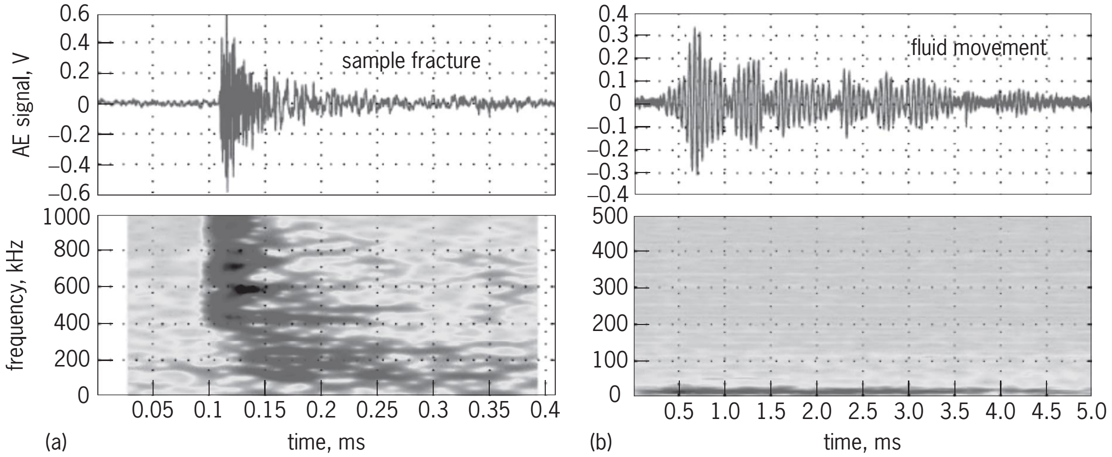

Fig. 3. Comparison of laboratory seismicity (*a*) from faulting and (*b*) from rapid fluid movement through the same faulted and damaged zone. The lower panels illustrate the power (dark shade) and frequency content (vertical axis) associated with the waveforms, showing dramatically different characteristics. (*Adapted from P. M. Benson et al., Laboratory simulation of volcano seismicity, Science, 322:249–252, 2008; reprinted with permission from AAAS*)

elevated temperature and pressure to test their accuracy. Such models assess how close a rock mass is to failure by calculating the inverse seismicity rate with time, which tends to zero as failure (eruption) is approached. This method has been applied successfully to both field data and laboratory data. Ideally, the method is applied to the trend in minima in inverse rate rather than the entire catalog; however, accurate forecasts can be made using the whole catalog when these minima cannot be distinguished.

Simulating volcano seismicity: Comparisons and pitfalls. A side-by-side comparison of seismicity recorded during the two stages of fracturing and fluid flow shows a very obvious change in frequency and power content (**Fig. 3**). A typical laboratory high-frequency (HF) event has considerable power in the 400–800-kHz frequency range, and dies off quickly with time. Conversely, LF events—induced by venting the pore fluid (water) via the top part of the apparatus, which has the effect of isolating the HF generation mechanism (faulting) from crack, conduit, and fluid resonance—show a signal with virtually no power present at frequencies above 20 kHz. The power is essentially monochromatic along the waveform. These observations are directly analogous to the observed VT seismicity and LF resonance on active volcanoes. Although the support for experimental work is high, the issue of how to scale the approximately 10-cm-size samples to kilometer-scale volcanoes is ever present. Fortunately, a simple inverse relationship exists between the length scales involved (cm to km) and the frequency seen in the observations, as the kHz frequencies measured in the laboratory scale to the 1–2 Hz measured in the field by the same proportion. A similar approach can be used with other physical parameters, such as viscosity. Although this is very much a first-order and simplified approach, the scale invariance seen from these analyses now allows researchers to address the scaling issue with confidence, whether they are dealing with magma, water, or hydrothermal fluid generally. Additional investigation of coupled mechanical/fluid volcano-tectonic mechanisms, which are directly applicable to the field setting, can be derived from the advanced analysis of the waveforms from the suite of sensors surrounding the laboratory sample. This permits the calculation of the type of event involved, such as an explosion, implosion, tensile fracture, or shear fracture (for example, a tectonic earthquake). Such analyses, known as moment tensor inversion, are commonly used by seismologists to determine relative plate motion after earthquakes. Taking all of these methods together, recent work in the laboratory with multisensor configurations has confirmed what volcanologists have suspected for a long time—that low-frequency seismicity is generated by fluid movement, resonance in fractures, and the interaction at the fluid/rock boundary. Laboratory work both at ambient and at high temperature is therefore playing a key part in improving the physical basis behind forecast models.

For background information *see* ACOUSTIC EMISSION; EARTHQUAKE; MAGMA; ROCK MECHANICS; SEISMOLOGY; VOLCANO; VOLCANOLOGY in the McGraw-Hill Encyclopedia of Science & Technology.

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Walking on water

Walking on water is a skill that has evolved independently many times during the course of evolutionary history, allowing a minority of nature's denizens to forage on the water surface and better avoid predators. Over 1200 species of insects and spiders are capable of walking on water, as are several larger creatures, such as some birds, lizards, and dolphins. While the weight of water walkers is supported by one of two means, a variety of ingenious propulsion mechanisms have evolved.

Resting on the water surface. Despite having a density slightly higher than that of water, and so being incapable of floating on the surface by virtue of buoyancy, small water walkers, such as insects and spiders, can reside at rest on the free surface, with their weight supported by the surface tension (**Fig. 1***a*). This property of an air-water surface, which has its origins in the intermolecular forces between polar water molecules, makes the water surface behave like a trampoline, resisting surface deflection and enabling it to bear weight. In order to avoid falling through the surface and then facing the daunting task of crossing it from below, a feat that typically requires that they generate a force comparable to 100 times their body weight, water-walking arthropods are covered by a dense matt of waxy hairs (Fig. 1*a* inset). By increasing the effective surface area of their bodies and thus the energetic cost of wetting, their hairy coat ensures their water repellency, thus allowing them to survive impacts with raindrops or momentary submersion as may arise from their interaction with a predator or a breaking wave. On the body cavity, a dense mat of hair ensures that water does not penetrate the spiracles through which they breathe, allowing some insects to breathe underwater for extended periods, others indefinitely.

Locomotion of water-walking arthropods. The dynamic role of the hair cover of water-walking arthropods has recently been recognized. On the driving legs, flexible grooved hairs point toward the leg tips (Fig. 1*a* inset); the resulting directional anisotropy ensures that the driving legs behave as traditional cross-country skis. As the creature strikes the free surface, either in the specialized rowing motion of the water strider and fisher spider or in the alternating tripod gait common to most terrestrial insects, the contact forces between the driving leg and the water are maximized. Conversely, these contact forces are minimized during the gliding phase and when the creature extracts its leg from the interface. This directional anisotropy is apparent when one watches a water strider on a flowing stream: the striders may reside at near rest if they are facing upstream; however, if they turn to face downstream, they are rapidly swept in that direction.

To the unaided eye, the only visible manifestation of the locomotion of most water-walking arthropods is a field of rearward-propagating surface waves generated by the driving stroke. Flow visualization studies demonstrate that these waves are generally accompanied by a pair of dipolar vortices (Fig. 1*b*). These studies indicate that the great majority of water-walking arthropods rely primarily on surface tension for weight support, and momentum transfer via subsurface vortices for their forward propulsion. Propulsion by momentum transfer via coherent vortical structures is a characteristic feature of biolocomotion through fluids, common to both flying birds and swimming fish. Compared to these creatures, water-walking creatures are relatively efficient in that they generate a propulsive force by striking the water surface, but are resisted primarily by air drag.

Less common propulsion mechanisms do not require a leg strike, but instead rely on manipulation of the water surface, either the surface tension or the surface geometry, and so are referred to as quasistatic (**Fig. 2**). As an emergency escape mechanism, certain insects release a surface active chemical, typically a lipid, in their wake; the resulting surface tension gradient propels them along the free surface for a limited distance (Fig. 2*a*). Some water-walking insects are too slow and weak to glide up or leap over the upward-sloping menisci that adjoin floating objects or emergent vegetation, and so are unable to escape the water surface to land, as is sometimes necessary in order to lay eggs or avoid predators. In order to do so, some species have developed an

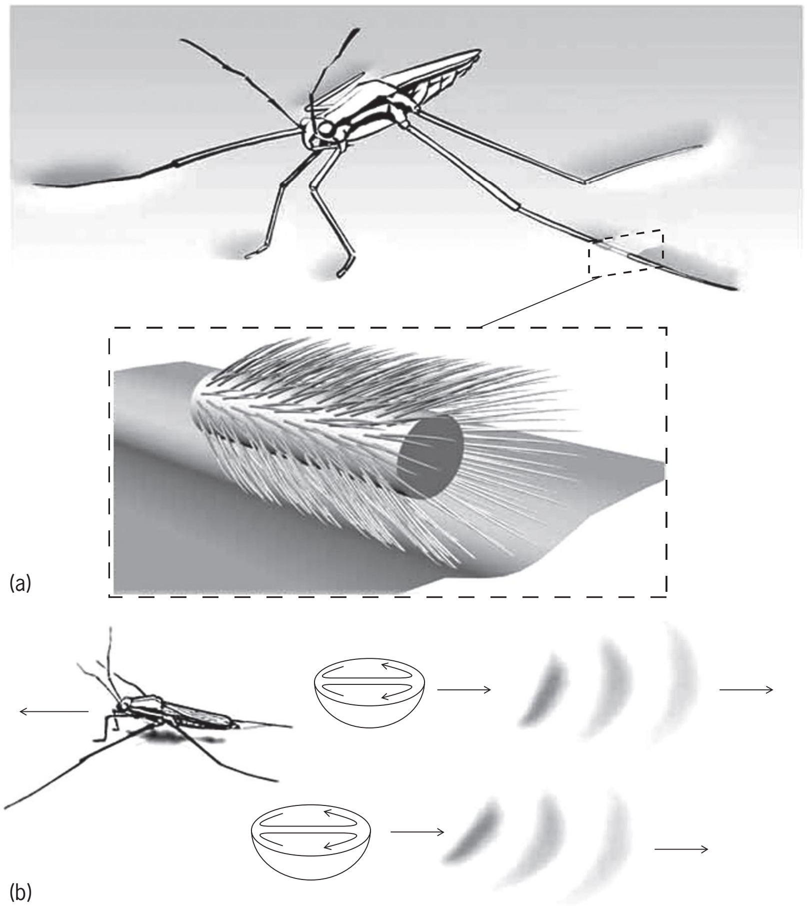

Fig. 1. The water strider, one of the most common water-walking insects. (*a*) At rest, the strider deforms the water surface and is supported by the surface tension. Inset shows the hair layer on the driving legs of the water strider. The leg is a hairy brush with tilted, flexible hairs. The resulting leg surface is water-repellent, and so prevents the strider from sinking through the interface; moreover, its directionality enhances the strider's propulsive efficiency. (*b*) To propel itself, the strider drives its central pair of legs in a rowing motion, generating a field of rearward-propagating capillary waves in addition to a pair of jets that roll up into a pair of dipolar vortices. (*D. L. Hu, B. Chan, and J. W. M. Bush, The hydrodynamics of water strider locomotion, Nature, 424:663–666, 2003*)

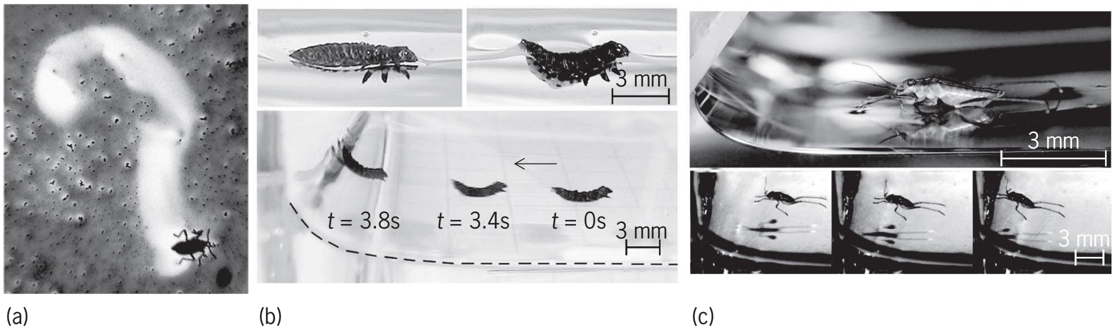

Fig. 2. Quasistatic water-walking techniques. (*a*) *Microvelia* utilizes Marangoni propulsion: by releasing a small volume of a surfactant, specifically a lipid, the insect generates a surface tension gradient that propels it forward. The surface divergence generated by the surfactant is evident in the clearing of blue dye from the free surface. Some insects can propel themselves against gravity, along upward-sloping menisci, simply by deflecting the free surface. (*b*) Wetting insects such as Collembola are circumscribed by a contact line with the water surface, and so may deform the free surface by arching their backs. Doing so propels them up the meniscus, from right to left. (c) Nonwetting insects such as *Mesovelia* climb menisci by clasping the free surface with their wetting unguis and pulling upward.

Fig. 3. Large water walkers. (*a*) Basilisk lizard (*photo courtesy of Joe McDonald*). (*b*) Western Grebe (*photo from the feature film "Winged Migration"*). (c) Tail-walking dolphin (*photo courtesy of Fran Hackett, New York Aquarium*). (*d*) Humans, who can walk on water only by using water-walking flotation skis such as those conceived by Leonardo da Vinci (*Leonardo da Vinci, Codex Atlanticus, folio 26, 1475–1480, found in Il Codice Atlantico di Leonardo da Vinci nella biblioteca Ambrosiana di Milano, Hoepli, Milan, 1894–1904*).

ingenious meniscus-climbing technique that relies on the attractive force between like-signed menisci, the force responsible for the formation of bubble rafts atop a glass of champagne. Wetting insects such as the beetle larvae are circumscribed by a contact line, and can propel themselves up a meniscus simply by arching their back to match its curvature (Fig. 2*b*). Water-walking insects, which are predominantly hydrophobic, clasp the surface with retractable hydrophilic claws on their front and rear pairs of legs, thereby generating a lateral force that draws them upward (Fig. 2*c*). The principal propulsive force arises from the menisci on the front legs. The rear legs simply balance torques on the creature, while the central pair of legs pushes downward in order to support the creature's weight.

Large water walkers. Creatures too large to rely on surface tension for weight support cannot generally reside at rest on the free surface (**Fig. 3**). Clark's grebe, a shorebird, sprints across the water surface as part of its mating ritual. The most impressive water walker is perhaps the basilisk lizard, and the largest water-walking creature is the tail-walking dolphin. Each of these creatures relies on dynamic weight support, striking the free surface so as to generate reaction forces that ultimately bear the creature's weight. The basilisk lizard also uses hydrostatic pressure for propulsion, pushing off the back of the cavity generated by the leg strike, thereby generating downward, rearward-propagating vortices that account for both weight support and forward propulsion. If humans were to walk on water, we would have to master a similar technique; however, we would have to run twice as fast as we can, and generate 15 times as much power. As it is, we are incapable of walking on water without floatation devices, such as those envisaged by Leonardo da Vinci (Fig. 3*d*) and employed by fifteenth-century ninjas.

Water-walking and microfluidic devices. Inspired by their natural counterparts, a number of water-walking devices of varying degrees of sophistication have been developed, and make clear the relative importance of the various anatomical adaptations of water walkers. Perhaps most importantly, the world of water-walking insects is dominated by surface tension, and so can serve to inform the design of microfluidic devices. For example, just as the rough, waxy surface of the lotus leaf has inspired the development of water-repellent surfaces commonly used in corrosion-resistant and self-cleaning surfaces, the anisotropic form of the hairy coating of water-walking insects has inspired the design of novel unidirectional superhydrophobic surfaces that may find application in directional draining and directed fluid transport in microfluidic devices.

For background information, *see* COLLEMBOLA; HEMIPTERA; INTERFACE OF PHASES; MICROFLUIDICS; PODICIPEDIFORMES; SURFACE TENSION; VORTEX in the McGraw-Hill Encyclopedia of Science & Technology.

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Wave processes and shoreline change

Shorelines are among the most strikingly dynamic geological features on the planet. Winds, waves, and tides are constantly reshaping the coast, moving the shoreline back and forth. Where waves have caused significant deposition along the coast, the shore consists primarily of sand and gravel. Of social, financial, and often sentimental value, the sandy coasts of the world increasingly are being developed despite the ongoing changes that endanger structures and infrastructure built near the shore. Increased rates of sea-level rise over the last century already threaten many developed coasts; these risks will only increase over the coming decades and centuries with predicted increases in the rate of sea-level rise. Coastal scientists endeavor to understand how coasts change. Predicting future coastal changes requires an understanding of how and why coasts have both eroded and accumulated over time. Although beaches and sandy coastlines, such as barrier islands, are currently mostly being eroded or are moving landward, these shores were originally formed through depositional processes. Coastal landforms can store information about the environmental conditions in the past and can help us better understand how the world's coasts could behave in the future. Until recently, the cause of several types of coastline shapes—regularly spaced coastal undulations and landforms—has been poorly understood.

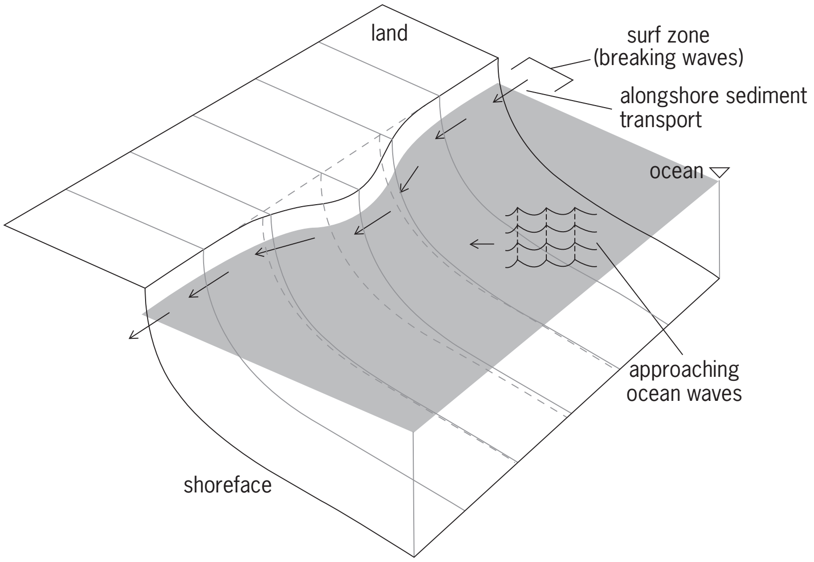

Fig. 1. Waves approach the shore and break in the surf zone. Alongshore sediment transport is driven by waves approaching the shore at an oblique angle.

Transformation of waves approaching a coast. Water waves, which are generated offshore by winds blowing across the ocean surface, are the dominant environmental force that drives change along sandy coastlines. As waves approach the shallower regions near the coast, the limited depth of the water affects their passage. This shoaling in shallower water makes waves slow down. As waves slow, conservation of energy tends to make them become taller. Eventually, as waves continue to slow (shorten) and increase in height, they become oversteep and break. The region where waves break and dissipate their energy is called the surf zone (**Fig. 1**). The large amounts of energy and momentum delivered by waves in the surf zone causes this region to be dynamic, characterized by strong currents that can transport significant quantities of sand. Another change occurs to waves if they approach the shore at an angle: As they slow down, they also refract, reducing the angle between wave crests and the shoreline.

Cross-shore sediment transport and shoreline change. Changes to a shoreline can best be understood by using a simplified framework that separates the coast into two component directions: alongshore (in a direction walking along the coast) and cross-shore (in a direction swimming directly offshore). Over a period of years, there can be significant cross-shore changes to a coast. Storms (with large waves) tend to be the most influential, as they typically transport large amounts of sand offshore during a relatively short period of time (the duration of the storm). However, between storms and during months or years of relatively calmer wave conditions, waves tend to return this sediment from offshore back into shallower regions and the beach. Although coastal changes from storms can be significant, the offshore and onshore movements of sand tend to cancel out over time periods of years and longer.

Transport of sediment along the shore and coastline change. The alongshore transport of sediment (sand) by breaking waves constitutes one of the most persistent and effective forces for moving sediment on the Earth. Waves breaking at an angle to the coast drive a current along the shore, within the surf zone. This current, combined with the mobilization of sediment by wave breaking itself, creates a drift of sediment along the coast, confined to the surf zone and moving in the alongshore direction that the incoming waves were traveling (Fig. 1). The quantity of sediment transported alongshore is affected by the height of breaking waves and the angle between waves and the shoreline (**Fig. 2*a***).

Although it may seem that this movement of sediment from one section of coast to another could itself be a cause of coastal erosion, the presence of this sediment "conveyor" does not necessarily mean that the shoreline location will be changing. At any position