PERSPECTIVES: GEOPHYSICS

Tides, Earthquakes, and Volcanoes

Junzo Kasahara

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^{-8}, 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 maxima at either high tide or low tide. Earthquakes activity was strongly correlated with low tide or high tide for several days.

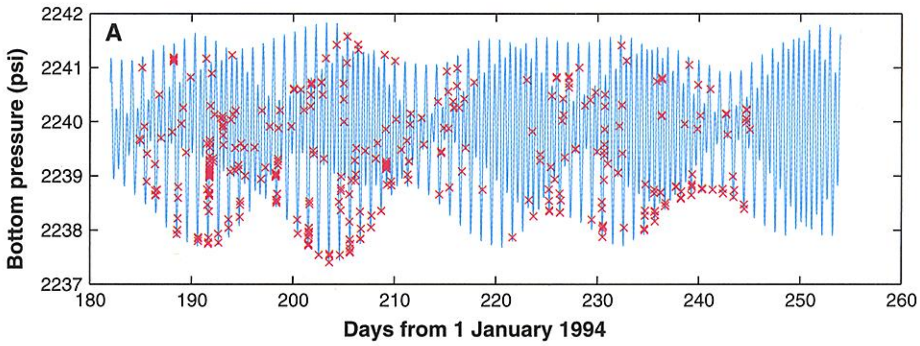
Miyake-jima erupted again on 8 July 2000. During this event, the 1.6-km-wide summit region collapsed and subsided to a depth of 500 m. After the summit collapse, five tiltmeters recorded 46 steplike changes accompanying intensive earthquakes; diurnal and/or semidiurnal periodicities were observed in the data (*6*). Thirty-three of the 46 tilt-steps coincided with maximum or minimum shear strain, 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*).

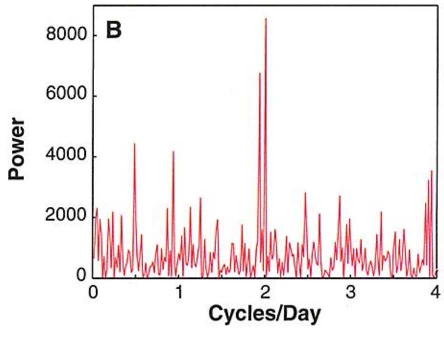
The effects of tides on submarine volcanism were not observed until the summer of 1994, when the U.S. Navy Sound Surveillance System (SOSUS) array identified intense earthquake activity around Axial Volcano on the Juan de Fuca Ridge (*11*). The ridge is located about 400 to 800 km west to southwest off the western coast of North America. The data showed a clear correlation between tidal change and earthquake activities on two occasions (*1*, *12*).

Shortly after the beginning of the earthquake activity, an OBS array was deployed at Axial Volcano at 130°W and 46°N. On the basis of 402 earthquakes observed over a 2-month period, Tolstoy *et al.* (*1*) found a strong correlation between earthquake activity and ocean tides. The correlation between pressure change at the ocean floor caused by the ocean tide and the peaks of seismic activity is extremely good at low tide (see panel A in the figure). Spectral analysis of earthquake activity shows a semidiurnal peak (panel B).

Harmonic tremors observed by the OBSs at Axial Volcano also showed semidiurnal spectral peaks, but did not show a clear correlation with low or high tide. Such tremors are often observed in volcanic regions and are characterized by sinusoidal ground oscillations. Schultz and Elderfield have suggested that harmonic tremor is caused by hydrothermal circulation in the oceanic crust, which in turn is induced by ocean tide (*13*). Thus, harmonic tremors may be caused indirectly by tidal waves.

Evidence for a tidal influence on earthquake activity was also obtained during an OBS observation at the Endeavor segment of the northern part of the Juan de Fuca Ridge (*12*). In 1995, 15 OBSs were deployed at Endeavor segment for 55 days. The records showed high seismic activity





Don't underestimate tidal forces. (A) Ocean tide recorded by bottom pressure recorder. Red crosses mark the time of earthquake occurrence. **(B)** Spectrum of earthquake occurrence for all recorded earthquakes. The spectrum has a clear semidiurnal period, indicating the influence of ocean tides. [Adapted from (*1*)]

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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 above observations on submarine and terrestrial volcanoes show that earthquakes in volcanic regions near the shore and on 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.

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PERSPECTIVES: APPLIED PHYSICS

Testing the Limits for Resists

Elsa Reichmanis and Omkaram Nalamasu

The invention of the point-contact transistor in 1947 heralded the dawn of the microelectronics era (*1*). Since then, advances in materials chemistry, particularly organic and polymer chemistry, have been crucial to microelectronics technology. Quantitative knowledge of the properties of the materials is crucial for understanding their resolution limits and for developing powerful new materials. On page 372 of this issue, Lin *et al.* (*2*) report a new tool for obtaining such knowledge at nanometer resolution.

Microelectronics technology is driven by the need to build devices that squeeze an ever-increasing number of individual circuit elements onto an ever-smaller piece of semiconductor material (*3*). Today, a state-of-the-art, fully processed silicon substrate containing hundreds of complex devices with millions of transistors each is not much larger than the first silicon-based single transistor fabricated in 1947 (see the figure).

The ability to shrink the feature size depends on the lithographic techniques used to make the circuit pattern. In optical lithography, light-sensitive materials (photoresists) are used to transfer the desired pattern to the wafer (*3*). A photomask blocks resist exposure in certain areas; in the exposed areas, the resist becomes soluble to the developer.

The resolution of an optical lithography projection system is limited by

$$w = k\lambda/\mathrm{NA} \qquad (1)$$

where w is the minimum resolvable feature, k is an empirical constant determined by the resist process used, λ is the exposure wavelength, and NA is the numerical aperture of the optical exposure tool.

Increasing NA or decreasing λ improves the overall resolution of the system. But the depth of focus decreases with increased NA, and avoiding spherical aberrations is difficult in very high NA optical systems. It is therefore desirable to use smaller wavelengths to improve resolution at high NA.

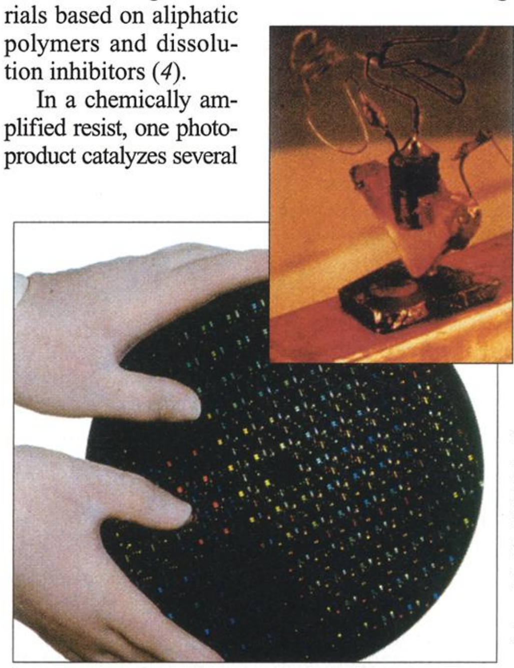
Use of smaller wavelengths in turn necessitates new optical (lens, photomask) and imaging (photoresist) materials and processes. When new optical lithographic technologies that use smaller wavelengths—especially 248 and 193 nm—were introduced, chemists responded by developing chemically amplified resist material technologies and 193-nm resist materials based on aliphatic polymers and dissolution inhibitors (*4*).

In a chemically amplified resist, one photoproduct catalyzes several hundred chemical events, thereby accelerating resist transformation. Hence, less ultraviolet light is required to form an image in the resist, and finer features with improved accuracy can be created. The mechanism (*5*) enabled the conflicting requirements of high sensitivity (low dose) and process tolerance to be balanced. It was the first revolutionary change in resist materials chemistry, leading to very sensitive, robust, high-resolution resist systems.

The advent of 193-nm photolithography resulted in yet another paradigm shift in resist material design. Traditional UV and deep-UV organic matrix resins were opaque at this wavelength. With 193-nm resists, the challenge was to design a resist system that was largely based on aliphatic components (polymers and dissolution inhibitors) but functionally identical to earlier resists built on poly(hydroxystyrene) and novolac resin chemistries (*6, 7*).

Materials and process modifications using chemically amplified resist technologies have enabled the extension of optical lithography to the sub–100-nm regime. The ultimate resolution capability of a resist is governed by a complex set of molecular interactions involving the matrix resin, photoacid generator, acid strength, acid and counterion molecular size, acid diffusion, environmental contaminants such as airborne bases, etc. The fundamental properties governing the intrinsic resolution limits of chemically amplified resist materials have largely been unexplored.

As noted by Lin *et al.* (*2*), quantitative measurements of material and transport properties in resist films with nanometer resolution are of paramount importance to understanding the resolution limits of candidate materials. When the critical device dimension falls below 100 nm, the required linewidth control of 2 to 5 nm approaches the molecular size of each individual polymer molecule (*8*). This necessitates qualitative—and, perhaps more important, quantitative—



Silicon-based transistor technology today and in 1947 (inset).

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