A Wave in the Earth

Arch C. Johnston

"Pärvie" is an old Lappish word meaning, roughly, "wave in the ground." The Pärvie fault of northern Sweden is just that and more: a 150-km-long slash across the land, which at its maximum resembles a 10-m tsunami crest frozen in the rock (see figure). How did it get there? Studies over the last two decades, principally by Lagerbäck (*1*), show that it formed suddenly by earthquake faulting during the late glacial to early postglacial times of the great Finnoscandian ice sheet (~8000 to 8500 years before present), suggesting a genetic relation between the two. Now Arvidsson on page 744 of this issue (*2*) adds the important dimensions of time and depth with evidence that the Pärvie and related postglacial faults (PGFs) are not completely dead and that they possibly extend through the entire thickness of the Baltic Shield crust.

Arvidsson's study concentrates on the smaller, ~50-km-long Lansjärv PGF for the practical reason that it was more accessible to a seismic instrument array for recording and locating current microearthquakes. The epicenters' concentration near the mapped PGF fault traces is clear. Furthermore, most epicenters fall to the east of the northerly trending scarps, nicely conforming with the easterly fault dips observed at the surface. The earthquake hypocenters, however, are too diffuse to define the fault dip at depth, but their range throughout the ~40-km-thick Baltic Shield crust is the first tantalizing evidence for great crustal depths of the PGFs. Other implications aside, the increased down-dip fault widths require significantly larger earthquakes to create the PGFs. For the Pärvie, for example, with fault width from Arvidsson (*2*), a moment magnitude of M_w = 8.2 is obtained; with another model (*3*), where the fault dip decreases and fault rupture dies out at shallow depths, the fault width is ~15 km, yielding M_w ~ 7.8. A similar calculation for Lansjärv yields M_w = 7.8 and M_w = 7.5, respectively.

Earthquake nucleation in the lower crust or the propagation of large shallow fault ruptures to lower crustal depths (~20 to 40 km) is controversial. In "normal" continental crust the abundant quartz and feldspar minerals become plastic at lower crustal pressures and temperatures, thereby inhibiting (or even prohibiting) brittle fracture, characteristic of earthquake faulting of the elastic upper crust. The brittle-plastic transition, however, is very sensitive to a host of poorly constrained parameters: not only composition and pressure-temperature regime, but also the presence of fluids and the rate at which the lower crust deforms in response to tectonic stresses. Evidence [now including (*2*)] has slowly accumulated that in thick, old continental shields, the conditions—particularly lower temperatures—do permit brittle faulting to great crustal depths (*4*); indeed, the Baltic Shield crust may be elastic throughout.

Rock tsunami. Two views of the Pärvie fault. (**Right**) Close view showing the fault scarp. (**Top**) Aerial view showing snow trapped in lee (footwall) side of the fault.

The permissibility of deep earthquake rupture in the oldest continental crust or in old oceanic lithosphere leads to a startling paradox. These regions are the least seismically active on Earth. Yet, aside from the tectonic plate boundaries, they are able to support larger earthquakes than other plate-interior regions, apparently because of the additional brittle or semibrittle fault area available at depth. At M_w = 8.2 ± 0.2, the Pärvie deep-faulting event would be the largest earthquake known within the stable continental regions (SCRs) of the tectonic plates (*5*). The analog in old oceanic lithosphere is the great 1755 Lisbon earthquake (M_w = 8.7 ± 0.4), the largest oceanic event not associated with subduction zones, in which faulting may have extended to depths of 60 km or more (*5*).

Because of their timing and the computed crustal stress changes conducive to shear failure, the Finnoscandian PGFs are regarded as a remarkable consequence of rapid crustal unloading as the ice sheets of the last ice age melted (*6*). The Pärvie and other PGFs, then, represent the faults of induced earthquakes, events that would not have happened without externally imposed failure conditions. Induced seismicity is not particularly uncommon, but the postglacial earthquakes are again and easily the largest known examples of this class. Surface quarrying can generate M_w = 2 to 4 earthquakes; deep mining and deep-well waste disposal, M_w = 5 to 6 events; and large hydro-reservoirs, M_w ~ mid 6 events. Excluding PGFs, there are no earthquakes exceeding M_w = 7 confidently considered induced. The earthquake magnitude seems to scale with the agent of change of crustal stresses: Great ice sheets can induce great earthquakes.

So where are the Canadian postglacial faults (*7*)? (Or Siberian?) The North American Laurentian ice sheet was larger than the Finnoscandian. This question has implications beyond purely scientific inquiry. Under normal conditions the ancient shields and cratons are the most aseismic zones of the continents. This seismic quiet makes them attractive to a number of countries (*8*) for possible high-level nuclear waste disposal sites; indeed, it is this prospect that supports most of Swedish PGF research (*9*). If it requires another ice age to come and go in order to generate the large PGF faults and earthquakes, then Arvidsson's results do not disqualify such geologic regions. His new information does, however, considerably raise the stakes, a development the Canadians and Russians should be following with great interest.

The author is at the Center for Earthquake Research and Information, University of Memphis, Memphis, TN 38152, USA. E-mail: johnston@ceri.memphis.edu

References and Notes

1. J. Lundqvist and R. Lagerbäck, *Geol. Foren. Stockh. Forh.* **98**, 45 (1976); R. Lagerbäck, *ibid.* **100**, 263 (1979); *ibid.* **112**, 333 (1990).
2. R. Arvidsson, *Science* **274**, 744 (1996).
3. R. Muir Wood, in *Earthquakes at North Atlantic Passive Margins: Neotectonics and Postglacial Rebound*, S. Gregersen and P. W. Basham, Eds. (Kluwer Academic, Dordrecht, Netherlands, 1989), pp. 141–173.
4. W.-P. Chen and P. Molnar, *J. Geophys. Res.* **88**, 4183 (1983); W.-P. Chen, *Seism. Res. Lett.* **59** (1988).
5. At M_w = 7.8 to 8.1, the 1811–1812 New Madrid earthquakes, in the central United States, rank as the largest estimated SCR events; A. C. Johnston, *Geophys. J. Int.* **126**, 314 (1996). The largest continental shield earthquakes do not exceed M_w = 7.
6. See (*3*) and A. C. Johnston, *Nature* **330**, 467 (1987).
7. A 20-km-long candidate PGF is under study in northern Manitoba; A. Ruffman, J. D. Mollard, E. Nielsen, I. McMartin, paper presented at Geological Association of Canada meeting, Winnipeg, Canada, 27 to 29 May 1996.
8. Not, apparently, to the United States, however, which has selected a site in tectonically active Nevada.
9. R. Stanfors and L. O. Ericsson, Eds., *Post-Glacial Faulting in the Lansjärv Area, Northern Sweden, SKB Technical Report 93-11* (Swedish Nuclear Fuel and Waste Management Company, Stockholm, 1993).