow earthquake characteristics.

2. How can geological observations test the slow earthquake hypotheses?

Multiple hypotheses have been proposed that can explain how slip velocities during slow earthquakes are limited, thereby differentiating them from regular earthquakes. Many of the hypotheses are developed from the rate and state friction framework and are supported by laboratory rock friction experiments. Others call for coupled frictional-viscous deformation. The relevance to natural systems is largely untested. Attendees examined the hypotheses and asked what geological structures might serve as records that the hypothesized mechanisms were active in ancient slow earthquakes, what geological features would lead the hypothesis to be rejected, and whether there are new geological observations that should be collected to test the hypotheses. For most hypotheses there are both deformation structures that are predicted to be consistent with the hypothesis and characteristics of deformed rocks that would reject the hypothesis. Some, such as a specific velocity-neutral condition and a dislocation creep-based mechanism might be indistinguishable from perceived "steady-state" structures. Work is needed from both the observational and geological communities to reconcile the relevant scales of deformation process and structures so that future field and microscale observations can contribute positively toward understanding slow slip.

CONSENSUS

Ultimately, the breakout discussions concluded that no signature has been identified in the rock record that uniquely identifies slow slip phenomena as observed with contemporary geophysical sensors but that does not radiate seismic waves. Overcoming this barrier may depend on a combination and linkage of deformation-related features, rather than a "smoking gun" (in contrast to frictional heat anomalies that record seismic slip). Defining the mechanisms accommodating slow slip is important for informing the physics of slow slip, but will likely require definition of different geological signatures in different settings. Future cross-disciplinary studies are needed to reconcile the observations of active slow slip with the rock record. This type of work will benefit from a clarification of terminology so that aspects of the deformation associated with slow slip can be compared across fields. The Penrose attendees are developing a set of papers to address these next steps and will invite community participation.

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