Crustal Deformation along the Nyainquentanglhe Detachment, Southern Tibet

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1. Introduction

The discovery of slow slip events (SSEs) along subduction megathrusts over the last decade has been transformative of our understanding of active tectonics (e.g. Dragert et al. 2001).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 Rokosky, 2007). Traditional models of the earthquake cycle that attempt to predict two modes of deformation, steady-state creep and seismic slip, have accordingly been replaced by models that, in addition, predict slow slip behavior (e.g. Liu and Rice, 2005).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 Mw 3 - 4 earthquakes occurred near the Nyainquentanglhe (NQTL) Detachment in southern Tibet. The swarm was preceded by an increase in the eastward component of velocities recorded at a cGPS station in the nearby city of Lhasa. This increase in cGPS velocity, which lasted from the beginning of 2001 to the end of 2002, is thought to be evidence of slow slip event (SSE) on the NQTL detachment. If this event is an SSE, it would be only the second intracontinental SSE ever observed. On October 6, 2008 an Mw 6.2 earthquake and a series of Mw 3-5 aftershocks occurred in the same region in which the 2002-3 swarm was observed. It is currently unknown if this set of events was preceded by anSSE, but studying their focal 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 the earthquakes are consistent with the observed eastward cGPS velocity increase, it could be assumed that they were triggered by the SSE.

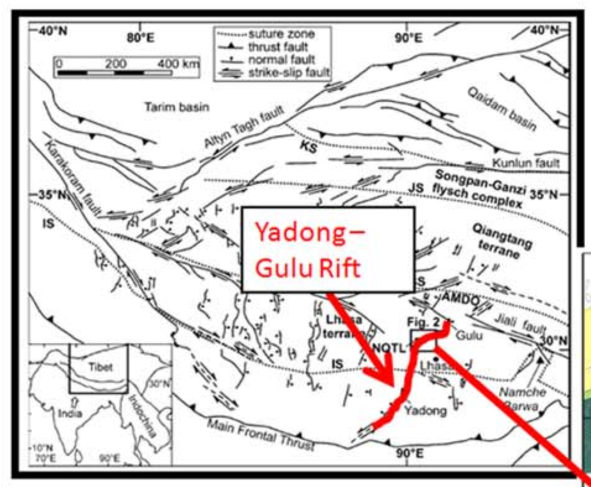


Figure 1.1 - The Yadong Gulu Rift (left). This is the most studied of the N-E striking rift systems in eastern Tibet. The Nyainquentanglhe (NQTL) detachment is located in the norternmost portion of the rift. It is a metamorphic core complex. Previous studies have produced detailed geologic maps and seismic reflection and refraction profiles of the region.

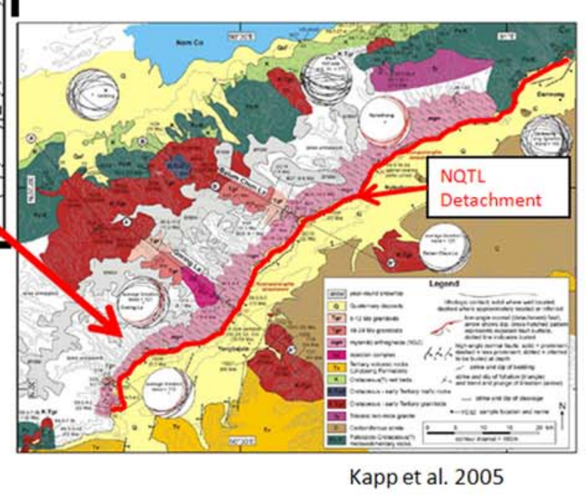
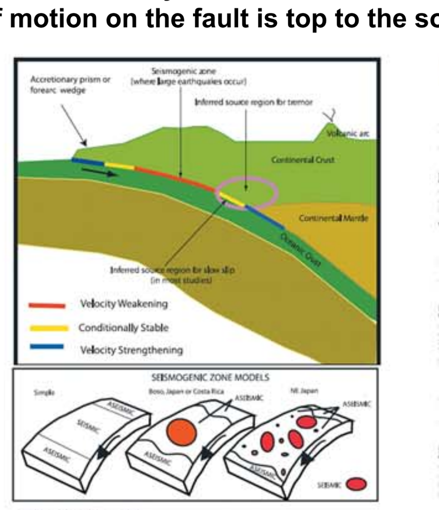


Figure 1.2 - Geologic map of the NQTL region (right). The NQTL detachment region is dominated by Cretaceous and Tertiary granitoids and orthogneisses as well as Paleozoic-Cretaceous metasedimentary rocks. The detachment is low-angle (22-37 degrees) and footwall mylonites reveal that the sense of motion on the fault is top to the southeast.



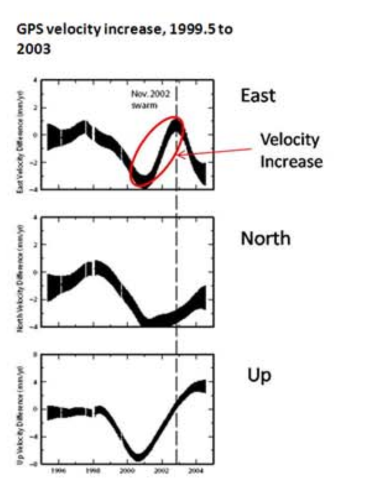


Figure 1.4 - (Right) SSEs are most often observed at subduction zones at the transition between conditionally stable and velocity strengthening zones along the megathrust e.g. Guerrero, Mexico and Cascadia. Wernicke et al. 2008, observed the first intracontinental SSE along a subcontinental scale extensional detachment in thenorthern Great Basin of Nevada (below). The occurrence of the SSE was inferred from changes in velocities observed at cGPS stations dispersed across the region.

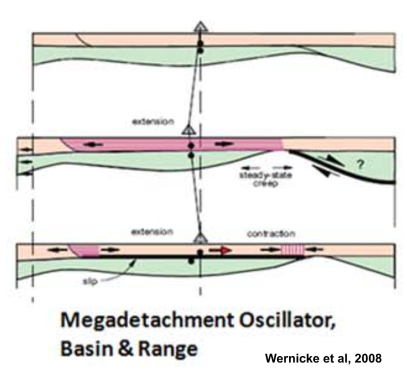
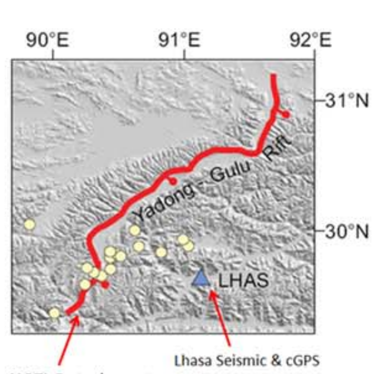


Figure 1.3 - (Above, right). The increase in the east component of velocity observed over the course of 1.5 years at the LHAS cGPS station in Lhasa, Tibet is likely evidence of a slow slip event (SSE) on the NQTL detachment, the region's largest fault. This SSE caused 1 cm of displacement at the surface and was followed by an earthquake swarm which lasted from November 2002 to January 2003.



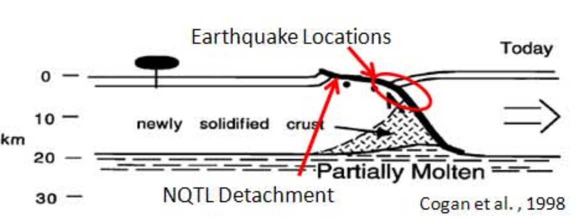


Figure 1.5 - Earthquake locations. The NQTL earthquake swarm was centered along the southeast corner of the region mapped in Kapp et al, 2005 near an area called the Yangbajain Valley. (Left) Earthquakes are shown in yellow and the Lhasa cGPS and broadband seismic stations are shown in blue. (Above) The position of the earthquakes with respect to the detachment are shown on a scehmatic drawing of a metamorphic core complex

2. Method

Because the swarm events and most of the 2008 aftershocks were too small to be detected teleseismically, their source mechanisms were determined using the Cut and Paste (CAP) inversion method. This method employs waveform 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 station data was available at the time this study began. More recently, data recorded during the 2008 events has become available from local broadband stations (LKZ,SNA,NMU,MZG, and DXI). 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.

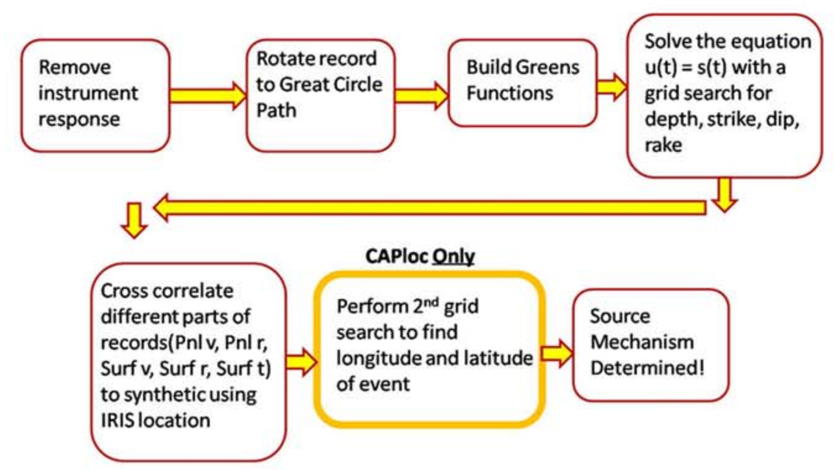


Figure 2.1 - Schematic of CAP/CAPloc Method (left). The goal of the method is to determine the the focal mechanism and/or location of the event. Synthetic seismograms are built using a grid search. The synthetic which is fit to the data with the smallest time shift and the highest correlation coefficient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

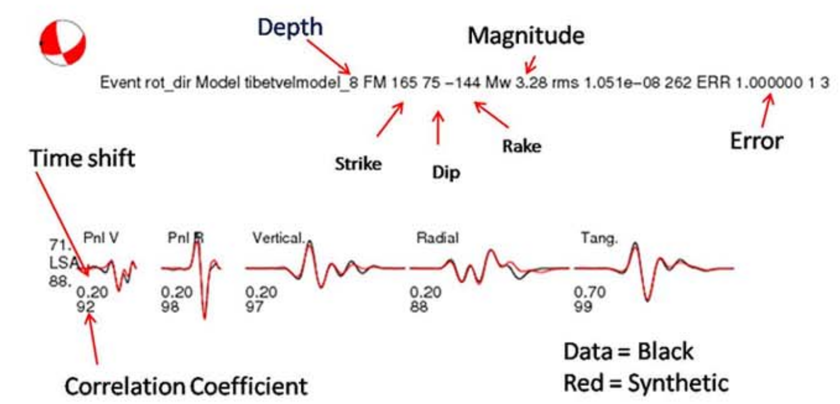


Figure 2.2 - An example CAP output (right). The magnitude and depth of the event as well as the strike, dip, and rake of the nodal planes are determined. The synthetic is shifted in time to fit the data.

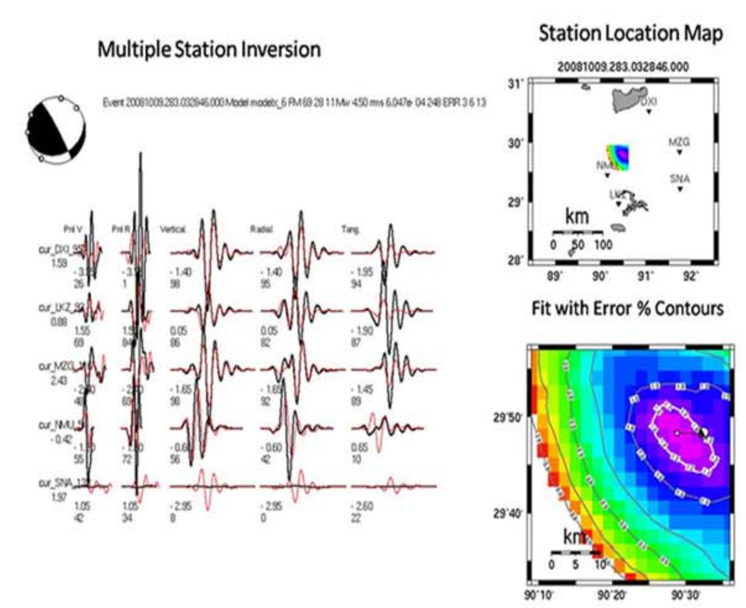


Figure 2.3 An Example CAPloc output (left). Data from multiple broadband stations is used in determining the focal mechanism and location of the event. There are multiple fits displayed because multiple stations were used to obtain a mechanism.

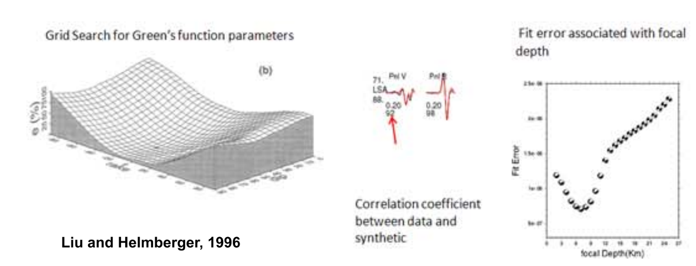


Figure 2.4 - Sources of Error (above). Strike, dip, rake, and depth used in calculating Green's functions were determined using a grid search method which reduces error. The mechanism depth is focal depth with the lowest error. The correlation coefficient reveals the quaility of the fit between the data, and synthetic and the time shift reveals inaccuracies in the x,y location of the event entered into CAP during the inversion

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 cGPS station LHAS. The larger deformation mechanism of the NQTL Detachment region remains unknown. The occurrence of the earthquake swarm and mainshock/aftershock series in the region suggest this portion of the NQTL may be the interface between velocity strengthening and weakening zones.

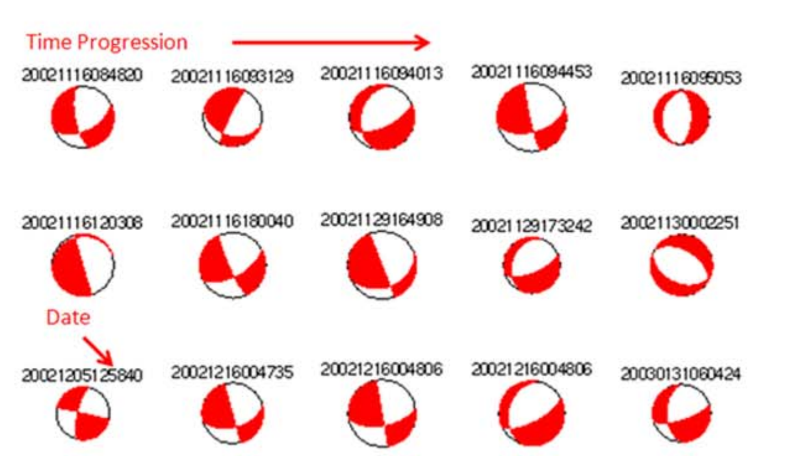


Figure 3.1 - Focal mechanisms from 2002-3 swarm obtained from single station CAP (in chronological order).

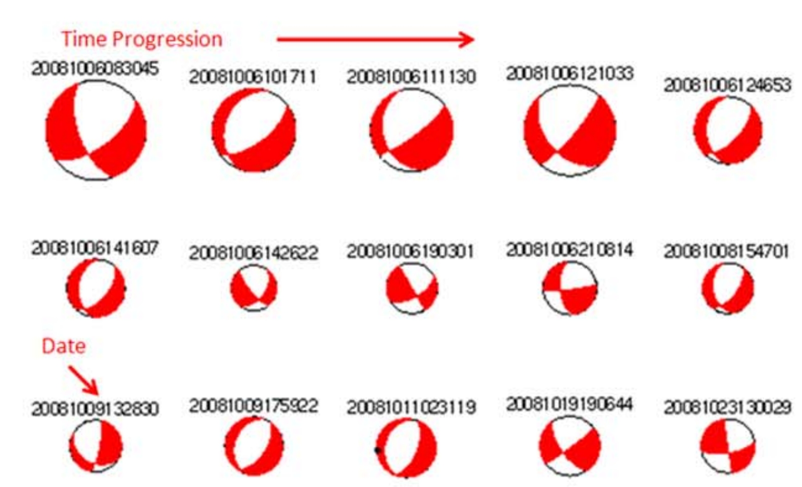


Figure 3.2 - Focal mechanisms from 2008 obtained from single station CAP (also in chronological order).

2002-3 Events (CAP) **2008 Events (CAP)**

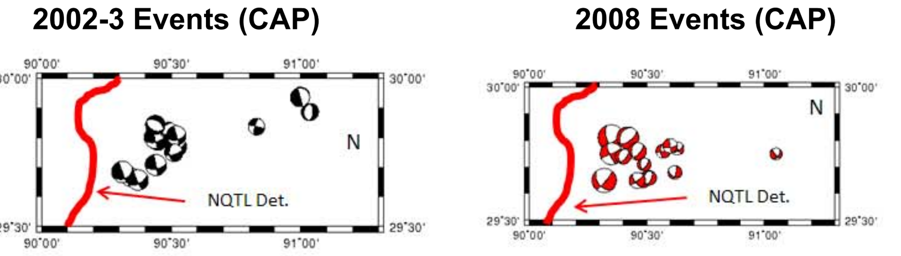


Figure 3.3 - Maps of focal mechanisms calculated using single station CAP (left). All events are less than 200 km from the NQTl and the cGPS and broadband stations in Lhasa. The events most commonly have depths of 8-9 km.

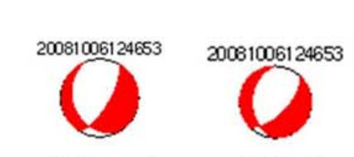


Figure 3.4 - CAPloc vs CAP results (right). Focal mechanisms obtained using single station CAP were checked against focal mechanisms obtained using multi-station CAPloc and were found to match well. As a result, we conclude that, in the case of the NQTL region, single stations CAP produces trustworthy results. This result is important because only one broadband station is available for inverting 2002-3 events.

Earthquake locations used in CAP code have all been obtained from IRIS. Because many of the earthquakes in question have small to moderate magnitudes (Mw 4>) and IRIS network seismic station coverage of the area is poor, the earthquake locations may be incorrect. In order assess that correctness of the IRIS locations we decided to run CAP at evenly spaced points within a 40 km radius of the IRIS location. The RMS error of the best CAP result obtained at each location in the grid was then compared the RMS error of the best CAP result obtained at the IRIS location. Preliminary results obtained on the first 9 events to the 2002-3 swarm show the IRIS location to produce the lowest error CAP result 66% of the time. When a result within the circular shaped grid had a smaller error, that location was within 2 km of the IRIS location. This distance is quite small in comparison to the size of the region (100km X 100km). At the moment, we can conclude that the IRIS locations are adequate.

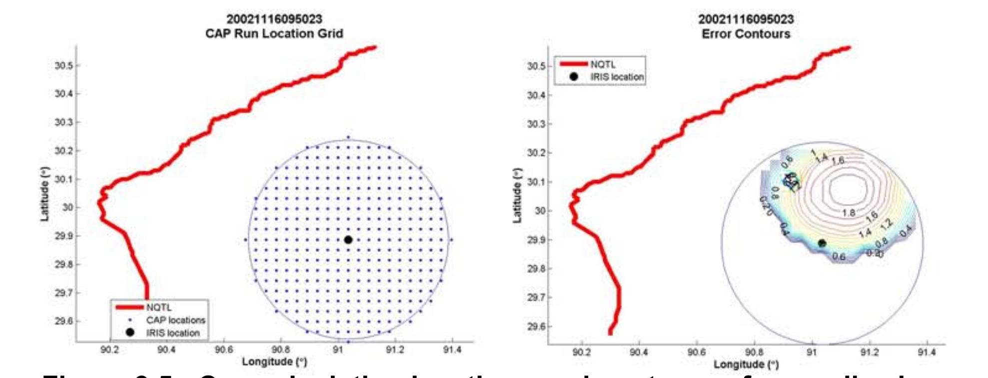
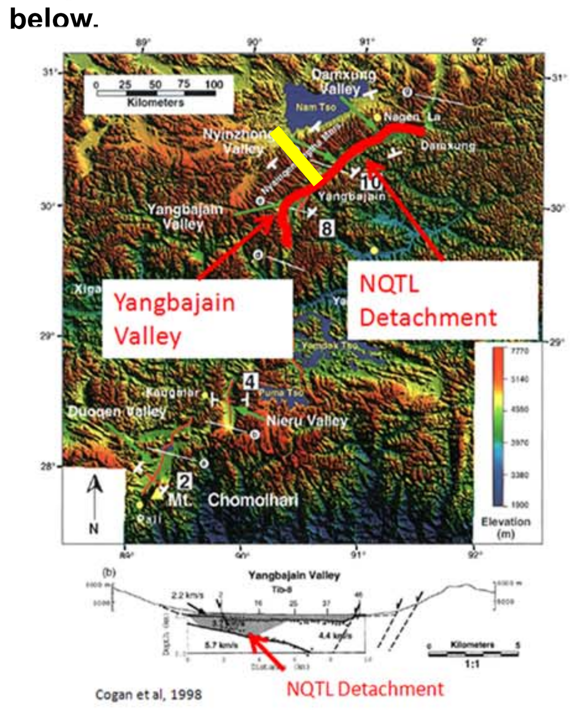


Figure 3.5 - Cap calculation locations and contours of normalized error. Grid box dimensions are 4km X 4km. Error at IRIS location is set at 1. All other errors are measured with respect to rms error at this location.

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. Slip vectors can be calculated from moment tensors derived from mecahnisms. These slip vectors indicate that fault slip associated with the 2002-3 swarm was eastward, while fault slip associated with 2008 events was westward. These events were found to be oblique strike-slip. Careful review of interpreted seismic lines through the study region and preliminary field studies suggest that the two sets of earthquakes occurred on antithetic faults. The set of faults on which the 2002-3 events occurred appear to have orientations similar to that of the NQTL and the set of faults on which the 2008 events occurred appear to be their conjugates.

Figure 4.1 - Yangbajain Valley Seismic Refraction data (below) During the late 1990s, project INDEPTH obtained seismic reflection and refraction profiles of the Yadong Gulu Rift. The Yangbajain Valley seismic refraction profile was obtained during this time. The seismic refraction profile of the Yangbajain valley images the NQTL detachment and is shown below.



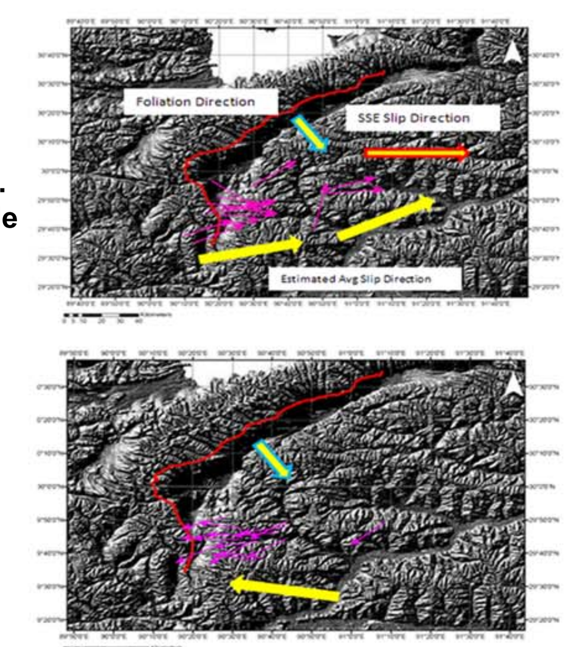
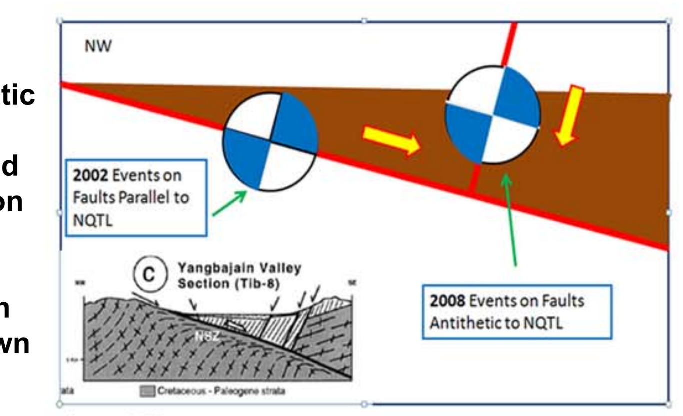


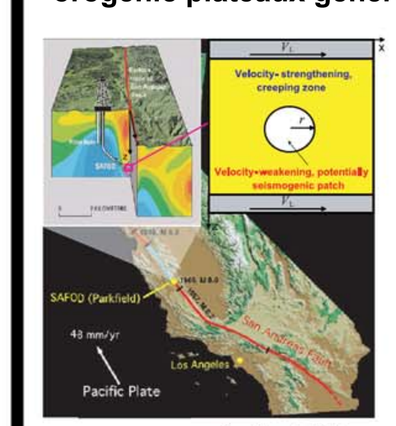
Figure 4.2 - Slip vectors calculated from focal mechanisms. 2002-3 events (Top). 2008 events (Bottom). Slip vectors are in magenta. The red rimmed arrow indicates the SSE slip direction determined from cGPS and th blue rimmed arrow indicates the foliation direction determined from Miocene metamorphic rocks found within the core complex.

Figure 4.3 (right). Schematic of focal mechanisms and associated faults projected onto an rough interpretation of the Yangbajain seismic refraction profile. The interpretation published in Cogan et al, 1998, is shown in the bottom left corner.



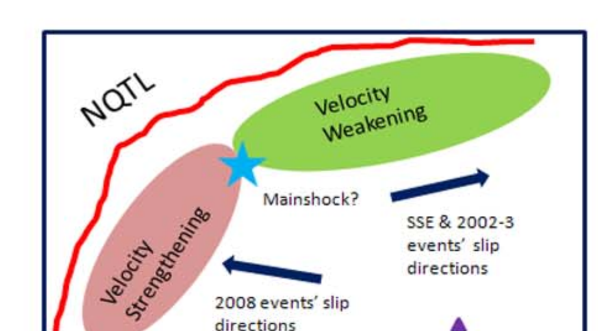
5. Conclusion

The series of earthquakes which occurred along the NQTL during 2002-3 and 2008 has provided great insight into the kinematics of deformation along detachments in Tibet. The similarity of these events and their associated apparent SSE to events recorded within the Basin & Range suggest that these findings may be applied to orogenic plateaus generally.



5.1. - (right) A Tibetan Parkfield?
The occurrence of the earthquake swarm and mainshock/aftershock series in the region suggest this portion of the NQTL may be the interface between velocity strengthening and weakening zones. Similar rheology may be observed in Parkfield, Ca.

5.2 - (left) Fault Segments with different mechanical properties? The swarm may have occurred within the velocity strengtheing segment and the mainshock may have occurred at the transition zone between the velocity strengthening and weakening segments



Bibliography. Chen, T., and N. Lapusta (2009), Scaling of small repeating earthquakes explained by interaction of seismic and aseismic slip in a rate and state fault model, Journal of Geophysical Research-Solid Earth, 114. Dragert, H., K. Wang, T. James. (2001), A silent slip event on the deeper Cascadia subduction interface. Science, 292, 1525. Cogan, M., K. Nelson, W. Kidd, C. Wu, INDEPTH Team (1998). "Shallow Structure of the Yadong-Gulu rift southern Tibet, from refraction analysis of Project INDEPTH common midpont data." Tectonics. Vol 17. No. 1. 46-61. Kapp, J., T. M. Harrison, P. Kapp, M. Grove, O. Lovera, D. Lin (2005). "Nyainqentanglha Shan: A window into the tectonic, thermal, and geochemical evolution of the Lhasa Block, southern Tibet." Journal of Geophysical Research. Vol 110. B08413. Liu, Y. J., and J. R. Rice (2005), Aseismic slip transients emerge spontaneously in three dimensional rate and state modeling of subduction earthquake sequences, Journal of Geophysical Research-Solid Earth, 110. Schwartz, S. Y., and J. M. Rokosky (2007), Slow slip events and seismic tremor at circum-pacific subduction zones, Reviews of Geophysics, 45, RG3004. Tan, Y , L. Zhu, D. Helmberger, C. Saikia (2006)."Locating and modeling regional earthquakes with two stations." Journal of Geophysical Research. B01306.