EarthScope and Natural Hazards Research

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Earth Science is always data limited, and a principal achievement of EarthScope will be a massively enhanced data acquisition capability. EarthScope aims to take advantage of recent technological developments in seismology, space geodesy, scientific drilling and instrumentation, and information technology to radically advance our capability to obtain the diverse data sets that are an essential prerequisite for multi-disciplinary Earth Science research. This avalanche of new data will fuel rapid advances in understanding active tectonics, earthquakes, and magmatic processes, capturing the public's imagination and delivering greatly improved assessments of earthquake and volcano hazards.

Research in natural hazard assessment is often thought to be very applied and nearly entirely empirical (even boring). However, while this work is firmly and appropriately observationally based, a strictly empirical approach is unlikely to lead to successful and informed hazard assessment. Instead, as I will show with four examples, addressing hazards questions requires an understanding of causative processes, mandating an research agenda that includes tasks ranging from applying state-of-the-art technology to developing theoretical models to explain the acquired data.

Using examples from 'EarthScope-like' data sets already in hand I will illustrate how, when integrated, these data contribute to earthquake and volcano hazard assessment and why we need to understand Earth processes to properly interpret and apply these observations. I also describe how implementation of EarthScope goals will greatly accelerate the progress in understanding necessary to achieve better hazard assessments.

Temporal Variations in Fault Slip Rates

Probabilistic earthquake hazard estimations depend strongly on well-determined slip rates on active faults. Both high precision geodetic measurements and careful geological studies can provide slip rate estimates. On fault zones where such rates have been obtained they sometimes agree within believed uncertainties (e. g. parts of San Andreas Fault system) and sometimes disagree (e. g. Basin and Range, B&R). Slip rates may vary over time scales ranging from tens of thousands of years to millions of years, as suggested by a recent synthesis of Wasatch fault zone rates [Friedrich et al., 2001]. Fault slip rates within the Great Basin estimated from geodetic, mostly GPS measurements made during the past decade generally appear to exceed Late Pleistocene and Holocene rates reported on the basis of geological analysis. Comparisons are available both for the strike-slip faults of the central Mojave Desert and Eastern California Shear Zone (ECSZ) and for normal or oblique slip faults of the Wasatch Fault Zone (WFZ), Walker Lane Fault Zone (WLFZ), and Central Nevada Seismic Zone (CMSZ). Differences reach a factor of 2 to 3 or greater. Causes of disagreement are uncertain. The discrepancy may be due to: (1) biases in the short-term geodetic record, for example due to 'fossil' effects of post-seismic relaxation from historical 19^{th} and 20^{th} century earthquakes; (2) temporal changes in slip rate during late Quaternary and Holocene time; or (3) incompleteness of the geologic slip rate data set in the Interior Western U.S. Each explanation has strengths but each has significant shortcomings. EarthScope, through continuous GPS deployments across the B&R (PBO) and geological investigations of young faults ('GEO-PBO') will directly address this slip rate dilemma, eventually providing the observations upon which appropriate slip rate estimates can be applied to earthquake hazard assessment.

Episodic Magmatic Deformation and Eruption Prediction

The emplacement of magma at depth and its migration towards Earth's surface produces measurable surface deformation and so tracking surface motions in space and time is a promising method for obtaining advance warning of impending eruptions. The unique capability of InSAR to provide complete areal mappings of surface displacements permits high resolution imaging of the magmatic and hydrothermal sources of deformation (the plumbing system) that lie beneath active volcanoes. This imaging gives estimates of the depth and geometry of these sources and vital clues to the physical processes that can lead to explosive eruptions. However, recent InSAR mappings of deformation around active magmatic systems have shown that episodic movements are occurring at even nominally dormant volcanoes.

These observations raise important questions about magma supply rate and the relative importance of magmatic and hydrothermal sources of deformation that must be addressed before surface displacement measurements can be confidently applied to eruption prediction. Furthermore, InSAR imaging alone is unlikely to provide the complete characterization of active magmatic systems necessary for forecasting eruptions. Within the U. S., synergies with PBO would provide this necessary ground complement of continuous GPS recording and borehole strainmeter arrays near 5-10 active magmatic systems. The unique role of InSAR would then be to provide long-term perspectives on current activity and periodically updated high resolution images of magmatic unrest in the buried roots of the volcanic plumbing system. In addition, monitoring of seismicity and determining crust and upper mantle seismic velocity structure using USArray deployments would augment the 'site characterization' for each PBO cluster necessary for identifying magma reservoirs and following the ascent of magma towards the Earth's surface. Recent work using dense broad band seismic arrays to invert for the moment tensors of very long period (VLP) seismic events suggests a further complement to deformation monitoring with PBO clusters.

Transient Postseismic Deformation and Earthquake Hazards

Stress changes that accompany earthquake faulting trigger aftershocks and can influence subsequent seismicity for many decades. However, the time-dependent component of stress transfer is poorly understood, limiting the confidence with which the long term stress transfer effects of large earthquakes can be quantified and applied to estimate future earthquake hazard. Crustal deformation measured in the months, years and decades following large earthquakes potentially provides crucial constraints on the long term stress transfer process, but until now progress has been slow. The increasing deployment of continuous GPS (CGPS) networks and the availability of InSAR mappings of post-earthquake deformation are changing this.

Pollitz et al. [2001] have recently shown how the combined use of GPS and InSAR data from the 9 months after the 1999 M=7.1 Hector Mine, California earthquake constrains the pattern, timing, and mechanism of transient deformation in the central Mojave Desert of Southern California. Their results were surprising in several ways. First, the InSAR mappings showed a long wavelength (~30 km scale length) movement pattern centered on the earthquake fault that required an upper mantle depth for the source responsible for surface motions. The surface deformation was well matched by viscoelastic ductile flow in the uppermost mantle and could not be explained by aseismic fault slip at depths greater than the rupture plane of the 1999 earthquake. Furthermore, the time decay of the transient motions observed both with CGPS and InSAR snapshots require that the ductile flow follow a non-linear relation between stress and strain rate that has long been expected from laboratory experiments on flow of rocks with olivine mineralogy. New observations in the years ahead, particularly those from CGPS stations of the SCIGN network, will place further constraints on the time scale and pattern of decay of transient motions towards the background, steady state deformation field. Both observations and models will serve to estimate the transfer of transient stress changes to adjacent faults of the region, both advancing understanding of this elusive process and contributing to earthquake hazard assessment.

EarthScope observations in the central Mojave and elsewhere will amplify on and refine our understanding of transient deformation. The potential role of lateral variations in lithospheric structure and rheology, and its relation to seismic velocity structure can be addressed through USArray deployments and seismic imaging of crust and upper mantle beneath the Mojave Desert. Denser CGPS station coverage planned in PBO will constrain possible along fault stress transfer on the central Mojave fault zone. Greatly improved accuracy, resolution, and repeat frequency of InSAR imaging of postseismic transients will provide unprecedented detail on transient movements from future earthquakes in many regions of the world, both deepening our knowledge of transient processes and sampling its likely variability in differing tectonic settings. And all of these advances in mechanistic understanding will feed back into better assessments of time-dependent earthquake hazard.

Structure, Tectonics and Earthquake Hazard in Los Angeles Basin

The Los Angeles (LA) Basin is underlain by thrust faults that pose a major seismic hazard to the region (e. g. Dolan et al., 1995). Because many of the faults do not reach the Earth's surface (i. e. they are blind thrusts) and since slip rates are generally low, quantifying the hazard these faults pose is extremely difficult. Multi-disciplinary studies currently underway illustrate both the successes and the challenges posed in applying modern Earth science methods to address this societally important problem. These studies also illustrate how the enhanced capabilities of EarthScope would accelerate further progress.

Application of paleoseseismology, seismic imaging and space geodesy has clarified many features of LA Basin tectonics but raised several new questions. Geological studies of exposed faults and growing folds that lie above blind thrusts contribute to a growing body of evidence on late Quaternary and Holocene fault activity [Dolan et al., 1995; Rubin et al., 2000]. Detailed reflection-wide angle refraction studies are imaging mid-crustal structures that may define active steeply dipping faults [Fuis et al., 2001]. Establishment of the dense SCIGN array of CGPS sites across the basin is beginning to define the pattern of current elastic strain accumulation and suggest the location of the currently most active structures [Walls et al., 1998; Argus et al., 1999; Bawden et al., 2001]. Although many studies infer that steeply dipping thrust faults root into a ~flat mid-crustal decollement, evidence for such a structure remains equivocal. Space geodetic measurements (GPS and InSAR) have begun to map present day deformation but shown that because of large, unanticipated aquifer pumping and recharge effects it has proven very difficult to constrain the spatial distribution of the 4 +- 1 mm/yr of contraction across the Basin [Bawden et al., 2001].

EarthScope capabilities will permit further refinements in understanding of this nominally densely instrumented region. Focussed USArray experiments with the flexible array can build upon the LARSE 1 and 2 profiles and address major unanswered questions, especially those related to imaging of active faults in the mid and upper crust. GEO-PBO resources can be applied to obtain more and better constraints on deformation rates for geologically youthful structures, taking particular advantage of new and emerging dating techniques. Experience with the SCIGN deployment in the LA Basin suggests that even further densification is needed to meet its design objectives, taking particular advantage of better and more frequently repeated InSAR mappings to site GPS stations at locations free from aquifer pumping effects.

References

Argus, D. F., et al., Shortening and thickening of metropolitan Los Angeles measured and inferred using geodesy, Geology, 27, 703-706, 1999.

Bawden, G.W., W. Thatcher, R. S. Stein, K. W. Hudnut, and G. Peltzer, New constraints on tectonic contraction across Los Angeles after removal of groundwater pumping effects, Nature, 412, 812-815, 2001.

Fuis, G., et al., 2001.

Dolan, J. F., Prospects for large or more frequent earthquakes in the Los Angeles metropolitan region, Science, 267, 199-205, 1995.

Friedrich, A, M., B. F. Wernicke, N. A. Niemi, R. A. Bennett, and J. L. Davis, Comparison of geodetic and geologic data from the Wasatch region, Utah and possible implications for the spectral character of deformation at periods of ten to ten million years, J. Geophys. Res., submitted, 2001.

Pollitz, F. F., C. W. Wicks, and W. Thatcher, Mantle flow beneath a strike-slip fault: postseismic deformation following the 1999 Hector Mine earthquake, Science, 293, 1814-1818, 2001.

Rubin, C., e t al., Science, 2000.

Walls, C., et al., Escape tectonics in the metropolitan Los Angeles region and implications for seismic risk, Nature, 394, 356-360, 1998.