PBO Mini Proposal: Tectonics of the Northern Walker Lane

Proposal Team	**Principal Area of Expertise**
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a. Tectonic Background and Current Knowledge

The region we propose for a GPS cluster as part of PBO, the Northern Walker Lane (NWL), extends from approximately Honey Lake in the north to Walker Lake in the south, and is roughly 100 km wide with the western boundary in the Sierra Nevada mountain block. The Reno–Carson City–Truckee–Tahoe urban areas, which are among the fastest growing in the United States, are in the west-central part of the zone, and seismic hazard assessment here will benefit from any improvement in understanding of the tectonics resulting from this project. Recent GPS results [Thatcher et al., 1999; Bennett et al., 1999] have discovered that the zone accommodates 4-8 mm/yr of relative motion across the Pacific-North America plate boundary (corresponding to ~30-70% of the total relative velocity across the Basin and Range province). Thus this is the region of highest strain rate east of the major strike-slip systems associated with the San Andreas fault in California. Consistent with that, the region has shown persistent seismic activity throughout the late 19th Century and entire 20th Century (in contrast to the Central Nevada Seismic Zone, where seismic activity has decreased gradually since the large earthquakes of the 1950's). The conspicuous mountains and valleys are typically associated with the normal faults of the region (Figure 1), some of which are among the most active normal faults in the western Basin and Range [e.g. dePolo, 1997]. However, consistent with the GPS results, major strike-slip faulting (right-lateral on north-west trends) is recognized at the southern and northern ends of the region. In the center, the mapped strike-slip faults all are perpendicular to the expected trend, i.e. they are left-lateral offsets on a north-east striking faults. The focal mechanisms in the region have dominantly strike-slip mechanisms, and several events for which detailed aftershock studies and source orientations are known occur on such northeast-trending faults.

b. Outstanding Problems

The Strain Deficit Problem: Time Dependence, Geologic Interpretation, or Model Problems?

The geodetic rate across the NWL is known to be 4-8 mm/yr. In comparison, integrating the estimated Quaternary slip rates based on analysis of known Quaternary faults only accounts for a fraction (at most 50%) of this strain rate in the northern and southern third of the region, and virtually none in the central section. The NWL "strain deficit" in the geologic record is the largest known anomaly of its kind over the entire Pacific-North American plate boundary. The geodetic results have been confirmed by two independent studies [Thatcher et al., 1999; Bennett et al., 1999]. More recent results from the current BARGEN continuous GPS array (shown as red dots in Figure 1) only serve to strengthen the significance of the discrepancy, as the BARGEN velocity errors are now estimated at < 1 mm/yr [Jim Davis and Brian Wernicke, personal comm.]. We therefore conclude that geodetic velocity errors are unlikely to explain this discrepancy.

One approach to resolving this discrepancy is to carefully characterize the surface kinematics of the NWL in three dimensions, and use this kinematic description to infer slip at depth on likely active structures. Three distinct possibilities (or some combination) are likely to emerge from this approach:

- The leading possibility is that geologic studies are currently missing important information, e.g., blind faults, inadequate spatial resolution, or large fault offsets yet to be discovered. To enable this line of inquiry, the geodetic network would have to be sufficiently dense to capture anomalous strain signals from obscure, previously undetected structures. For this, localization of sources of strain is of paramount importance. In the event that this alternative has merit, it would be crucial to incorporate a program of intensive geologic mapping of structures in the NWL. While this is not strictly an activity of PBO per se, the UNR team is in a particularly strong position to do this with in-house expertise in geologic mapping, Quaternary and structural geology, geophysics, and seismology.
- A second possibility is that current day motion differs from recent Quaternary motion, implying either a recent rapid permanent change in the plate-boundary tectonics of this region, or that current motion reflects some transient behavior. Although this might be difficult to prove directly, such an explanation may be favored if the alternative possibilities can be ruled out by data. In the event that PBO indeed points towards this class of explanation, we propose an investigative approach that integrates analysis of the geologic evolution of NWL and evidence from late Quaternary earthquakes to formulate and constrain hypotheses for recent geologic change in deformation rates.
- A third intriguing possibility has arisen from research in progress by Jim Brune on the validity of current assumptions of the relationship of seismic moment to actual slip on dip-slip faults. Using both foam rubber models, and computer simulations, Brune's results indicate that the discrepancy between model results and theoretical predictions grow larger as the dip angle decreases. For normal faults the discrepancy may be a factor of ~2 (at 45°). On theoretical grounds, this discrepancy may arise from invalid assumptions regarding infinite space and transparency of the fault during rupture. We propose to investigate (1) direct observational geodetic data on crustal deformation around very active normal faults to complement this promising line of research, and (2) the consequences of invalid assumptions, especially with regard to the known geodetic-geologic discrepancy. Therefore, enabling the study of fault mechanics should also be a design criterion of the geodetic network.

Investigation leading to the resolution of the geological strain deficit in the NWL is important for two main reasons:

- There is significant potential for scientific discovery regarding time-dependent behavior, blind structures, or fault mechanics in a complex three-dimensional strain field involving dextral motion parallel to the plate boundary, as well as northwest-southeast extension and possibly north-south shortening.
- A correct accounting for strain accumulation is essential for assessment of earthquake hazards in the Reno-Carson City-Truckee-Tahoe urban zone. This population corridor (which includes the State Capital, and is second in population only to Las Vegas-Henderson in Nevada) is centrally located in the NWL. Earthquake hazard assessment and assistance with civilian response planning is central to the activities of the Seismological Laboratory and the Nevada Bureau of Mines and Geology at UNR, so UNR is well-positioned to translate the discoveries of this research into societal benefits.

Vertical Motion Problem: Need for Constraints on Neogene Evolution and Dynamic Models

A different, but perhaps related outstanding problem is that there are no convincing geodetic data on the current rates of vertical *tectonic* motions anywhere in the world. The reason for this is that tectonic motions are typically believed to be << 1 mm/yr and can easily be swamped by postglacial isostatic adjustment and current elastic response to loading from continental water storage, atmospheric pressure, and ocean tides. Recent progress has been made in understanding these signals [van Dam et al., 1995; van Dam et al., GRL in review]. The NWL at the transition between the Sierra Nevada (which may be uplifting) and the Basin and Range province (which may be subsiding) presents the possibility for unambiguous detection and quantification of vertical motion associated with tectonic processes. From a tectonic perspective, this would provide critical data for evaluating models of the Neogene evolution of the western Cordillera, with important paleogeographic [e.g., Axelrod, 1992, vs. Wolfe et al., 1997], paleoclimatic, and geodynamic implications. In the latter case, delineating vertical motions will greatly elucidate the isostatic response to the evolving plate boundary (e.g., northward migration of triple junction and edge of subducting slab). In addition, we have the opportunity in this region to constrain vertical motion associated with actively tilting fault blocks (i.e., rotating about a horizontal axis). The vertical component is also important for assessing models of normal fault mechanics, which apparently are more poorly understood than previously appreciated (as evidenced from Brune's work). A combined high spatial resolution map of the full 6 components of the surface velocity gradient (2-d surface strain-rate plus tilt rate) would therefore provide powerful constraints on Neogene evolution and dynamic modeling.

From a geodetic perspective, the errors arising from water vapor in the troposphere above the NWL would be relatively minimal in this desert region, and the team at UNR has extensive experience in the modeling and interpretation of vertical geodetic signals [various Blewitt refs]. Based on our understanding of seasonal signals [Blewitt, JGR in review, 2000], a reasonable goal over a decadal time scale would be to resolve secular vertical motion to within 0.3 mm/yr. The relatively short distance across the NWL should lead to more precise relative vertical positioning between the Sierra Nevada and Basin and Range (through common mode cancellation). Thus the geodetic goal would be to map out precisely determined vertical rates across the NWL with sufficient spatial resolution to identify structures responsible for the relative vertical motion, which would then be compared with the geologic evidence and evaluated in the context of the regional tectonic evolution.

The Holocene Seismic Discrepancy: Precarious Rocks and Understanding Seismic Hazard

The strike-slip Honey Lake Fault Zone (HLFZ) towards the northern extent of our proposed region of study has been interpreted to be the locus of a few to several major Holocene earthquakes [Willis and Borcherdt, 1993]. Yet a spectacular zone of precarious rocks exists in the Fort Sage Mountains, near (1-7 km) the HLFZ. The appearance and geomorphic conditions of the rocks indicate they have been in precarious positions for thousands of years [Brune, 1996, etc.]. Preliminary estimates of toppling accelerations are about 0.3 g. Based on current attenuation curves it would appear that these rocks would be shaken down by ground motion from either an M=6.5 event on the Honey Lake fault (or M=6 on the Fort Sage Mountains normal fault). The USGS-CDMG hazard maps for this region indicate a very high hazard, with 2,500-yr recurrence accelerations of over 0.8 g. This severe discrepancy is important to resolve for an adequate understanding of seismic hazard. Independent verification of the rate and type of faulting in the region is of paramount importance in this regard. Geodesy can play a key role towards this by quantifying current rate and style of strain accumulation in the HLFZ.

c. Deployment

We have already established that the deployment must be able to characterize the three-dimensional surface kinematics of the NWL. Figure 1 shows a nominal array of 45 continuously operating GPS stations that have been carefully selected according to several criteria. We understand quite well the rules governing deployment of a GPS network to optimally characterize the kinematics. We also emphasize that the deployment strategy is meant to optimally complement the geologic interpretation, which is equally important in understanding the NWL strain discrepancy. The stations must be continuously operating for two reasons. Firstly, velocity gradients determined in the NWL should have 20 ns/yr precision to address the science goals effectively (~0.2 mm/yr over a spacing equal to the thickness of the seismogenic zone), which should certainly be achievable over 5-10 yr (based on a current network of similar spacing at Yucca Mountain). Secondly, any hope of producing useful vertical velocity results at the level of tenths of a mm/yr necessitates continuous monitoring, which allows for assessment of our ability to calibrate for vertical variation not associated with tectonic activity (discussed previously). To a lesser extent, this argument also applies to the horizontal components. The temporal aliasing of epoch campaigns would preclude the discrimination of competing hypotheses with a high degree of confidence.

Recent work [*Blewitt*, GRL in press] on optimal network design to resolve fault kinematics implies specific rules with regard to station placement. For example, stations placed mid-way between parallel strike slip faults are optimally located to resolve slip partitioning. The density of the array should have spatial resolution of the order of the thickness of the seismogenic zone, as the surface expression of slip at depth is low-pass filtered. Analytical results on resolving the actual 3-d location of slip at depth indicates that optimal station placement is at ~8 km normal to the fault plane.

Our approach stresses the importance of an areal, rather than linear array. While a linear array may be appropriate for most of the Basin and Range, the tectonics of the NWL show distinctive changes in style of faulting moving from south to north. The kinematics are governed by not only northwest-striking right lateral faults one might expect, but also by northerly striking normal faults, and even by northeast-striking left lateral faults approximately normal to the NWL trend (Figure 1).

An areal array has an advantage over a linear array in that the four components of the horizontal strain tensor rate plus two components of tilt can be determined. In comparison, a linear array only captures 3 of these 6 components, and unlike an areal array, cannot resolve rigid rotation, dilitation, 2-d engineering shear, and therefore the direction and magnitude of maximum extension. Interpretation of GPS transects therefore are either limited in potential, or require additional assumptions, e.g., that the array orientation lies normal to the direction of maximum extension. One advantage of linear arrays is the decreased station separation (assuming a fixed number of stations), but the improved resolution in this one dimension is at the expense of intepretative ambiguity arising from unexpected structures (which are of course 3-d). (Of course, two parallel linear arrays do better in resolving additional features of the strain tensor than a single one, but considering the geological complexity of the area (Figure 1), even parallel traverses are insufficient.)

Maps of the various components of the strain rate tensor have proved to be useful in identifying how regions accommodate the integrated strain imposed by the kinematic boundary conditions [Holt et al., Kahle et al., Clarke et al.]. For example, we would explore to what extent vertical-axis block rotation plays a role in the NWL, which may be an essential component towards understanding the complex interaction of faulting styles. Mapping out the strain tensor provides a much stronger constraint on dynamic models than relative velocities from a 1-d array, and provides more potential to explain unexpected results (hence more potential for discovery).

We note that the south to north variation in the map of strain tensor components might also shed some light on the evolution of the NWL. For example, if we take the hypothesis that at any given time, the northernmost extent of the NWL is somehow controlled by the location of the Mendicino triple junction (and hence the edge of the subducting slab), we might predict that in going from south to north, the style of faulting in the NWL approximately represents its evolution (backwards) in time. This might allow us to test recent ideas relating the increasing maturity of an evolving fault system with its decreasing complexity [Wesnousky, 1998]. Such an evolutionary study would benefit not only from hard geodetic data, but also from geologic evidence and interpretation, a point we emphasize throughout this proposal as important for the success of such a PBO deployment.

However, the merits of this proposal would be substantially decreased if it were not possible for PBO to supply an areal network with inter-station spacing of the order of the thickness of the seismogenic zone (10-15 km), which would necessarily imply ~45 stations in the NWL. Given that the geologic-geodetic discrepancy is mostly concentrated in the NWL and thus the corresponding potential for discovery in this region is great, we suggest the panel consider an appropriately proportional allocation of resources. We note that the mini proposal by Thatcher et al. is complementary and in fact essential to provide a regional context for our proposal. We therefore strongly support Thatcher et al.'s proposal (but taken alone, it would be insufficient to achieve the scientific objectives laid out here). We also strongly support an initiative to complement the current BARGEN array [Wernicke et al.] for a broader context. We also note that the overlap of stations in the NWL between Thatcher et al.'s and our proposal is approximately 12 (out of Thatcher et al.'s total of 60). Our proposed proportion allocated to NWL is therefore 45 out of 93, which is roughly in proportion to the respective strain rates.

As a final note, Wesnousky's grad student Rich Briggs has been collecting campaign-mode data traversing the study area, the results from which may help to improve the final network design.

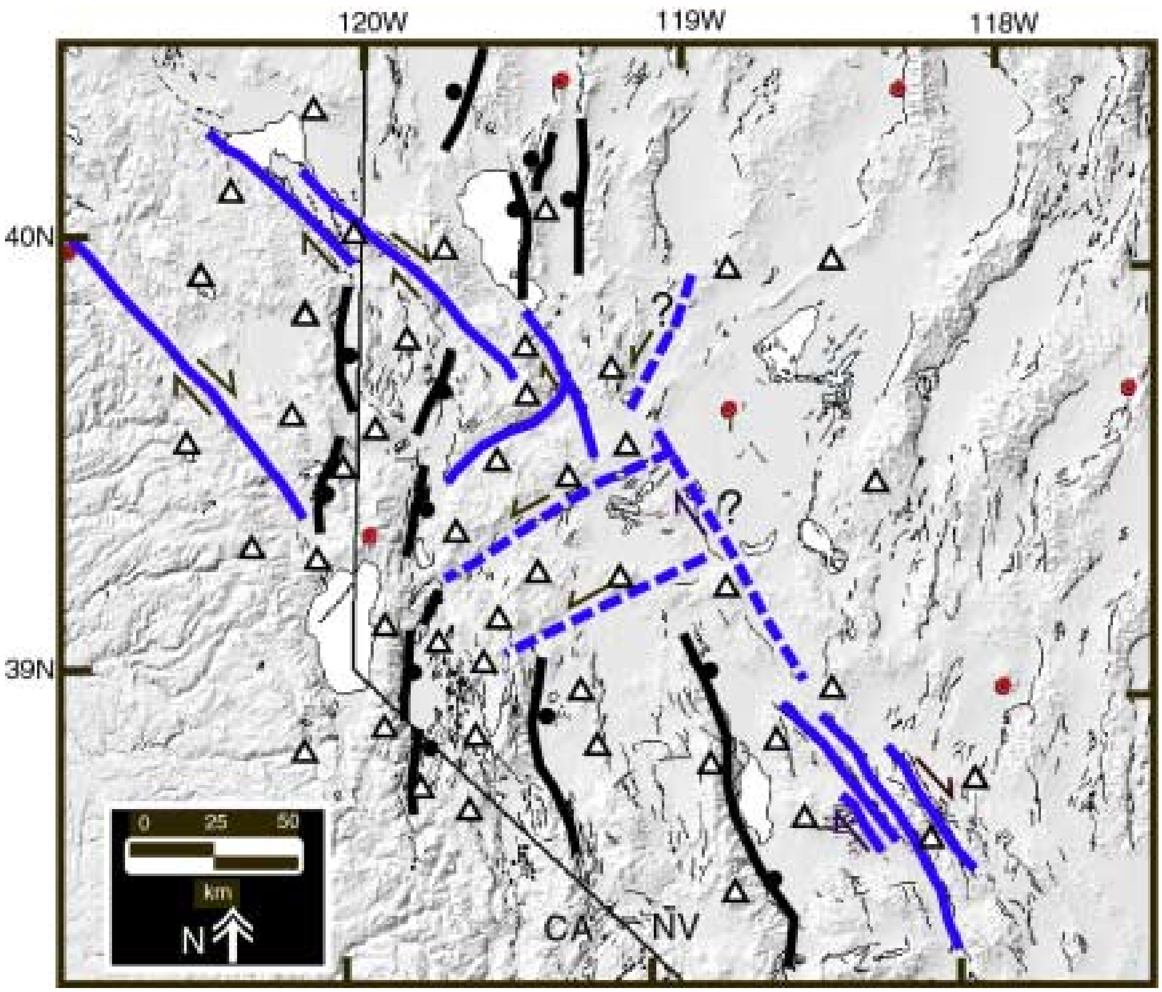

Figure 1: Map of proposed 45-station network in the Northern Walker Lane (triangles), shown in the context of topography and late Quaternary faults. Note the complex interaction between strike-slip faults (blue) and normal faults (black, with sense indicated by black dot). The dashed, questioned north-west strike-slip fault is entirely speculative, but would seem to be required for any reasonable model of the deformation. Approximately 12 of these stations are redundant with proposal by Thatcher et al. Existing continuous GPS stations (BARGEN) are shown as red dots. (*Acknowledgement: Thanks to Rich Briggs for assistance with this figure*)