Introduction

In this Small Grants for Exploratory Research (SGER) proposal, we request funding for a seismic and geodetic experiment to capture the characteristics of an anticipated slow earthquake (SE) predicted to occur on the flanks of Kilauea volcano on March 17, 2007. We propose a joint seismologic and geodetic experiment that would temporarily densify the seismic and geodetic networks at Kilauea in order to clarify the relationship between SE deformation and triggered seismicity during the next Kilauea SE. Additionally, we propose to deploy an array of seismometers capable of detecting non-volcanic tremor should it also accompany a SE. This proposal is in concert with a parallel supplemental request to EAR I &F led by Paul Segall of Stanford for temporary deployment of additional tiltmeters in the region. The time critical nature of this anticipated slow earthquake requires immediate short-term funding for the basic deployment costs and has motivated this SGER proposal. We are here only requesting the basic funding to collect this valuable time-critical data. Any requests for analyses funds will be later submitted separately for formal review through the regular NSF-EAR Geophysics Program.

Slow earthquakes have been discovered in a number of different tectonic environments (subduction zones, the San Andreas fault, Kilauea volcano) and are one of the most exciting current topics in seismology and geodesy. Slow earthquakes have been especially well studied in subduction zone environments including the Nankai trough in Japan, Cascadia, Guerrero, Mexico, and Alaska (Dragert et al., 2001; Freymueller et al., 2001; Heki et al., 1997; Kostoglodov et al., 2003; Lowry et al., 2001; Miller et al., 2002; Rogers and Dragert, 2003). Slow slip in subduction zones is often associated with non-volcanic tremor, although there is debate over whether the tremor occurs along the subduction zone interface or within the upper plate. One of the most interesting features of many slow slip events is their apparent periodicity: for example, in the southern Vancouver Island - northern Puget Sound region slow slip episodes repeat every 13 months. The physical processes giving rise to the slow slip and associated tremor are the subject of intensive ongoing research by the community of earthquake scientists. The observations and search for theoretical explanations have stimulated some provocative and potentially important hypotheses: for example, Lowry (2006) has recently proposed that periodicity of subduction zone SEs could arise as a resonant response to climate-driven stress perturbations (Lowry, 2006).

In the past decade, Kilauea volcano’s south flank has been the site of at least 7 slow (or ‘silent’) earthquakes (SEs) identified with continuous GPS (CGPS) data (Brooks et al., 2005; Brooks et al., 2006; Cervelli et al., 2002; Desmarais et al., 2006; Desmarais et al., 2005; Foster et al., 2006; Segall et al., 2006). The SEs can be divided into 'Western' and 'Eastern' families defined by similar patterns of horizontal motions (Brooks et al., 2005; Desmarais et al., 2006) (Figure 1) and, of these, the Western family are periodic and separated by 774 +/-7 day periods (Brooks et al., 2006) (Figure 2).

The Kilauea SEs are unusual in that they are associated with triggered microearthquakes, although it is not yet known whether nonvolcanic tremor is also present. A distinct swarm of microearthquakes is triggered in the same place by the periodic SEs (Brooks et al., 2006; Segall et al., 2006) (Figure 1). There is currently some disagreement about whether microearthquakes occur on the regional decollement (~8±1km; Segall et al. (2006)) or, potentially, at shallower structural levels (Wolfe et al., In Prep.). Resolving the discrepancy is important because the location of the microseismicity could be used to help constrain the
Figure 1. GPS displacement vectors for all slow earthquakes identified from 1997 - 2005. A) Location map with key reference GPS stations. B) Velocities of GPS sites due to long-term creep. C), F) & I) yellow vectors show the three events categorized as the "eastern family:" 01 Mar 1998, 20 Nov 1999, 04 Jul 2003. D), E), G) & H) red vectors show the four events categorized as the "western family:" 20 Nov 1998, 09 Nov 2000, 16 Dec 2002, 26 Jan 2005. Grey dots show seismicity (<10km) within +/- 5 days of each SE.

Figure 2. Time series showing the relative northward motion of selected GPS sites. Time series have been offset vertically for clarity. SEs indicated by vertical lines, colored as in Figure 1. Red lines, 'western' periodic SEs; yellow lines, 'eastern' SEs; dashed blue vertical line, 09 Sep 1999 dike intrusion. The repeat period of the 'western' events is indicated.
location and further our mechanistic understanding of the SEs themselves (Segall et al., 2006). If periodicity is maintained, then the next Western family SE and its accompanying microearthquakes are predicted to occur on, or about, March 17, 2007.

Kilauea Slow Earthquakes and Triggered Microseismicity
Segall et al. (2006) used relocations of high-frequency earthquakes triggered by the January 2005 SE, seismicity rate theory and Coulomb stress modeling to conclude that the SE (and other similar events) occurred at a depth of ~8 km on a sub-horizontal fault plane below Kilauea’s south flank. Their earthquake hypocenters were based on differential locations relative to a well-located set of earthquakes from Hansen, Thurber and others (2004). Depth of slip is difficult to constrain from the geodetic data alone and so, if correct, this work would have important implications for characterizing failure mechanics and hazards associated with SEs in this and other regions worldwide. Moreover, the reliability of the Coulomb stress modeling critically depends on the accuracy of estimated locations and mechanisms of triggered seismicity.

The UH team, however, led by Cecily Wolfe, has recently performed high precision relocations using waveform cross correlation data (Figure 3). On the day of the January 2005 SE as well as SEs in September 1998 and November 2000, swarms of triggered seismicity are significantly above the background rate (which is ~1 earthquake per day). The triggered seismicity consistently relocates on distinct map-view clusters aligned in the direction of the SE displacements themselves. These results strongly suggest that the triggered earthquakes induced by SEs occur on preexisting fault zones that are near failure.

In addition to Segall et. al’s interpretation regarding mechanism and depth of faulting, the UH team believes that current and prior relocation work permits two alternative interpretations. First, Got and Okubo (Got and Okubo, 2003) suggested that their relocated events from 1998 do not illuminate a sub-horizontal fault plane but rather a deeper, steeply south-dipping reverse fault. This hypothesis is contrary to the assumed mechanism for the Coulomb stress models of Segall et al. (2006). The UH relocations do not image such a dipping reverse fault, but rather result in subhorizontal band at ~5 km depth. This solution is consistent with Morgan et al. (Morgan et al., 2003) who used seismic reflection data to identify moderately landward-dipping fault planes at similar depths.

While the epicenters are well constrained in the UH data set, we are concerned that poor station geometry as well as near source velocity heterogeneity may bias the relocated depth of events in this region. This proposed experiment will provide a significant improvement in station coverage of triggered microearthquakes that will allow robust determination of hypocenter locations. Just as important, the experiment will contain a dense array of seismometers (200 m spacing) that will allow detection and temporal characterization of SE associated nonvolcanic tremor. Such dense tremor arrays have already been found to yield excellent detection and temporal characterization of nonvolcanic tremor in Cascadia (La Rocca et al., 2005, Steve Malone, personal communication, 2006)

Proposed Work: Seismic and GPS Deployment
We propose a temporary deployment of 18-20 seismometers and 6 CGPS stations that will augment the permanent seismic and GPS stations already in place (Figure 4). The
deployment will be carried out jointly by USGS, UH, and UW scientists and the funding will be split between UH and UW. Of the 18-20 seismometers 15-17 will be 3-component short period instruments and 3 will be broad-band instruments from UW’s pool. 6-8 of the short period instruments will be dedicated to array focused on detecting non-volcanic tremor. The USGS team, led by Paul Okubo from HVO, is expected to provide 15-17 of the short period stations; the UW team, led by Cliff Thurber, will provide 3 instruments.

We have chosen target sites for the seismometers that will accomplish the dual goals of providing the highest quality science products as well as most easily accommodating the often-challenging logistics of working on Kilauea’s south flank. Installation will be carried
out by the joint USGS/UW/UH/Stanford team. Data retrieval and station servicing will be carried out primarily by USGS with some help from UH and Stanford. Instrument removal will be carried out by the complete team.

The GPS stations will be either Trimble NetRS or Leica RS500 dual-frequency geodetic grade receivers with either Zephyr or choke-ring antennae. Our goal is to have them operate at 1s recording intervals, though this will have to be re-evaluated once the actual frequency of data retrieval becomes established. The UH geodesy team, led by Ben Brooks, will contribute all of the GPS instruments and monuments from its pool of equipment.

The installation and servicing (including downloading data) of the seismic stations is the primary objective of this SGER request. Because Brooks is providing the essential GPS equipment, any proposed GPS work can be added on to the seismic deployment and data retrieval at negligible cost to this proposal. Installation will commence in January of 2007 and removal is expected to occur in December of 2007.

Expected Results
In the event that the predicted SE and triggered microearthquakes occur, we anticipate the following important results:

1) We will resolve the apparent discrepancy between the Stanford and UH relocation results by more accurately locating the triggered microearthquake hypocenters. With these new accurate locations we can also readily tie SE-related events from previous episodes to the locations of events obtained during our deployment, with the permanent USGS stations providing the tie (e.g. Segall et al., 2006). We stress, however, that to detect tremor the array must be deployed when an SE occurs.

2) By determining focal mechanisms for the triggered events with the densified network we will be able to eliminate mechanistic assumptions from the Coulomb stress modeling to further clarify the relationship between slow slip and microseismicity.

3) We will be able to thoroughly assess whether the SEs are accompanied by non-volcanic tremor or not.

4) We will constrain the precise timing of the SE-related displacements and the onset of triggered seismicity. The proposed Stanford tilt instruments will be very important for this effort as well.

Permitting
A major concern has been permission from the National Park Service for permitting. The HVO Scientist in Charge, Jim Kauahikaua, has handled the request for all instrumentation (seismic, GPS, and tilt) with the Park. On November 8, 2006 we received notice from Jim that the NPS Resources Council had approved the project, and that a formal letter of acceptance is forthcoming.
References


