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A Search for Seismicity Patterns that Reflect Mechanical Erosion of Locked Patches Due to Creep

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Abstract

The purpose of this project was to illuminate the relationship between microseismicity “streaks” and neighboring, predominantly aseismic “holes” that are observed on creeping faults in northern California. Two hypotheses have been proposed to describe this relationship: (some) streaks mark the boundary between frictionally locked and aseismically creeping patches; and/or some are sandwiched between two creeping patches. Simple analytical expressions from fracture mechanics suggest that bounding streaks experience a growing stress concentration, a change in conditions that might be reflected in microseismicity patterns such as increasing rates, moment release or maximum magnitudes. We identified dozens of streaks on the creeping section of the San Andreas fault and the Calaveras fault and analyzed their microseismicity for such patterns, including a systematic study of the behavior of repeating earthquake sequences. We found no obvious signals on streaks that would betray mechanical erosion of locked patches by aseismic creep. In particular, streaks with moderate earthquakes that are inferred to have ruptured beyond the streak and thus indicate a frictionally locked neighboring hole do not show evidence for accelerating seismicity, increasing moment release or maximum magnitudes, or systematically increasing moment release rates in repeating earthquake sequences. As a result, we are re-assessing how locked patches respond to frictional erosion by aseismic creep through numerical simulations on rate-state faults. These simulations suggest that the simple analytical expressions do not reflect the complexity of the response, and thus could explain why no obvious signal was found in the data.

1 Introduction

On northern California’s creeping faults, the nature and origin of narrow, near-horizontal ribbons of tightly concentrated seismicity - streaks -, along with neighboring fault patches that are mostly devoid of seismicity - holes -, remain largely enigmatic. In particular, it is debated to what extent streaks mark the boundaries between creeping and locked patches, and to what extent they are bounded on both sides by creep [Rubin et al., 1999; Waldhauser and Ellsworth, 2002; Sammis and Rice, 2001; Rubinstein and Beroza, 2007].

In contrast, the strike-slip streaks identified by Gillard et al. [1996] in Kilauea’s Upper East Rift can be explained by a simple mechanism that might play an important role elsewhere. The authors explained the streak of micro-earthquakes as marking the boundary of the frictionally locked section of the volcano’s flank above the deeper, aseismically creeping portion of Kilauea’s rift system. Moreover, the authors observed seismicity patterns of increasing moment release rates and accelerating seismicity on the streak, which they reproduced with a model of the progressive mechanical erosion of the locked shallower portion of the fault, loaded by the growing stress concentration due to creep of the underlying rift system. Gillard et al. [1996] speculated that this mechanical erosion of stuck asperities by loading from below might play an important role in seismogenesis along major strike-slip faults elsewhere.

Figure 1: Study regions (boxes) and epicenters [from Waldhauser and Schaff, 2008].
Motivated by the finding in Kilauea that the mechanical erosion of locked zones by creep from below was expressed in observable changes in seismicity patterns, we searched for similar changes on streaks in northern California that might betray a similar mechanism. Our aim was to assess the extent to which aseismic holes might be frictionally locked or aseismically creeping, and to thereby constrain the origin and nature of the seismic streaks.

2 Data and Methods

We used the relocated catalog by Waldhauser and Schaff (2008), which comprises over 450,000 earthquakes throughout all of northern California from 1984 to 2009. Median relative location uncertainties are ~30 m for events constrained with correlation data and ~70 m for those constrained by phase picks only. In Figure 1, we show the three regions (boxes) that we selected for analysis because of the numerous streaks.

In Figure 2, we show a cross section of seismicity in the northern San Andreas fault box along with identified streaks. We analyzed the seismicity on each streak for accelerating rates, increasing moment release, and increases in maximum magnitude. We also identified repeating earthquake sequences (RES) on streaks as potential proxies for rate changes. We defined an RES by a sequence of at least three earthquakes that have the same magnitudes to within 0.3 magnitude units and whose hypocenters (projected onto a vertical plane) fall within one source radius of the first event. Additionally, no hypocenters from other earthquakes may fall within the estimated source area of the first event nor may the hypocenter of the first event fall within the source area of another
earthquake. To estimate rupture size, we assumed a 3 MPa stress drop, a circular crack model and a moment-magnitude conversion by Abercrombie [1995]. Once identified, we calculated recurrence intervals within each RES and used a least-squares fit to the observed recurrence intervals over time to identify a trend in both the recurrence interval and the moment. If streaks bound creeping/locked patches, then the basic hypothesis is that the RES might accelerate and/or increase their moment release rates.

3 Results

We began by analyzing the seismicity patterns on those streaks on which earthquakes occurred that were too large to be accommodated on the streak. We supposed that these earthquakes ruptured into neighboring holes and thus indicated that the neighboring holes were frictionally locked and good targets for seismicity patterns that reflect a growing stress concentration. In Figure 3, we show as an example a candidate streak from the northern San Andreas fault box that comprises several RES as well as moderate earthquakes at its southern end that appear to have ruptured into aseismic holes. We observe that the streak responds to the 1989 Loma Prieta earthquake with increased seismicity, but we observe no obvious accelerations of seismicity, or increases in moment release or maximum magnitudes. Other candidate streaks behave similarly.

![Figure 3: Top left: Seismicity on an identified streak in the northern San Andreas box. Circles indicate estimated source areas, and (arbitrary) colors denote identified repeating earthquake sequences (RES). Top right: cumulative number of earthquakes (black) and cumulative moment (red). Bottom left: “paleo-plot” of seismicity along strike (colors denote RES). Bottom right: Magnitudes versus time (colors denote RES).](image)

To further investigate seismicity patterns on the streaks, we analyzed the trends of the RES on identified streaks. In particular, we estimated the trend of recurrence intervals and moments over time. In Figure 4, we show the spatial distribution of trends of all RES for the streak shown in Figure 3. Although there is some scatter, the recurrence intervals of most RES appear to be
shortening, especially at the southern bottom, below the moderate earthquakes that appear to have ruptured into a frictionally locked hole.

Unfortunately, we did not observe spatially coherent evidence of shortening recurrences and/or increasing moments on streaks that are inferred to bound locked/creeping patches. In Figure 5, we show the trends of all identified RES in the northern box of the San Andreas fault. The RES in the northern section that was strongly affected by the 1989 Loma Prieta earthquake are mostly slowing down, presumably as part of the decaying aftershock sequence. The prominent central upper streak contains all three groups of RES, without any obvious spatial consistency. The same ambiguous picture emerges from the other streaks: RES that are speeding up and releasing more moment may be on the same streak as or even adjacent to RES that are slowing down and releasing less moment. The results are qualitatively similar across all three study regions (not shown) [Werner and Rubin, 2011].

We also measured the correlations between the largest magnitude of a streak (moderate magnitudes are inferred to indicate neighboring locked patches) and characteristics of the RES. These characteristics included the fraction of repeaters per streak, the trend of the recurrence interval, the trend of the moment, and the ranges of the recurrence intervals and moments. None produced a robust correlation that might be expected from simple analytical expressions derived by Gillard et al. [1996] for mechanical erosion.
4 Discussion

Several possibilities exist to explain the lack of robust microseismicity patterns that reflect gradual mechanical erosion of predominantly aseismic holes. It seems unlikely that streaks are generally sandwiched between creeping segments because of the existence of moderate earthquakes that are inferred to rupture into the holes [e.g., Rubinstein and Beroza, 2007]. Nonetheless, some experiments and simulations suggest that, under certain conditions, surfaces may transition from stable creep (velocity-strengthening) at low slip rates to unstable seismic rupture (velocity-weakening) at higher slip rates [e.g., Tsutsumi and Shimamoto, 1997; Noda and Lapusta, 2013]. Mechanical erosion of patches with such frictional properties would probably need to be simulated numerically to better understand expected microseismicity patterns.

Of course, a simpler alternative explanation is that the analytical expressions derived by Gillard et al. [1996] are inadequate for the streaks considered here. One important assumption made by the authors involves a zero shear stress environment on the locked fault as a result of an observed dyke intrusion. Shear stress was assumed to increase from near-zero to Coulomb failure strength as a result of steady sliding below the fault and thus explain the accelerating rates and increasing magnitudes. However, stress drops from moderate earthquakes tend to be much smaller than the total shear stress on faults [e.g., Zoback et al., 1987]. The larger shear stress baseline might mask the expected patterns.

To investigate further whether the simple analytical estimates by Gillard et al. [1996] survive in the presence of different friction laws and loading geometries, we have run numerical simulations of earthquake cycles on deformable rate-state faults. The simulations involve an infinitely long anti-plane strike-slip fault within a 2D elastic medium below a free surface. At the fault’s lower extension, we applied a constant velocity. The fault has a velocity-strengthening lower part and a velocity-weakening upper part to mimic the conditions of a locked patch driven from below by aseismic creep. To obtain lots of microseismicity between system-size earthquakes that rupture the entire patch, we ensured that the nucleation lengthscale is orders of magnitude smaller than the depth extent of the locked fault. We used both the aging and the slip law to evolve state.
Our simulations (not shown) suggest that microseismicity during the inter-seismic period is predominantly driven by afterslip below the weakening-to-strengthening transition \cite{WernerRubin2012, WernerRubin2013}. The afterslip immediately reloads the transition zone and initiates microseismicity that slowly decays with time as the afterslip pulse decays. In contrast, we observe few instances of foreshock activity, and have thus far been unable to reproduce the patterns we would have expected from the simple analytical estimates. This suggests that the seismicity patterns expected during mechanical erosion of locked holes driven by aseismic creep may be more complex than we believed at the outset of this project.

5 Conclusions

Motivated by the expectation that a growing stress concentration at the boundary of locked and creeping fault patches may give rise to microseismicity patterns of increasing rates, moment release or maximum magnitudes, we searched for evidence of such a signal on dozens of streaks on the Calaveras and San Andreas faults. Some of these streaks are expected to bound locked/creeping patches, especially those on which moderate earthquakes have nucleated that are inferred to rupture into neighboring predominantly aseismic holes. Our search yielded no robust evidence for such seismicity patterns on streaks. We also identified and quantified the trends of recurrence intervals and moment release rates of numerous repeating earthquake sequences on the streaks, but again found no spatially coherent evidence for increasing moment release rates of repeaters on streaks inferred to bound locked patches.

Although several explanations can account for the absence of such a signal, a simple one is that the expected response from mechanical erosion is more complex than predicted by the simple analytical expressions obtained by \cite{Gillard1996}. Numerical simulations of the progressive loading of a locked patch by aseismic creep from below on deformable faults endowed with rate-state friction support this view. The simulations suggest that the period between earthquakes that entirely break locked patches is dominated by microseismicity driven by afterslip, which reloads the transition zone rapidly at the beginning of the cycle. The resulting higher shear stress contrasts with the assumption made by \cite{Gillard1996} that the shear stress is near zero at the beginning of the slow loading. Thus far, we have not seen consistent foreshock patterns in the numerous simulations we have run that would provide suitable targets for observational searches. As a result, the simulated response appears more complex than expected from the simple analytical expressions we used as the basis for the observational search and we are now concentrating on a basic understanding of the earthquake cycle simulations \cite{WernerRubin2013}.
References

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