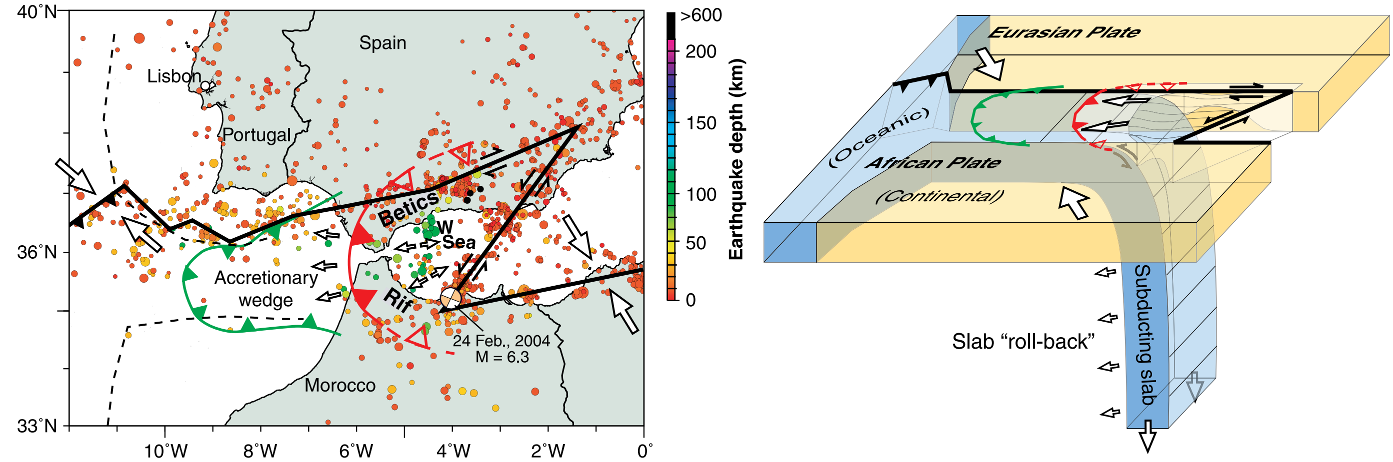

Seismicity and tectonics. (**Left**) Simplified tectonic boundaries and seismicity (from U.S. Geological Survey PDE Catalog 1980–2004, $M > 3$) in the southern Iberia region. Arrows indicate relative motions of major plates and tectonic blocks. Bathymetric contours are shown at 1000-m intervals (from General Bathymetric Chart of the Oceans 1-min digital Atlas). The dashed line shows the inferred limit between continental and oceanic lithosphere. (**Right**) Three-dimensional block diagram indicating sinking and roll-back of oceanic lithosphere belonging to the African Plate.

the form of coarse-grained, sandy "turbidite" deposits laid down by submarine gravity slides during great earthquakes (*13*). These deposits suggest that events of the magnitude of the Great Lisbon earthquake occur periodically at ~1000- to ~2000-year intervals.

As the 250th anniversary of this greatest natural disaster in recorded European history approaches, the Gulf of Cadiz has become the target of a concerted international effort, supported by the European EuroMargins Program. Five oceanographic cruises are planned between summer 2004 and 2005. Three new proposals have been submitted to the Integrated Ocean Drilling Program to search for clues beneath the sea floor. Together, the new studies may help to unlock the secrets of this region's past and its likely future.

References and Notes

1. J. M. Martinez-Solares, A. Lopez, J. Mezcua, *Tectonophysics* **53**, 301 (1979).
2. M. A. Baptista *et al.*, *J. Geodyn.* **25**, 159 (1998).
3. I. Jimenez-Munt, M. Fernandez, M. Torne, P. Bird, *Earth Planet. Sci. Lett.* **192**, 175 (2001).
4. J. P. Platt, R. L. M. Vissers, *Geology* **17**, 540 (1989).
5. L. Lonergan, N. White, *Tectonics* **16**, 504 (1997).
6. M.-A. Gutscher *et al.*, *Geology* **30**, 1071 (2002).
7. S. Duggen, K. Hoernle, P. van den Bogaard, C. Harris, *Earth Planet. Sci. Lett.* **218**, 91 (2004).
8. C. Faccenna *et al.*, *Tectonics* **23**, TC1012, 10.1029/2002TC001488 (2004).
9. D. Stich, C. J. Morales, J. Ammon, *J. Geophys. Res.* **108**, 2148, 10.1029/2002JB002057 (2003).
10. L. M. Pinheiro *et al.*, *Mar. Geol.* **195**, 131 (2003).
11. M.-A. Gutscher, E. Thiebot, J.-P. Rehault, Proceedings of the European Geosciences Union Meeting, Nice, France, 25 to 30 April 2004. *Geophys. Res. Abstr.* 6, CD-ROM (2004).
12. I. Grevemeyer, N. Kaul, M.-A. Gutscher, Proceedings of the European Geosciences Union Meeting, Nice, France, 25 to 30 April 2004. *Geophys. Res. Abstr.* 6, CD-ROM (2004).
13. S. M. Lebreiro, I. N. McCave, P. Weaver, *J. Sediment. Res.* **67**, 856 (1997).
14. This article is IUEM contribution 925.

GEOSCIENCE

Tidal Triggering Caught in the Act

Ross S. Stein

The lunar tides beat our entire planet, rhythmically stressing and relaxing every geological fault twice daily. These tiny stress changes may trigger small shocks on faults critically stressed for failure in future large earthquakes. Tantalized by this possibility, scientists have long searched for earthquakes triggered by tides, but the results have been, at best, equivocal. Tidal triggering does occur beneath some active volcanoes and mid-ocean ridges (*1*), and several studies report triggering of extensional and thrust earthquakes (*2, 3*). Yet strike-slip earthquakes, which are by far the most common, have shown little or no tidal influence (*2, 4*). In a recent paper in *Earth, Planets and Space*, Tanaka *et al.* (*5*) provide powerful insights into how tidal triggering works on strike-slip and thrust faults.

The stress imparted by earthquakes strongly influences the occurrence of subsequent earthquakes, such as aftershocks and successive main shocks (*6–8*). Seismicity rates increase where the Coulomb stress is calculated to rise (increased shear and unclamping), and generally drop where the Coulomb stress is calculated to decrease, a phenomenon most evident among strike-slip earthquakes. If, then, stress governs seismicity, why can we not more readily see a seismic response to the ubiquitous and predictable tides?

Stress magnitude is one answer. Typical earthquake-induced stress changes are about 1 to 10 bars, whereas the tidal Coulomb stresses are about 0.01 bar. The tidal effect is thus much weaker and might lie below a threshold. Frequency is another answer. Theoretical arguments (*9*) and laboratory evidence (*10*) suggest that the tidal oscillations are too brief to nucleate abundant earthquakes. Either way, if the tides only subtly influence seismicity or do so only near magma chambers, they are all but useless as a seismic sentinel.

Tanaka *et al.* (*5*) find that earthquakes are triggered by the tides only when the tidal stress adds to—that is, acts in the same direction as—the regional tectonic stress. Nearly all previous studies sought for an increased rate of earthquakes when the tidal stress is high or rising. In a sense, Tanaka *et al.* reframe the tidal triggering hypothesis in terms of the tidal stress azimuth rather than its phase. Reckoned this way, up to 10% of earthquakes are tidally triggered, an unexpectedly high percentage. Such a relationship had been predicted (*9*) but not demonstrated. Perhaps the biggest surprise is that tidal triggering is more common in Japan's tectonic regions than in its volcanic sites (*5*).

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The conclusion of Tanaka *et al*. rests on a two-part analysis, the first step of which appears decidedly tenuous. In one hundred 1° by 1° regions covering the Japanese archipelago, they compute the azimuth of the tidal compressional stress for 90,000 earthquakes, normalized by the tidal compressional stress for the same earthquakes but with randomized occurrence times. Tidal triggering is identified when the number of earthquakes departs from a uniform distribution. Tanaka *et al.* find tidal triggering in 13 regions. But at the 90% confidence level used in their analysis, 10 out of 100 regions should exhibit tidal triggering just by chance. An excess of three does not constitute causality.

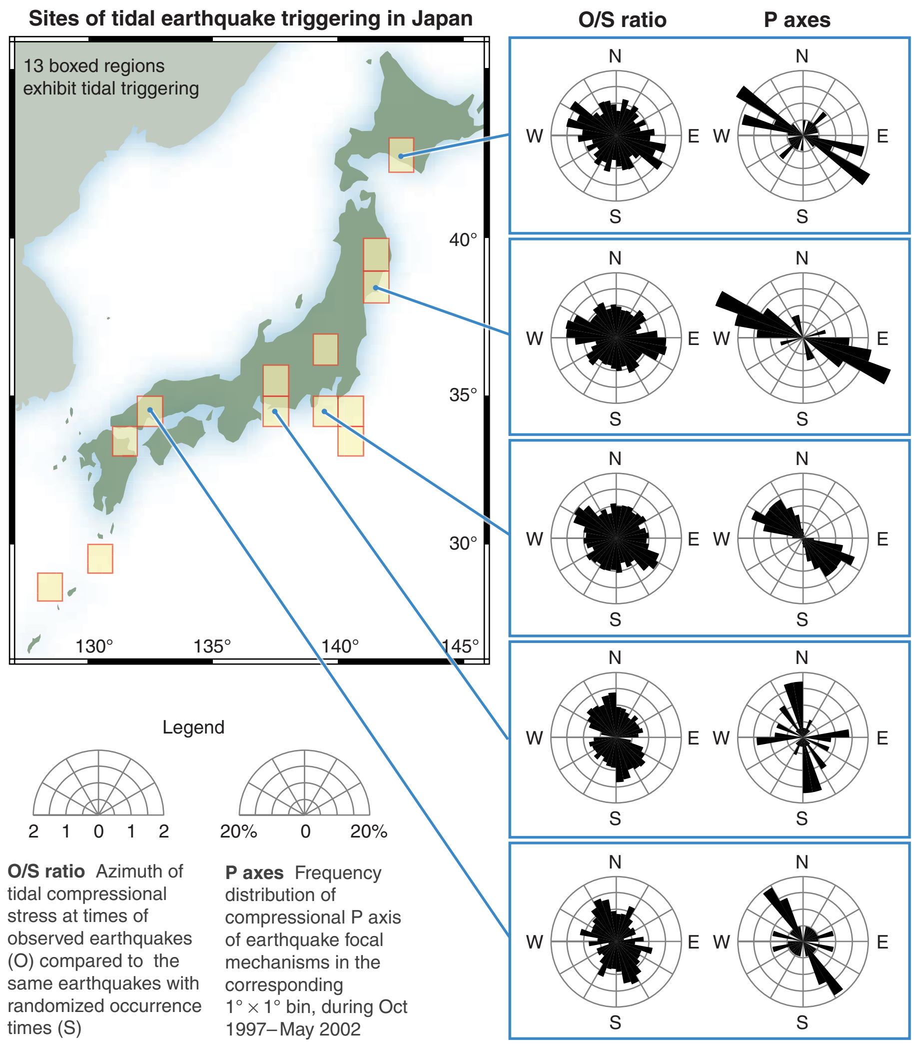
Undaunted, the authors next compare the azimuth of tidally triggered shocks to the azimuth of tectonic compression for the 10 of the 13 regions where this is possible. Suddenly, a long-sought signal emerges from the noise: a correlation between the peaks in the tidal and tectonic compression directions (see the figure).

Tanaka *et al.* also shed light on the Coulomb stress analysis of earthquakes. In doing so, they reveal why a widely used technique for studying earthquake triggering (*11*)—resolving stress changes on planes optimally oriented with respect to the net regional and earthquake stress—has worked so well. It is because earthquakes are triggered by amplifying the tectonic stress under which faults operate. A large stress change that would force a fault to slip in a direction other than the one in which it has evolved has little effect, whereas a tiny nudge in its natural slip direction can nucleate an earthquake. The results reported by Tanaka *et al*. also upend arguments that the high rate of tidal oscillations all but precludes triggering (*12*). Given that most shocks in Japan are thrust or strike-slip, they also challenge arguments that triggering cannot be detected in strike-slip regimes.

The Achilles' heel of the analysis by Tanaka *et al.* is why the tidal effect is evident in only 13% of the Japanese archipelago. The authors suggest that regions must reach a critical stress before the small tidal increments can trigger earthquakes. They support their claim by arguing that large shocks have preferentially struck regions exhibiting tidal triggering (*3*). But there are other plausible explanations.

First, the 13 regions could be subject to unusually strong tides. Tanaka *et al.* should therefore test whether the seismicity rate is proportional to the tidal phase when the tidal and tectonic stresses align. Second, faults might need to be uniformly oriented for tidal triggering to be detectable. Tidal triggering is identified in only one region with a complex stress and faulting pattern. Third, the 13 regions could have unusually low fault friction. To test this hypothesis, the authors should invert for the azimuth of the tectonic stress rather than plot the P axes. The latter represent the principal compression only if fault friction is low, because antithetical faults are then orthogonal to each other and share the same P axes. For high fault friction, antithetical faults form at acute angles to the principal compression direction, and their P axes would diverge.

Whether the study by Tanaka *et al.* proves to be a breakthrough depends on what happens next. Reproducing the results in California and Taiwan would strengthen if not cement the case. Examining cases with unusually large tidal stress changes due to ocean loading will test whether the oscillatory nature of tidal stress—rather than its small magnitude—inhibits triggering (*13*). Finally, Tanaka *et al.* should set up a formal forecast to see if large earthquakes strike the 13 regions at a higher rate than strike the rest of Japan. If so, then the dream of tidal monitoring of earthquake hazard could yet come true.



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Tidal pull on Japan's shocks. Tanaka *et al.* (*5*) find that earthquakes are triggered by the tides when the tectonic stress, represented here by the compressional P axes of focal mechanisms, aligns with the tidal stress. Compare the left and right rose diagrams in each blue box; all shown are correlated at the 90% confidence level. But there is a catch: Just 13 of 100 regions exhibit tidal triggering, only slightly above the 90% confidence level. For the full data set, see the supporting online material.

References

1. M. Tolstoy *et al.*, *Geology* **30**, 503 (2002).
2. H. Tsuruoka *et al.*, *Geophys. J. Int.* **122**, 183 (1995).
3. S. Tanaka *et al.*, *Geophys. Res. Lett.* **29**, 10/1029/2002GL015386 (2002).
4. J. E. Vidale *et al.*, *J. Geophys. Res.* **103**, 24567 (1998).
5. S. Tanaka *et al.*, *Earth Planets Space* **56**, 511 (2004).
6. R. A. Harris, *J. Geophys. Res.* **103**, 24347 (1998).
7. R. S. Stein, *Nature* **402**, 605 (1999).
8. G. C. P. King, M. Cocco, *Adv. Geophys.* **44**, 1 (2000).
9. J. H. Dieterich, *Tectonophysics* **144**, 127 (1988).
10. N. M. Beeler, D. A. Lockner, *J. Geophys. Res.* **108** (2003).
11. G. C. P. King *et al.*, *Bull. Seismol. Soc. Am.* **84**, 935 (1994).
12. C. H. Scholz, *Nature* **425**, 670 (2003).
13. E. S. Cochran, J. E. Vidale, S. Tanaka, *Eos, Trans. AGU* **84**, Fall Meet. Suppl., abstr. S32F-02 (2003).

Supporting Online Material

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Fig. S1
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