tainly does. We are in an era filled with parental quandaries such as the type of daycare to provide, the inner-city specter of the dissolution of the family, teen pregnancy, and low government spending on child-related social services during critical periods of brain development. This current study must spur on work examining how early experience alters the trajectory of our own development.

References

1. D. Liu et al., Science **277**, 1659 (1997).
2. S. Levine, ibid. **126**, 405 (1957).
3. D. Francis et al., Ann. NY Acad. Sci. **794**, 136 (1996).
4. M. Meaney, D. H. Aitken, C. Van Berkel, S. Bhatnager, R. M. Sapolsky, Science **238**, 766 (1988).
5. S. Levine, in Society, Stress and Disease, L. Levi, Ed. (Oxford Univ. Press, London, 1975), pp. 43–50.
6. M. Meaney, unpublished data.
7. S. Schanberg, G. Evoniuk, C. Kuhn, Proc. Soc. Exp. Biol. Med. **175**, 135 (I984).
8. L. Jacobs, Brain Behav. Evol. **44**, 125 (I994); S. Gaulin, in The Cognitive Neurosciences, M. Gazzaniga, Ed. (MIT Press, Cambridge, MA, 1995).
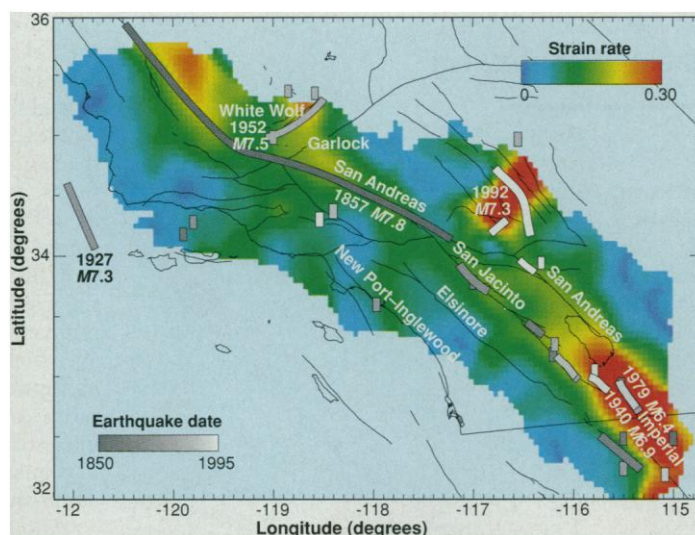
GEOSCIENCE

Southern California Deformation

David D. Jackson, Zheng-kang Shen, David Potter, Xiao-Bin Ge, Li-yu Sung

After the 1906 San Francisco earthquake, H. F. Reid discovered that triangulation surveys made before the earthquake revealed substantial deformation in a broad zone surrounding what we now call the San Andreas fault. On the basis of those observations, Reid developed his "elastic rebound" theory, which has motivated the study of crustal strain by modern geodetic methods. Laser measurements of line length and position measurements made with very long–baseline interferometry (VLBI) and the Global Positioning System (GPS) are now common. From these measurements, scientists can identify faults that lack clear evidence of surface deformation, determine the rate of motion on faults for which surface displacements from historical earthquakes cannot be attributed to a known time interval, and test whether today's slip rates on major, well-studied faults are the same as those determined from geological studies. Combined with detailed models relating earthquake occurrence to strain and stress accumulation, such geodetic observations may also help to identify the places where earthquakes are most likely in the next few decades.

The Southern California Earthquake Center (SCEC) is collecting and interpreting geodetic survey data for southern California to monitor fault motions and earthquake potential. A major product of the study is a set of deformation velocity estimates for 287 sites in southern California that reveal the

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Maximum horizontal strain rates in southern California (in microradians per year; see the color scale at top right). Black curves denote the faults and coast and state boundary lines. Gray squares and thick gray curves represent epicenters and surface rupture traces of past earthquakes over magnitude 6. The degree of grayness reflects the time elapsed since that earthquake.

horizontal component of the crustal deformation resulting from fault motion and viscous flow below depths of about 10 km (1).

The study uses laser data collected by the U.S. Geological Survey and other agencies since 1970, VLBI data from the National Aeronautics and Space Administration since 1980, and GPS data from many government agencies, universities, and private companies since 1986. Because geodetic survey data measure relative positions or lengths between sites, most of the data had to be reprocessed to assure that assumptions made in linking individual survey projects were consistent. Because the velocities are intended to reveal the "interseismic" deformation field (between earthquakes), displacements directly attributable to the earthquake ruptures had to be removed from the data. In the affected areas, data from after the 1994 Northridge earthquake and before the 1987 Whittier Narrows and 1992 Landers earthquakes were discarded. In marginal regions, models of earthquake displacements were used to correct for any possible seismic disturbances.

The resulting map of deformation velocities (2) on a plate-boundary scale is so accurate and spatially dense that strain rates can be determined directly. The velocity data have revealed that geodetically determined cumulative deformation across the plate boundary agrees well with the long-term deformation predicted by plate tectonic theory (3). After resolving the displacements onto individual faults, we find reasonable agreement with geologically estimated fault slip rates (4). This agreement implies that present crustal deformation between earthquakes is relatively steady, not deviating much from its long-term average rate (here "long-term" refers to thousands of years, the age of datable features displaced by faults). Such agreements are comforting because modern seismic hazard estimates usually assume that immediate (years and decades) earthquake potential is proportional to the long-term slip rate on faults.

In spite of the overall agreement between short- and long-term rates, the spatial distribution of the present strain rate is still surprising. The figure shows a map of maximum horizontal shear strain rate, faults, and the rupture zones of major earthquakes. The regions of highest shear strain rate are not on the major faults as would be expected, but rather (with one exception) they are in the regions surrounding previous earthquakes. Earthquakes in 1992 [Landers, magnitude (M) 7.3], 1979 (Imperial Valley, M 6.4), and 1952 (White Wolf, M 7.5) have apparently caused the largest "strain reactions." Older earthquakes, in 1927 (M 7.3) and 1857 (M 7.8), have left only subtle imprints on today's strain rate. In general, the earthquakes with ongoing aftershock sequences are those with noticeable strain effects. The only "hot-spot"

not associated with a known earthquake is in a region north of 35°N, just east of the San Andreas fault. Active folding associated with the Kettleman Hills–Coalinga Anticline may explain the high strain rate here; however, data in this region are relatively less certain.

That past earthquakes would perturb the strain field is not a new idea. That postseismic effects could regionally dominate is, however, stunning. This result shows that although earthquakes probably would not change the overall rate of relative motion across a plate boundary, they could change regional deformation rates over a period of time from years to decades, depending on the magnitudes of the earthquakes. These postseismic effects will complicate efforts to determine long-term slip rates on faults using geodetic data. Relating the strain field to future earthquakes will require an understanding of the effects of past ones. But we can also announce good news: These new data provide tantalizing quantitative information about the crust's time-dependent, inelastic properties. Such properties will, after all, determine how stresses from plate tectonics and past earthquakes provoke future quakes. The observations provide a valuable window into the mechanism of inelastic stress release.

References and Notes

1. Z.-K. Shen *et al.*, *Eos*, in press.
2. Horizontal Crustal Deformation Velocity Map, Version 1.0, Crustal Deformation Working Group, Southern California Earthquake Center, http://scec.ess.ucla.edu/velmap/welcome.shtml
3. A revised global tectonic deformation model, NUVEL-1A [C. DeMets, *Geophys. Res. Lett.* **22**, 3545 (1995)], predicts a deformation rate of 49 mm/year across plate-boundary dextral motion in California, compared to the value of 50 mm/year estimated by this geodetic study.
4. An earthquake probability report for southern California by SCEC scientists [D. D. Jackson *et al.*, *Bull. Seismol. Soc. Am.* **85**, 379 (1995)] summarizes fault slip rates mainly on the basis of geological estimates.
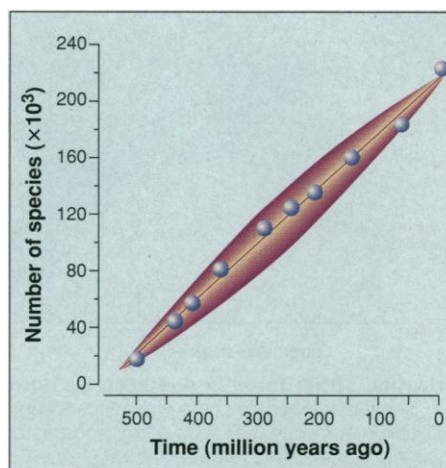

EVOLUTION

Tempo and Mode of Speciation

Michael L. Rosenzweig

How does one living species become two? And does the evolution of new species proceed fitfully or smoothly? If fitfully, what sort of cataclysms trigger progress? These are the basic questions that Klicka and Zink illuminate on page 1666 of this issue in a fascinating study of the timing of songbird speciation (*1*). From this and other recent work, mixed messages emerge: Speciation serves more than one master. And its regularity depends on the scale at which it is measured.

Birds do not make very good fossils, so they contributed little to our understanding of the principles of evolution until the development of molecular tools such as mitochondrial DNA (mtDNA) sequencing. Because minor variations in mtDNA appear to have no consequences for fitness, mtDNA can be a neutral indicator of time and a valuable evolutionary clock. As more time passes, more random differences will accumulate between species. Now, knowing how to tell molecular evolutionary time, we can ask basic questions about bird evolution whose answers should apply more generally.

Evolutionists believe that speciation usually begins with the subdivision of species into isolated populations by a geographical barrier (allopatry). What better barrier than a continent-sized glacier knifing down through North America and slicing many of its major environments into eastern and western segments? Because many western and eastern species of birds are sisters, evolutionists attributed their speciation to geography and to its ally, the glacial scalpel.

Klicka and Zink show that we were wrong, at least about the glaciers. It makes one want to reexamine a whole class of geographical case histories—cases that emerged before molecular evidence became available. Were we also wrong to conclude from them that sympatric mechanisms of speciation—mechanisms that do not require geographical subdivision—are unimportant?

Sympatric speciation differs most significantly from geographical speciation in that it is triggered by ecological interactions (*2*). It targets ecological opportunities and produces new species with a high probability of survival. Evidence from fossils now strongly indicates that sympatric speciation was crucial in the radiation of innovative forms of life (*3*). And new mathematical theory (*4*) has removed any remaining genetic qualms about it.

Nevertheless, geographical allopatric speciation usually dominates other mechanisms. To conclude otherwise would require us to explain away too many facts. For example, of the world's 18,818 species of fish, 36% live in fresh water although only 1% of the Earth's surface is fresh water, and fish productivity and population are considerably higher in marine continental shelves and upwelling currents. The myriad opportunities for fishes to form geographical isolates in fresh waters as compared with salt looks like unassailable evidence in favor of the dominance of geographical speciation.

Another fact: The number of species in a biological province such as the Neotropics depends on the area of the province. Larger provinces have more species, and the relation is virtually linear (*2*). Dynamic theory based on geographical allopatric speciation predicts that correlation. Sympatric speciation does not.

The tempo of speciation also speaks in favor of a geographical mechanism. Sympatric speciation predicts that new species will emerge at an ever decreasing rate. But species form rather steadily during most periods. We see this in the fossil record (*5*), as well as in North American songbird DNA. And geographical speciation predicts it.

Yet, like a digital clock, genetic change is discrete at the finest scale. A digital clock seems to operate spasmodically at the scale of a second, but quite smoothly at that of an hour. Surely, at the scale of an individual base substitution, mtDNA change must resemble a "second hand." But the glacial hypothesis sought to extend fitfulness to a larger scale: 10^5 to 10^7 years.

The new DNA data from songbirds demonstrates that speciation events did not clus-

Virtually constant accumulation of species throughout Phanerozoic time. The concave and convex curves show the limits to the curvature of the data given their rate variation (*15*). Maximum rate: 611 species/million years; minimum rate: 292 species/million years.

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