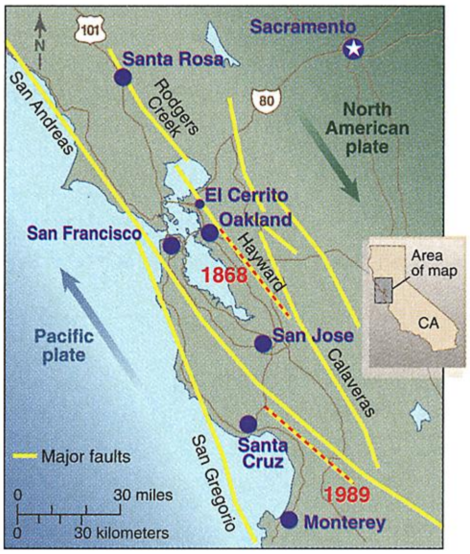
PERSPECTIVES: **SEISMOLOGY**

Watching the Hayward Fault

Robert W. Simpson

The Hayward fault on the east side of San Francisco Bay creeps continuously at the surface at an average rate of about 5 millimeters per year, deforming buildings and cracking pavement, aqueducts, the University of California at Berkeley football stadium, and anything else unlucky enough to lie across its active trace (*1*). It also produces major earthquakes, the last being a magnitude (*M*) ~ 6.8 event in 1868 on the southern part of the fault (*2*). It may seem paradoxical that a fault creeping at the surface produces large earthquakes. How can it simultaneously store and release strain energy? Such a situation could hold if the earthquakes actually occur on locked brittle regions (called asperities) at midcrustal depths below the creeping zone. Most seismicity along the Hayward fault occurs above 12-km depth, probably because the deeper reaches of the fault are warm and slip in ductile fashion, at long-term rates estimated from offset features at the surface to be about 9 to 10 mm/year. This deep slip causes stress on asperities in the brittle region and at the same time drives the creep at the surface by transferring stress elastically around the locked regions (*3*). Creep at the surface is slower than the long-term slip rate because of the retarding effect of the locked patches, so that when one or more locked patches fail in an earthquake, a deficit of surface slip needs to be made up, either in coseismic rupture or as postseismic afterslip.

On page 1178 of this issue, Bürgmann *et al.* (*4*) propose that a 20-km stretch of the northern Hayward fault is creeping over the entire depth range in which earthquakes might nucleate and that major earthquakes can therefore not originate in this region. The 1999 Working Group on Earthquake Probabilities in the San Francisco Bay region (*5*) benefited from information shared by Bürgmann and his colleagues. The Working Group estimate of the probability for an earthquake on the northern Hayward fault segment was 16% for the next 30 years [down from a previous estimate of 28% (*6*)], in part because of the new information from Bürgmann *et al.* However, at 32%, the probability estimate for the Hayward–Rodgers Creek fault system as a whole (see the upper figure) remains the highest of any fault system in the region. Note that the probability of earthquakes on nearby faults or fault segments is only one ingredient in the assessment of seismic hazard. The 1989 Loma Prieta earthquake demonstrated this clearly, with catastrophic damage in San Francisco and Oakland occurring more than 90 km from the epicenter.

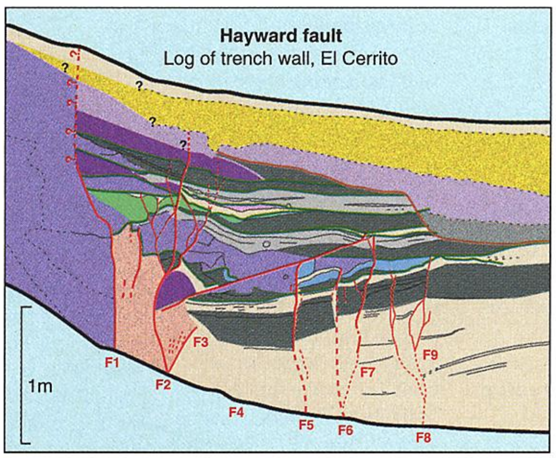


Major faults in the San Francisco Bay region. The locations of 1868 and 1989 earthquakes are marked with dashed red lines.

Bürgmann *et al.* have used two relatively new techniques in their study of the northern Hayward fault. Satellite-based interferometric synthetic aperture radar (InSAR) allowed them to monitor deformation at Earth's surface over a broad region. A locked patch at depth would be expected to warp the surface in characteristic ways that should reveal its location and depth. The authors find no detectable evidence for such warping. The absence of warping requires any locked patches to be deeper than about 6 km; the best model fit was obtained when there were none at all. Because InSAR allows deformation to be seen in "map view," it has a distinct advantage over traditional point geodetic observations, which are inevitably limited by sparse sampling.

The second technique used by the authors is the careful study of repeating microearthquakes. These small events have virtually identical seismic signatures, strongly suggesting that the same asperity is breaking again and again, typically on a time scale of months or years. Such sequences are valuable because they can provide an estimate of the slip rate–like a creepmeter installed at depth. The technique has afforded detailed pictures of slip at depth on the San Andreas fault and has raised new and intriguing questions about fault behavior (*7–9*). Bürgmann *et al.* report the existence of two clusters of repeating earthquakes under the northern Hayward fault at 6- and 10-km depth, with estimated slip rates of 6 to 7 mm/year for each.

But there is an enigma. Paleoseismologists have excavated trenches across the Hayward fault at the Mira Vista golf course in El Cerrito, squarely above the 20-km stretch studied by Bürgmann *et al.* The trenches expose a complex stratigraphy involving multiple fault strands (see the lower figure), interpreted to indicate at least four (and maybe seven or more) surface-rupturing earthquakes in the past 2200 years, the last occurring between 1640 and 1776 (*10*). Thus, even if Bürgmann *et al.* are correct in suggesting that this stretch is unable to originate large earthquakes on its own, it does appear to have ruptured during past earthquakes, which presumably originated to the south or north. The 1999 Working Group proposed three such scenarios, namely (i) simultaneous failure of the northern Hayward fault and the southern Hayward fault; (ii) failure of the northern Hayward fault with the Rodgers Creek fault (the extension of the Hayward fault to the north); (iii) or failure of all three fault segments together in one very large event (*5*). Additional trenching investigations are required to assess these possibilities.



Worm's-eye view of the Hayward fault. Log of a trench wall excavated across the Hayward fault at the Mira Vista Golf Course, El Cerrito (*10*). Colors show various geologic units. Red lines indicate fault strands.

Ultimately, all earthquakes in the San Francisco Bay region derive from the northwest motion of the Pacific plate relative to North America, but the details of how stresses are transferred to

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the individual subparallel faults remain unclear. According to one hypothesis, a horizontal detachment fault exists under the San Francisco Bay region at a depth of 10 km or more, connecting the major faults and effectively transferring stress between them (*11*). Such a connection could play a major role in enhancing fault interactions. For example, a large earthquake on the San Andreas fault could delay the timing of future earthquakes on the Hayward fault, perhaps by decades (*12*). Alternatively, plate tectonic stresses might be transferred to locked patches by aseismic slip on vertical continuations of the faults at depth (*13*). Geodetic data collected in the right locations may help distinguish between these different loading scenarios (*14*).

A better understanding of the driving mechanism behind earthquakes in the San Francisco Bay region is essential. Unlike the nearby San Andreas fault, the Hayward fault does not sleep silently between major earthquakes. As a result, it offers researchers a valuable natural laboratory for observing the earthquake machinery at work and for testing hypotheses. The use of powerful new techniques, such as those of Bürgmann *et al.*, offers hope that the Hayward fault may reveal some of its secrets in the coming years.

References and Notes

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15. I thank numerous colleagues for helpful comments and insights.

PERSPECTIVES: NEUROSCIENCE

More to Seeing Than Meets the Eye

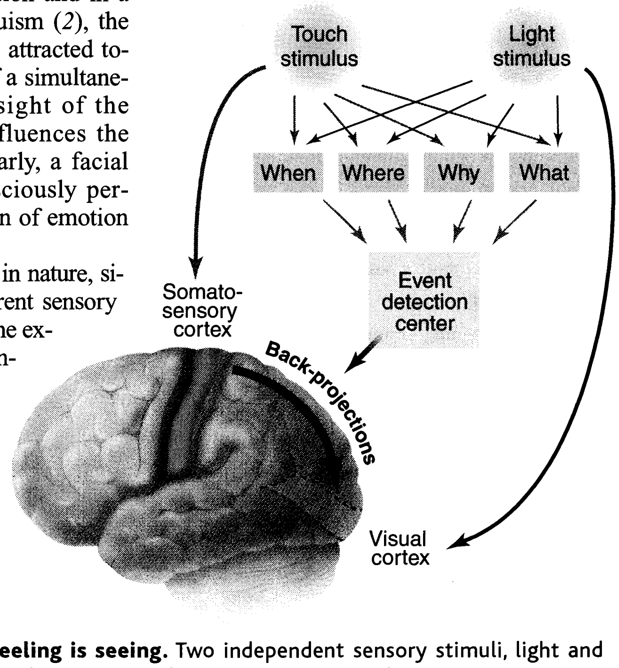
Beatrice de Gelder

The outer layer of the cerebral cortex is divided into different areas specialized for detecting and processing sensory signals from the eyes and ears and from receptors for touch, taste, and smell. Differences between these sensory areas may reflect variations in the rate of evolution of the five senses and the special information processing requirements for each type of sensory signal. Everyday experience illustrates that, despite their differences, the sensory regions of the cortex must be cooperating with each other by integrating the sensory stimuli they receive from the outside world. Now, on page 1206 of this issue (*1*), Macaluso *et al.* report an elegant example of this cooperation and provide empirical justification for the aphorism that there is more to seeing than meets the eye. They show that the administration of a tactile (touch) stimulus and a visual stimulus to human volunteers at the same time and on the same side of the body enhanced neural activity in the lingual gyrus of the visual cortex, above that achieved with the visual stimulus alone. The authors propose that neurons in the somatosensory (touch) area of the cortex project back to the visual cortex, thus keeping the visual cortex informed about touch stimuli that are received simultaneously with visual stimuli.

How widespread is the interaction of one sensory area of the cerebral cortex with another (cross-modal impact), and how general is the underlying neural mechanism? Cross-modal information exchange between the auditory and visual cortex has been found in speech perception and in a few other cases. In ventriloquism (*2*), the apparent direction of sound is attracted toward the displaced location of a simultaneous visual stimulus—the sight of the speaker's lip movements influences the hearing of speech (*3*). Similarly, a facial expression, even if not consciously perceived, modifies the perception of emotion in the voice of the speaker (*4*).

Our experience tells us that in nature, simultaneous signals from different sensory organs are the rule rather than the exception. But, in fact, most connections between different sensory signals are irrelevant, such as hearing the call of a seagull as we watch the waves crashing against the rocks. So, how does the brain discern what sounds go with what sights? The cross-modal interactions that produce the unified objects and events that we perceive around us require a very high degree of selection. Too many interactions in the brain would create an internal booming, buzzing confusion to match the one surrounding us. But it is only biologically important combinations of sensory stimuli that are likely to be endowed with hard-wired neural pathways in the brain. When it comes to packaging individual sensory stimuli together into a single event (see the figure), the brain, like a good playwright, is likely to ask "when" (time), "where" (space), "what" (identity), and "why" (why does the stimulus matter to the organism).

Integration of different but related sensory stimuli does not require the glue of attention or awareness (*5*, *6*). Recently, multisen-



Feeling is seeing. Two independent sensory stimuli, light and touch, are processed in the visual cortex and somatosensory cortex, respectively. Each sensory signal carries the information of where, when, what, and why to the brain. An event-detection system in the brain alerts the organism to the co-occurrence of the two stimuli and to the fact that they may be connected. Confirmation that the signals are indeed connected is provided by the event-detection system when it receives two simultaneous sensory signals. In this case, the event-detection system is the bundle of neurons that projects from the parietal areas of the somatosensory cortex back to the visual cortex and provides the cross-modal effect.

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