For example, the flow stress of a face-centered cubic metal like copper or aluminum (that is, the stress level at which plastic deformation sets in) is essentially independent of the mobility of individual dislocations and is almost entirely dominated by the interaction of dislocations with each other and with other material defects. This flow stress is proportional to the square root of the dislocation density in the material or, equivalently, to the inverse of the mean dislocation spacing (*4*).

Strain hardening is the change in flow stress with strain. Calculation of strain hardening therefore requires knowledge of the evolution of the dislocation density along the deformation path. Because dislocation motion is complex, simulating the evolution of an ensemble of dislocations is a formidable task. However, the recent development of efficient methods for simulating three-dimensional discrete dislocation dynamics and the increase in computing power now enable the simulation of simple strain paths and small deformations. In such simulations, Madec *et al.* (*2*) have identified a specific type of dislocation interaction, the collinear interaction, which drastically reduces dislocation line length and dislocation density, thereby contributing substantially to strain hardening.

The quantitative understanding of the individual contributions to strain hardening should soon enable accurate statistical simulations, along the lines of recent two-dimensional studies (*5*), of dislocation density evolution for more complicated strain paths. These statistical methods could be used to determine the flow stress of a material in classic engineering simulations.

The accurate prediction of strain hardening is important for simulating the forming process, but even more so for determining residual stresses and spring-back (the release of the elastic deformation) after forming. Today, the automotive industry and others are making considerable investments into the accurate experimental determination of the parameters that determine these processes. However, a material may follow so many different strain paths in the forming of a complicated shape that it is impossible to cover them all. Furthermore, the details of the forming process, including boundary conditions and surface treatment, play a similarly important role as the strain path.

Although dislocation simulations are still very far from engineering requirements, they are intrinsically well suited to study the influences of boundary conditions and the differences between thin film and bulk deformation (*6*). It is likely that such simulations will play an important role in guiding future engineering solutions.

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OCEAN SCIENCE

Internal Tides and Ocean Mixing

Chris Garrett

The rise and fall of the sea with the tides are accompanied by tidal currents that move water from place to place. These currents generate turbulence as they flow over the rough seafloor; in shallow waters, this mixing can reach the sea surface, keeping the water cooler than might be expected from surface warming by the Sun. But the tides are also indirectly responsible for mixing in the deep ocean (*1*–*3*), affecting ocean circulation, productivity, and climate. The associated energy loss is linked to the evolution of the Earth-Moon system (*4*, *5*).

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Away from shallow, well-mixed regions, most of the ocean is stratified, with light water above denser water. If there are just two layers, "internal" waves can occur at the interface between them, although with longer periods than for the more familiar surface waves because of weaker restoring forces. They can be created by the tidal movement of water between the shallow continental shelves and the deep ocean (see the figure). It is as if the continental slope were a giant wavemaker being pushed in and out. The resulting internal wave of tidal period often breaks up into large internal waves of shorter period. The associated currents can interact with wind-generated waves at the sea surface to produce alternating bands of rough and calm water that are visible from space (*6*).

In places with broad continental shelves and large tidal sea-level changes, the internal tides (internal waves associated with tides) can be so large as to be a concern for offshore drilling operations. By creating internal turbulence and mixing, they can also bring nutrients to the sunlit upper layers of the ocean, fueling biological growth.

The role of internal tides on the continental shelf has long been recognized (*7*), but the propagation of internal tides into the vast, density-stratified deep ocean has been considered a minor contributor to deep-ocean mixing. This is partly because much of the tidal sea-level change at the coast is associated with changes in tidal currents along the coast rather than tidal currents across the shelf edge. Thus the latter, and the ensuing internal tides, are smaller than might have been expected.

Over the past decade it has become clear, however, that substantial internal tides can be generated by the to and fro of tidal currents over mid-ocean ridges and other rough topography on the ocean floor. These internal tides, which can propagate obliquely upward in the smooth density stratification of the deep ocean, play an important role in deep-ocean mixing.

To understand the role of this mixing, consider a simple picture of ocean circulation. At high latitudes, particularly in the Southern Ocean, the water can become so cold and dense that it sinks to the seafloor. In the absence of other influences, it would slowly fill the ocean basins, remaining cold until it reached the sunlit upper few tens of meters. But temperature is observed to change much more gradually with depth. This observation has led to a model in which the upwelling of cold water is balanced by downward mixing of heat (*8*). The global energy requirement for this mixing is about 2 terawatts [1 terawatt (TW) = 10^{12} W, equivalent to about 1000 large power stations].

This value is comparable to the rate at which the Earth-Moon system loses rotational energy (known from the observed acceleration of the Moon in its orbit). But until recently, most of this dissipation was thought to be associated with turbulence in shallow seas. It was thus assumed that mixing in the deep ocean is mostly caused by the instability and overturning of internal waves generated by wind, with internal tides playing a minor role.

Ocean tide maps from satellite radar altimetry have changed this picture. First, the rate of working of tidal forces on the observed spatial patterns has confirmed a loss of 3.2 TW from the Earth-Moon system. This value is consistent with the observed

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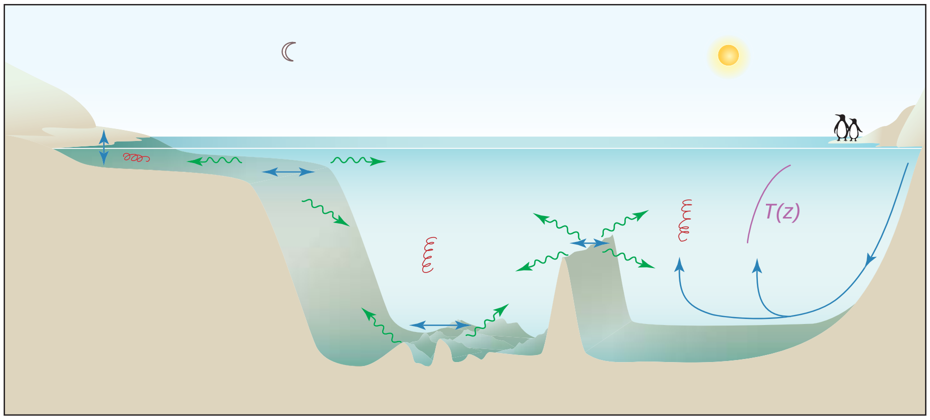
The author is in the Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia V8W 3P6, Canada. E-mail: garrett@uvphys.phys.uvic.ca



Tides in the ocean. (**Left**) The to and fro of tidal currents generates internal waves at the edge of the continental shelf and over topographic features in the deep ocean. These internal waves can lead to turbulence and mixing. (**Right**) This mixing plays a role in maintaining a gradual transition between the sun-warmed surface layer of the ocean and the upwelling cold, dense water formed at high latitudes. $T(z)$ denotes the temperature profile as a function of depth z.

recession of the Moon at 38 mm/year (*4*). Another 0.5 TW or so comes from tides driven by the Sun. Second, and this is more revolutionary, the tidal maps have shown that, while most of the energy is indeed lost in shallow seas, close to 1 TW is lost in the deep ocean over rough topography (*9*).

The simple picture of ocean circulation presented above has also been challenged (*10*), with much greater roles given to wind-driven ocean circulation, air-sea interaction, and 100-km-scale eddies. In this scenario, only about 0.6 TW of mixing energy is required to reproduce the observed ocean structure. The true energy requirement may lie between the two estimates of 0.6 and 2 TW, but internal waves generated by the tides do seem to be more important than those generated by the wind. The latter are estimated to carry about 0.5 TW into the deep ocean (*11*), and a small contribution may also come from internal waves generated as low-frequency, nontidal, currents flow over rough seafloor topography.

Measurements of current over mid-ocean ridges confirm the importance of internal tides (*12*), and the surface signature of their propagation away from ridges is also evident from satellite altimetry (*13*). At smaller scales, deep-ocean observations of turbulence and mixing show a variation over the spring-neap cycle (between large tides near full and new moon and smaller tides near the Moon's quarters) as the main tidal currents over rough topography wax and wane (*2*). Moreover, a revival of theoretical models developed in the 1970s (*14*), as well as new computer models (*15*), support the idea that a considerable amount of energy is converted into internal tides in the deep sea, eventually leading to turbulence and mixing.

A comprehensive recent observational program (*3*) has shown that at the Hawaiian Ridge, local internal tides can lead to a peak-to-trough range in the depth of density surfaces of as much as 300 m, with intense local mixing. As expected from theory, however, most of the energy generated radiates away. This is also thought to be true of internal tides generated over the less dramatic but more extensive areas of fracture zone topography (*14*).

It remains unclear, both theoretically and observationally, whether this radiated energy feeds internal waves and turbulence throughout the ocean or is lost in further encounters with the seafloor. Thus, a clear picture and understanding of the vertical and horizontal patterns of ocean mixing is still lacking. But it is clear that ocean tides do much more than cause the rise and fall of sea level. The effects of internal tides must be represented correctly in computer models of ocean circulation and climate. They may also help us to understand the history of the Earth and Moon. The study of ocean tides, with its long and fascinating history (*5*), is again at the center of attention.

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CELL BIOLOGY

An Age of Instability

David A. Sinclair

If there's one thing we've learned from the last 50 years of research on bakers' yeast, it is not to underestimate how much this tiny fungus can tell us. We now know that yeast provide key insights into such complex human disorders as variant Creutzfeld-Jacob disease, Parkinson's disease, and cancer. Even so, it is not hard to imagine the skepticism facing Mortimer and Johnston in the 1950s as they tried to convince the scientific community that this unicellular organism might be useful for understanding human aging (*1*). Less skepticism should greet the report by McMurray and Gottschling (*2*) on page 1908 of this issue. These investigators show that yeast cell aging is accompanied by increased genetic instability, a hallmark of cancer. This finding might help researchers to understand the link between cancer and old age in humans.

In the final decades of life, one's chance of developing cancer rises exponentially (*3*). In fact, at age 70 the risk of developing cancer is more than 10 times the risk three decades earlier. It is tempting to think that cancer occurs later in life because of a steady accumulation of mutations. Certainly, cells isolated from the elderly have more chromosomal abnormalities than cells from the young. But the story is not so simple because rates of spontaneous mutation are too low to account for the extensive genome rearrangements found in tumors (*3*). Experiments in mice have confirmed the suspicion that mutation rates increase with age (*4*).

The molecular basis of this increase in mutation rate is still under debate. The most popular explanation is the "mutator phenotype," which is thought to arise when genes required for preventing or repairing DNA damage are mutated, leading to runaway DNA instability (*5*). Although

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The author is in the Department of Pathology, Harvard Medical School, Boston, MA 02115, USA. E-mail: david_sinclair@hms.harvard.edu