Summary of results
Comparing Mechanical and Geodetic Models of Los Angeles Basin Faults

The primary goal of this project was to evaluate the subsurface geometry of buried faults within the Los Angeles basin using geodetic data from SCIGN with continuum mechanics forward models. The funded research resulted in three products:

1) model generated dip and strike slip rates along a preliminary fault configuration of the Los Angeles Basin,
2) development of a methodology for assessing interseismic strain in regions of complex or intersecting non-vertical faults and
3) an evaluation of the interseismic strain accumulation within the basin from forward models and a comparison to SCIGN data.

The calculated slip-sense and magnitude of slip from the preliminary three-dimensional fault model closely match much of the available paleoseismic data. The close correspondence with paleoseismic is not considered significant beyond an indication that such models may be able to provide a reasonable estimate of the magnitude of slip on faults that are not exposed. The model also accurately captures relative movements along faults in this system, with several exceptions that provide insight into potential errors in the proposed subsurface fault geometry.

Within this study, we have developed an innovative methodology for estimated interseismic deformation within regions of complex or intersecting faults. This two-step method allows us to estimate interseismic surface velocities from the mechanical three-dimensional models of Los Angeles basin faults by estimating the long term secular velocities at the locking depth and simulating geologic creep of material below the locking depth using a horizontal crack. The incorporation of a horizontal crack weak in shear at the seismogenic locking depth permits any degree of fault complexity within the seismogenic crust. We tested the effectiveness of this method by simulating an isolated vertical strike-slip fault for which there are successful standard models for comparison. For the vertical strike-slip fault, the interseismic deformation using a horizontal crack matches well the standard methodologies.

This new method of estimating interseismic surface velocities was applied to the preliminary three-dimensional fault model of the Los Angeles Basin to compare with SCIGN data collected in the recent interseismic period. At this time the errors in the SCIGN velocities exceed the sensitivity of the model to changes in subsurface fault configuration.
Introduction

Our knowledge of slip rates along Los Angeles faults is constrained to limited paleoseismic observations [e.g. Clark et al, 1984, McNeilan et al, 1996, Grant et al, 1997], and indirect fault modeling efforts [Davis et al, 1989; Shaw and Suppe, 1996, Cooke and Kameda, in press]. Dip slip rates along buried faults in the Los Angeles Basin have been inferred from two-dimensional kinematic reconstructions using geometric rules [Davis et al, 1989; Shaw & Suppe, 1996] and from two-dimensional forward models based on continuum mechanics [Cooke and Kameda, in press]. Although the forward mechanical models based on kinematic reconstructions show promising correlation with paleoseismic observations in parts of the basin, these two-dimensional studies have not considered the important strike-slip component of deformation within this complex transpressional fault system. Additional data would help constrain three-dimensional fault configuration and slip rates; GPS data may provide constraints on three-dimensional models and so we test the ability of SCIGN to help resolve the fault configuration within the Los Angeles basin.

Our main goal is to evaluate the subsurface geometry of buried faults within the Los Angeles basin. We present our work to date on estimating fault geometry and slip rates by combining kinematic models of geodetic data from SCIGN with continuum mechanics models. SCIGN data gives us the deformation within the Los Angeles basin with unprecedented spatial resolution. However, even with this excellent data set, a fairly wide range of kinematic models will be consistent with the observed surface velocities [Johnson, 1995].

The funded research resulted in three products: 1) model generated dip and strike slip rates along a preliminary fault configuration of the Los Angeles Basin, 2) development of a methodology for assessing interseismic strain in regions of complex or intersecting non-vertical faults and 3) an evaluation of the interseismic strain accumulation within the basin from forward models and a comparison to SCIGN data.

Model generated dip and strike slip rates
A three-dimensional model of the fault configuration in the Los Angeles Basin is constructed (Fig. 1) based on previously published arrays of two-dimensional cross-sections [Davis et al., 1989; Oskin et al. 2000; Shaw and Suppe 1996; Wright, 1991], the California Geologic Survey (CGS) fault compilation and discussion with other workers in the region [Shaw, pers com and Dolan, per com]. This preliminary fault configuration may incorporate large deviations from subsurface structure. We hope that such deviations are evident from discrepancies between the model results and paleoseismic slip rates or SCIGN velocity data. The boundary element method numerical model POLY3D is used to assess the response of this fault configuration under horizontal contraction in an orientation derived from surface GPS observations [e.g. Feigl, 1993, Argus 1999], in order to simulate present-day deformation within the Los Angeles Basin. POLY3D utilizes angular dislocations assembled in triangular elements [Thomas, 1994], which allows simulation of complex non-planar fault surfaces rather than rectangular planes. Significant effort was made to smooth fault intersections and reduce unrealistic gaps and overlaps of elements within the model. In Poly3D, traction-free faults are simulated within an isotropic and homogeneous elastic half-space.

The sense of slip along modeled faults matches available paleoseismic data (Table 1) although the slip magnitudes within the model are generally less than paleoseismic estimates (Fig. 2). Significant disparities between the model results and larger paleoseismic values include: (1) reverse slip along the Puente Hills blind thrust faults (Upper Elysian Park, Los Angeles and Coyote Hills), (2) reverse slip along the northern-most portion of the Whittier fault, (3) strike-slip along the Raymond fault and (4) strike-slip along the Palos Verdes Fault. The potential sources of these discrepancies provide insight into probable errors in the proposed subsurface fault configuration.

With the exception of the Santa Fe Springs fault, all of the blind thrust faults of the Puente Hills system have less slip in the mechanical models than the paleoseismic estimates (Fig. 2). The preliminary fault configuration used in this study confines each of these thrust faults to the hanging wall of the Whittier fault (Fig. 1); however, the nature of the intersection of the Puente Hills thrusts and the Whittier fault is not constrained by existing data sets. If the blind thrusts continue to greater depth, offsetting the Whittier fault, the increased fault dip-length would yield greater reverse slip rates on the faults. Furthermore, although slip rates along the Santa Fe Springs fault would also increase with greater dip-length, the addition of the Montebello fault within the hanging wall of the Sante Fe Springs fault (not included in the preliminary model) may act to reduce the reverse slip. These questions are now being investigated in a project funded by SCEC2.

The paleoseismic reverse slip on the Whittier fault was observed at the northern-most portion of this fault and is not representative of average dip slip on the fault. This paleoseismic value compares more favorably to the dip slip along the northern portion of the modeled Whittier (Fig. 3).
than the average value plotted in Fig 2, This analysis demonstrates the benefit of a three-
dimensional model with non-uniform slip rates; paleoseismic observations can be compared to
model results at a particular structural position rather than to average rates.

The low levels of strike-slip along the along the modeled Raymond fault relative to paleoseismic
observations may be due to inadequate modeling of faults neighboring the Raymond. The Sierra
Madre fault, in particular, may contribute to strike slip along the Raymond fault. The discrepancy
in strike-slip along the Palos Verdes Fault may be a consequence of erroneous fault configuration
or missing neighboring faults. An alternative interpretation for Palos Verdes may incorporate a
vertical fault, which may more easily accommodate strike slip and result in greater modeled slip
rate.

**Interseismic strain accumulation**

Interseismic horizontal surface displacements are estimated with the preliminary model via an
innovative methodology implementing a deep horizontal detachment to simulate decoupling of the
seismogenic and lower crust (Fig. 4). We developed a two-step method that allows us to estimate
interseismic surface velocities from the mechanical three-dimensional models of Los Angeles basin
faults by estimating the long term secular velocities at the locking depth and simulating geologic
creep of material below the locking depth using a horizontal crack. We can estimate the long-term
secular velocities at the locking depth using POLY3D models by incorporating a horizontal crack
weak in shear at the base of the seismogenic crust. The secular deformation on this crack is then
prescribed along the base of an unfaulted elastic crust, with a thickness equal to the estimated
seismogenic crust. An infinitesimally thin horizontal crack at the locking depth serves to decouple
the upper seismogenic crust from lower portions of the elastic half-space. This approach extends
from that used by *Shen et al* [1996] and bypasses the obstacles of fault interaction for regions of
complex three-dimensional faulting.

We tested the effectiveness of this method for estimating interseismic velocities at the surface. The
test simulates an isolated vertical strike-slip fault for which there are successful standard models for
comparison. For this test, we were able to recover the same interseismic surface deformation (Fig.
5c) as the standard model for a vertical strike-slip fault (Fig. 5a). Furthermore, these results
favorably compare to a model of interseismic strain calculated by subtracting the coseismic
deformation from the overall geologic deformation (Fig. 5b). While this is methodologically more
complicated than necessary for a vertical strike slip fault, this method will allow us to avoid having
to extend dipping and intersecting faults of the Los Angeles basin in a kinematically unreasonable
manner. The key to this method is that in the POLY3D model, the horizontal crack below the
brittle faults deforms, so that displacements at the base of the seismogenic zone represent the long
time geologic deformation and not the downward continuation of coseismic deformation. This
method avoids having to specify a lower crustal structure (narrow shear zones vs. distributed shear)
since we are not using the geodetic data to invert for slip rates. However, it should be pointed out
that this method assumes that any viscoelastic relaxation caused by prior earthquakes in the region
has died away.

We tested that we have parameterized the locking depth and surface deformation estimates
correctly by first testing this method on the simple vertical strike slip fault example. Once we were
able to reproduce the analytical model of interseismic strain along a vertical strike slip fault, we
proceeded with estimating the interseismic strain from the more complicated LA basin fault
geometry.

We determine how sensitive the existing GPS network is to changes in fault geometry by
comparing the interseismic surface strain for the full preliminary model and a model missing the
Lower Elysian Park thrust, Compton Thrust and the detachment between these structures. Because
net slip on the Compton ramp is one of the largest within the preliminary model, sensitivity of the
surface strain pattern to removal of this fault will test if the resolution of SCIGN is great enough to
resolve variations in fault geometry. Velocities at SCIGN stations are shown in Figure 6, along
with the predicted surface deformation from the two different fault models. All velocities are
referenced to a station on the Palos Verdes peninsula and the velocity error ellipses represent the
95% confidence interval. While there is a good agreement between the model predicted surface
velocities and the SCIGN results, the discrepancy between the fault models is smaller than the
errors in the current SCIGN velocities. Over time, the errors in the SCIGN velocities should
decrease as velocity estimates are made over longer time periods, with more data. However, at this
time we are not able to use the SCIGN velocities for distinguishing between fault models.

Conclusion

The calculated slip-sense and magnitude of slip from the preliminary three-dimensional model
closely match much of the available paleoseismic data. The close correspondence with
paleoseismic is not considered significant beyond an indication that such models may be able to
provide a general sense of the magnitude of slip to be expected on faults that are not exposed. The
model also accurately captures relative movements along faults in this system, with several
exceptions that provide insight into potential errors in the proposed subsurface fault geometry. The
three-dimensional nature of the models facilitates more precise comparison of model results and
paleoseismic results than models that average slip along entire fault segments. Furthermore, the
three-dimensional models provide insight into out-of-plane movement along faults previously limited to cross-sectional analysis.

Within this study, we have developed an innovative methodology for estimated interseismic deformation within regions of complex or intersecting faults. The incorporation of a horizontal crack weak in shear at the seismogenic locking depth permits any degree of fault complexity within the seismogenic crust. For a vertical strike-slip fault, the interseismic deformation using a horizontal crack matches well the standard methodologies. This new method was applied to the preliminary three-dimensional fault model of the Los Angeles Basin to compare with SCIGN data collected in the recent interseismic period. At this time the errors in the SCIGN velocities exceed the sensitivity of the model to changes in subsurface fault configuration.

Abstracts related to this work


References
Dolan, Gath, Grant, Legg, Lindvall, Mueller, Oskin, Ponti, Rubin, Rockwell, Shaw, Treiman, Walls and Yeats, 2001, Active faults in the Los Angeles Metropolitan Region, SCEC group C report.
Wright, T.L., Structural Geology and Tectonic Evolution of the Los Angeles Basin, California, in Active Margin Basins, Biddle, K.T., ed. (AAPG 1991)
Table 1: Model slip results

<table>
<thead>
<tr>
<th>Fault</th>
<th>Slip sense</th>
<th>Average reverse slip (mm/year)</th>
<th>Average strike slip (mm/year)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baldwin Hills</td>
<td>R-RL</td>
<td>0.24±0.05</td>
<td>-0.14±0.03</td>
</tr>
<tr>
<td>Compton</td>
<td>RL-R</td>
<td>0.34±0.27</td>
<td>-0.53±0.31</td>
</tr>
<tr>
<td>Coyote Hills</td>
<td>R</td>
<td>0.27±0.11</td>
<td>0.02±0.04</td>
</tr>
<tr>
<td>Upper Elysian</td>
<td>R</td>
<td>0.17±0.07</td>
<td>-0.05±0.05</td>
</tr>
<tr>
<td>Lower Elysian</td>
<td>R</td>
<td>0.52±0.14</td>
<td>-0.09±0.23</td>
</tr>
<tr>
<td>Hollywood</td>
<td>R-LL</td>
<td>0.52±0.10</td>
<td>0.51±0.10</td>
</tr>
<tr>
<td>H’wood Raymond</td>
<td>R-LL</td>
<td>0.49±0.13</td>
<td>0.47±0.06</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>R</td>
<td>0.25±0.09</td>
<td>-0.12±0.10</td>
</tr>
<tr>
<td>Newport-Inglewood</td>
<td>RL</td>
<td>0.07±0.05</td>
<td>-0.60±0.22</td>
</tr>
<tr>
<td>Palos Verdes</td>
<td>RL-R</td>
<td>0.86±0.24</td>
<td>-1.08±0.24</td>
</tr>
<tr>
<td>Raymond</td>
<td>LR-R</td>
<td>0.30±0.08</td>
<td>0.45±0.11</td>
</tr>
<tr>
<td>Redondo Canyon</td>
<td>R</td>
<td>0.39±0.12</td>
<td>0.02±0.05</td>
</tr>
<tr>
<td>Santa Ana</td>
<td>LR-R</td>
<td>0.26±0.08</td>
<td>-0.37±0.39</td>
</tr>
<tr>
<td>Santa Fe</td>
<td>R</td>
<td>0.34±0.14</td>
<td>-0.03±0.05</td>
</tr>
<tr>
<td>Santa Monica</td>
<td>LR-R</td>
<td>0.47±0.11</td>
<td>0.50±0.20</td>
</tr>
<tr>
<td>Whittier</td>
<td>RL</td>
<td>0.43±0.33</td>
<td>-1.07±0.34</td>
</tr>
<tr>
<td>Workman Hills</td>
<td>RL-R</td>
<td>0.32±0.06</td>
<td>-0.64±0.12</td>
</tr>
</tbody>
</table>

*Negative strike-slip indicates right-lateral movement, positive is left-lateral.
Figure 1: Map view of faults within the preliminary 3D model of the Los Angeles Basin. The coast is outlined in red. Coordinates are in UTM kilometers. A interactive 3D version of this image is viewable at http://www.geo.umass.edu/faculty/cooke/LA.html
Figure 2: Map view of reverse (A) and strike (B) slip rate distribution along faults within the three-dimensional mechanical model. Blue strike slip rates have left-lateral slip sense and red have right-lateral slip sense. The Palos Verdes Fault, Whittier Fault and Compton Ramp have the greatest slip rates within the model.
Figure 3: Comparison of reverse (A) and strike (B) slip rates from model results and paleoseismic estimates. Blue strike slip rates have left-lateral slip sense and red rates have right-lateral slip sense. Paleoseismic estimates taken from SCEC group C report, active Faults in the Los Angeles Metropolitan Region (2001). The modeled slip rates are generally lower than the paleoseismic.
First step of analysis: determine displacements at the base of the seismogenic zone at -20 km due to remote contraction and fault slip. A horizontal crack weak in shear deforms due to slip along interacting faults and regional contraction.

Second step of analysis: determine surface expression of strain accumulation at the base of the seismogenic zone. Prescribed displacements on the horizontal crack are transmitted through the 20 km of locked elastic crust (no slip events).

Figure 4: Methodology for investigating interseismic strain accumulation in regions of complex faulting.
Figure 5: Testing of methodology of estimating interseismic strain with a vertical strike-slip fault. A) standard vertical fault model with slip applied to vertical fault below the seismogenic locking depth. B) interseismic deformation is calculated by subtracting the coseismic component of deformation from the overall geologic deformation. C) Interseismic deformation estimated using a horizontal crack at the seismogenic locking depth favorably compares with the other approaches.
Figure 6: Horizontal surface velocities calculated from fault models and from SCIGN data. The error ellipses on the SCIGN data velocities represent the 95% confidence limit.