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Strain accumulation, earthquake occurrence, fault interaction, and the accommodation of plate motion in the metropolitan Los Angeles area

Donald F. Argus (Jet Propulsion Laboratory, California Institute of Technology, Pasadena)

Summary. The metropolitan Los Angeles area is contracting from north to south at ~8 mm/year, the rate of convergence between the Channel islands and the San Gabriel mountains estimated using geodesy. This rate is among the highest in the United States except for shear across the San Andreas fault system and contraction across the Cascadia subduction zone. The determination of variations in strain accumulation in space and time is important for understanding earthquake occurrence and fault interaction. Postseismic transients and interaction between strike-slip earthquakes along the San Andreas system and thrust earthquakes in metropolitan Los Angeles play an important part in the accommodation of Pacific-North America plate motion. Therefore, we propose that the Southern California Integrated GPS Network (SCIGN) be part of the Plate Boundary Observatory. A total of 200 permanent GPS sites are in place in southern California; another 50 will be installed by early 2001. Continuing observations at the 250 sites will yield a lot scientific information. Geodesy will complement SAR interferometry, fault slip rates from paleoseismology, strainmeters, the TRINET seismic network, and the LARSE seismic refraction and reflection experiments, making metropolitan Los Angeles among the world's best studied plate boundary zones.

SCIENCE OBJECTIVES

Accommodation of plate motion

The 130-km-long Mojave segment of the San Andreas fault trends ~30° CCW of the direction of Pacific-North America plate motion. Therefore, strike-slip along the San Andreas cannot take up all the plate motion. Contraction perpendicular to the San Andreas must occur elsewhere. One manifestation of the resulting complicated tectonics is the intersection of the dextral San Andreas with the sinistral Garlock fault. Another is the east California shear zone, a series of dextral faults across the Mojave desert splaying from the southern San Andreas fault system.

N-S contraction appears to have built the high mountains of the central Transverse ranges over the past few million years. Geodetic observations, however, show that the San Gabriel mountains are no longer contracting [Lisowski et al., 1991]. Instead, northern metropolitan Los Angeles is observed using SCIGN to be contracting at ~5 mm/year [Walls et al., 1999; Argus et al., 1999] (Figure 1). A total of ~8 mm/year of convergence must be accommodated between the Channel islands and the San Gabriel mountains [Argus et al., 1999]. Thus, metropolitan Los Angeles plays a significant role in the accommodation of Pacific-North America plate motion. Some SCIGN sites span the San Andreas fault system and most are in metropolitan Los Angeles. Observations at the 250 sites will constrain how plate motion is partitioned among the San Andreas system, the east California shear zone, and the contractional belt between the Channel islands and the San Gabriel mountains.

Earthquake occurrence and mountain building

Two large earthquakes have occurred in the northern metropolitan Los Angeles contractional belt over the last 30 years. The 1994 M=6.7 Northridge earthquake generated ~2 m of NNE reverse slip along a S-dipping thrust. The 1971 M=6.6 San Fernando earthquake generated ~2 m of SSW reverse slip along a N-dipping thrust at the front of the San Gabriel mountains. Both earthquakes released NNE-SSW contraction that had accumulated in the contractional belt. The 1994 shock produced the strongest ground motions ever instrumentally recorded in an urban setting in North America and the greatest financial losses from a natural disaster since 1906 (USGS and SCEC, 1994). SCIGN is measuring the strain buildup that will be released in earthquakes. Identifying where and when strains are highest might contribute to assessing the likelihood of earthquakes in different places (Figure 2).

The young and rugged topography immediately south of the San Gabriel mountains

[Yeats et al., 1994] lies at the center of the contractional belt identified using geodesy. Thus, SCIGN is yielding information on mountain building.

Fault and earthquake interaction

GPS observations across metropolitan Los Angeles provide an opportunity to study the interaction between strike- and reverse-slip faults. How strike-slip faults such as the San Andreas, San Jacinto, Elsinore, Palos Verdes, and Newport-Inglewood faults are associated in time and space with reverse-slip faults such as the Sierra Madre, Verdugo Hills, Elysian Park, and Puente Hills thrusts is an outstanding scientific problem. A great earthquake along the San Andreas fault and a large earthquake along a thrust fault in metropolitan Los Angeles might occur at the same time, much as happened during the great 1957 Gobi-Altay earthquake, Mongolia [Bayarsayhan et al., 1996].

How earthquakes cluster in time and space is also unanswered. The 1992 M=7.2 Landers earthquake, which ruptured the east California shear zone, appears closely associated in time and space with the 1999 M=7 Hector Mine earthquake, which ruptured east of the east California shear zone. Whether the 1992 shock triggered the 1999 shock is being investigated.

The rate of shear accumulating near the San Andreas fault is high, about 0.4×10^{-6}/year in the 25 km on either side of the fault [Lisowski et al., 1991]. Ten earthquakes have broken the San Andreas in the last 1400 years [Sieh et al., 1989], the last one being the 1857 M=8.2 Fort Tejon earthquake, which generated 3 to 10 m of slip [Sieh, 1978]. Thus, most or all of the high shear strain observed to be centered on the San Andreas fault will probably be released along it. This high likelihood must be considered when assessing the elastic strain that will be released in earthquakes in metropolitan Los Angeles and when evaluating how Pacific-North America plate motion is partitioned (Figure 2).

Time variations in interseismic strain

Quantifying postseismic transients is important for understanding the relationship between interseismic strain accumulation and earthquake strain release. Postseismic transients of varying amplitude, extent in time, and duration in space have been estimated for the 1992 Landers earthquake [Bock et al., 1997; Savage and Svarc, 1997, Deng et al., 1998] and the 1994 Northridge earthquake [Donnellan et al., 1998; Savage et al., 1998; Deng et al., 1999]. Some studies attribute transients to more slip along the rupture zone, while others attribute transients to deep slip or deep viscoelastic relaxation immediately beneath the rupture. GPS observations across the metropolitan Los Angeles contractional belt provide an opportunity to study postseismic transients in a thrust faulting regime.

Triangulation data record a large postseismic transient arising from the M=8.2 San Francisco earthquake with exponential decay time equal to ~35 years [Kenner and Segall, 2000]. Such long lasting transients might also result from a great earthquake rupturing the San Andreas system or a large earthquake in metropolitan Los Angeles. GPS data measured a large postseismic transient after the 1992 Landers earthquake with exponential decay time of several years arising from deep slip beneath the rupture [Savage and Svarc, 1997]. SAR interferograms over the postseismic period suggest that pore fluid flow generated vertical motions associated with the postseismic transient [Peltzer et al., 1998]. Continuing GPS observations across metropolitan Los Angeles will provide an opportunity to study how interseismic strain accumulation varies over tens of years.

Annual fluctuations due to aquifers

SAR inteferometry and several GPS sites record uplift of the Santa Ana basin in the autumn and winter (October to April) and its subsidence in the spring and summer (April to October) [G. W. Bawden, Seism. Soc. Amer. meeting, 2000]. Vertical motions are several cm. Horizontal motions are several mm. The fluctuations appear to be caused by [G. W. Bawden, personal comm., 2000] the filling and emptying of the Santa Ana aquifer, the water-bearing bed of sedimentary rock yielding considerable water to wells and springs in Orange County. Whether the aquifer fluctuations are due to natural causes (rainful is maximum in the winter and minimum in the summer) or to pumping of the aquifer by man is being investigated. The aquifer fluctuations probably overwhelm the plate tectonic signal we seek to measure, but SAR interferograms show the lateral extent of the fluctuations to be fairly small [G. W. Bawden, Seism. Soc. Amer. meeting, 2000].

Complementary techniques

The LARSE seismic refraction and reflection experiments yield information on the decollment from which thrust faults in metropolitan Los Angeles might splay [cf. Ryberg and Fuis, 1998]. The TRINET seismic network provide information on microseismicity and the mechanism of earthquake rupture. Abundant fault slip rates from paleoseismology provide further observations against which to compare geodetic observations. Indeed, such complementary techniques will make the metropolitan Los Angeles area among the world's best studied deforming zones.

Strainmeters have provided important information about episodic creep along the San Andreas fault system near San Juan Bautista [Gladwin et al., 1994]. Strainmeters in southern California would provide information on transients or the lack of them, thus complimenting the GPS observations. One laser strainmeter will be installed as part of SCIGN in Glendale (in northern metropolitan Los Angeles). A long history of observations of strains and tilts exists at Pinyon Flats observatory. Scientists (F. Wyatt, D. Agnew, M. Gladwin, and R. Gwther) are proposing to install two laser strainmeters and many borehole tensor strainmeters in southern California as part of the Plate Boundary Observatory.

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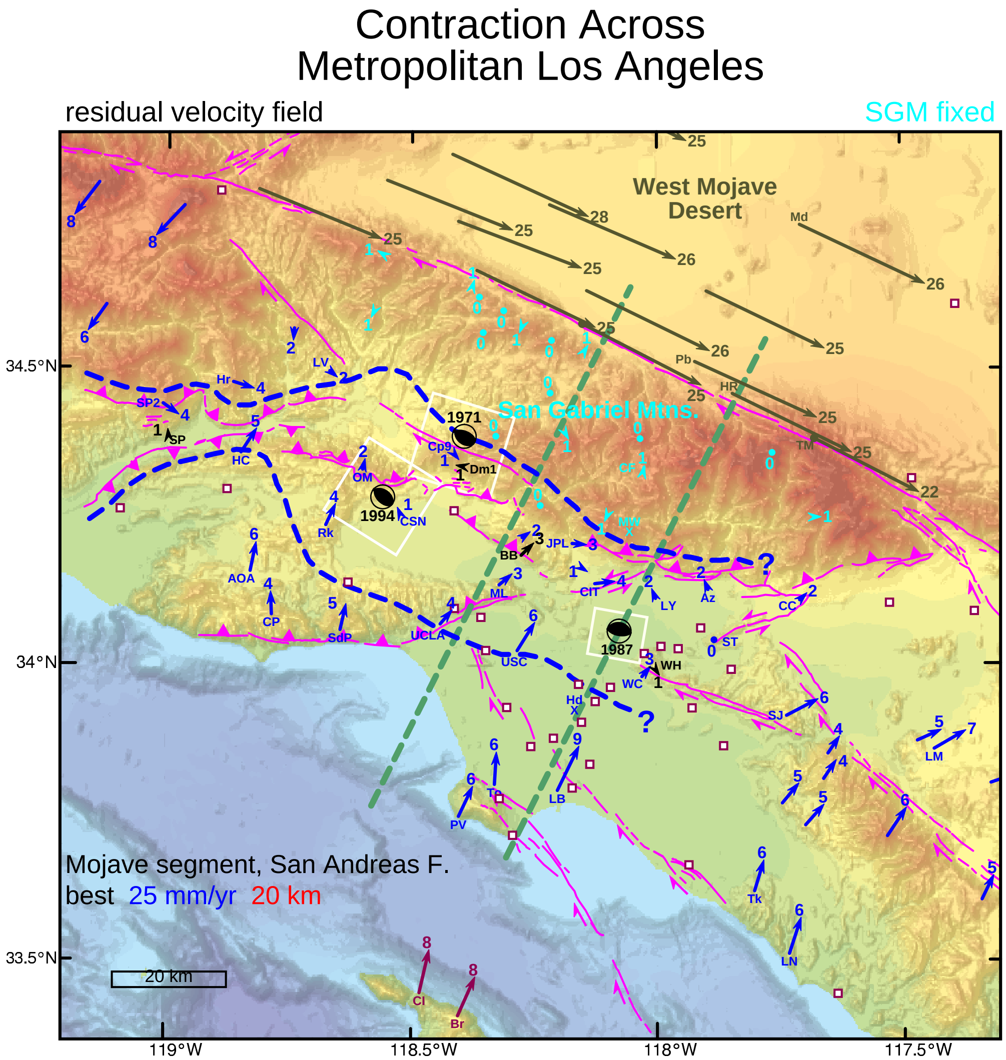

Figure 1. The mean interseismic velocity field after removing elastic strain associated with locking of the San Andreas fault. The velocity field in metropolitan Los Angeles is determined primarily from GPS observations from 1995 to 2000 at 35 SCIGN sites. The strain field along the few tens of km on either side of the San Andreas, in the San Gabriel Mountains and west Mojave Desert, is determined mainly from USGS trilateration data from 1970 to 1990. VLBI results and measurements of campaign GPS sites made by the Southern California Earthquake Center (SCEC) contribute to the estimation of the velocity field elsewhere. This velocity field was determined by D. F. Argus using velocity solutions from (permanent GPS) M. B. Heflin, (campaign GPS) D. Dong and scientists at MIT and UCLA, (VLBI) C. Ma, (SLR) R. J. Eanes, and (trilateration) M. Lisowski. Its determination is independent of the official SCEC v2.0 velocity field except for the campaign GPS velocity solution.

Motions are described in a reference frame in which the San Gabriel Mountains are fixed. The elastic strain accumulating in a model in which the Mojave segment of the San Andreas slips at 25 mm/year beneath a locking depth of 20 km has been removed. The San Gabriel mountains appear to constitute a rigid block. The west Mojave Desert appears to be moving relative to the San Gabriel Mountains toward the ESE at 25 mm/year, the rate of deep slip assumed for the San Andreas. NNE contraction across the San Gabriel Mountains is observed to be about zero. Contraction perpendicular to the San Andreas fault instead is observed to be occurring across northern metropolitan Los Angeles. The dashed blue lines bound the contractional belt. Contraction at about 5 mm/year is occurring across the narrow Ventura Basin (between (HC) Happy Camp and (Hr) Hopper). The data constrain the location of 5 mm/year of contraction to lie across a wide zone spanning the San Fernando Valley (4 mm/year of contraction may be occurring anywhere between (Rk) Rocketdyne and (Cp9) Camp 9.) Near downtown Los Angeles contraction at 6 mm/year appears to be occurring across a fairly narrow zone between (USC) the University of Southern California and (JPL) the Jet Propulsion Laboratory. The location of the contractional belt is constrained poorly east of downtown (where much of the contraction may be occurring south of (WC) Whittier College). The dashed green lines show the location of the profile in Figure 2. The open maroon squares show the locations of 50 SCIGN sites established in 1998 or 1999. The velocities of these sites will soon be determined well enough to further constrain the velocity field.

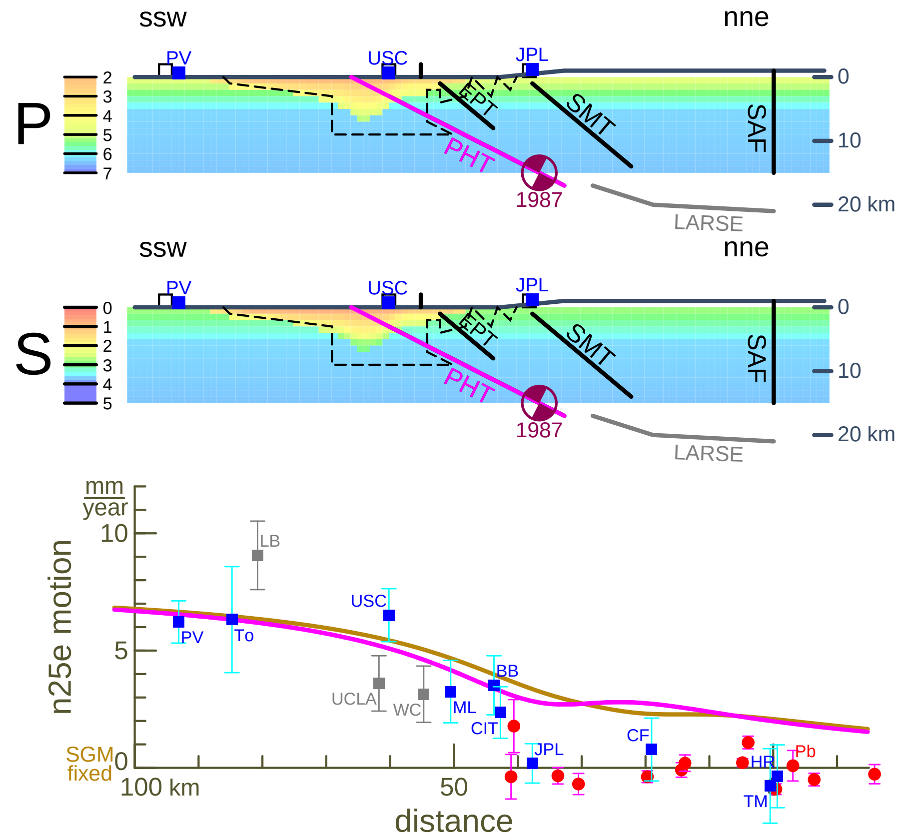

Figure 2. The NNE component of velocity as a function of distance along a NNE profile from Palos Verdes to the San Andreas fault. SCIGN observations indicate that the Channels Islands are moving toward the San Gabriel Mountains at 8 mm/year. Contraction at 6 mm/year appears to be occurring across a fairly narrow zone between (USC) the University of Southern California and (JPL) the Jet Propulsion Laboratory. Three NNE-dipping thrust faults are suspected to take up the contraction, the (PHT) Puente Hills thrust, the (EPT) Elysian Park thrust, and the (SMT) Sierra Madre Thrust. A large earthquake rupturing the Puente Hills thrust (beneath downtown Los Angeles) or the Elysian Park thrust (which reaches the surface just north of downtown) would cause a lot of damage to the urban center.

An edge dislocation model in which (magenta curve) the Puente Hills thrust is locked from the surface to 17 km deep and takes up all of the 8 mm/year of motion between the Channels Islands and the San Gabriel Mountains beneath 17 km deep predicts a more shallow gradient in the NNE component of velocity than estimated between USC and JPL. An edge dislocation model in which (gold curve) the 8 mm/year of motion is distributed evenly between the Puente Hills and Sierra Madre thrusts predicts motions similar to the one-fault model. Thus, fault locking to 17 km deep cannot explain the observations in a simple edge dislocation model. Fault locking must be only 5 km deep to satisfy the observations. However, the rupture zones of the 1971 San Fernando (0–15 km deep), the 1994 Northridge (8–19 km deep), and the 1987 M= 5.8 Whittier Narrows (13–17 km deep), suggests that the seismogenic layer extends down to at least 15 km deep.

How might the models and observations be reconciled? In the edge dislocation models the thrust faults are assumed to extend infinitely along strike. Perhaps reverse slip along the thrusts may end to the ESE and WNW of downtown. Or perhaps some of the deformation of the blocks bounding the thrusts is not elastic as assumed. The crust in the models is assumed to be homogeneous. In reality a soft deep layer of sediments overlies hard crystalline basement (the dashed line in the profile shows the limits of the sedimentary basin [Davis et al., 1989]). The elastic and viscous response of the sedimentary basin and crystalline basement to fault locking can be approximated using finite element models. We are constructing models that base the varying rheology on the seismic structure (P- and S-wave velocity, density) estimated by the Southern California Earthquake Center [H. Magistrale, personal comm., 2000]. The high contraction rate observed across the Ventura Basin is inconsistent with simple edge dislocation models of locking of the two thrust faults bounding the basin, the Oak Ridge and San Cayetano Thrusts in the entire seismogenic layer. Incorporating a soft deep sedimentary basin into the dislocation model, however, results in contractional rate high enough to match that observed [Hager et al., 1999].