Report on SCEC Proposal: Workshop Support to Explore the Geological Fingerprints of Slow Slip and Tremor
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This proposal was submitted in November 2018, on behalf of the organizing committee for the Workshop, with the intention that the workshop be held in March 2020. We also planned to submit a proposal to the Geological Society of America for support as a Penrose Conference, but as it turned out, GSA cancelled the funding round for 2020, so we decided to postpone the workshop until March 2021, which was very fortunate in view of the Covid-19 outbreak. We submitted a proposal to GSA in November 2019, and this was funded with a grant of $20,000. We have in addition submitted a proposal to the GeoPRISMS program in February, and we await their decision. With the SCEC and Penrose awards we have enough funding to run the workshop: any additional funds from NSF will allow us to cover travel costs for participants.

Note that because the provisionally scheduled workshop date is in March 2021, we will likely need an extension to this grant at the end of this year.

We have developed a detailed plan for the workshop, including identifying and contacting keynote speakers and discussion leaders, and we have a detailed plan for a day field trip on Catalina as part of the conference. We plan to advertise the workshop, and invite participants, in June. Our current list of speakers is as follows:

- Amanda Thomas, seismologist, University of Oregon, USA.
- Laura Wallace, geodesist, GNS Science, New Zealand.
- Åke Fagereng, geologist, Cardiff University, UK.
- Joan Gomberg, seismologist, U. S. Geological Survey, USA.
- Jean-Paul Ampuero, geophysicist, Caltech, USA.
- Jacqueline Reber, experimentalist, Iowa State University, USA.
- Kohtaro Ujiie, geologist, Tsukuba University, Japan.
- Sarah Penniston-Dorland, geologist, University of Maryland, USA.
- Alissa Kotowski, geologist, University of Texas, USA.
- Greg Hirth, experimentalist, Brown University, USA.
- Jessica Hawthorne, seismologist, Oxford University, UK.

We believe that the list of keynote speakers listed above is gender-balanced and includes scientists at a range of different career stages including postdoc, early-career scientists, and well-established scientists. Additional speakers will be drawn from the participants who register for the meeting. All participants will have the opportunity to speak in the lightning talks.

The provisional schedule for the workshop, and the planned field trip stops, follow.

Tentative Workshop Agenda		
DAY 0		Attendees arrive at Wrigley Institute, evening icebreaker
DAY 1	8:30-10:15	<u>Introduction to Slow Earthquakes</u> Introduction and Welcome Plenary talks of primary observations 1. Seismology - Amanda Thomas 2. Geodesy - Laura Wallace 3. Geology - Åke Fagereng
	10:15-10:35	*Coffee break*
	10:35-12:35	<u>Perspectives on the Mechanics of Slow Earthquakes</u> 4. Mechanics of slow earthquakes - Joan Gomberg 5. Numerical insights - Pablo Ampuero 6. Experimental results - Jacqueline Reber Discussion open on all topics 30 mins
	12:35-1:35	*Lunch break*
	1:35-3:35	<u>Geological Perspectives on Slow Earthquakes</u> 7. Effective stress conditions/role of fluids - Kohtaro Ujiie 8. Metamorphic reactions - Sarah Penniston-Dorland 9. Structures that occur at different scales - Alissa Kotowski 10. Grain-scale deformation mechanisms - Greg Hirth
	3:35-4:00	*Coffee break*
	4pm and continuing through evening	Lightning talks introducing posters then poster session for all attendees to share their perspectives on geology of slow earthquakes
DAY 2	9:00-12:30	Morning Session: Field trip to sites 1 & 2. Discussion on the exposures. Focus to be the key processes and physical properties of rocks that might be relevant to slow earthquake physics
	12:30-1:30	*Lunch break in the field*
	1:30-5:00	Afternoon Session: Field trip to sites 3 & 4. Discussion on the exposures. Focus to be the key processes and physical properties of rocks that might be relevant to slow earthquake physics
	Evening	Posters

DAY 3	8:30-10:15	“Tech talks” – Speakers to be drawn from the applicants. This session is intended to be an opportunity for detail-focused, technical talks rather than overviews.
	10:15-10:35	*Coffee break*
	10:35-11:45	Panel discussion: what are the key unknowns in slow earthquake physics. Panelists to be drawn from Keynote Speakers and other Key Participants or other participants.
	12:35-1:35	*Lunch break*
	1:35-3:00	What are the hypotheses? Convener summary of common threads arising from white papers (30 mins) Keynote Talk: What are the geophysical hypotheses? Jessica Hawthorne Orientation into breakout groups (self-assigned). One group per hypothesis (we expect 3 or 4).
	3:30-5:00	Breakout group discussions of proposed hypotheses: discussion of limitations/advantages, suggested modifications, prioritization
	5:00 onwards	Poster session continues
DAY 4	8:30-10:15	Introductory remarks to prompt the breakout groups Breakout group discussions to develop a list of geological, seismological, or geodetic observables or rock mechanics experiments to test hypotheses. Strategies for data collection.
	10:15-10:35	*Coffee break*
	10:35-12:30	Small group breakouts on targeted topics and future planning.
	12:30-1:30	Lunch
	1:30-3:00	Summary, wrap-up, discussion of immediate plans for publications arising from the meeting, other communication dissemination. Acknowledgements and clean-up.
	3:00 onwards	Return trip to the mainland, arrival around 5pm for evening flight departures from LAX. Conveners stay behind for the afternoon to write reports, draft summary paper etc.

Field Trip Stops

Stop 1. Catalina Harbor, south side, 33°25'40.47"N, 118°30'22.29"W.
Metagraywackes of the Catalina Blueschist Unit. This is the lowest tectonic unit on Catalina Island, and in this area the rocks carry the relatively low-grade assemblage quartz + white mica + chlorite + lawsonite + albite. The disruptive structure and abundant quartz veining is characteristic of the deformational style in much of this unit. Thick-bedded coarse-grained metasandstone has a detrital texture visible in outcrop, and there are some thin pebbly bands. Finer grained rocks have a slaty-type cleavage, produced by pressure solution, and bedding is largely obscured by boudinage and quartz veining. The veins indicate high fluid pressure during deformation, which may reflect compaction, dehydration reactions such as clays → white mica, or fluids moving up the subduction channel from greater depths.

Stop 2. View stop, junction of Middle Canyon Road and Escondido Ranch Road, 33°22'46.60"N, 118°28'39.99"W. This location provides a good overview of the metamorphic units in the center of the island. To the north is Little Harbor, where we will spend part of the morning looking at rocks of the Blueschist Unit, and beyond that Little Springs Canyon, which is occupied by a klippe of the overlying Greenschist Unit. To the northwest the hills are formed from resistant rocks of the Amphibolite Unit; further to the right Catalina Airport is visible, which is built on the ultramafic mélange that forms the structurally highest part of the Catalina Schist. We will spend time in that area this afternoon. To the west the peaks of Black Jack (with the communications tower) and Orizaba are made up of Early Miocene volcanic rocks. We are currently standing on one of the dissected geomorphic surfaces, dipping gently SW, which characterize the landscape in this part of the island.

Stop 3. Little Harbor. 33°23'13.54"N, 118°28'22.98"W. Walk to the north end of the beach, to see a metaconglomerate body that forms part of the Blueschist Unit. Rounded clasts are formed mainly from plutonic and volcanic rocks, likely sourced from the magmatic arc to the east. Clasts and matrix are metamorphosed in the glaucophane-lawsonite schist facies: hornblende in metagabbro and pyroxene in metadacite are replaced by glaucophane, plagioclase is replaced by lawsonite. Bedding is difficult to see, but is vertical. The conglomerate shows little penetrative deformation. If the tide allows, we can scramble around to the west side of the conglomerate body, and see its contact relations with deformed metagreywacke sandstone and shale. The conglomerate clearly formed a resistant body immersed in a viscous matrix, which has been invoked as a possible explanation for seismic tremor and slow slip.

Stop 4. Little Harbor, south side. From the parking lot at the south end of the beach, we will hike along a scrambly trail that runs ~250 m SW along the coast. Take care: the trail has been washed out in places. The route takes us through exposures of mafic blueschist, metasedimentary rocks (primarily dark graphitic phyllite), and a variety of fragmental rocks that have been described as mélange. In the melange, note flattened fragments of metasandstone, black phyllite, mafic blueschist, and various soft pale greenish rocks that have a broadly ultramafic composition (Fig. 1.5c). The latter are composed of varying proportions of Mg-rich chlorite, Mg-glaucophane, serpentine, and talc, and clearly reflect substantial metasomatic alteration of the original rock. Small flecks of bright green fuchsite (Cr-mica) or mariposite (Cr-chlorite) may have formed from primary chrome spinel. The fragments and matrix of the melange have all been metamorphosed in the blueschist facies. We will discuss possible origins for this type of melange.

In a cove at the end of the trail (33°22'51.82"N, 118°28'33.59"W) we will see metabasalt with pillow texture, nodular metachert, and fallen blocks of metaconglomerate showing varying degrees of deformation. There is also an excellent exposure of a sheeted vein complex in black phyllite. This may mark a fault or shear zone within the unit, formed during subduction and accretion, and illustrates the interplay between hydraulic fracturing and solution-precipitation creep characteristic of subduction zone deformation at depths of ~40 km.

Stop 5. Ben Weston Beach, 33°22'16.70"N, 118°28'49.13"W. This requires a fairly steep descent from the parking place to the beach. On the way down, note exposures of various rocks attributable to the Blueschist Unit, including metagreywacke, black phyllite, glaucophane schist, serpentinite, and talc or chlorite rich schist. The beach is shown on topo maps as Mills Landing, but is known to islanders as Ben Weston Beach. On the north side there is an impressive cliff exposure of metasedimentary rocks showing a large-scale overturned fold in metagreywacke sandstone (greenish-buff color) and shale (dark phyllites). Note the concentration of quartz veins in the phyllites, reflecting their differing mechanical properties. The fold is associated with the primary schistosity in the rocks; this has been modified by small-scale folding and crenulation, producing interference structures between the two phases of folding.

On the south side of the beach, small-scale second generation folds are developed, folding the primary schistosity. The metasediments here are intensively veined: vein minerals include quartz, albite, and carbonate minerals. Some of the quartz veins reflect hydraulic fracture, others appear to be replacive, to the point that original sandstone beds appear to have been largely replaced by quartz. Albite veins are largely replacive; they are commonly black, due to included graphite, and the graphite inclusions delineate ghost schistosity and crenulation cleavage inherited from the original rock.

Stop 6. Catalina Airport, 33°24'08.2"N 118°24'45.4"W. We will follow a segment of the Catalina Trail down the hill to the south for 200 m, and see a steatite bowl factory set up by native Americans prior to depopulation of the island in the 19th century. Steatite figurines and bowls (known by the Spanish term *ollas*) were traded extensively around southern California. The steatite is massive talc rock forming part of the ultramafic mélange at the top of the Catalina Amphibolite Unit. We will then walk further down the trail, passing a number of garnet hornblendite blocks, and find an exposure in a dry gully of the deformed mélange matrix, composed of various proportions of chlorite, serpentine, talc, and ortho- and clino-amphiboles. The origins of the mélange remain a puzzle, and most of the rocks have compositions suggesting extensive metasomatism, but it is generally interpreted as being a result of tectonic mixing in a subduction channel. We will also see blocks of massive serpentinized peridotite. It is plausible that the peridotite originally formed part of the subduction zone hanging wall (i.e., the mantle wedge). PT conditions obtained from the both the garnet hornblendite blocks and the mélange matrix are in the range 8-11 kbar and 640-750°C.