plosive. An improved understanding of the flammability and explosion limits for their ternary mixture at elevated temperature and in the presence of solids is needed. Given that the reactor operates at the edge of the reactor materials' durability envelope, mixing and control issues will be important.

Along with technical hurdles, business forces will inevitably determine the pace of commercialization. The reactor volume for the present process will be considerably lower than that of an ethane cracker; however, catalyst replacement and disposal costs will have to be factored into the economic analysis. A head-to-head analysis of carbon atom utilization and operating costs versus ethane cracking is needed. A key issue is whether the technology can be easily retrofitted into existing plants. Detailed characterization of products and pilot studies containing recycled streams should help answer these questions. For new plant constructions, an acceptable technical risk and financial hurdle rate will have to be defined.

The Bodke *et al.* report calls to attention several horizons for future research. The possibility of using similar chemistry for synthesis of other chemicals, especially in cases where endothermic and exothermic reactions are coupled, needs further exploration. To alleviate safety concerns, basic research on the explosion and flammability limits of gas mixtures with and without solids present is needed. The nature and morphology of the active catalytic site, surface kinetics, and the role of homogeneous reactions in determining product selectivity in these reactors will need to be better understood. Modeling tools containing heterogeneous and homogeneous kinetics will have to be extended to include mixtures of higher molecular weight hydrocarbons. From a materials standpoint, thermally stable supports and reactor design concepts may have to be developed. Despite the technical challenges, the chemistry, and the high temperature, short contact time reactor technology developed by Bodke *et al.* is likely to present opportunities for discovery and engineering in what is considered by some to be a mature industry.

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PERSPECTIVES: EARTHQUAKE GEOPHYSICS

Deep Slip Rates on the San Andreas Fault

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Parkfield, California, located along the San Andreas fault, is affectionately known to the local inhabitants and some Earth scientists as the "Earthquake Capital of the World," but to most people the town—with a population of 34, according to a sign at the outskirts—is hardly on the map. Because of an unusually regular sequence of magnitude (M) ~ 6 earthquakes since 1857 (*1*), the Parkfield segment of the San Andreas fault has been the subject of a focused earthquake prediction study since 1985. The approximately $M6$ earthquakes in the Parkfield sequence occurred on average every 22 years, with the last one in 1966. In 1985, the next event was thus forecast to occur in 1988 ± 5 years (*1*). Although the expected earthquake has still not occurred, the data have become a rich source of information about the behavior of this part of the San Andreas fault system, and the observations may have important implications for other areas of earthquake hazard where the population density far exceeds that at Parkfield.

A fascinating example of what such a data set can tell us about fault behavior is presented by Nadeau and McEvilly on page 718 of this issue (*2*). At Parkfield, an array of seismometers is installed in boreholes at ~250 m below the surface. Borehole seismometers have much higher sensitivity than surface instruments because they are remote from surface noise sources. The borehole seismometers are arrayed around the epicenter of the 1966 earthquake, close enough to the epicenter to locate earthquakes with magnitudes as low as about −1.

Over the past 11 years, most of the 6000 microearthquakes detected by the Parkfield seismometer array occurred in spatially distinct clusters. Most of the 300 clusters that have been recognized (*2*, *3*) have experienced a sequence of up to 20 repeating "characteristic" earthquakes. Each microearthquake is virtually identical to the others in the same sequence, not only in location but in seismic characteristics. It seems that at each cluster, the "same" earthquake occurs over and over again.

Even though both cluster and noncluster microseismicity occurs, over 99% of the area of the San Andreas fault plane slips without microearthquakes (*2*). It is not known why most of the surface area of the fault creeps quietly, whereas only certain very localized spots slip via microearthquakes, but my guess is that it results from differences in rock type. It has been shown (*4*) that frictional sliding of some rock types becomes harder as the slip velocity increases (velocity strengthening) and weaker for other rock types (velocity weakening). Elastically loaded velocity-strengthening materials slide stably, whereas velocity-weakening materials slide unstably (*5*). This explanation seems to fit the spatial distribution of microseismicity at Parkfield. To the southwest of the fault, the rocks are relatively homogeneous granites, whereas the Franciscan formation on the northeast side is much more heterogeneous (*6*). The Franciscan rocks east of the 1966 epicenter are a melange, with clumps of harder rock including sandstone, greenstone, and chert dispersed in softer mudstones. Laboratory data on similar materials suggest that these clumps are velocity weakening, whereas the mudstone is velocity strengthening (*4*). This would result in microearthquakes where the harder clumps rub the granite across the fault and in fault creep everywhere else. The suggestion is that every time enough stress has built up by slow slip between the surrounding mudstone and the granite, each small harder patch jerks forward in another microearthquake.

Regardless of the correct explanation for the clusters of repeating earthquakes, Nadeau and McEvilly (*2*) have put them to good use to determine the slip rate for the fault at depth as a function of space and time. Creepmeters across the fault show how it slips at Earth's surface, but slip at depth has to date only been inferred by indirect methods (*7*, *8*). The observations reported by Nadeau and McEvilly (*2*) are not as direct as would be obtained by a creepmeter installed across the fault at a depth of 10 km, but this would be a technically almost impossible task. The assumptions involved in their inferences of slip rate are simple and any errors introduced should not change the general interpretation. Each repeating earthquake has virtually the

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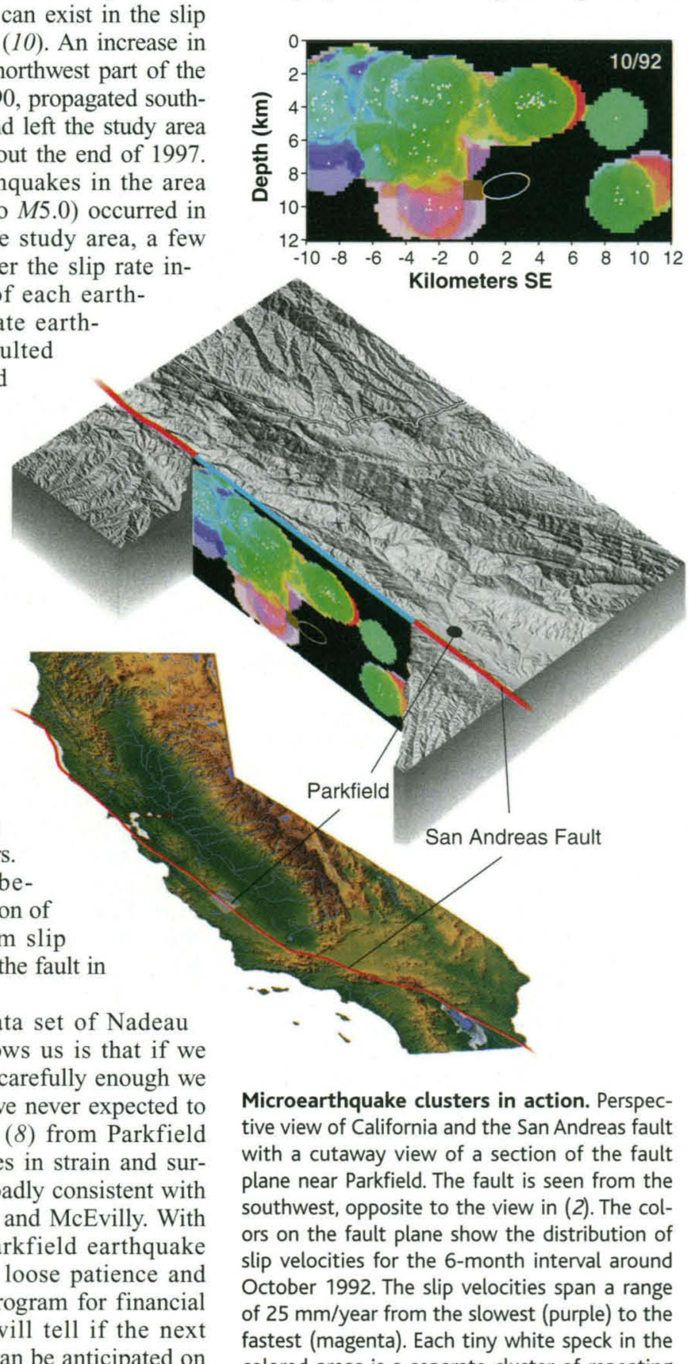
same seismic waveforms and amplitudes as the others in that cluster. The authors use the average seismic moment for each cluster to obtain its characteristic slip distance. This slip distance is then divided by the time interval between successive events in the repeating sequence to give a slip rate for the cluster during this time interval (*9*).

The results illustrate the temporal and spatial variability that can exist in the slip rate on an active fault (*10*). An increase in slip rate began in the northwest part of the study area in about 1990, propagated southeast along the fault, and left the study area to the southeast by about the end of 1997. The four largest earthquakes in the area since 1987 (at *M*4.2 to *M*5.0) occurred in the middle part of the study area, a few months to 2 years after the slip rate increased in the area of each earthquake. These moderate earthquakes may have resulted from the increased loading rate seen in the recurrence-derived slip rate increases. The southeastward migration of increased slip rate along the fault might reflect migration of stress as a result of flow in the lower crust or upper mantle. Changes in slip rate of up to 20 mm/year are indicated at selected places on the fault, over time spans as short as 4 years. This is remarkable because it is a large fraction of the average long-term slip rate of 33 mm/year on the fault in this area (*11*).

The interesting data set of Nadeau and McEvilly (*2*) shows us is that if we look at the fault zone carefully enough we can learn things that we never expected to find. Other data sets (*8*) from Parkfield show temporal changes in strain and surface slip that seem broadly consistent with those seen by Nadeau and McEvilly. With luck, the next *M*6 Parkfield earthquake will occur before we loose patience and stop the monitoring program for financial reasons. Only time will tell if the next Parkfield earthquake can be anticipated on the basis of measurements of increased loading rate or any of the other types of measurement being made there.

Any fault that shows both creep and earthquakes is likely to show similar time and space variations in slip rate that might help us to understand fault mechanics and predict earthquakes in other fault zones if adequately dense borehole arrays of seismometers can be installed. It is noteworthy that the segment of the San Andreas fault reported on by Nadeau and McEvilly (*2*) is the location of a proposed deep drill hole that would cross the fault zone at 3- to 4-km depth near one of the repeating clusters (*12*). If this drilling takes place, we may learn more about the origin of the clusters and better understand the earthquake process by making direct measurements of many physical parameters right where small earthquakes are occurring.



Microearthquake clusters in action. Perspective view of California and the San Andreas fault with a cutaway view of a section of the fault plane near Parkfield. The fault is seen from the southwest, opposite to the view in (*2*). The colors on the fault plane show the distribution of slip velocities for the 6-month interval around October 1992. The slip velocities span a range of 25 mm/year from the slowest (purple) to the fastest (magenta). Each tiny white speck in the colored areas is a separate cluster of repeating earthquakes (see expanded panel at the top for details). The white ellipse shows the aftershock area of a *M*4.7 earthquake that occurred in October 1992 and may have been promoted by an increase in slip rate to its north in the previous months. The brown square shows the hypocenter of the 1966 *M*6 earthquake.

SOURCE: S. WALTERS/USGS

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