Strain Partitioning Across Metropolitan Los Angeles

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Abstract

Geodetic data indicate that after northern Metropolitan Los Angeles is shortening at a rate of about 6 mm/yr between downtown Los Angeles and the San Gabriel Mountains. Fission track thermochronology indicates that the San Gabriel Mountains are undergoing bedrock uplift at a rate of 1 mm/yr. Assuming that the shortening crust is isostatically compensated the total crustal thickening of the San Gabriel block is 4.5–5.5 mm/yr. We assume that all of the uplift of the San Gabriels is due to the major frontal fault system (e.g. the Sierra Madre fault) yielding a total slip on the system of 5.5 mm/yr. This leaves 2.8 mm/yr of shortening to be accommodated by faults to the south, near downtown Los Angeles. By using strain rates and observed stress drops for typical southern California earthquake we estimate that earthquakes should occur at intervals of 700–1600 years on fault segments within the belt.

Introduction

Geodetic data indicate that after removal of shear from the regional strike-slip fault systems northern Metropolitan Los Angeles is shortening at a rate of about 6 mm/yr between downtown Los Angeles and the San Gabriel Mountains (Argus et al., 1999). Both the San Gabriel Mountains and the southern Los Angeles basin behave as blocks. Fission track thermochronology indicates that the San Gabriel Mountains are undergoing bedrock uplift at a rate of 1 mm/yr. We use the uplift rate of the mountains to estimate thickening of the San Gabriel Mountains block and the slip rate on the frontal fault system bounding the block. We are then able to account for additional slip and potentially responsible faults through elastic modeling.

Crustal Thickening

We use a simple bouyancy calculation to determine the thickening rate of the San Gabriel Mountains, which can be used to estimate shortening associated with the range. If we assume that the shortened crust is isostatically compensated and that the crust only thickens, then the thickness of the root, r, is related to the amount of uplift, u, by:

$r = u \bullet \rho_c / (\rho_l - \rho_c)$,

where ρ_c is the density of the crust, and ρ_l is the density of the lithosphere. Using typical values of ρ_c=2.7 and ρ_l=2.7 3.3, this means that 1 mm of uplift per year corresponds to adding 4.5 mm to the root, for a total crustal thickening of 5.5 mm/yr.

If the lithosphere is also thickening (as in forming a drip as observed by tomography) it will add a further dense addition to the root, which would need to be compensated more by the crustal root. The equation in this case has two unknowns, the crustal root thickness and the lithospheric thickness:

$r=u\bullet\rho_c/(\rho_l-\rho_c)+L\bullet(\rho_a-\rho_l)/(\rho_l-\rho_c)$,

where L is the amount of thickening of the lithosphere and ρ_a is the density of the asthenosphere that is being displaced by the thickening lithosphere. $(\rho_a-\rho_l)$ is due to the fact that the thickening lithosphere is cooler than the material it displaces. This change in density is pretty small compared to $(\rho_l-\rho_c)$, but L could be large. A change in density due to cooling is $\rho\alpha\Delta T$, where ρ is density, and α is the volumetric coefficient of thermal expansion—typically 10^{-5} per °K , and ΔT is the change in the temperature. If the lithosphere is 300° cooler than the mantle it displaces, $(\rho_l-\rho_a)$ would be about $3.3x1010^{-5}\bullet 300=0.1$ g/cm^3. So 10 mm of thickening per year would result in 0.1 mm additional root to the crust. There is a tradeoff between thickening of the lithosphere and the crust, and the calculation for r that gave 4.5 mm/yr is a minimum value for the densities used. It is possible that the crust is not fully compensated, however, these values give bounds on the rate of crustal thickening underneath the San Gabriel Mountains.

Fault System

The Sierra Madre, Whittier, Puente Hills, and Elysian Park fault systems are thrust faults within the zone of active shortening observed in the geodetic data. The Sierra Madre fault system is bounded by the granitic San Gabriel Mountains on the north and sediments on the south. We, therefore, make the assumption that the Sierra Madre fault system, being the major frontal fault system, takes up the bulk of the uplift of the San Gabriel Mountains. Using simple geometry, a thickening of 4.5 mm/yr would result in 5.5 mm/yr average slip on the Sierra Madre fault. Therefore, 3.2 mm/yr of the observed horizontal shortening is attributable to this fault system leaving 2.8 mm/yr that must be accounted for elsewhere.

Because, in general, the faults south of the Sierra Madre system are buried, the structure of the northern metropolitan region is not clear. Competing models show either a low angle dipping Puente Hills thrust fault that roots at the base of the Sierra Madre fault, or a master thrust or decollémont with higher angle sub-parallel thrust faults extending to near the surface (Figure 1). We developed some simple elastic dislocation models to determine which faults might be responsible for the observed deformation. Future work will include more realistic finite element modeling.

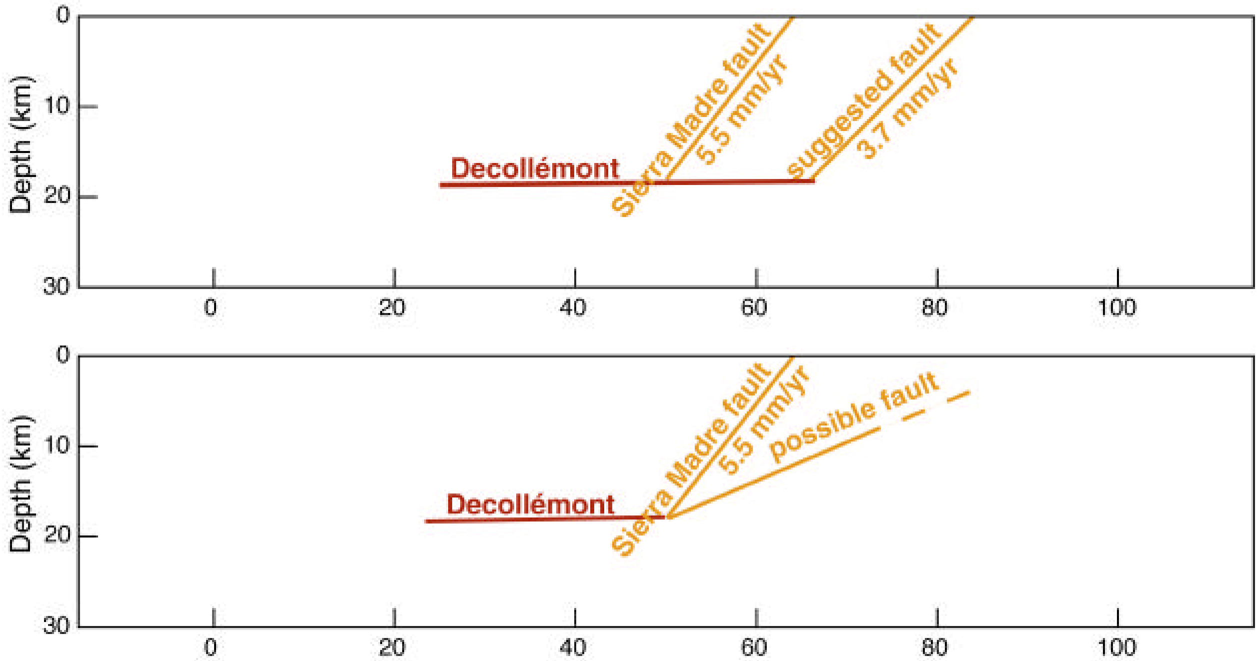

Figure 1: Two suggested fault models for the Los Angeles metropolitan region. South is to the right side of the figure. Elastic models of the geodetic data fit the top panel but not the bottom panel. The decollémont terminates at the San Andreas fault on the north side in this figure.

A Savage type backslip model does not work for thrust faults in which most of the deformation is observed outside of the hanging wall of the fault. Elastic dislocaiton models, in which the fault slips on the on the seismogenic or locked portion of the fault, mimic the long term deformation, but the interseismic surface deformation is smeared out compared to the dislocation model. We observe this by comparing dislocation and finite element models in which the lower crust is allowed to deform viscously in response to earthquakes (Hager et al., 1999). The viscoelastic finite element models will use the faults suggested by the dislocation models.

The suite of models we have examined thus far indicate that sub-parallel thrust faults rooting into a possible decollémont are more likely responsible for the observed surface deformation than a model that includes only the Sierra Madre and Puente Hills faults. The models suggest that a second thrust fault, south of the Sierra Madre fault, accommodates the additional deformation. The second fault should be about 20 km south of the Sierra Madre fault and maintain a fairly steep dip. Interestingly, in these models, the San Gabriel Mountains exhibit block-like deformation, due primarily to the steep dip of the Sierra Madre fault. Realist finite element models that take into account lateral heterogeneities, in which the rigid granitic San Gabriels bound compliant basin sediments accentuate this effect.

The vertical motion from the models mimics that observed in the topography. The uplift rate is higher on the more steeply dipping and faster slipping Sierra Madre fault and therefore the San Gabriel Mountains are higher than the mountains due north of downtown Los Angeles. While our estimated slip rate for the Sierra Madre fault is higher than that estimated by Rubin et al. (1998), it is well within the rates estimated for the frontal fault system to the east and to the west. It is also comparable to the rate given in the SCEC Phase II report.

Strain Rate, Stress Drop, and Recurrence Intervals

Using the Ventura basin as a test case we show that the strain rate, crustal rigidity, and slip per event can be used to determine average fault recurrence interval. Inversion of GPS observations across the Ventura basin as well as fault trench studies suggest that the Oak Ridge fault plays a minor role in basin shortening and that the San Cayetano fault takes up the majority of the shortening. A 4 m slip per event on the San Cayetano fault, based on recent trenching, divided by the shortening rates yields an average recurrence interval of 400 years for the fault. Multiplying the strain rate (0.7 μstrain/yr) by the local rigidity of 19–24 GPa based on P- and S-wave velocities produces a stress rate of 0.13–0.17 bar/yr. Multiplying that stress rate by the recurrence interval yields a stress drop per event of 54–67 bars for a typical event. This is within the range observed for southern California earthquakes.

Extending this method to Los Angeles enables us to estimate the average recurrence of earthquakes within the band of shortening. The strain rate in northern metropolitan Los Angeles is about 0.3 μstrain/yr suggesting a stress loading rate of 0.06–0.08 bar/yr. Dividing a stress drop per event of 50–100 bars by the stressing rate yields a recurrence interval of 700–1600 years for the faults within the band of observed shortening. About half of the events should occur on the Sierra Madre fault based on slip rates, hence this fault should have major events approximately every 1300–3000 years. The remaining faults should rupture every 1500–3000 years.

Acknowledgments

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References

[1] Argus, D., M.B. Heflin, A. Donnellan, F.H. Webb, D. Dong, K.J. Hurst, G.A. Lyzenga, M.M. Watkins, and J.F. Zumberge, 1999, Shortening and Thickening of Metropolitan Los Angeles Measured and Inferred Using Geodesy, *Geology,* **27**, 703–706.

[2] Hager, B.H., G.A. Lyzenga, A. Donnellan, and D. Dong, 1999, Reconciling Rapid Strain Accumulation with Deep Seismogenic Fault Planes in the Ventura Basin, California, *J. Geophys. Res.,* **104**, 25,207–25,219.

[3] Rubinc, C.M., Lindvall, S.C., Rockwell, T.K., 1998, Evidence for large earthquakes in metropolitan Los Angeles, *Science,* **281**, 398–402.