Workshop on Incorporating Geodetic Surface Deformation Data into UCERF3

Conveners | Kaj Johnson, Elizabeth Hearn, David Sandwell, and Wayne Thatcher

April 1-2, 2010

Kellogg West Conference Center and Lodge, Pomona, CA
Mountain Vista Room

Summary. The purpose of the workshop is to begin scientific consideration of how to incorporate GPS constraints on strain rates and fault slip rates into the next generation California earthquake hazard assessment ("UCERF3"). A principal outcome of the meeting will be (1) an assessment of secure science ready for UCERF3 applications, and (2) an agenda of new research objectives for SCEC in support of UCERF3 and related probabilistic hazard assessments.

The format of the workshop includes three topical sessions, with limited number of invited presentations scheduled and lots of open discussion time, and an evening poster session. Time is allotted for groups to discuss main scientific issues:

- Earthquake cycle deformation and influence of postseismic transients
- Strain rate map methodologies and issues
- Block modeling methodologies and GPS fault slip rate estimation
- Reconciliation of differing GPS fault slip and strain rate estimates

All participants were requested to submit poster presentation. A small number of short (~5 minute) presentations were solicited from the submitted poster abstracts. Actual (e.g. SCEC CMM4 GPS field) or synthetic test data sets were distributed prior to the workshop for modeling test cases. Kinematic and dynamical fault modelers, strain rate mappers, and block modelers thus were able to run their codes to supply outputs for discussion at the workshop.

Thursday, April 1, 2010

Introductory Remarks

08:00 Workshop goals, format, and desired outcomes (*Wayne Thatcher*)

08:20 Purpose of UCERF3 and potential role of space geodesy (*Ned Field*)

08:40 Questions and Discussion

Session 1. Strain Rate Mapping Methodologies and Issues

09:00 The science of constructing strain rate maps (Chair: *David Sandwell*)

09:30 Open Discussion

10:00 Selected Short Contributions – 5 minutes each

(*Bill Hammond, Bridget Smith-Konter, Jack Loveless, Zheng-Kang Shen, and Tom Herring*)

10:30 Break

10:45 Results of community modeling exercise (*David Sandwell*)

11:15 Open Discussion of community modeling results

Participants: *Thorsten Becker, Peter Bird, Andy Freed, Jack Loveless, Bill Holt, Sharon Kedar, Corne Kreemer, Rob McCaffrey, Fred Pollitz, Bridget Smith-Konter, Carl Tape, and Yuehua Zeng*

12:00 Lunch

Session 2. GPS Fault Slip Rate Estimation from Block Models

13:00 Block modeling overview (Chair: *Kaj Johnson*)

13:15 Fault geometry and elastic block models (*Brendan Meade*)

13:30 NeoKinema Model predictions for California strain and slip rates (*Peter Bird*)

13:45 Open Discussion

14:15 Selected Short Contributions – 5 minutes each

(*Laura Wallace, Takeshi Sagiya, Wayne Thatcher, Yuehua Zeng*)

14:45 Break

15:00 Selected Short Contributions – 5 minutes each

(*Rob McCaffrey, Bill Hammond/Jayne Bormann*)

15:15 Results of community modeling exercise (*Kaj Johnson*)

15:30 Open Discussion of community modeling results

16:00 Breakout sessions

- Effect of transients and elastic heterogeneity on earthquake cycle deformation
- GPS slip rate estimation: Secure science and new research directions
- Strain rate field estimation: Secure science and new research directions

17:00 Adjourn

18:00 Dinner

19:00 Poster Session (2 hours)

Friday, April 2, 2010

Session 3. Earthquake Cycle and Other Effects on Interseismic Deformation

08:00 How much do earthquake cycles effects influence geodetic estimates of stressing and fault slip rates? (Chair: *Elizabeth Hearn*)

08:30 Physics-based models of interseismic deformation: What physics is relevant? (*Yuri Fialko*)

09:00 Open Discussion

09:30 Selected Short Contributions – 5 minutes each

(*Gina Schmalzle, Brad Hager*)

10:00 Break

10:30 Results of community modeling exercise (*Elizabeth Hearn*)

Participants: *Eric Hetland, Brendan Meade, Bridget Smith-Konter, Kaj Johnson, Yuri Fialko, Elizabeth Hearn*

11:00 Open Discussion of community modeling results

11:30 Reports of breakout group chairs

- Effect of transients and elastic heterogeneity on earthquake cycle deformation
- GPS slip rate estimation: Secure science and new research directions
- Strain rate field estimation: Secure science and new research directions

12:00 Lunch

13:00 Invited Presentation: Geologic slip rate estimation (*Ray Weldon*)

13:30 Discussion: Geologic and GPS slip rates -- What next?

14:00 Wrap-Up Session: Directed Discussion (*Wayne Thatcher, Kaj Johnson, Liz Hearn, David Sandwell*)

- Next steps for reconciling strain rate maps
- Next steps for reconciling geodetic estimates of fault slip rate

15:00 Workshop Adjourn

15:30 Conveners meet to draft Workshop Summary (1.5 hours)

Submitted Abstracts

Limitations of strain estimation techniques from discrete deformation observations

S.C. Baxter, S. Kedar, J.W. Parker, F.H. Webb, S.E. Owen, and A. Sibthorpe

An interactive strain analysis tool was developed and used to study several common classes of model-free strain estimation techniques from geodetic deformation measurements. It is demonstrated that without a-priori knowledge of the full deformation field, highly structured artifacts persistently appear in the strain rate field at and above the spatial scale of the network that samples the deformation field. These artifacts may be impossible to distinguish from real features. This work shows that estimation techniques of the real, non-linear strain rate from a sampled deformation field, using standard linear techniques, lead to apparent spatial variations in the calculated strain rate field that are biased by spatial sampling and orientation of the sampling network with respect to the deformation field. While such aliased strain rate representations provide some gross representation of the underlying real strain rate field, they contain numerous small-scale artifacts. In the absence of a tectonic model, the interpretation of strain rate from heterogeneous networks is at best challenging and at worst so biased by the experimental set-up (i.e., the network geometry with respect to the underlying tectonic source) that the estimated strain rates are of limited direct use.

With current station distribution, strain rate analysis may be useful for the interpretation of large-scale features and their temporal evolution. It may also be cautiously used to visualize and interpret the spatial variability of the deformation field associated with a specific tectonic model. However, significant uncertainties in the strain rate remain, especially in areas of non-linear deformation rate. The current geodetic networks, although providing unprecedented coverage of tectonic deformation, are still too sparse to reliably depict strain rate features at the scale of the fault width and depth.

Approaches to using GPS in seismic hazard assessment in New Zealand

J. Beavan, L. Wallace, N. Litchfield, M. Stirling, R. Van Dissen, and J. Haines

For GPS velocities or strain rates to have an impact in present-day seismic hazard modeling they must be converted to a form that can be used in probabilistic seismic hazard assessment (PSHA). Converting the long-term motion and elastic strain accumulation measured by GPS to a set of earthquake sources that represent strain release is the main problem to be overcome. As one example, we are using interseismic coupling estimates from GPS to develop earthquake sources for the Hikurangi subduction thrust for the next version of the New Zealand (NZ) National Seismic Hazard Model.

GPS can be used to estimate long-term geological slip rates on faults through the use of elastic block models or by modeling the deformation pattern across individual faults. In NZ, we have integrated GPS velocities and active fault slip rates using an elastic block model approach, and with a few exceptions the slip rates at the block-bounding faults show good agreement between the two datasets. In some cases, the NZ GPS velocity field highlights regions where rates of deformation are higher than expected, which may indicate the presence of hidden or poorly characterized active faults.

A way to compare fault slip and GPS data on a regional basis, including both major and minor active faults, is to convert both to a common form. For each dataset we have calculated strain-rate averaged over the crustal thickness, and with spatial resolution equivalent to about the crustal thickness, using the Haines & Holt code in which the crust is represented by a thin shell approximation. The geodetic data consist of about 800 GPS velocity determinations, while the fault data consist of about 500 active faults whose style and slip rate have been determined by geological methods. Differences in the resulting GPS and geological strain-rate maps are due mainly to the presence of elastic strain in the GPS strain-rate field, but also indicate regions where there are inconsistencies between the GPS and geological data (or invalid assumptions in the model).

One potential approach to using the GPS strain accumulation field in PSHA is to remove from the GPS strain field the modeled elastic and long-term contributions from faults with well known slip rates and earthquake histories, and to use the residual strain field to constrain the background seismicity that is input to the PSHA (see also Wallace et al., this workshop). We will show a 'work in progress' example of how this might be used in NZ.

NeoKinema results for a simplified fault network in southern California

P. Bird

Kinematic finite-element code NeoKinema (v.2.4) was used to simulate neotectonic deformation of southern California, for a comparison test in SCEC's GPS/UCERF3 workshop. A simplified fault network of 87 linear segments and a GPS dataset of 789 southern California interseismic benchmark velocities (without covariance) was provided by organizer Kaj M. Johnson. Other data and modeling procedures were as in Bird [2009, JGR]: a F-E grid of 3985 elements was excerpted from that western US model, and velocities of its boundary nodes were taken from preferred WUS model GCN2008088. All runs used most-compressive horizontal principal stress azimuths from the World Stress Map. Most runs used geologic offset rates from statistical analyses of dated offset features from Bird [2007, Geosphere, Table 2] or Bird [2009, Table 4]. Locking depths were from Fault Model 2.2 of the 2007 Working Group on California Earthquake Probabilities [2008] or from Nazareth & Hauksson [2004]. A set of 50 runs showed that optimal NeoKinema weighting parameters are approximately (L0 = 5000 m, A0 = 1E8 m2, mu_ = 1.2E-15/s). The best composite model had RMSl misfits of 2.48 s for GPS, 2.78 s for geologic rates (weighted by segment potency), and 2.60 s for stress directions. (GPS misfits can be reduced below 1.88 s, but then stress-direction misfits rise above 4 s.) These misfit levels are higher than the ~1.8 s obtained by Bird [2009] for the western US as a whole; this may be because the southern California region is more complex, and/or because the fault network for this exercise is oversimplified. RMS rates of distributed permanent strain were also 2.6x higher (at 1.3E-15 /s = 4%/Ma), probably for the same reason(s).

Two end-member cases were then run with one dataset removed: one case had no GPS data; the other case had GPS data but all geologic offset rates set to 0±50 mm/a. Predicted fault offset rates in these cases were very similar; all 3 pairwise correlation coefficients are 0.9 or higher. This shows that NeoKinema is a robust estimator that works well with different data mixtures. Another interesting discovery was that deleting the geologic data did not improve the fit to the GPS data, nor vice versa. This indicates that available geologic and geodetic data are generally compatible in the southern California region, although they may suggest different slip rates for a specific fault segment when that segment is analyzed outside of its regional neotectonic context.

Spatially Varying Slip Rates on the Southern San Andreas Faults Reflect Fault Geometry and Interaction

M.L. Cooke and J. Herbert

Three-dimensional numerical models that incorporate the irregular shape of active faults within the San Andreas fault system show that slip rates are far from uniform along each fault segment. Depending on the degree of non-planarity of the fault surface and interaction with other faults, slip rates along the San Andreas at the Earth's surface can vary by 5 mm/yr within 10 km. The slip rates from our three-dimensional Boundary Element Method (BEM) models match well the geologic slip rates available at various sites along the San Andreas but do not match well some block model slip rate estimates. The BEM model predicted slip rates along the San Jacinto and faults of the southern Eastern California Shear Zone also match well many geologic slip rates. The San Andreas and San Jacinto Faults show a trade-off in strike slip rates with low slip rates regions of the San Andreas corresponding with high slip rates along the San Jacinto. Similarly dip slip. Building from the success of the geologic time-scale models, we develop three-dimensional interseismic models by prescribing slip rates from the geologic time-scale model below the locking depth on all active faults. The velocities of surface points show good match to many of the GPS stations in the region. Residuals may reflect heterogeneous basement rock properties, local inaccuracies in fault geometry or inaccurate tectonic boundary conditions. To explore the tectonic boundary conditions, we consider the potential effect of mantle downwelling below the San Bernardino Mountains.

Block Models of Walker Lane and Great Basin Tectonic Deformation, Slip Rates and Seismic Cycle Effects

W.C. Hammond, J. Bormann, S. Jha, G. Blewitt, and C. Kreemer

We have developed block models for the northern, central and southern Walker Lane and western Great Basin constrained by GPS from the regional continuous networks (e.g. EarthScope Plate Boundary Observatory) and our own semi-continuous GPS network, the Mobile Array of GPS for Nevada Transtension (MAGNET). These models combine data on the location of active faults and GPS velocity gradients to infer rates of slip on the faults. In this region numerous fault systems work to accommodate ~25% of the Pacific North/America relative motion through a complex pattern of dextral, normal and sinistral slip. The models portray the pattern of crustal deformation, but we find that because of the complexity of deformation there the final result depends significantly on the regularization of the inversion used to find the optimal slip rates. Additionally, postseismic relaxation from past historic earthquakes has a significant impact. We have used the VISCO1D software (Pollitz, 1997) to estimate the contribution from historic earthquakes in central Nevada, and southern California to the contemporary deformation field, and on the slip rates inferred in block models. In this presentation we compare and contrast the patterns of slip across different portions of the Walker Lane, and show the effect that our corrections for viscoelastic relaxation have on the final models.

Development of a Consensus Western North America Crustal Motion Field

T.A. Herring

We discuss and present a preliminary version of a consensus crustal motion field for western North America determined by combining the GPS secular motion (velocity) estimates from GPS analyses carried out by different groups. The current combinations include analyses from the Plate Boundary Observatory (990 sites), the

NASA Measures program (944 sites), SCEC CMM4 (885 sites), UCLA Western United States (1299 sites), University of Nevada, Reno (UNR) (1043 sites), US geological survey (1224 sites), Rensselaer Polytechnic Institute/MIT Pacific North West (548 sites), and Natural Resources Canada North America and Canadian Reference solutions (182 and 69 sites). When all fields are combined, in Western North America, there are 2078 unique secular motion estimates with horizontal velocity uncertainties less than 2.0 mm/yr and 1226 sites with uncertainties less than 0.5 mm/yr. In this poster, we examine the input velocity fields, and the methods used to combine the fields, estimate uncertainties, and account for non-secular motions in the data sets. Collaborators in submitting fields and reaching consensus include Danan Dong (JPL); Zheng-Kang Shen (UCLA); Corne Kremer and Geoff Blewitt (UNR); Jerry Svarc and Wayne Thatcher (USGS); Rob McCaffrey (RPI)/Robert King (MIT); and Michael Craymer (NRCan).

GPS Strain Rates, Optimal Fault Slip Rates, and Predicted Moment Rates in Western U.S. Plate Boundary Zone

W.E. Holt, E. Klein, and L.M. Flesch

We invert GPS observations to obtain an estimate of the continuous velocity gradient tensor field throughout the plate boundary zone of Western U.S. Given the strain rates within a selected volume we then calculate the best-fit fault geometry (strike, dip and rake) that accommodates the minimum moment rate. A fault locking depth must be assumed and we adopt a simple uniform locking depth model of 15 km throughout the plate boundary zone. Given the assumed locking depth, it is also possible to infer the fault slip rates. We present results obtained to date using the SCEC 4.0 velocity field, EarthScope PBO observations, and campaign observations.

Preliminary strain results from 3D continuum mechanics models (FLAC3D) of the San Andreas Fault System

B.P. Hooks and B.R. Smith-Konter

We report preliminary results from three-dimensional mechanical models of the Pacific-North American plate boundary designed to reproduce the strain and vertical displacement associated with long-term (10,000 years) motion along the San Andreas Fault System. These models rely upon a continuum mechanical treatment modified by the inclusion of discontinuities based upon the location of major faults. The solutions were completed using a commercial finite difference software package (Itasca, 2006; Fast Lagrangian Analysis of Continuum; FLAC3D) that solves for large strains using applied stress or velocity conditions. A non-associated strain-weakening plasticity that allows for localization of strain is used for the model crustal rheology. Gridded and smoothed Plate Boundary Observatory horizontal velocities are applied to the base of the model and dynamically drive all deformation. Model discontinuities behave according to the Coulomb sliding criteria and are assigned representative fault frictional properties. The role of topographically generated vertical shear and normal stresses are determined through the inclusion of gridded topographic model derived from a published dataset. Preliminary results reproduce stress accumulation and strain rates along major strands of the San Andreas Fault System and vertical deformation patterns are reproduced for most of model, with noted anomalies along the creeping segment and within the Salton Sea area. We continue to analyze initial and boundary conditions to generate model results that better reproduce the observed deformation patterns. Future models will include dipping faults, fluid pore pressures, and a temperature dependent rheological model. Our ultimate goal is to develop a model that reproduces the vertical deformation observed within southern California constrained by short-term tide gauge (100 years) and longer-term (>1000 years) geologic markers.

Inferring locked and creeping areas of major faults in southern California with a visceolastic earthquake cycle model

K. Johnson and R. Chuang

We examine how well we can resolve locking and creeping areas of faults using geodetic data and a viscoelastic earthquake cycle model. Our model consists of fault-bounded blocks in an elastic crust overlying a Maxwell viscoelastic lower crust and uppermost mantle. It is a kinematic model in which long-term motions of fault-bounded blocks is imposed. Interseismic locking of faults and associated deformation is modeled with steady back-slip on faults and imposed periodic earthquakes. We discretize the San Andreas and San Jacinto faults into many small rectangular patches and assume that faults are either locked between earthquakes (and rupture periodically during earthquakes) or creep at constant resistive stress. The patches are assigned a binary parameter to specify whether the patch is locked or creeping. We solve for the binary parameters on patches and fault slip rates using a probabilistic Monte Carlo method (Fukuda and Johnson, 2010).

We conduct a resolution test to determine how well locked and creeping areas are resolved. The spatial distribution of creeping and locked regions in the upper 12 km is resolved but the depth of locking is often not well resolved. A comparison of the inversion method using the viscoelastic cycle model and an elastic half space model shows that the inversions of real data and synthetic data with the elastic model systematically favor deeper locking depths on southern California faults than the viscoelastic cycle model. Locking depths of 8-12 km are inferred from earthquake cycle models for the San Andreas and San Jacinto faults while deeper locking depths of 12-25 km are inferred from elastic models.

Impact of fault system geometry and interaction on slip and stressing rates in southern California

J.P. Loveless and B.J. Meade

In southern California, the relative motion between the Pacific and North American plates is accommodated across a ~200 km wide fault system. We simultaneously estimate micro-plate rotations, fault slip rates, elastic strain accumulation rates, and spatially variable coupling on fault surfaces using a block model, based on the SCEC rectilinear Community Fault Model geometry and GPS data combined from six networks. We use the catalog of derived fault slip rates to analytically calculate stressing rates on the San Andreas fault (SAF) from Parkfield to south of the Salton Sea. We compare resolved shear stress rates resulting from slip on all fault segments in the block model (“total stress”) to those due to slip on only SAF segments (“self stress”). Differences between total and self stress rates of up to 200% exist where the SAF intersects other faults; such differences are expected given abrupt along strike changes in SAF slip rate that occur at these fault junctions. However, differential stress rates of nearly 40% are maintained along the Mojave and San Bernardino segments of the SAF, indicating that fault network interactions play a significant role in dictating stress accumulation. We compare stressing rates to paleoseismic records and find a positive correlation between the number of events rupturing the Mojave-San Bernardino segments and the differential stressing rates, suggesting that fault system interactions influence long-term patterns of macro-seismicity. Specifically, slip on neighboring faults results in increased SAF stressing rate that may allow large earthquakes to rupture these segments more frequently than the more isolated Carrizo and Indio segments.

We also demonstrate a new algorithm for investigating the activity and interaction of closely spaced faults in regions such as the Eastern California Shear Zone (ECSZ). By starting with a block model geometry that includes representations of all mapped faults in the ECSZ and systematically perturbing the geometry by removing one or more structures, we construct covariance matrices indicating the influence that including one structure in the model has on slip rates estimated for all other faults. This "knockout" algorithm provides a means for assessing 1) which faults play the most important roles in accommodating interseismic deformation and 2) how the inclusion or exclusion of a particular structure affects the partitioning of deformation throughout the fault system.

Interseismic Deformation along Finite and Intersecting Faults: Application to the Los Angeles and Ventura Regions, CA

S.T. Marshall, M.L. Cooke, and S.E. Owen

The block modeling approach is commonly utilized to model plate boundary deformation along a network of interconnected faults in southern California. However, in the greater Los Angeles and Ventura regions, the assumption of interconnected faults is irreconcilable with abundant geologic and seismologic data suggesting a geometrically-complex network of finite faults. To better simulate the mechanics of the finite and intersecting faults of the greater Los Angeles and Ventura regions, we have developed a two-step Boundary Element Method (BEM) implementation that evokes similar assumptions to traditional elastic block models, but does not require interconnected fault surfaces and allows fault surfaces to mechanically interact. In the first step, geologic deformation is simulated (coseismic + interseismic) by allowing the entirety of the fault surface to freely slip. Then, to simulate interseismic deformation, fault slip resulting from the geologic model is prescribed as sub-seismogenic crustal creep along faults with the seismogenic portions of faults locked. This workflow effectively reproduces the classic dislocation models of Savage and Burford. A distinction of this approach is that unlike interseismic models that prescribe geologic slip rates on faults or models that invert for slip, we will first develop a geologic timescale model to determine secular fault slip rates and distributions that are mechanically compatible with regional tectonic deformation and then use these slip distributions to drive interseismic deformation. We apply this technique to the Los Angeles and Ventura regions and find that geologic model results match well geologic slip rate data and interseismic model results match well heterogeneous GPS velocity patterns. Because model predicted rates of convergence match well geodetic rates with geologically reasonable fault slip rates, short term geodetic and long term geologic shortening rates are likely compatible.

Seismic Hazard in Western Canada from Global Positioning System vs. Earthquake Catalogue Data

S. Mazzotti

Probabilistic seismic hazard analyses are principally based on frequency-magnitude statistics of historical and instrumental earthquake catalogues. This method assumes that return periods of large damaging earthquakes (100s–1000s yr) can be extrapolated from 50-100 yr statistics of small and medium earthquakes. The method has obvious limitations when applied to areas of low-level seismicity where the earthquake statistics may be poorly constrained. In this study, we test an alternative approach to assess seismic hazard in Western Canada. We use horizontal velocities at ~250 Global Positioning System (GPS) sites in BC and Alberta to calculate strain rates and earthquake statistics within seismic source zones. GPS-based strain rates are converted to seismic moment, earthquake frequency-magnitude statistics, and seismic hazard using a logic-tree method. The GPS-based earthquake statistics and seismic hazard are then compared to those derived from the earthquake catalogue. In one zone (Puget Sound), the GPS seismic hazard estimates are in good agreement with those from earthquake statistics. In nearly all other zones (e.g., most of BC and Alberta), the GPS seismic hazard estimates are significantly larger than those from the earthquake catalogue by one or two orders of magnitude. This discrepancy could indicate that the earthquake catalogue significantly under predicts long-term seismic hazard in areas of low-level seismicity. Alternatively, significant aseismic deformation may occur over long time-scales, which would imply that the GPS strain rates over predict the true seismic hazard. We discuss the nature and limitations of both methods in light of our results for Western Canada, with the goal of defining a method to incorporate GPS strain rate data into probabilistic seismic hazard assessments.

Southern California Block Model Incorporating GPS, Fault Rates and Earthquakes

R. McCaffrey

The Southern California SCEC GPS/UCERF3 test block model is analyzed using the program DEFNODE (www.rpi.edu/~mccafr/defnode) and the distributed SCEC GPS velocity field along with geologic information on faults and slip vectors from crustal earthquakes. The inversion solves for the locking depths on faults and the angular velocities of a set of blocks separated by the faults. The test crustal block model is modified from McCaffrey (2005; JGR B07401) and the fault and earthquake data used here are a subset of those used in that paper. In addition to the prescribed test case based on GPS velocities alone (that will be compared to other such inversions), I also compare joint inversions that include fault/earthquake slip information with the GPS and fault/earthquake slip information alone. When the 76 fault slip data and 54 earthquake slip vector data are used alone, the normalized rms (Nrms) misfits of both are near unity and the GPS are fit poorly (GPS Nrms = 14.2; using GPS alone the GPS Nrms = 3.6 after culling the GPS velocities to remove the 22 largest misfits). This suggests that the GPS and chosen slip data and uncertainties are not simultaneously compatible with the test block model. Using all three data types together resulted in model parameters similar to the GPS-only case (as expected given the number of data) and Nrms of slip rate and slip vector data degraded to 2.0 and 3.0, respectively. The incompatibility may be explained by an incorrect block model, incorrect data and/or uncertainties, or that the GPS and geologic information span time ranges that are too different.

New GPS Observations to Constrain Deformation Patterns on Faults in the Northern San Andreas System and the Central California Coast Region

J.R. Murray-Moraleda and J. Svarc

Although the UCERF2 earthquake probability estimates are based on a comprehensive and varied collection of observations and interpretations, there are still many potential earthquake sources that are relatively poorly characterized. In the work presented here we target such faults in two areas, the northern San Andreas system and the central California coast region, by undertaking focused GPS data collection and modeling to better constrain the style and rate of deformation in these areas. The results of these studies will provide useful new information for future probabilistic hazard assessments.

The UCERF2 slip rates and aseismic slip factors for the Maacama, Bartlett Springs, and Hunting Creek-Berryessa faults, for which the expected maximum earthquake magnitude is greater than M 7.0, have been assigned largely based on extrapolation of rates from their southerly extensions (e.g., the Hayward-Rogers Creek or Concord-Green Valley faults). However, the degree of segmentation that characterizes these faults, their slip rates, and the rates and spatial extent of creep are poorly understood. We have established spatially-dense networks of campaign GPS sites along the Green Valley/Berryessa/Hunting Creek, Bartlett Springs, and Maacama faults. Data from these arrays will be modeled jointly with more broadly-spaced data from continuous GPS sites and near-fault data from alinement arrays to better characterize slip rates, fault creep, and segmentation.

The central California coast region, from the vicinity of the San Simeon earthquake epicenter southward to Point Conception, is a complexly deforming and seismically active zone for which few measurements of deformation rates had been made. We are developing a densified GPS velocity field for this region, leveraging data from continuous sites, campaign GPS measurements in archives, new campaign GPS data, and observations from several semi-permanent GPS sites we established for this project. These data will be used in combination with a variety of other geophysical observations to identify actively deforming structures, elucidate how strain is partitioned between shear parallel to the San Andreas fault and contraction perpendicular to other regional faults, test thick-skinned and thin-skinned crustal models, and investigate deformation of the central coast in the context of broader-scale deformation of the San Andreas system.

A seismic Risk Model for the Marmara Sea Region, Turkey

M. Nyst, T. Onur, and P. Seneviratna

Our seismic risk for Istanbul and the Marmara Sea Region in Turkey consists of 3 modules: 1) a seismic source model, 2) a ground motion model, and 3) a vulnerability model. Active crustal faults and background seismicity are the main components of the seismic source model. To generate hazard maps this source model is combined with a ground motion model that consists of a weighted scheme of local Turkish (i.e., Kalkan & Gülkan, 2004) and global ground motion models (Next Generation of Ground-Motion Attenuation (NGA) Models, developed for the western US, but showing good results in Turkey).. Using an exposure layer that represents the economical residential building stock in Istanbul and consists of concrete multi-story buildings, examination of probable maximum loss estimates and damage ratio maps gives insight into the key drivers of risk across the region.

We consider several individual versions of the seismic source model, before combining the source models in a logic tree approach. Keeping the ground motion and vulnerability components constant while varying the input data for the source model will help us understand the impact of different data types on earthquake risk in the Istanbul area: 1) Geological time-independent and time-dependent (i.e., Kalkan et al., 2009; Parsons et al., 2003) slip rates on active crustal faults and background seismicity based on the historical seismic catalog, 2) Slip rates on boundaries from block model studies calculated from GPS data (Aktug et al., 2009), 3) Smoothed strain rates on area sources calculated from GPS data (Aktug et al., 2009).

Fault system behavior of the Eastern California shear zone: Unsteady loading rates and clustered earthquake activity

M. Oskin

Clustering of major earthquakes over periods of years to decades is observed historically and in paleoseismic records. Seismic hazard forecasts may be improved by identifying a cluster in-progress and its relationship to fault loading processes. I present long-term (ca 50 kyr) fault slip-rates from the Eastern California shear zone (ECSZ), where both paleoseismic and historic earthquake clusters are recognized, to test if the interseismic loading rate is transiently elevated during the present cluster of activity. The sum of six fault slip rates that average a few to several tens of earthquakes is less than or equal to 6.2±1.9 mm/yr. This long-term rate is only half the present-day loading rate of 12±2 mm/yr across the 60 km-wide shear-zone. This discrepancy began prior to the 1992 Mw 7.3 Landers earthquake, and its magnitude precludes residual post-seismic deformation following other large historic earthquakes in southern California. These observations support that significantly elevated regional strain accumulation rate may be characteristic of clustered earthquake activity, and that interseismic loading may oscillate between different fault sets within a hierarchal fault system.

Where is the real transform boundary in California?

J.P. Platt and T.W. Becker

An intriguing aspect of the geodetically defined velocity field in California is that the zone of highest strain-rate is not centered on the surface trace of the San Andreas fault (SAF). In southern California it is centered between the SAF and the San Jacinto Faults, and north of the San Francisco Bay area it lies as much as 40 km E of the SAF. To determine whether this reflects the pattern of long-term, permanent deformation, we analyzed the velocity field on swaths across the transform, located so as to avoid intersections among the major fault strands. Slip rates and flexural parameters for each fault were determined by finding the best fit to the velocity profile using a simple arctan model, representing the interseismic strain accumulation, and the uncertainties were estimated from the trade-off between the locking depth and the slip rate. We show that slip rates estimated in this way compare well within uncertainties with neotectonic (1 – 100 ky) estimates, which suggests the present-day velocity field is representative of long-term motions. We suggest that the present-day velocity field is therefore reasonably representative of the long-term field, and that it provides an image of the long-term response of the continental lithosphere to relative plate motion.

We find that the transform is a zone of high strain-rate up to 80 km wide that is straighter than the SAF, and has an overall trend closer to the relative plate motion vector than the SAF. Most sections of the SAF take up less than half of the total slip rate, and slip is transferred from one part of the system to another in a way that suggests the SAF should not be considered as a unique locator of the plate boundary. Up to half of the total displacement takes place on faults outside the high strain-rate zone, distributed over several hundred kms on either side. Our findings substantiate previous suggestions that the transform has the characteristics of a macroscopic ductile shear zone cutting the continental lithosphere, around which stress and strain-rate decrease on a length scale controlled by the length of the transform and the bulk rheological properties of the lithosphere.

On the resolution of shallow mantle viscosity structure using post-earthquake relaxation data: Application to the 1999 Hector Mine, California, earthquake

F. Pollitz and W. Thatcher

Most models of lower crust/mantle viscosity inferred from post-earthquake relaxation assume one or two uniform-viscosity layers. A few existing models possess apparently significant depth-dependent viscosity structure in the shallow mantle, but the resolution of such variations is not clear. We use a geophysical inverse procedure to address the resolving power of inferred shallow mantle viscosity structure using post-earthquake relaxation data. We apply this methodology to nine years of GPS-constrained crustal motions after the 16 October 1999 M=7.1 Hector Mine earthquake. After application of a differencing method to isolate the post-earthquake signal from the 'background' crustal velocity field, we find that crustal velocity diminishes from ~ 20 mm/yr in the first few months to <~ 2 mm/yr after two years. Viscoelastic relaxation of the mantle – with a time-dependent effective viscosity prescribed by a Burgers body – provides a good explanation for the postseismic crustal deformation, capturing both the spatial and temporal pattern. In the context of the Burgers body model (which involves a transient viscosity and steady-state viscosity), a resolution analysis based on the singular value decomposition reveals that, at most, two independent constraints on depth-dependent steady-state mantle viscosity are provided by the present dataset. Uppermost mantle viscosity (depth <~ 80 km) is moderately resolved, but deeper viscosity structure is poorly resolved. The simplest model that explains the data better than that of uniform steady-state mantle viscosity involves a linear gradient in logarithmic viscosity with depth, with a small increase from the Moho to 220 km depth. However, the viscosity increase is not statistically significant. This suggests that the depth-dependent steady-state viscosity is not resolvably different from uniformity in the uppermost mantle. This carries implications for the use of viscoelastic models to correct the GPS-derived interseismic velocity field for the perturbing effects of significant past earthquakes.

Consistency and mostly inconsistency between geodetic and geologic fault slip rates in central Japan

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We have been conducting dense GPS observation around several active fault zones in the Japanese mainland to investigate detailed crustal deformation pattern as well as tectonic loading process of inland active faults. These observations demonstrate consistency and inconsistency between geodetic and geological slip rates.

GPS results around the Itoigawa-Shizuoka Tectonic Line fault system, central Japan, demonstrate significant lateral heterogeneity in the deformation pattern along the fault trace. The Gofukuji Fault in the central part shows a typical arctangent type displacement pattern across the fault trace representing a left-lateral strike slip motion. Estimated fault slip rate is about 7 mm/yr, consistent with the geological value. On the other hand, highly concentrated fault normal compression is apparent around the Kamishiro fault in the northern part. Along this fault segment, E-W contraction of ~10mm/yr is accommodated within only 5km from the fault trace, implying a possibility of aseismic fault creep in the shallow part of the fault. This conjecture seems incompatible with geological investigation result because evidence of dynamic rupture has been found but no surface fault creep has been detected. On the other hand, around the Atotsugawa fault system, we detected right-lateral motion of about 10mm/yr and convergence of a few mm/yr across the fault trace. The sense of the deformation is generally consistent with the geologic feature, but the displacement rate is a few times larger than the geologically estimated fault slip rate.

Block-fault modeling of regional GPS data also indicates that fault slip rates at block boundaries mostly overestimate geologic values.

These results indicate significant contribution of inelastic deformation in accommodating relative motion around fault zones. Inconsistency becomes more prominent around where significant contraction occurs across the fault. Such inelastic deformation may account for a long-lasting controversy about the strain rate of the Japan Islands that the geodetic strain rate is larger than the geologic one by an order of magnitude. But the deformation mechanism responsible for this inconsistency has not been resolved and more studies are needed.

Temporal Evolution of Faults: An Example from the Eastern California Shear Zone

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The Eastern California Shear Zone (ECSZ) is a relatively young (<10 Myr) system of sub-parallel strike-slip faults including the White Mountain – Owens Valley – Airport Lake fault zone to the west, the central Saline Valley – Hunter Mountain – Panamint Valley fault zone, and Fish Lake – Furnace Creek – Death Valley fault zone to the east. Geologic data indicate that the Fish Lake – Furnace Creek – Death Valley fault system has been the major accommodator of shear throughout most of ECSZ history. A new, detailed Global Positioning System (GPS) velocity field spanning the ECSZ north of the Garlock Fault and south of Saline Valley indicates that the locus of maximum shear shifted westward. Elastic and viscoelastic coupling models are used to estimate slip rates of the three major strike-slip fault systems and solve for the position of maximum shear at depth. This study finds the maximum velocity gradient for the central fault zone occurs close to the Ash Hill Fault, a dominantly strike-slip fault west of the Panamint Valley Fault, part of a paired strike-slip - normal fault system, with the strike-slip fault being the dominant fault. The geodetic rate estimated on the Ash Hill – Panamint Valley – Hunter Mountain fault system using a series of viscoelastic half-space models is 5.5±0.6 mm/yr, assuming a viscosity of 1x1020 Pa s, a rigidity of 50 GPa, a Poisson's Ratio of 0.25 and an elastic layer thickness of 15 km. The Owens Valley and Death Valley fault rate estimates are 1.6±0.3 mm/yr and 2.9±0.4 mm/yr, respectively. The rate estimate for the Ash Hill – Panamint Valley – Hunter Mountain fault system is faster than geologic estimates (1.6 – 4 mm/yr). This result is interpreted to indicate a simplification of the ECSZ with time, combined with progressive westward migration of deformation.

Late Pleistocene-Holocene Slip Rates along the Denali fault system, Alaska

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The Denali fault system shares many similarities to the San Andreas in southern California. It extends ~1100 km from the Yukon Territory to western Alaska. Following the M7.9 2002 Denali fault earthquake slip rates studies have been conducted at seven locations along the Denali and Totschunda faults. The results of these, summarized below, are from Matmon et al. (2006). Piercing points include offset alluvial fans, inactive rock glaciers, and glacial moraines ranging in age from 2.4 ± 0.3 to 17.0 ± 1.8 ka based on cosmogenic 10 Be concentrations; offsets range from 25 to 170 m. These ages and offsets yield late Pleistocene-Holocene average slip rates a) on the Denali fault of 8.4 ± 2.2 (east of the Denali-Totschunda intersection and unruptured in 2002), 12.1 ± 1.7 (central 2002 Denali rupture segment), and 9.4 ± 1.6 mm/yr (between the 2002 epicenter and Denali National Park and unruptured in 2002) and b) on the Totschunda fault of 6.0 ± 1.2 mm/yr. The combined Denali-Totschunda slip rate of 14.4 ± 2.5 mm/yr and it's ~ 5mm decrease to the west reflects transpressive curvature of the Denali fault system resulting in shortening across it and partitioning of slip onto thrust faults to the north and west. Observations suggest slip rates during the sampling period have remained generally constant but this interpretation would benefit from additional mid-late Holocene slip rate values.

Derivation of horizontal strain rates from interpolation of geodetic velocity field

Z-K. Shen and Y. Zeng

We present an algorithm to calculate horizontal strain rate distribution through interpolation of geodetically derived velocity field. It is an under-determined inverse problem to derive smoothly distributed strain rates using discretizedly located geodetic observations. A priori information, in the form of weighted smoothing, is required to facilitate the solution. Our method is revised from our previous approaches (Shen et al., 1996, 2007). At a given location, the velocity field in its vicinity is approximated by a linear function and can be represented by a constant velocity, three strain rate components, and a rotation rate at that point. The velocity data in the neighborhood, after reweighting, are used to estimate the field parameters through a least-squares procedure. Data weightings are done with following considerations: (a) Data are weighted according to station azimuthal span measured between two strike directions from the point under consideration to its two flank neighboring sites. (b) A distance weighting factor is assigned according to station distances to the point, in the form of exp(-△2/σ2), where △ is the station distance, and σ is a decay coefficient. (c) The distance decay coefficient σ is optimally determined from a trade-off curve between the data postfit residual χ2 and the total data weighting factor W, where W is the sum of all the weighting factors under consideration. The last step is necessary because geodetic stations are usually unevenly distributed, and different degree of smoothing is needed according to the in situ data strength. We apply this method to derive the strain rate field for southern California from the SCEC CMM4 velocity field. Besides the strain rate field, we also show spatial distribution of the total weighting factor W, which is a measure of the local data strength and the amount of smoothing required for an optimal solution. We also add a feature in our code to exclude plastic strain rates associated with fault creeping from strain rate solution. It is done by setting up a barrier along the creeping section of a fault and blocking data from the other side of the fault from entering into the interpolation calculation.

Where GPS Block Models Are (And Are Not) Useful in Southern California

W. Thatcher and J. Murray-Moraleda

Modeling GPS velocity fields in seismically active regions worldwide indicates deformation can be efficiently and usefully described as relative motions among elastic, fault-bounded crustal blocks. These models are providing hundreds of new decadal fault slip rate estimates that can be compared with the (much smaller) independent Holocene (<10 ka) to late Quaternary (<125 ka) rates obtained by geological methods. Updated comparisons show general agreement but a subset of apparently significant outliers. Some outliers have been discussed previously and attributed either to a temporal change in slip rate or systematic error in one of the estimates. Here we focus particularly on recent GPS and geologic results from southern California and discuss four criteria for assessing the differing rates.

In southern California (and elsewhere), subjective choices of block geometry are unavoidable and introduce significant uncertainties in model formulation and in the resultant GPS fault slip rate estimates. To facilitate comparison between GPS and geologic results in southern California we use the SCEC Community Fault Model (CFM) and geologic slip rates tabulated in the 2008 Uniform California Earthquake Rupture Forecast (UCERF2) report as starting points for identifying the most important faults and specifying the block geometry. We then apply this geometry in an inversion of the SCEC Crustal Motion Model (CMM4) GPS velocity field to estimate block motions and intra-block fault slip rates and compare our results with previous work. </p>

In most parts of southern California, for example, north of the San Andreas Big Bend and SE of Los Angeles--our block geometry closely resembles that assumed in previous studies. In these regions GPS slip rates can be reliably estimated and values for individual faults generally agree from one study to another and are also consistent with geologic estimates. However, there is no consensus on block geometry in the Transverse Ranges, Los Angeles Basin and Central Mojave Desert, where CFM faults are densely distributed, UCERF2 slip rates on several faults are comparable, and a simple block description may not be useful. It is notable that a number of documented disagreements between GPS and geologic slip rates occur on faults in these complex deforming zones (e.g. central Garlock fault, Eastern California Shear Zone, Big Bend San Andreas), in part reflecting the substantial epistemic uncertainty in GPS rate estimates for these faults.

Incorporating GPS data into a probabilistic approach to assess rock deformation hazard in Japan

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We have developed a method to of using GPS data to estimate probabilistic rock deformation hazard. We will show results from the application of our method to northern and southwest Japan. The methodology is being developed to assess the likelihood of future long-term (i.e. 104 – 105 years) rock deformation at potential locations for deep geological disposal of high-level nuclear waste in Japan. In addition to assessing the possible future hazard of permanent rock deformation, this method may provide a practical means of incorporating GPS data into Probabilistic Seismic Hazard Assessment (PSHA).

Elastic strain related to interseismic coupling on the subduction zones surrounding Japan dominates the GPS-derived contemporary strain field there. To isolate crustal strain related to tectonic deformation occurring within the upper plate (which is of interest for rock deformation hazard), we use the block modeling method of McCaffrey (1995, 2002) to estimate the degree of interseismic coupling on the offshore subduction boundaries. We then subtract the velocities due to subduction interface coupling (from the block model) from the GPS velocity field, and use the strain mapping method of Haines and Holt (1993) and Beavan and Haines (2001) to map out the residual strain, which we assume is related to tectonic deformation in the upper plate.

To assess the epistemic uncertainty in our GPS derived strain rates, we have implemented a logic tree approach. For the northern Japan region, we conducted an expert elicitation with a panel of Japanese experts. With this panel, we developed a logic tree that resulted in 36 alternative tectonic block/fault coupling models, and 148 alternative GPS strain rate models. This suite of models produces a distribution of strain rate values for any given location in the case study region, and allows the estimation of the likelihood of exceedance of specific strain values for each location.

A similar approach to ours could be used in California. For example, modeling could be done to assess and remove the effect on the GPS velocity field of contemporary strain due to interseismic deformation on the San Andreas fault (and other well-known faults in the region), while the residual strains may be related to deformation on hidden or uncharacterized active faults. These residual strains can be converted to seismicity via the Kostrov equation, and then used in the seismic hazard model as input to the background seismicity model.

Geologic constraints on the slip rate of the Mojave San Andreas fault

R.J. Weldon

While much attention has focused on the apparent discrepancy between geologic and geodetic slip rates for the southernmost San Andreas fault, the greatest difference in geologic and geodetically inferred rates is on the Mojave portion of the fault. While there are a few published geologic rates as low as 20 mm/yr and as high as 50 mm/yr, a consistent case can be made for a slip rate of 30-35 mm/yr for a range of offsets that span a thousand years to 4.5 million. This rate is 10-15 mm/yr greater than published geodetic rates. The presentation will review the evidence from several key published studies and will present new evidence from 3 new unpublished sites that are currently being investigated.

A Kinematic Fault Network Model of Crustal Deformation for California and Its Application to the Seismic Hazard Analysis

Y. Zeng and Z-K. Shen

We invert GPS observations to determine the slip rates on major faults in California based on a kinematic fault model of crustal deformation with geological slip rate constraints. Assuming an elastic half-space, we interpret secular surface deformation using a kinematic fault network model with each fault segment slipping beneath a locking depth. This model simulates both block-like deformation and elastic strain accumulation within each bounding block. Each fault segment is linked to its adjacent elements with slip continuity imposed at fault nodes or intersections. The GPS observations across California and its neighbors are obtained from the SCEC WGCEP project of California Crustal Motion Map version 1.0 and SCEC Crustal Motion Map 4.0. Our fault models are based on the SCEC UCERF 2.0 fault database, a previous southern California block model by Shen and Jackson, and the San Francisco Bay area block model by d'Alessio et al. Our inversion shows a slip rate ranging from 20 to 26 mm/yr for the northern San Andreas from the Santa Cruz Mountain to the Peninsula segment. Slip rates vary from 8 to 14 mm/yr along the Hayward to the Maacama segment, and from 17 to 6 mm/yr along the central Calaveras to West Napa. For the central California creeping section, we find a depth dependent slip rate with an average slip rate of 23 mm/yr across the upper 5 km and 30 mm/yr underneath. Slip rates range from 30 mm/yr along the Parkfield and central California creeping section of the San Andres to an average of 6 mm/yr on the San Bernardino Mountain segment. On the southern San Andreas, slip rates vary from 21 to 30 mm/yr from the Coachella Valley to the Imperial Valley, and from 7 to 16 mm/yr along the San Jacinto segments. The shortening rate across the greater Los Angeles region is consistent with the regional tectonics and crustal thickening in the area. We are now in the process of applying the result to seismic hazard evaluation. Overall the geodetic and geological derived hazard models are consistent with the current USGS hazard model for California.