is initiated by double-stranded breaks. One could also imagine that recombination events are initiated but aborted in ways that do not leave lethal DNA lesions or even genetic evidence of their previous existence. If double-stranded breaks in flies are made by a homolog of the yeast topoisomerase II–like Spo11 protein (*9*, *10*), there may be reversible cleavage of DNA. The cell might receive a signal that recombination has been initiated but, in the absence of a key subsequent step that is prevented by *mei-P22* or *mei-W68*, the cleaved DNA would simply be re-ligated. In this scenario, synaptonemal complex formation would then depend on the signal generated by transient double-stranded break formation, but not on recombination per se.

Moreover, the fact that the synaptonemal complex appears in the absence of recombination does not rule out the possibility that normally the complex forms in direct response to recombination. In meiotic mutants the establishment of the complex might be delayed for many hours, forming between unrecombined but well-paired chromosomes. Delayed complex formation between regions that cannot undergo recombination occurs in mice (*11*), and a similar event happens in yeast haploid cells tricked to undergo meiosis, even though there are no homologous chromosomes (*12*). This idea is lent some credibility by the existence of meiotic pairing sites that might bring *Drosophila* chromosomes into alignment (*2*).

In riposte, a drosophilist might note that there is already some evidence that the formation of double-stranded breaks in yeast is influenced by previous interaction of homologous sequences at "hot spots," although synaptonemal complex formation per se does not seem to be required. Also, the absence of some complex components significantly reduces double-stranded break formation (*13*).

The results of McKim *et al.* convince us that the events we normally think of as recombination—detectable crossing over or gene conversion—are not required to form the synaptonemal complex in a metazoan, even though this does seem to be the case for yeast. Whether synaptonemal complex formation is a prerequisite to initiate recombination in higher eukaryotes remains unknown. One may hope for a mutation in flies that eliminates a vital synaptonemal complex component to see whether recombination is also abolished.

Most organisms likely use a combination of recombination-dependent and recombination-independent mechanisms for homolog recognition and pairing, as they prepare to segregate their chromosomes. The reliance on one mechanism or the other may depend on genome complexity, the number of chromosomes, and the sites where recombination is initiated. For the moment, yeast and flies seem to be showing us two extremes.

References and Notes

1. K. McKim *et al.*, *Science* **279**, 876 (1998).
2. R. S. Hawley, *Genetics* **94**, 625 (1980).
3. M. Zetka and A. Rose, *Trends Genet.* **11**, 27 (1995).
4. B. M. Weiner and N. Kleckner, *Cell* **77**, 977 (1994).
5. A. S. Goldman and M. Lichten, *Genetics* **144**, 43 (1996).
6. Reviewed in G. S. Roeder, *Genes Dev.* **11**, 2600 (1997).
7. Reviewed in N. Kleckner, *Proc. Natl. Acad. Sci. U.S.A* **93**, 8167 (1996).
8. M. Sym, J. Engebrecht, G. S. Roeder, *Cell* **72**, 365 (1993).
9. S. Keeney, C. N. Giroux, N. Kleckner, *ibid.* **88**, 375 (1997).
10. A. Bergerat *et al.*, *Nature* **386**, 414 (1997).
11. M. J. Moses *et al.*, *Chromosoma* **84**, 457 (1982).
12. J. Loidl, K. Nairz, F. Klein, *ibid.* **100**, 221 (1991).
13. V. Rocco and A. Nicolas, *Genes Cells* **1**, 645 (1996).

GEOSCIENCE

Sliding Skis and Slipping Faults

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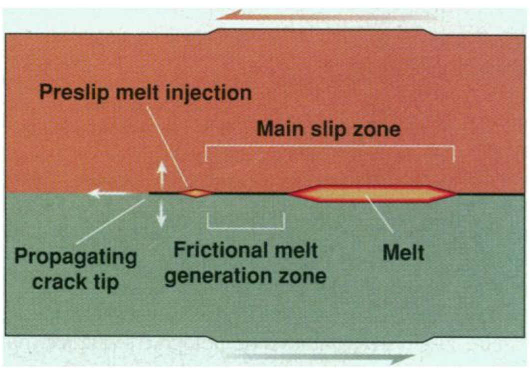
One of the first things taught in elementary physics is that friction increases with the force applied perpendicular to a sliding surface (the normal force). As innumerable high school experiments with sliding blocks attest, increasing the normal stress increases the forces resisting block movement. This property has long posed a quandary for understanding deep earthquakes, which occur as far as 670 km beneath Earth's surface (*1*). At such depths, the crushing pressure from many kilometers of overlying rock should hold faults locked tight; yet, deep earthquakes are common. Thus, some mechanism must be invoked to either eliminate the excessive normal stresses or explain the shear sliding without brittle frictional behavior. On the basis of analyses of the largest recorded deep earthquake, which occurred beneath Bolivia in 1994, Kanamori *et al.* (*2*) propose on page 839 of this issue that deep earthquakes may occur as a result of melting. They suggest that melting during such an earthquake forms a thin fluid layer that reduces friction in much the same way that a thin layer of water reduces the friction between a ski and the underlying snow (*3*).



Melting, slipping, and sliding. Model for faulting with lubrication induced by frictional melting, originally developed to explain geological observations of pseudotachylytes in exhumed fault zones [after Spray (*9*)]. As the active slip zone moves along the fault, melting is induced by friction. If rupture propagation is slow, some melt may be injected ahead of the main slip zone, perhaps facilitating crack propagation. Kanamori *et al.* (*2*) propose that a similar model may explain large deep earthquakes such as the 1994 Bolivia event.

There are several other ways to explain the shear motion associated with deep earthquakes in the presence of large confining pressures. Friction along an interface may be reduced or eliminated if a fluid is present at a pressure near the confining pressure. This mechanism is thought to weaken shallow faults and may provide a mechanism for deep earthquakes if water can be carried to such depths within hydrous minerals (*4*). Another proposal, transformational faulting, suggests that deep earthquakes are associated with solid-state phase transitions to denser phases of olivine (*5*). Laboratory experiments suggest that when such transitions have been kinetically inhibited, the metastable transformations occur suddenly and can be accompanied by shear dislocations (*6*). However, the fault widths of recent large deep earthquakes seem to be too large to be accommodated within the metastable olivine material (*7*).

Kanamori *et al.* (*2*) note that the Bolivia earthquake had several unusual properties, including a very slow rupture velocity, high stress drop, and a low ratio of radiated seismic energy to total strain energy (seismic efficiency). The high stress drop indi-

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cates that a lot of heat was produced (*8*), which would have been sufficient to generate melt if the width of the slipping zone was narrow (less than 30 cm). In addition, the source process was highly dissipative, indicating that little of the available energy was radiated seismically and suggesting that much of the energy may have been used in melting material near the fault.

The details of the melting model are speculative, in that the width of the slip region cannot be determined from seismic analysis and is thus unconstrained. In addition, no specific mechanical model by which the melt promotes crack growth has been proposed. Models that have been proposed to explain melting in shallow faults that are observed geologically (pseudotachylytes) offer a possible analog. In one such model (see figure), a zone of frictional melt production moves with the rupture front along the fault (*9*). Melt covers the fault within the slip region, thus providing lubrication that facilitates slip. Melt injection under high pressure may also occur ahead of the melt zone, facilitating crack propagation through the medium. Melt production tends to reduce friction along the fault, but this action will then reduce the production of melt. In this way, an equilibrium between friction, melt production, and melt lubrication may be reached, allowing the fault to propagate smoothly.

Another major question is what initiates the crack propagation that grows into the large earthquake rupture. Melt can only lubricate the fault after it is produced by friction along an already slipping interface, so the melting model makes no statement about what type of instability creates the initial slip. One possibility is that transformational faulting initiates the rupture, which then propagates through the melting mechanism proposed by Kanamori *et al*. If true, the melting mechanism may explain why the fault widths of the largest deep earthquakes are incompatible with the transformational faulting mechanism and also suggests why other large deep earthquakes can propagate outside of the Wadati-Benioff zone formed by smaller earthquakes (*10*).

A melting model for deep-earthquake fault propagation may also help to explain growing evidence that the deep-earthquake rupture process is fundamentally temperature sensitive in a way that shallow earthquakes are not. For example, deep earthquakes show much different magnitude-frequency relations and aftershock production in different subduction zones, with warmer slabs showing much lower occurrence rates for small earthquakes and very few aftershocks (*11*). In addition, there is some evidence that the rupture parameters of the largest deep earthquakes are also correlated with slab temperatures (*12*). Melt-assisted faulting would presumably be sensitive to the temperature of the slab material and may operate well only in warmer slabs such as South America.

It is not clear whether this proposal can explain all deep earthquakes. The very characteristics that suggest melting for the Bolivia earthquake—the high stress drop, low rupture velocity, and low seismic efficiency—are actually the characteristics that make it seem most anomalous. For example, both of the other recent large deep earthquakes (1994 Tonga and 1996 Flores Sea) show lower stress drop, higher rupture velocity, and higher seismic efficiency (*10, 12, 13*).

Therefore, the melting model of Kanamori *et al.* may only be applicable to the largest deep earthquakes, a group that includes the 1954 Spanish deep earthquake and the 1970 Colombia event, in addition to the 1994 Bolivia earthquake. These earthquakes seem to occur only in regions without smaller earthquakes, suggesting that temperatures there may be too hot for the nucleation of typical earthquakes, and that a melting "runaway" effect may result in great earthquakes once shear failure is initiated. Ideally, we would like to observe a larger number of these events to clarify the true nature of these unusual earthquakes. Unfortunately, these isolated, exceptionally large earthquakes are very rare, and seismologists will probably be kept waiting for years, if not decades, for another event like the 1994 Bolivia earthquake.

References

1. C. Frohlich, *Annu. Rev. Earth Planet. Sci.* **17**, 227 (1989).
2. H. Kanamori *et al.*, *Science* **279**, 839 (1998).
3. D. Lind and S. P. Sanders, *The Physics of Skiing* (Springer-Verlag, New York, 1996).
4. C. Meade and R. Jeanloz, *Science* **252**, 68 (1991).
5. S. H. Kirby *et al.*, *ibid.*, p. 216; H. W. Green and H. Houston, *Annu. Rev. Earth Planet Sci.* **23**, 169 (1995); S. H. Kirby *et al.*, *Rev. Geophys.* **34**, 261 (1996).
6. H. W. Green *et al.*, *Nature* **348**, 720 (1990); P. C. Burnley *et al.*, *J. Geophys. Res.* **96**, 425 (1991).
7. D. A. Wiens *et al.*, *Nature* **372**, 540 (1994); P. Silver *et al.*, *Science* **268**, 69 (1995).
8. D. McKenzie and J. N. Brune, *Geophys. J. R. Astron. Soc.* **29**, 65 (1972).
9. J. G. Spray, *J. Geophys. Res.* **98**, 8053 (1993).
10. J. J. McGuire *et al.*, *ibid.* **102**, 15163 (1997).
11. D. A. Wiens and H. J. Gilbert, *Nature* **384**, 153 (1996).
12. D. A. Wiens, *Geophys. Res. Lett.*, in press.
13. S. Goes *et al.*, *ibid.* **24**, 1295 (1997).

WEBWATCH

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http://chemfinder.camsoft.com/

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Botany online

http://herb.biol.uregina.ca/liu/bio/idb.shtml

The Internet Directory for Botany (IDB) online is an immense collection of links and information about all aspects of the plant kingdom, arranged in an easily navigable and searchable form. Links are given to arboreta, herbaria, botantical gardens, and university botany and biology departments. Checklists of flora, taxonomic databases, and image collections are gathered here too. The result of an international effort, the IDB is hosted at the University of Regina, Saskatchewan, Canada, and mirrored in nine other countries.

Japanese science

http://fuji.stanford.edu:80/JGUIDE/jguide.html

One of the better compilations of links to information about science and technology in Japan can be found at Stanford University. There are copious lists of university, corporate R&D, and government laboratory Web sites, along with pointers to scholarly societies and research groups such as the Japan Technology Evaluation Center at Loyola University. Other resource pages at the site provide information about using computers with Japanese language software.

Edited by David Voss

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