Singing Icebergs

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From July until November 2000, several episodes of sustained seismic tremor were recorded at the seismological network at Neumayer Base near the continental margin of Dronning Maud Land, Antarctica (Fig. 1A) (*1*). The signals resemble harmonic volcanic tremor in terms of their duration, magnitude, and spectral features (*2*). The most spectacular tremor event, which spanned 16 hours, was recorded on 22 July 2000 (Fig. 1B). The spectrum of parts of this event consisted of narrow peaks with a fundamental frequency around 0.5 Hz and more than 30 integer harmonic overtones (Fig. 1B, between times E and F). The spectral peaks varied slightly with time (frequency gliding), and amplitude was inversely proportional to frequency (times C to F). The tremor signals change from harmonic to nonharmonic and vice versa (times D and E) and show period-doubling phenomena, as do volcanic tremors (*3*). The spectra of the tremor episodes show the same fundamental frequencies, harmonic overtones, and simultaneous gliding of the spectral peaks at all four stations of the network with an aperture of 280 km, suggesting a source effect (fig. S2).

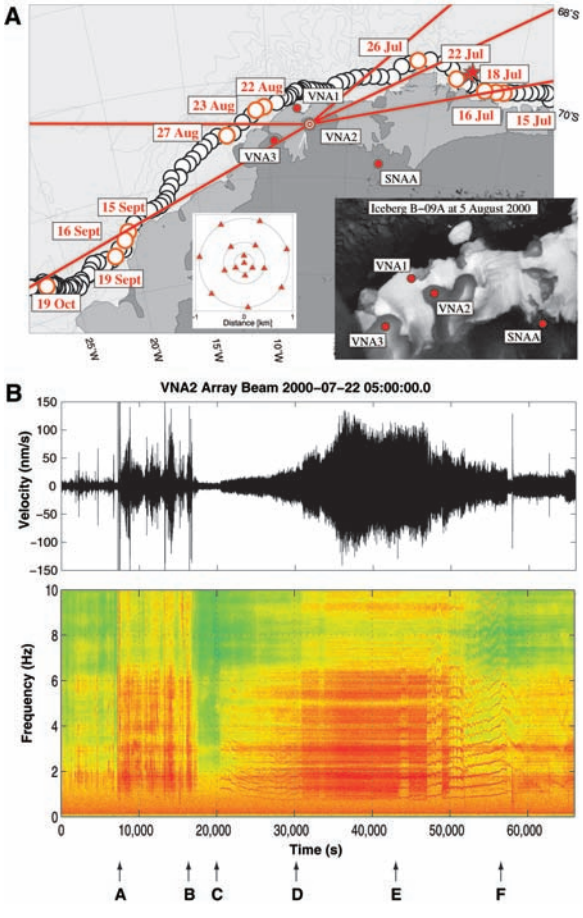

Fig. 1. The stations of the Neumayer Base seismological network, the iceberg B-09A, its track, tremor location, example tremor seismogram, and corresponding spectrogram of the event recorded on 22 July 2000. (**A**) Western Dronning Maud Land, showing daily averaged positions of B-09A from Quik-SCAT satellite radar backscatter images (*5*). Its position at the times of harmonic tremors are shown in red. The left inset shows the geometry of the small aperture array VNA2. The backazimuths of the tremor signals are shown as red lines. The two stars indicate the epicenters of the two events preceding the strong tremor of 22 July 2000. The right inset shows a satellite image (*6*) of B-09A on 5 August 2000. (**B**) VNA2 array beam seismogram (top) and corresponding spectrogram (bottom) of the 22 July 2000 tremor (Audio S1).

To identify the source, we estimated backazimuths from array frequency–wave number (fk) analysis for harmonic tremor episodes for nine events, and we obtained systematically changing directions pointing to a moving source. In addition, the 22 July signals were preceded by two local earthquakes, which we located to offshore the continental margin (Fig. 1A). These two events resembled volcanic "tornillo" events, characterized by a slowly decaying, peaked frequency coda (fig. S3). Comparing the earthquake epicenters with satellite images, we recognized iceberg B-09A as the source of the tremors and earthquakes. The backazimuths of the tremor signals followed the track of the iceberg as it moved westward (Fig. 1A). The tremors were recorded up to 820 km away. We calculated the reduced displacement (*4*) to estimate the strength of the tremor signals and obtained values comparable to strong volcanic tremors observed, for example, at Kilauea and Mount St. Helens.

We propose that, analogous to the sources of volcanic tremors, the iceberg tremor signals represent elastic vibrations of the iceberg produced by the flow of water through its tunnels and crevasses. A scenario for tremor evolution on 22 July 2000 is that the iceberg drifted westward with the Antarctic Coastal Current at ~0.23 m/s. At time A (Fig. 1B), the iceberg collided with the shallow sea floor of a northward-protruding escarpment of the continental margin, causing a seismic shock with an estimated local magnitude $M_l = 3.6$, equivalent to a seismic energy release of $E = 2.7 \times 10^9$ J. Assuming an elliptical shape with half-axes of 15 and 25 km, a height of 400 m, and density of ice equivalent to 915 kg/m^3, iceberg B-09A has a kinetic energy of 1.1×10^{13} J, which is converted to only a small amount of seismic energy during the initial collision. The collision continued as the iceberg slid along the continental shelf, pushed by the coastal current. This sliding and eventual catastrophic collapses explain the diffuse spectral features during times A to B. During the quiescence period B to C, water flow may have pushed the iceberg northward around the escarpment. The following episode of harmonic and chaotic tremor C to F may reflect fluid flow through the iceberg from ongoing oscillations after the collision, the changed orientation of the iceberg relative to the coastal current, or differential flow as the iceberg accelerated.

References and Notes

1. The four stations of the network consist of one short-period seismometer (VNA1) close to Neumayer Base on the floating Ekström Ice Shelf, two remote broadband sensors, VNA2 and VNA3, deployed on grounded ice, and SNAA at the South African base Sanae IV on solid rock (Fig. 1A). VNA2 is the central sensor of a small-aperture detection array, consisting of 16 sensors on three concentric rings with diameters of 2 km (Fig. 1A, left inset) (*7*).
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Supporting Online Material
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Figs. S1 to S3
Audio S1

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