Kinematics & Dynamics of Continental Extension in the Basin and Range Province

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Background on Tectonic Setting and Current Knowlededge Base

The Basin and Range (B&R) Province is one of the pre-eminent regions—perhaps the type locality—for studying the kinematics and dynamics of continental extension. Its clear physiographic expression and sparsely vegetated desert landscape produce excellent bedrock and alluvial exposures that have drawn geologists to the region for over a century. Extensive geological, geophysical and geodetic studies provide an excellent knowledge base upon which to build, and here we propose new work using PBO resources that will be integrated with concurrent geological and geophysical studies supported by other programs.

Geologic mapping and structural analysis have shown that the Province has extended by about a factor of two in the late Cenozoic. Earthquake activity and crustal deformation measurements indicate that this process is continuing today. Holocene (last 10,000 year) faulting is concentrated near the western and eastern boundaries of this 800-km-wide region, with more diffuse faulting spread throughout the Province. To first order, GPS-measured deformation mimics this pattern, with the majority of the current straining localized across the Wasatch fault zone (WFZ) on the east and on the central Nevada seismic zone (CNSZ) and Walker Lane fault zone (WLFZ) on the west (see Fig. 1). Additional deformation occurring at much lower strain rates may be spread more evenly across the remainder of the zone. Seven earthquakes of M~7 have occurred along the CNSZ in the 20th century (in 1915, 1932, 1934, and in 1954, when 4 events occurred). Although no historical activity has occurred on the WFZ, extensive paleoseismic study shows evidence of M~7 earthquakes every ~300 years. Elsewhere, Holocene faulting provides abundant evidence of major earthquake activity.

During the past 30 years, and especially since the early 1990's, geodetic measurements have begun to fill in the pattern of present day deformation across the Province. Precise laser ranging measurements begun in the 1970's by the U. S. Geological Survey (USGS) showed elastic strain accumulation at rates of about 50 nstrain/yr occur across the WFZ and CNSZ. Results from very long baseline interferometry (VLBI) showed that the integrated velocity across the Province is about 12 mm/yr. During the past 5 years both survey-mode (SGPS) and continuous (CGPS) GPS networks have begun to refine the broad outlines sketched by the VLBI and earlier ground-based geodetic results. They have shown where deformation is most strongly focussed and where it is more diffuse, stimulating comparisons between the patterns and rates of active deformation recorded geodetically with those obtained by studies of geologically youthful deformation.

Outstanding Problems

Recent years have seen a renaissance in B&R research that has been inspired at least in part by the new GPS results. Cumulatively these studies define new problems and suggest novel approaches to longstanding issues. Although GPS deployments will play a crucial role in addressing these problems it is likely that only an integrated multi-disciplinary program will ultimately resolve matters definitively. In what follows we define several of those problems where PBO can have a crucial impact, outlining in broad-brush terms both how GPS can contribute and how other geological and geophysical investigations can be integrated with PBO activities. In the subsequent section we specifically outline what PBO deployments are needed to address the GPS needs and mention other studies that will contribute to overall scientific goals.

1. Geodetic vs Geologic Slip Rates:

A direct result of the GPS work has been a recognition that geodetic estimates of extension and slip rates are incompatible with those obtained from geologic studies of Holocene and late Quaternary faulting. This difficulty was first documented for the WFZ [Savage et al., 1995; Martinez et al., 1998] but it is clear from comparisons that can be made for the CNSZ and WLFZ that the same problem applies there.

Several alternative explanations could resolve this discrepancy. First, the GPS results could be wrong, either because the existing measurements are not spatially or temporally representative or because the models used to relate geodetic strain rates to fault slip are flawed in some way. Second, the geologic slip rate estimates could be inadequate, perhaps because the geologic study areas fail to encompass all regions where significant fault offsets occur. Third, each estimate could be correct but apply to distinct, incompatible time intervals—that is, fault slip rates differ between those measured now via GPS and those averaged over the Holocene.

Each of these alternatives has testable consequences. More and better quality GPS networks will determine whether results obtained to date are typical or exceptional. More ingenious or inspired modeling will show whether or not current fault models really do rule out compatibility between slip rate estimates. Additional geologic studies in the rapidly deforming zones can refine Holocene slip rate estimates and include all fault structures capable of accommodating significant slip.

2. Long Term Temporal Slip Rate Variations

The disagreement between geologic and geodetic slip rates could be the current manifestation of Quaternary and Holocene patterns of fault activation and dormancy evident in the landscape of the B&R. Wallace [1977] first noted differences between the youthful character of range front morphology in the CNSZ, the eroded ranges farther east in Nevada, and the even more subdued ranges in western Utah. He concluded that the CNSZ faults had been active in the Holocene while most of the eastern faults had experienced greater activity more than ~100 ka BP and were either permanently inactive or merely dormant at present. He subsequently suggested [Wallace, 1984] that B&R fault activity might be quite variable in space and time, with tectonism being focussed in particular ranges for 10s or 100s of thousands of years, then shifting as much as several hundred km to adjacent, previously inactive ranges.

While present day geodetic methods cannot test Wallace's suggestion, establishing (or not) firm differences between geodetic and geologic slip rates and explaining this difference would contribute importantly towards resolving the origin of long term slip rate variations. More directly, if slip rates vary significantly over time scales of $\sim 10^2$ to $\sim 10^5$ years this change should be imprinted on the fault-generated topography of the Province [Wallace, 1978] and can be quantified using process based modeling of landscape evolution. Modeling the dynamical conditions necessary to initiate continental extensional faulting and examining circumstances under which activity could vary in space and time would complement the observation-based geomorphic models and mechanically test the possibility of long range migration of tectonic activity.

3. Driving Mechanism of Continental Extension

Continental deformation results from an interplay among driving forces applied at the boundaries of the deforming region, internal forces due to lateral and depth-dependent density gradients within the lithosphere, and resisting forces dependent on lithospheric rheology. Current tectonism in the B&R is driven primarily by motions of the bounding Sierra Nevada and Oregon Coastal microplates on the west and by internal buoyancy forces due to lateral density gradients in the crust and upper mantle lithosphere of the Province.

The role of GPS and PBO deployments is to outline the patterns of present day steady-state deformation, providing the current surface boundary condition needed to constrain dynamical models of the deformation. This includes both mapping internal deformation within the Province and constraining the Euler vectors of relative motion of the bounding microplates and any rigid elements of B&R lithosphere.

Complementary seismologic and potential field measurements and dynamical modeling experiments are needed to augment the kinematic description of the deformation provided by GPS. Forces due to lateral density gradients (gravitational potential energy or GPE of the lithosphere) are obtained either by constraining lithospheric density structure seismically or by direct mapping of geoid height within the deforming region. USArray deployment of seismograph arrays ('Bigfoot') will contribute towards tomographic mapping of lithospheric density structure, and better geoid models for the western U. S. obtained from new satellite gravity missions can be input to modeling GPE driving forces.

Lithospheric rheology is more difficult to constrain, with only regional bounds provided by the isostatic rebound due to latest Quaternary unloading of Lakes Bonneville and Lahontan. In practice, rheology can be obtained from the dynamical models by inputting driving forces and iteratively deriving the rheological distribution that best fits the current surface deformation field. Results obtained thus far [e.g. Flesch et al., 2000] show how crucial GPS results are in constraining these models, since the derived rheology distribution closely mimics the current deformation field.

Deployment Requirements

As illustrated in the preceding sections, much is known about the B&R but much yet remains to be discovered. Here we argue that PBO capabilities are uniquely suited to addressing several major issues and outline a specific deployment plan to address them.

Obtaining a detailed spatially (and temporally) unbiased mapping of the current deformation field is an important priority of PBO that would contribute crucially towards solving each of the 3 problems outlined in the previous section of this proposal. In the B&R an integrated program of both dense campaign GPS networks and carefully sited permanent GPS arrays are needed to achieve this observational objective. Here we propose 60 new CGPS sites (Fig. 1) supported by a ~200 site augmentation of existing SGPS networks (Fig. 2).

Rationale for Deployment

Because of the size of the Province (~800 km east-west and at least 600 km north-south) and the observed localization of deformation into narrow (sometimes < 50-km-wide) zones, many GPS stations are needed to adequately sample the deformation field. Initial results from both campaign and continuous networks show the field is spatially inhomogeneous, so not all areas need be sampled with equal density. Nonetheless, PBO resources are inadequate to monitor the whole province with permanent sites, and we recommend establishment of a campaign network of ~400 SGPS stations in the region. This can be accomplished in part by building on current networks of the USGS, National Geodetic Survey (NGS), University of Nevada Reno (UNR), and University of Idaho (UI) with repeated or initial epoch measurements of ~200 sites that are supported by other programs. Additional needed sites, about 200 in all, can be established and resurveyed using PBO's pool of 100 new receivers earmarked for campaign GPS measurements.

Several considerations indicate that campaign networks alone will be inadequate to address the major objectives of PBO in the B&R. **First**, the precision of campaign measurements will be insufficient to measure low strain rate deformation (~10 ns/yr or less) that may characterize significant parts of the Province. Reconnaissance geological studies [e.g. DePolo, 1998] indicate that at least 50 range front faults in Nevada slip at rates of ~0.2 mm/yr, and though these may be individually difficult to characterize via GPS, collectively they may take up an important proportion of B&R extension. Results from a ~100-km-station-spacing continuous network [Bennett et al., 1998] suggest such distributed deformation, and a six year span of campaign measurements from adjacent sites [Thatcher et al., 1999] is not sufficiently precise to confirm or refute the existence of this low rate deformation field. **Second**, some of the current GPS deformation field may be contaminated by transients related to 20th century earthquakes on the CNSZ [Wernicke et al., 2000]. Between 1915 and 1954 a ~250 km-long zone ruptured completely but for a 40-km-long segment ('Stillwater gap') that probably last slipped ~300 years ago (J. Caskey, personal communication, 2000). Since average repeat times for such large CNSZ earthquakes may be 10 ka, there is a strong possibility that postseismic transients still persist, though their magnitude and spatial distribution are uncertain. CGPS measurements made over the likely ~20-year lifetime of PBO may well be capable of detecting the expected subtle decay of strain rates symptomatic of postseismic adjustment. Realistic model calculations (F. Pollitz, personal communication, 2000) suggest these transient velocities are ~1 mm/yr or less at present, but such perturbations would be significant contaminants of the steady state field in and adjacent to the CNSZ, where strain rate gradients are 50 ns/yr or less. At greater distances from the CNSZ such a transient could swamp out the more subtle steady-state signals.

Proposed Network

Figure 1 shows the locations of stations proposed for continuous GPS sites in the Nevada B&R. We suggest two quasi-linear arrays, one of 35 stations crossing all of north-central Nevada, and a second of 15 stations to the south and west. The main array has ~25 km station spacing except across the WLFZ and CNSZ, where it is densified to ~15 km. The second, shorter array has ~15 km spacing throughout. It traverses what is likely to be the most intensely deforming zone in Nevada and lies immediately north of where the Eastern California Shear Zone (ECSZ) (or southern Walker Lane to some) bifurcates into the central WLFZ and the CNSZ.

In addition, we propose ~10 additional sites, shown schematically on Fig. 1, aimed at determining the Euler vectors of suspected rigid sub-regions of the Nevada B&R. Precise specification of these sites depends upon first establishing if such regions exist, primarily relying on existing GPS data (much of which will mature within the next several years), and then locating stations aimed at best constraining Euler pole location and rotation rate.

All sites shown in Fig. 1 are approximate, but would be located to (1) meet the scientific goals enumerated above, (2) complement related synergistic activities (see below), and (3) conform to logistical realities. Depending on PBO scheduling, siting will also depend to some degree upon results of campaign GPS surveys to be completed in Nevada within the next several years (see next paragraph). These results may be expected to begin filling in the regional picture of current deformation and suggest refinements in CGPS deployment strategy.

Figure 2 shows known high quality survey-mode GPS network sites in Nevada and adjacent regions. Under the PBO banner we would plan to re-survey these sites (many have only initial epoch measurements to date) and to establish ~200 new ones that both fill in obvious gaps and densify coverage adjacent to the two CGPS profiles shown in Fig. 1. We emphasize that this SGPS work, much of it already supported by other programs, is not a major focus of this proposal but would provide essential underpinning for the CGPS deployments proposed here.

Related Proposals

Several other mini-proposals of which we are aware will put forward complementary deployment plans. Another proposal for the Nevada B&R emphasizes the unique advantages of this region for tracking relatively subtle, long-lived post-seismic transients from 20th century CNSZ earthquakes. One for the northern WLFZ proposes dense CGPS coverage to decipher the detailed kinematics of this extremely active region. A related proposal covering Utah describes a complementary network suggested for the Wasatch Fault Zone and adjacent regions. A Greater Yellowstone proposal includes stations covering not only the caldera but surrounding normal-faulted ranges both north and south of the Snake River Plain in ID and MT. A mini-proposal for instrumenting Cascade volcanoes includes a network to cover the Mt. Shasta-Medicine Lake region of NE California, crossing the northwestern extension of the WLFZ where B&R oblique extension merges with Cascade arc volcanism. We support each of these mini-proposals because they nicely complement the deployment proposed here and contribute importantly to addressing the 3 science goals described in the preceding section.

Synergistic Activities

As mentioned earlier, PBO deployments can only contribute a part of the effort needed to address and solve the major problems we outline. An important strength of our proposal for PBO resources is the parallel efforts now underway which complement a GPS measurement program.

First, **paleoseismic studies** are now underway or soon to be initiated on several range front fault zones. Three groups are committed to determining slip rates and earthquake histories on the CNSZ faults (M. Machette et al., USGS/Golden; J. Caskey, SF State U.; A. Ramelli and C. DePolo, NV Division of Mines and Geology). S. Wesnousky and students (UNR) are working on several ranges (Shoshone, Rubey, Shawawe) along the Interstate 80 corridor and in the central WLSZ. A. Friedrich (Caltech) is carrying out an integrated paleoseismic and surface exposure age dating project on the Cortez Range. J. Oldow (UI) is doing structural mapping and SGPS campaigns on the central WLSZ. Second, P. C. England and two entering graduate students (Oxford University, U. K.) are collaborating with USGS/Menlo Park on **DEM-based geomorphic modeling** of landscape evolution coordinated with site specific paleoseismic constraints and **lithospheric dynamic models** of extension consistent with GPS results. Third, the Seismological Laboratory of UNR operates the **Western Nevada Seismic Network (WNSN)**, which encompasses much of the most actively deforming parts of the Nevada B&R, providing precise micro-earthquake epicenter locations, fault plane solutions of larger events, and constraints on crust-upper mantle structure beneath the region. Fourth, **campaign GPS surveys** throughout the B&R done by many groups (USGS/Menlo Park, UNR, UI, NGS) and supported by diverse programs (NASA, NSF, USGS) provide an increasingly firm knowledge base upon which to construct PBO mini-clusters in the B&R. Finally, we will request **USArray deployment** in our study area, both to refine crust and mantle lithosphere seismic velocity and density structure and to provide basic information on earthquake hypocenters and focal mechanisms outside the span of the WNSN.

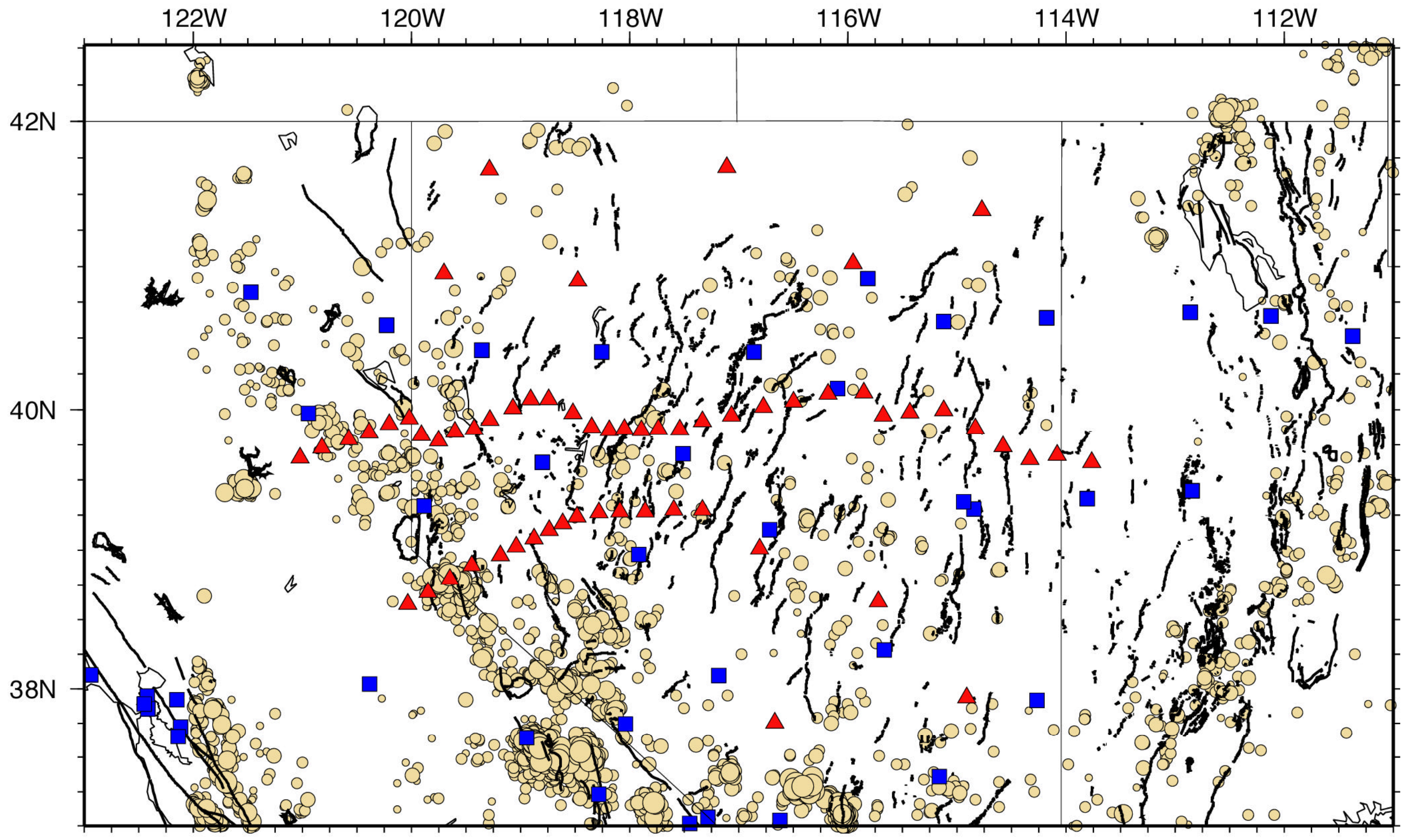

Fig. 1: Proposed continuous GPS sites (triangles), with active faults, earthquake epicenters (grey dots, size proportional to magnitude), and current CGPS sites (squares) in the region.

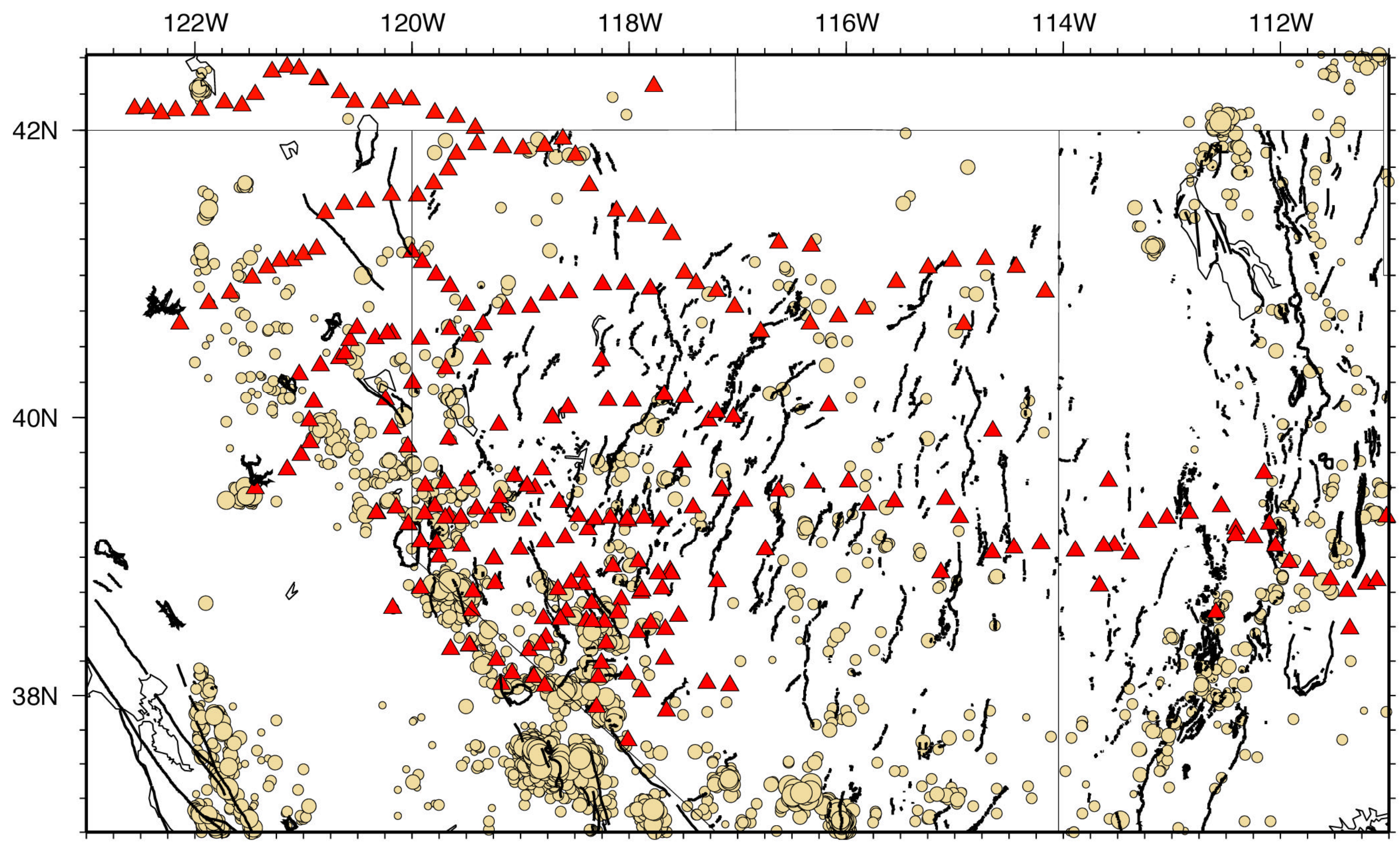

Fig. 2: Existing survey-mode(SGPS) sites (triangles), with active faults, earthquake epicenters (grey dots, size proportional to magnitude). The majority of the sites have been recently established. 200 additional SGPS sites (not shown) will be established to fill gaps and complement CGPS arrays shown in Fig. 1..