1. Introduction

The discovery of slow slip events (SSEs) along subduction megateectonics over the last decade has been transformational of our understanding of active tectonics (Ozawa et al, 2007). In effectively every case where geodetic data has been obtained in active forearc regions, SSEs with millimeter to centimeter scale amplitudes and durations ranging from a few weeks to as much as years are observed (Schwartz and Molnar, 2002). Traditional models of the earthquake cycle that attempt to predict two modes of deformation, steady-state creep and seismic slip events, have accordingly been replaced by models that, in addition, predict slow slip behavior (e.g., Liu and Rice, 2005). Between November 2002 and January 2003, a swarm of M 5 - 4 earthquakes occurred near the Nyaingquenang (NQ) Detachment in southern Tibet. The swarm was preceded by an increase in the eastward component of velocities recorded at a GPS station in the nearby city of Lhasa. This increase in GPS velocity, which began from the beginning of 2001 to the end of 2002, is thought to be due to slow slip event (SSE) on the NQTL detachment. If this event is an SSE, it would only be the second intracontinental SSE ever observed. On October 6, 2008 an M 7.2 earthquake and a series of the 3-5 aftershocks occurred in the same region in which the 2002-3 swarm was observed. It is currently unknown if this series of events was preceded by an SSE, but suggesting their local mechanisms could provide insight into the deformation which preceded them. The goal of this project is to illuminate the nature of deformation along the NQTL, by combining what is known about the surface and subsurface geology of the region with the source mechanisms of the earthquakes which have occurred there. If the source mechanisms, locations, and depths of events are consistent with the observed eastward GPS velocity increase, it could be assumed that they were triggered by the SSE.

2. Method

Because the swarm events and most of the 2009 aftershocks were too small to be detected teleseismically, their source mechanisms were determined using the Cut and Paste (CAP) inversion method. Three methods: (1) seismology, (2) seismology and active tectonics, (3) and (4) modeling techniques to produce the synthetic seismogram which best fits the data. Records from one station, LHA at Lhasa, were used to perform all the inversions for the earthquakes because no other regional stationary data was available at the time this study began. More recently, data recorded during the 2009 events has become available from local broadband stations (UL, XJ, SW, SW1, CDZ, and DH). This new data has made it possible to perform a preliminary set of multi-station inversions using CAPloc, an extension of the CAP method which allows for event location determination.

3. Results

The resulting focal mechanisms reveal that all earthquakes occurred at 3-20 km depth and their mechanisms were strike-slip, normal, or a combination of strike slip and normal with slip vectors generally oriented along the strike of the NQTL detachment. From these results, it can be concluded that the earthquakes in the swarm were likely triggered by the motion observed at GPS station LHAS. The larger deformation mechanism of the NQTL Detachment region remains unknown. The occurrence of the earthquake swarm and mainshock/faults in the region suggest this portion of the NQTL may be the interface between velocity strengthening and weakening zones.

4. Interpretation

Focal mechanisms determined using CAP and CAPloc can be used to improve our understanding of the kinematics of deformation in the region around the NQTL. Slow slip vectors can be calculated from moment tensors derived from mechanisms. These slip vectors indicate that fault slip associated with the 2002-3 swarm was eastward, while fault slip associated with 2009 events was westward. These events were found to be oblique strike-slip. Careful review of interpreted seismic lines through the study area suggests preliminary field studies suggest that the sets of earthquakes occurred on antithetic faults. The set of faults on which the 2003-4 events occurred appear to have orientations similar to that of the NQTL, and the set of faults on which the 2009 events occurred appear to be their conjugates. For example, the Yaangquen Valley Seismic Refraction profile (see below) during the late 1990s, project INDCET and observed seismic reflectors and refraction profiles of the Yaangquen Valley. The Yaangquen Valley seismic refraction profile was obtained during this time. The seismic refraction profile of the Yaangquen valley images the NQTL detachment and is shown below.

5. Conclusion

The series of earthquakes which occurred along the NQTL during 2002-3 and 2009 has provided great insight into the kinematics of deformation along detachments in Tibet. The similarity of these events and their associated apparent SSEs to events recorded within the Basin & Range front suggest that these findlings may be applied to other orogenic plateaus generally.

Figure 1.1 - The Yalong Oulu Rift (left). This is the most studied of the NE striking rift systems in eastern Tibet. The Yalong Oulu Rift (YOR) detachment is located in the northern margin of the south-central core complex. Previous studies have produced detailed geologic maps and tectonicin reflecting and refraction profiles of the region.

Figure 1.2 - Schematic of CAP/CAPlac Method (left). The goal of the method is to determine the focal mechanism and/or location of the event. Synthetic seismograms are built using a grid search. The synthetic which is fit to the data with the smallest time shift and the highest correlation coefficient is considered to represent the focal mechanism. Graver's functions are built using a method called F-4 factorization.

Figure 2.1 - Schematic of CAP/CAPlac Method (left). The goal of the method is to determine the focal mechanism and/or location of the event. Synthetic seismograms are built using a grid search. The synthetic which is fit to the data with the smallest time shift and the highest correlation coefficient is considered to represent the focal mechanism. Graver's functions are built using a method called F-4 factorization.

Figure 2.2 - An example CAP output (right). The magnitude as depth of the event as well as the strike, dip, and rake of the fault plane are determined. The synthetic is shifted in time to fit the data.

Figure 2.3 - An Example CAPloc output (left). Data from multiple broadband stations is used in determining the focal mechanism and location of the event. There are multiple fits displayed because multiple stations were used to obtain a mechanism.

Figure 2.4 - Scans of time (s) plotted. Strike, dip, rake, and depth used in calculating Kirchhoff and Green's functions is presented. The mechanism depth is fixed at the depth used in the Kirchhoff. The choosen central coordinate (x, y, z) are used for reference. The focal mechanism is shown in the z-component of the event where the CAP loc source is.

3. Results

The resulting focal mechanisms reveal that all earthquakes occurred at 3-20 km depth and their mechanisms were strike-slip, normal, or a combination of strike slip and normal with slip vectors generally oriented along the strike of the NQTL detachment. From these results, it can be concluded that the earthquakes in the swarm were likely triggered by the motion observed at GPS station LHAS. The larger deformation mechanism of the NQTL Detachment region remains unknown. The occurrence of the earthquake swarm and mainshock/faults in the region suggest this portion of the NQTL may be the interface between velocity strengthening and weakening zones.

Figure 3.1 - Focal mechanisms from 2002-3 swarm obtained from single station CAP (also in chronological order).

Figure 3.2 - Focal mechanisms from 2008 obtained from single station CAP (also in chronological order).

Figure 4.1 - Yaangquen Valley Seismic Refraction data (below). During the late 1990s, project INDCET obtained seismic reflectors and refraction profiles of the Yalong Oulu Rift. The Yaangquen Valley seismic refraction profile was obtained during this time. The seismic refraction profile of the Yaangquen valley images the NQTL detachment and is shown below.

Figure 4.2 - Slip vectors calculated from focal mechanisms. 2002-3 events (top), 2008 events (bottom). Slip vectors are in magnitude. The top right arrow indicates the SSE slip direction, the SSE slip direction is from GPS and the blue arrow indicates the post-earthquake slip direction as determined from inversion models.

Figure 4.3 - Schematic of focal mechanisms and post-earthquake fault slip onto an rough interpretation of the Yaangquen seismic refraction profile. The Yaangquen Valley seismic refraction profile in Cogan et al, 1996, is shown in the bottom left corner.

Figure 5.1 - (right) A Tibetian Parkfield? The occurrence of the earthquake swarm and mainshock/faults in the region suggest this portion of the NQTL may be the interface between velocity strengthening and weakening zones. Similar Homing behavior is observed in Parkfield, CA.

Figure 5.2 - (left) Fault Segments with different mechanical properties? The swarm may have occurred within the velocity strengthening and weakening segments.