large earthquakes and volcanic eruptions occur at subduction zones, major faults, volcanoes, and oceanic ridges. They are driven mainly by plate motion, but other factors can also trigger earthquakes and volcanism. For example, tides have long been implicated in their generation, although evidence has been sparse. A recent paper in Geology (1) makes the strongest case yet for tidal forcing of earthquakes and volcanism at mid-ocean ridges.

Gravitational forces exerted by the Moon and the Sun cause ocean tides in the ocean and Earth tides in the solid Earth, with diurnal and semidiurnal periods. In and near the ocean, Earth tides and ocean tides are tightly coupled.

The elastic strain resulting from Earth tides is extremely small, on the order of $10^{-6}$, which seems too small to trigger earthquakes and volcanism (2). Nevertheless, the idea that tides may influence these geophysical events has been discussed since 1930, when an interesting earthquake sequence was observed during an earthquake swarm east of Ito on the Izu Peninsula, central Japan.

The Ito swarm was thought to be related to volcanism, although magma was not identified at the time. Nasu et al. (3) observed that for several days, the hourly numbers of earthquakes were higher during low tide than during high tide. They suggested that the swarm was triggered by the ocean tide, but did not offer a convincing triggering mechanism.

Very few diurnal or semidiurnal earthquake activities of this kind have been observed during the Ito swarms, although month-long swarms have occurred frequently since 1930. But at least one other example of semidiurnal variation in earthquake swarm activity was detected near Ito in 1978 (4). Analysis of stress due to ocean loading effects suggested a strong influence of ocean tides.

A statistical examination of the correlation between tidal force and earthquake activity has shown a slightly higher probability of earthquake occurrence for a normal fault source mechanism (5). The probability is highest for mid-ocean ridge earthquakes. But because of the dearth of examples of diurnal and/or semidiurnal earthquake sequences, tidal effects on earthquakes were not accepted until recently.

The eruptions of Miyake-jima, ~180 km south of Tokyo, in 1983 and 2000 proved to be a turning point.

In October 1983, earthquake activity started 1.5 hours before a huge eruption, and massive lava flows occurred at Miyake-jima. An ocean bottom seismometer (OBS) deployed nearby on the sea floor recorded numerous earthquakes (2). The eruption began at low tide. For the next 2 weeks, the hourly number of earthquakes showed maximum at either high tide or low tide. Earthquake activity was strongly correlated with low tide or high tide for several days.

Miyake-jima erupted again on 8 July 2000. During this event, the 1.6-km-wide summit region collapsed and subsided to a depth of 500 m. After the summit collapse, five tiltmeters recorded 46 steplike changes accompanying intensive earthquakes; diurnal and/or semidiurnal periodicities were observed in the data (6). Thirty-three of the 46 steplike changes coincided with earthquake activity, which is strongly influenced by ocean tides. Tidal effects on volcanism were also proposed for the Pavlof volcano in Alaska (7), several Hawaiian volcanoes (8), Mount St. Helens (9), and the Mayon volcano (10).

The effects of tides on submarine volcanism were not observed until the summer of 1994, when the U.S. Navy Sound Surveillance System (SOSUS) array identified intense earthquake activity around Axial Volcano on the Juan de Fuca Ridge (11). The ridge is located about 400 to 800 km west to southwest of the western coast of North America. The data showed a clear correlation between tidal change and earthquake activities on two occasions (1, 12).
at or just after low tide. The earthquake frequency nearly doubled at the lowest tides and at the highest cubic and extensional stresses. This result is similar to that at Axial Volcano (1).

The observations on submarine and terrestrial volcanoes show that earthquakes in volcanic regions near the shore and in mid-oceanic ridges display strong correlations with tidal forces. Fault movements that generate earthquakes may be accelerated by tidal stresses with directions suitable for creating shear movements.

The direction of stress at the critical stage of fault failure and the presence of seawater penetrating into opening cracks at shallow crustal depth may explain why diurnal or semidiurnal changes in earthquake activity have been observed only for short periods during seismic events. By themselves the tidal forces are too small to generate earthquakes, but in the critical stage of faulting they can trigger volcanic earthquakes.

References
Tides, Earthquakes, and Volcanoes
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