Garcia's study is that they apply sensitivity analysis — allowing for a degree of parameter uncertainty — to evaluate the robustness of their results. For instance, they find that the estimated muscle mass is very sensitive to differences in limb posture, but is less sensitive to other parameters, such as muscle-fibre length. Collectively, these uncertainties contribute to up to a threefold variation in the estimated muscle mass for the various models of *Tyrannosaurus*, but the conclusion is unchanged. Palaeontological analysis of functional performance in fossil organisms will always be an uncertain science, dependent on the availability of fragmentary, long-dead material. So it is welcome when new analytical approaches such as this, and others (such as finite element analysis[10]), are brought to bear on such problems.

But what of the reputation that *Tyrannosaurus* has as a fearsome hunter? Hutchinson and Garcia's results suggest that the creature would have had little success chasing smaller, more fleet-footed prey; it may even have fed on carrion. But I suspect that it could still have moved fast enough to attack other large dinosaurs whose locomotive ability was also limited.

The dinosaurs are famous for being the largest creatures that ever inhabited our planet. But as a group they represent a broad range of size and diversity of form, with a similarly wide range of locomotive capacities and lifestyles[11,12]. It will be interesting to see what insights future investigations of dinosaur diversity yield as new analytical and computational approaches are explored. ■

*Andrew A. Biewener is at the Concord Field Station, Harvard University, Old Causeway Road, Bedford, Massachusetts 01730, USA.*
*e-mail: abiewener@oeb.harvard.edu*

JOHN SIBBICK/NHMPL

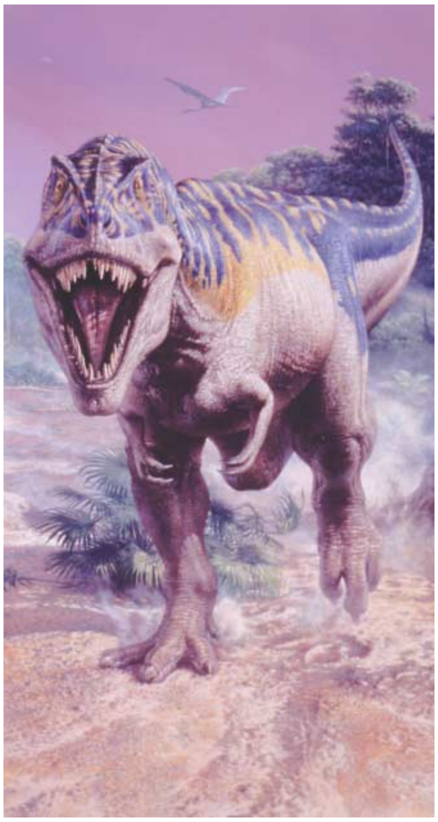

Figure 1 **Was *Tyrannosaurus* as fleet of foot as we thought? Hutchinson and Garcia[5] analysed the muscle mass and forces in the legs of alligators and chickens, and then extrapolated their results to a 6,000-kg tyrannosaur. Their findings fly in the face of Hollywood legend — *Tyrannosaurus* did not have enough leg muscle to run.**

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**Earth science**

# Slip-sliding away

Steven N. Ward

The side of an oceanic volcano, one of the Hawaiian islands, has been caught sliding towards the sea. The distance concerned was only a few centimetres. But it could be an indicator of a huge landslip to come.

Seeing is believing. For Earth scientists especially, the adage holds considerable weight because the 'seeing' is so rare. The geological record tells us that mountain ranges have been built and then washed down to the sea; that entire ocean basins have opened and closed like a door; and that ice a mile thick blanketed the globe a dozen times over. Scientists believe that these events took place, but still, they are hard to imagine. For most people such incidents might smack more of science fiction than science fact — but then, seeing is believing.

Who, having viewed film of Mount Pinatubo exploding, or the aftermath of a large earthquake, doesn't accept that 'big stuff' really does happen? In their paper on page 1014 of this issue[1], Cervelli *et al.* provide a glimpse of what might end up to be big stuff — the whole side of an oceanic volcano falling into the sea, an event known as flank collapse.

Over time, virtually all oceanic volcanoes grow, become too steep, and slough off flank material. We know this to be true because sonar surveys around most volcanic island chains reveal dozens of old, overlapping debris fields. The Hawaiian islands alone host 70 collapse fields dating from 20 million years ago. Adding up the number of debris fields from all of the ocean's volcanic islands yields the estimate that one flank collapse happens somewhere in the world every 10,000 years on average. Flank collapses are nature's great landslides. Embracing up to 5,000 km$^3$ of rock, they compare to a one-and-a-half-kilometre-thick slice of the state of Rhode Island or the island of Majorca racing sideways for 30 or 60 km. In contrast, when Mount Saint Helens erupted in 1980, only 3 km$^3$ of material blew away.

While flank collapses of oceanic volcanoes are common geologically, none has been caught in action — until now. Cervelli and colleagues' glimpse[1] of the action came from a network of 20 continuously recording stations of the global positioning system (GPS) scattered about the southeast slope of Kilauea volcano on Hawaii's big island. In November 2000, over a 36-hour period, these GPS stations witnessed a 20-km-long and 10-km-wide chunk of the southeast flank move seaward at the speed of 6 centimetres per day. For geophysicists accustomed to tectonic motions of a few millimetres per year, a few centimetres per day is like rocket travel.

To soothe any doubting Thomas, Cervelli *et al.* spend half of the report reviewing the details of their analysis. The effort is certainly thorough enough to dispel any notion that the signal is a fluke or masquerading noise. For me, their map of a dozen GPS displacement arrows (Fig. 1 on page 1015) all pointing out to sea far beyond their error ellipses tells the whole story. What else can they indicate but some early stage of one of those flank collapses that litter the geological record? A 2,000-km$^3$ piece of Hawaii is slip-sliding away.

In terms of predicting a collapse, the authors interpret their observations more cautiously than I do. By means of dislocation modelling, however, they confirm that the observed GPS displacement field could be explained by 10 cm of offset on a shallow dipping surface that lies 4.5 km under their network and that probably extends well out to sea. The offset was a silent earthquake, if you will, on the fault that may eventually detach the whole flank. Thankfully, the November 2000 slide stopped short, but what would it take to dislodge the whole block? Experts believe[2–5] that intense intrusion of the flank by molten magma dikes

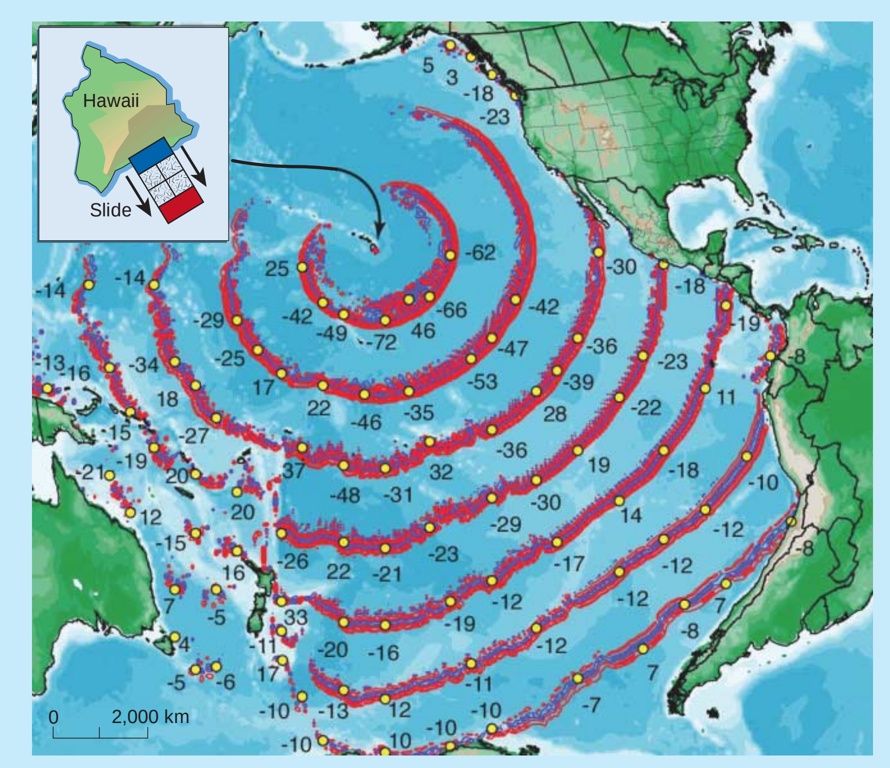

Figure 1 **Computer simulation[7] of the tsunami waves that might be set off in a collapse of Kilauea's southeast flank. The simulation assumes that a block 40 km long, 20 km wide and 2,000 m thick (blue, inset) slides for 60 km at 70 m $s^{-1}$. The tsunami wave fronts are pictured at two-hour intervals from 2 to 14 hours. Red and blue contours are wave elevations and depressions, respectively, and the numbers are sample wave heights in metres. Tsunamis from this collapse would have 1.72 $10^{19}$ J of energy (equivalent to about 4,100 megatons of TNT), and focus slightly towards the southeast. The waves span 280° of arc, sparing only locations to Hawaii's north and west. Tsunamis from volcanic flank collapses can dwarf those generated by earthquakes of any plausible magnitude. The model predicts potentially devastating 30-m waves beaching on the west coast of North America. These decay to 10 m in height by the time of their arrival at the tip of South America.**

might provide the extra nudge, especially if the detachment fault is also lubricated by the injection of high-pressure groundwater.

Last year, Simon Day and I published an article[6] on the tsunami waves that might be generated by the collapse of another oceanic island volcano, Cumbre Vieja on La Palma in the Canary Islands. Our computer simulations predicted that a tsunami stirred by a 500-$km^3$ landslide there could span the entire Atlantic basin, keeping amplitudes of 10–20 metres. Based on these calculations, if a 2,000-$km^3$ piece of Kilauea ever does push into the sea, it could, under certain conditions, parent a tsunami that will strike much of the Pacific Rim (Fig. 1). Historical time has not seen a tsunami of this scale, but many researchers argue that geological deposits and landform shapes preserve the signature of older ones.

The implication that volcanic island collapses could raise extensive tsunamis grips both one's imagination and concern. Could potential collapses be monitored and perhaps forecast? Cervelli *et al.* demonstrate that current GPS technology deployed in networks at 5-km intervals can provide real-time detection of even seismically silent shifts in volcanic edifices: small, silent shifts that may presage a fully fledged flank failure. The world's oceanic volcanoes are stages best not left unwatched. In a few years, dedicated radar satellites may take up volcano guard duty. For now, GPS provides one of the sharpest views.

People should not lose sleep over large but rare natural hazards. They should not run blind either, particularly when a useful eye exists. Until the next volcanic island does collapse we will never know how nature's great landslides play out, but for me, Cervelli and colleagues' article supports the case that seeing is believing. ■

*Steven N. Ward is at the Institute of Geophysics and Planetary Physics, University of California at Santa Cruz, Santa Cruz, California 95064, USA.*
*e-mail: ward@es.ucsc.edu*

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**Daedalus**

## Support for neutrons

**Nuclear matter, the stuff that neutron stars are made of, is essentially a mass of neutrons packed together. It weighs millions of tons per cubic millimetre; even a microscopic quantity would be hard to keep at the Earth's surface. Last week Daedalus argued that neutron-rich material would be stable, as neutron stars are. He is now working out how to hold it against gravity.**

**He planned to make it by persuading the electrons of an atom to dive into the nucleus. If not all of them did this, the result would still be normal atoms, with electrons orbiting the space outside each nucleus. Each atom would be superheavy, its dense nucleus stabilized by a vast excess of neutrons. The resulting solid would be a hundred times as dense as water, and very strong. The jewel in the crown of such materials, and the strongest of them all, would be superheavy diamond.**

**Daedalus recalls the Eiffel Tower, which has a sharply diverging base that supports its top load. He is designing a tiny 'Eiffel Pyramid', topped with a microscopic sliver of pure nuclear matter. The wider layers beneath are dense, strong, intermediate matter; under these are wider layers of less dense matter; the broad base of the Pyramid is less dense still, the strongest normal matter. The Eiffel Pyramid could test Daedalus's bold prediction that nuclear matter should absorb neutrinos.**

**Normal matter is mainly empty space, so neutrinos go straight through it; indeed, billions of neutrinos a second penetrate all normal matter in every direction. Even the Sun, from which neutrinos escape so easily, has such a low density that it would float in strong potassium carbonate solution. But nuclear matter is over $10^{15}$ times denser. It should absorb the neutrino background. Indeed, black holes and neutron stars could be the only neutrino sinks known.**

**Daedalus would love to exploit our own neutrino background in this way. He will be alert for warming at the top of his Eiffel Pyramid of nuclear matter — a sign that neutrinos are being absorbed. How splendid it would be to capture neutrinos, the ultimate waste product of the Universe, and use their energy for our own needs. The neutrino flux would be useful even as background heating; if it generates temperatures above 100 °C it could be used to raise steam and power. Compared with the vast sums expended on the magnetic fusion reactor ITER, and the ever-receding dream of fusion power, the idea of exploiting free solar or cosmic neutrinos looks quite attractive.**

David Jones