Modulation of Tremor and Modulation of Noise: Same Natural Phenomenon?

by Igor Beresnev

INTRODUCTION

One of the high-profile developments in seismology over the past decade has been the observation of episodic tremor and slip (ETS) and nonvolcanic tremor (NVT) as a subset of the phenomenon (Peng and Gomberg, 2010; Vidale and Houston, 2012). Sensitivity of an NVT occurrence to very small, dynamic, low-frequency stress perturbations in the Earth's crust has been documented. For example, Rubinstein *et al.* (2007, 2008) reported pulsations of the envelope of the high-frequency (generally above 1 Hz) tremors with much longer periods of Earth tides and surface waves from large earthquakes. The phenomenon has been termed modulation.

In reading through the recurring reports of the phenomenon of triggered NVT, I was struck by the resemblance to much earlier observations that dated back to the 1970s and 1980s.

NONVOLCANIC TREMOR AND HIGH-FREQUENCY SEISMIC NOISE

Conceptually, very similar observations were conducted in the 1970s by Russian investigators Rykunov *et al.* (1978, 1979). For example, Figure 1 (from Rykunov *et al.*, 1978) shows the envelope of the background microseisms (which the authors termed "high-frequency seismic noise" [HFSN] or "seismic emissions") in a narrow passband of 30 ± 0.1 Hz. The top two panels show a typical undisturbed level of the envelope. The authors discovered near-periodic pulsations of the background microseism levels after the occurrence of distant $M \sim 7$ earthquakes, shown in the bottom four panels, with periods coinciding with certain periods of the free oscillations of the Earth. As in the recent NVT observations, the phenomenon was called modulation.*

*Both journals in which Rykunov *et al.*'s papers appeared have been translated from Russian, and the references are provided from the translated versions. *Doklady* was published by Scripta Publishing Co. in cooperation with the American Geological Institute, and *Izvestiya* was jointly published by the American Geophysical Union and the Geological Society of America. However, by a peculiar twist of fate, Rykunov *et al.*'s (1978) article was not included in the translation. Figure 1 is shown from that article merely for the reason of print quality—the paper by Rykunov *et al.* (1979) contains a similar figure but of poorer typographical quality.

The concept of seismic emissions can be understood by mentally continuing the Gutenberg–Richter earthquake frequency plot into the hypothetical region of continually diminishing magnitudes. At the limit, one could contend that the distinct events merge into a continuous background hum of small acts of emissions. Such a construction is consistent with the modern notion of self-similarity.

Similar follow-up results were published by several groups in the Union of Soviet Socialist Republics (USSR) throughout the 1980s. One result is particularly remarkable in the context of the recently published ETS and NVT data. In Figure 2 (Belyakov *et al.*, 1990), curve A shows a time series of the number of bursts of microseisms (counts/hour) in the band of 30 ± 2 Hz. Curve B is the theoretical rate of change in the gravity due to moon- and sun-induced tidal disturbance. The authors noted that the peaks in the intensity of bursts of noise coincide with "the time of the greatest rate of crust-stretching deformation produced by Earth tides." The correlation between the two curves is spectacular.

Table 1 highlights the similarities in the methodologies and phenomena discovered between the early and present reports. If the term "nonvolcanic tremor" is replaced with "high-frequency seismic noise" (HFSN), the two sets of results, spaced by some 30 years, become virtually identical. Both invoke the concept of critical stress, stating that radiation occurs on pre-stressed fractures (faults) already near failure, and both describe the phenomenon as modulation. Both sets of results also analyze noise-envelope records in a relatively narrow high-frequency band and infer a similar low value of triggering stress.

The vertical scale in Figure 1 permits calculation of the amplitude of the ground velocity corresponding to the experiments of Rykunov *et al.* (1978, 1979). At the frequency of 30 Hz, the amplitude is $\sim 2\pi \times 30 \times 100 \times 5 \times 10^{-13}$ ≈ 10 nm/s. For comparison, Peng and Gomberg (2010; their figure 1a) show a record of tremor, filtered between 2 and 8 Hz, with the amplitude of ~ 300 nm/s. Although the level reported by Rykunov *et al.* (1978, 1979) is significantly lower, it is consistent with the much narrower frequency band (30 ± 0.1 Hz) of their instrumentation.

The discoveries in the USSR in the 1970s called attention to the extreme tensosensitivity of the crustal rocks, or their propensity to respond to weak, long-period stressing by the emissions of bursts of high-frequency seismic energy. The phenomenon was intensively studied through the 1980s, with

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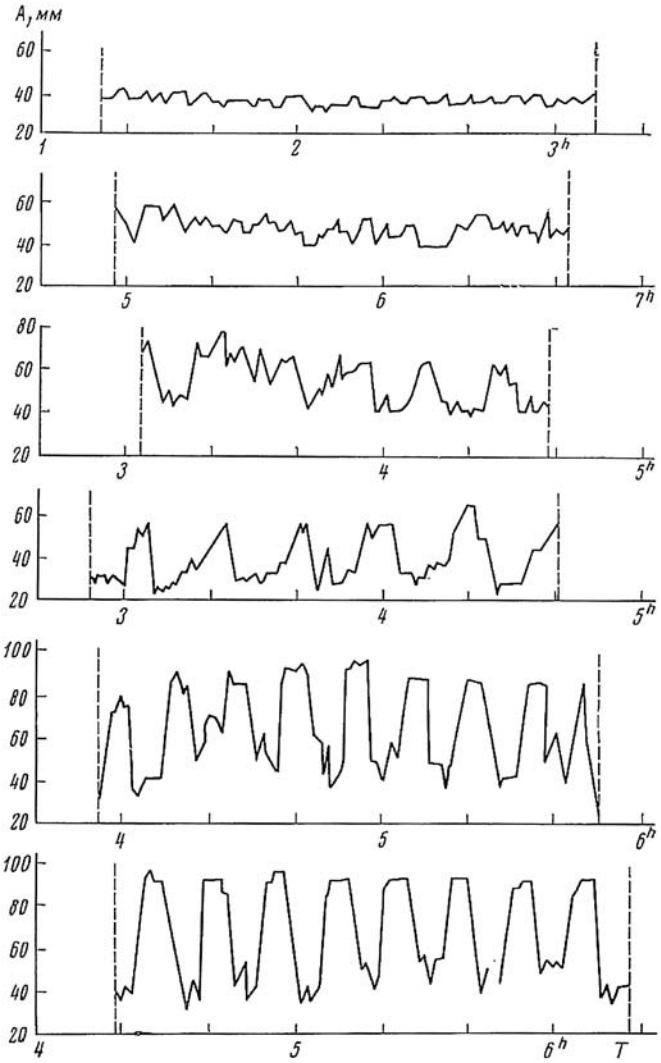
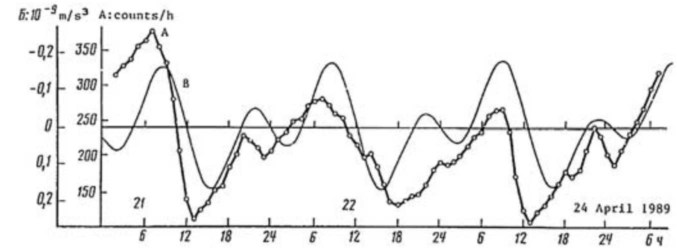


▲ **Figure 1.** Examples of HFSN envelope in a narrow band of 30 ± 0.1 Hz. Time is in hours on the horizontal axis. In the vertical scale, 1 mm = 5×10^{-13} m of ground displacement. (From Rykunov *et al.*, 1978.)



▲ **Figure 2.** Curve A shows the number of HFSN bursts per hour as a function of time of the day over three days. Noise records were filtered in a narrow band of 30 ± 2 Hz. Curve B shows the theoretical rate of gravity change due to tides. The innermost y-axis is for curve A; the outermost y-axis is for curve B. (From Belyakov *et al.*, 1990).

the ambitious long-term goal of potentially creating stress-relief technologies for earthquake-prone faults by disturbing them with man-made seismic sources to prevent failure due to stress accumulation. Experiments were carried out to establish whether similar triggering of high-frequency emissions could be induced by artificial low-frequency vibrations. The effect, called vibrosensitivity, was observed in field experiments that were conducted with the author's participation. An increase in the intensity of high-frequency noise in the 60–1000 Hz range was documented in response to low-frequency harmonic vibrations in the 10–40 Hz range (Beresnev and Nikolayev, 1990; Privalovskiy and Beresnev, 1994). By analogy to the adjacent fields of physics, it was proposed to model the Earth's crust as an active medium (Scott, 1970; Engelbrecht, 1984). Such a medium is charged with elastic energy and resides in a state of precarious equilibrium. Small external disturbances upset this equilibrium and cause part of the energy to be released in the form of induced microseismic noise.

This line of investigations, which spanned about a decade, virtually ground to a halt with the demise of the USSR and the evaporation of generous state funding for research and education.

Table 1
Similarities between Present and Past Observations

Similarity	Earlier Observations	Present Observations
Process of interest	High-frequency seismic noise (HFSN)	Nonvolcanic tremor (NVT)
Concept of critical stressing	HFSN radiation triggered at cracks being close to the failure threshold (Rykunov *et al.*, 1979)	NVT radiation triggered at near-failure faults (Peng and Gomberg, 2010)
Modulation character	HFSN modulated by long-period seismic phenomena (Rykunov *et al.*, 1979)	NVT modulated by tides and long-period seismic waves (Rubinstein *et al.*, 2007, 2008)
Analysis of amplitude of envelope in a narrow-frequency band	Bandpassed at 30 ± 0.1 Hz (Rykunov *et al.*, 1979), 30 ± 2 Hz (Belyakov *et al.*, 1990)	Bandpassed between 1 and 8 Hz (Rubinstein *et al.*, 2008)
Value of triggering stress	10–100 KPa (Rykunov *et al.*, 1979)	15–40 KPa (Rubinstein *et al.*, 2008)

SUMMARY AND CONCLUSIONS

Contemporary observations of modulated NVT have been principally confined to the subduction zones in Cascadia and Japan. However, experiments by both Rykunov *et al.* (1978, 1979) and Belyakov *et al.* (1990) were conducted in a stable continental environment of the Russian craton. Yet the phenomena seem remarkably similar, which suggests that they may be more universal than initially thought by research groups on both sides of the spectrum.

Present-day investigators may be unaware of the discoveries published two to three decades earlier in the literature relatively unknown in the West. However, there is no reason why these early results should remain in obscurity; rather they should be considered complementary to the recent observations that extreme tenso- and vibrosensitivity of the Earth's crust may not be limited to active tectonic boundaries. The underlying mechanism in both cases is apparently the critically stressed features (cracks, faults) ready to release their energy under the triggering effect of slow, weak, dynamic disturbances. The modulation of tremor and the modulation of noise could be two faces of the same natural phenomenon.

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