tional coupling and consequent line broadening), whereas muonated radicals can be easily detected in the gas phase. Muonated centres have been detected whose hydrogen-atom analogues have never been detected by ESR spectroscopy[6,7]. Moreover, because of their greater sensitivity, muons can be used to study the kinetics of surface reactions. Perhaps surface studies such as that described by Reid *et al.* will prove to be yet another area in which the use of muons is advantageous, although it will never be a popular method because of the extreme difficulties in obtaining muon beam time. And it must be borne in mind that the muon technique is quite limited in the types of radicals that can be detected, in contrast with ESR spectroscopy, which is also a powerful tool for studying radicals on surfaces. It seems likely, however, that those who do have access to muons will be inspired by the results of Reid *et al.* to try to probe surface reactions of industrial importance, particularly from a kinetic viewpoint. □

Martyn C. R. Symons is in the Department of Chemistry at the University of Leicester, University Road, Leicester LE1 7RH, UK.

1. Reid, I.D., Azuma, T. & Roduner, E. *Nature* **345**, 328–330 (1990).
2. Kiselev, A.V. & Lygin, V.I. *Infrared Spectra of Surface Compounds* (Wiley, New York, 1975).
3. Boddenberg, B., Haul, R. & Opperman, G. *Naturwiss.* **56**, 636–640 (1969).
4. Cox, S.F.J. & Symons, M.C.R. *Hyperfine Interactions* **32**, 689–706 (1986).
5. Carrington, A. *Microwave Spectroscopy of Free Radicals* (Academic, London, 1974).
6. Patterson, B.D. *Muons and Pions in Materials Research* (eds Chappert, J. & Grynszpan, R.I.) ch.10 (North Holland, Amsterdam, 1984).
7. Cox, S.F.J. & Symons, M.C.R. *Chem. Phys. Lett.* **126**, 516–525 (1986).

EARTHQUAKES

Seismic cycle not so simple

Max Wyss

UNTIL now it has seemed reasonable to model the seismic cycle of great earthquakes along plate boundaries as follows: at the time of a great earthquake a rupture with approximately uniform slip releases most of the available energy throughout the extent of the rupture outlined by the aftershocks. Then, plate motions accumulate strain energy at an approximately constant rate over the recurrence period (thirty to several hundred years, depending on the location), until the strain level at which rupture occurs is again reached. At that time a great earthquake re-ruptures the same plate boundary segment. This process would result in a seismic cycle of approximately constant recurrence time, because the loading rate and rupture dimensions are constant. The rupture lengths may repeatedly be the same because some geometric tectonic features may define segments of the plate boundary that will rupture in one earthquake. By showing that earthquakes that re-rupture a particular segment of plate boundaries are not similar, Thatcher[1,2] (first in *Nature* and now in full in the *Journal of Geophysical Research*) has deprived seismologists of part of their favourite model for the generation of great earthquakes.

In cases that conform closely to this model, one speaks of a characteristic earthquake[3]. There are, however, also sequences of earthquakes in nearly the same location with regular recurrence times but significantly different magnitudes[4]. Thatcher points out that the simple recurrence model is based partly on the incorrect assumption that the slip is evenly distributed over the rupture area, when in reality most of the energy release comes from a fraction of the rupture area, where the slip is large. He also shows that characteristic earthquakes are the exception rather than the rule along the circum-Pacific plate boundaries. Segments that have historically ruptured in one great earthquake often re-rupture in two or three smaller events, a few years apart. But did these subsequent ruptures really achieve the same strain release as the large one?

As Thatcher observes, the sum of the seismic moment release in several smaller events is much smaller (in the best documented case, 80 per cent less) than that of a single large event. Thus, one cannot think of the two types of rupture as equivalent, even though large events that are multiple ruptures might be interpreted as a sequence of smaller earthquakes occurring within minutes rather than within decades. The slip in the smaller earthquakes, which make up one part of the cycle, may be as little as 20 per cent of the slip in the previous cycle (the large single event), or 40 per cent over half the width of the plate boundary. One might hesitate to call something a 'seismic cycle' which is defined by subsequent episodes of energy release of 100 per cent and 20 per cent. It would be more correct to argue that in the second instance nothing has happened (no energy release) to a first approximation, than to take the view that the same cyclic event (100 per cent release) has happened again.

Thatcher retains the idea of a seismic cycle because the entire plate boundary segment is ruptured in great earthquakes each time, and the intervals remain the same. But do they? Thatcher argues that they do. But this idea may also have to be modified when developing a more complicated model. In the several cases for which Thatcher gives more than one recurrence time (at least three repeated ruptures) the differences between the shortest and longest recurrence interval is on average 67 per cent of the shortest interval (16 per cent and 207 per cent for the extreme cases). Examples of even greater variation of recurrence interval (40 to 300 years) for large ruptures with similar amount of slip exist for segments of the San Andreas fault[5]. Perhaps the whole simple model of recurrence of great earthquakes may have to be substantially revised because the energy release in re-ruptures and the recurrence time vary greatly.

The main value of Thatcher's work is that he has pointed out the inadequacy of a simple model of recurrence that was easily understood and seemed to make sense. The more complicated model he has proposed[1,2] for explaining the varied nature of re-rupture may not convince all readers. He has not considered the possibility of asperities (strong spots at the fault surface) changing their role from barriers to rupture initiation points as a function of the strain accumulated in them. Also, the amount of slip variation in one earthquake along the fault is not discussed quantitatively, leaving the reader wondering whether a 30 per cent difference in slip is enough to separate asperities from weak fault segments, and how much aseismic fault creep is necessary in Thatcher's model to balance the long-term plate motion along the boundary.

It is not particularly comfortable when 'well established', simple and sensible models are discredited. Thatcher has done this and raised additional questions, which may lead to more changes of the recurrence model of great earthquakes. As Thatcher emphasizes, the role of asperities[6-10], their distribution and their activation in subsequent cycles must become clear before we can fully understand the rupture process along great faults and make substantial progress in predicting earthquakes. □

Max Wyss is in the Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Campus Box 216, Boulder, Colorado 80309-0216, USA.

1. Thatcher, W. *Nature* **341**, 432–434 (1989).
2. Thatcher, W. *J. geophys. Res.* **95**, 2609–2623 (1990).
3. Bakun, W. H. & McEvilly, T. V. *J. geophys. Res.* **89**, 3051–3058 (1984).
4. Wyss, M. *Science* **234**, 726–728 (1986).
5. Sieh, K., Stuiver, M. & Brillinger, D. *J. geophys. Res.* **94**, 603–623 (1989).
6. Wesson, R. L., Burford, R. O. & Ellsworth, W. L. *Proc. Conf. Tectonic Problems of the San Andreas Fault System* (eds. Kovach, R. L. & Nur, A.) 303–321 (Stanford University, Stanford, 1973).
7. Aki, K. *J. geophys. Res.* **84**, 6140–6148 (1979).
8. Lay, T. & Kanamori, H. in *Earthquake Prediction* (eds Simpson, D. W. & Richards, P. G.) 579–592 (Am. Geophys. Union. Washington, D.C., 1981).
9. Wyss, M., Johnston, A. C. & Klein, F. W. *Nature* **289**, 231–234 (1981).
10. Aki, K. *J. geophys. Res.* **89**, 5867–5872 (1984).