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titanic collision of a Mars-sized planetesimal with the proto-Earth sometime in the first 100 million years of solar system history.[5]

It is not my intention to discuss these fascinating topics, however, but to point out that in conjuction with ongoing work on them there has been much fundamental progress in the understanding of impact cratering physics. This includes computation, theory, and experiment. The application of this new and evolving understanding promises not only greater insight into the events mentioned above, but to the general problem of how the solar system was assembled.

Impact cratering, unlike nearly any other geophysical phenomenon, involves a very broad range of mass, length, and time scales, each with a rich physics. This makes any analytical theoretical description of the process approximate in one regard or another. The advent of economical, high-speed computation promises to transform our knowledge of cratering aspects that are inaccessible to experiment. These include large-scale impacts, the growth of craters to so-called late times, and cratering of complex and novel targets. Calculations have now been carried out from early to late times.[6,7] The modification stage of large cratering events, in particular the transition from transient cavity expansion to gravity-driven rebound of the crater floor, has been observed. Such rebounds have been inferred from field data and analytical models, but interpretation or even existence of crater rebound has remained controversial in the planetary geology community. This work illuminates the physics of the origin of flat crater floors (as opposed to simple bowl shapes), central peaks within them, and multiple-ring mountains seen around the largest craters on the Moon and other planetary bodies.

Code calculations also allow effects of complex target geometries to be explored. A water layer overlying a rock halfspace (for simulating impact into the Earth's ocean) is an obvious example.[6,7] Less obvious is "cratering" of the Earth's atmosphere. Here the vertical pressure and density structure and (in some cases) the Earth's sphericity render the "target" complex. The role of impact in accretion and ablation of the Earth's primordial atmosphere (and those of other solid planets and satellites) is just beginning to be modeled.

Our ability to interpret the results of large code calculations, high-explosive field trials, and laboratory-scale experiments has also greatly improved owing to greater comprehension of scaling.[8] Because many cratering phenomena occur at scales much larger than the impactor, it can be replaced by an equivalent point source of energy and momentum. Older energy-scaling rules are thus revised. While it is premature to declare this new scaling complete, it has proved remarkably successful. For instance, extrapolation from laboratory impact experiments in water is accurate for both 19th-century water-drop experiments and code calculations of multimegaton explosions in water.

Experimental support for the theories comes mainly through the use of centrifuges to simulate greater physical scales by means of elevated gravity.[8] Also novel experimental situations continue to pose theoretical challenges, among them cluster (or dispersed) impactors,[9] impact vaporization, and spallation and whole-target fragmentation.[10]

Much further progress and unexpected discoveries and applications are anticipated. One example is the issue of solar system bombardment history. Untangling the role of comets, asteroids, and circumplanetary debris in cratering the various satellites and planets may disentangle the collisional and dynamical evolution of these small-body populations and the relative/absolute chronologies of planetary surface processes. In turn, we may thus work, step by step, back through the history of accretion of the planets.[11-13]

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Plate Tectonic Prediction Fulfilled

Why, according to a recent survey,[1] do 81% of Americans believe the Earth's surface to be covered by moving tectonic plates, when only 47% accept the notion that humans are descended from more primitive animals? Apparently many of those skeptical of the geologic record of life are convinced by the evidence for past production and consumption of the Earth's surface. Both plate tectonics and natural selection are theories of slow change that depend on a reading of the geologic record for their principal support. Evolution, however, has been subject to much longer public and scientific debate. Charles Darwin published *The Origin of Species* in 1859.[2] Fifty-six years later Alfred Wegener proposed, in *The Origin of Continents and Oceans,* that the continents drifted around the globe.[3]

The leap from Wegener's hypothesis to plate tectonics, in which the continents are envisioned as moving with the sea

floor rather than plowing through it, followed in 1965. Until now, neither species evolution nor continental motion could be observed during a human lifetime, but plate tectonics is no longer a matter of geologic conjecture: During the past four years the movement of the Earth's dozen plates has been measured, centimeter by centimeter, across four continents and three oceans.

Because of the stately pace of the plates, which slide at rates of 1 to 10 cm /yr on a substrate of partially melted rock, detection of plate motion awaited measurements of intercontinental baselines accurate to several centimeters. Currently three independent techniques yield comparable plate velocities and directions.[4]

To measure the relative movement of plate interiors, reflectors were launched into Earth orbit and several ground-mounted lasers were engaged in a three-dimensional positioning analogous to triangulation, called satellite laser ranging. During the past four years, observation of quasars—extragalactic radio sources emitting a random "universal bar code" that can be timed and cross-correlated between receivers—has given us the most precise method to gauge baselines spanning the girth of the Earth. This method, known as Very Long Baseline Interferometry (VLBI), has measured the relative motion of five of the Earth's plates to a precision of one part per billion.[5] Finally, a growing constellation of military NAVSTAR satellites that broadcast their position to small mobile receivers (the Global Positioning System) now provides the most versatile method to measure baselines shorter than 500 km.

The space and terrestrial observations yield a stunning result: the plate rates measured during the past few years are—within the measurement uncertainty—identical to those deduced for the past several million years from the geologic record. This discovery attests to the fidelity of the geologic record of our planet's past. More important, it means that the gravitational forces that drive the plates and the viscous forces that resist their motion must stay balanced over millions of years. The jerk of occasional great earthquakes at plate edges, and the perhaps million year cycle of transient convection—eddies of flowing rock beneath the plates—may thus leave the plates unperturbed.

Ten million years ago the Pacific plate began to take a western sliver of California with it on its northward march toward Alaska, the cut now known as the San Andreas fault system. The faults provide our best opportunity to measure plate movement and deformation on land. The stick-and-slip motion along the uppermost 10 km of the faults accounts for California's plentiful supply of earthquakes (see Fig. 1). During the past two million years, just under 5 cm/yr of relative plate motion has been accommodated by slip along the San Andreas fault system. Displacement of ancient tributaries across the fault reveals that during the past 15,000 years, the central San Andreas has slipped an average of 3–4 cm/yr. Recent resurvey of century-old triangulation monuments installed by the U.S. Coast and Geodetic Survey to construct maps for the Gold Rush shipping traffic indicates a rate of at least 3.3 cm/yr during the past century.[4] The most recent VLBI measurements yield a rate across the San Andreas system of 3–4 cm/yr.[6] Thus a consistent picture of plate movement emerges on time scales sampled at 4, 100, 15,000 and 2,000,000 years.

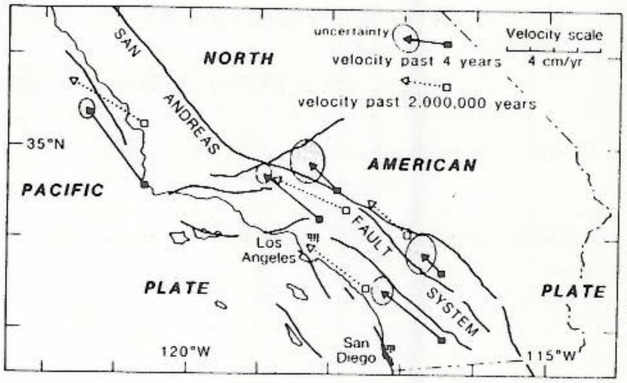

FIG. 1. Velocity vectors for the movement of the Pacific plate relative to the North American plate in southern California, deduced from four years of VLBI measurements (solid arrows) and from geologic rates of fault slip and sea-floor spreading (dotted arrows).

The claim that we have finally measured the contemporary motion of continents oddly echoes one made prematurely by Alfred Wegener in 1929: "We begin the demonstration of our theory with the detection of present-day drift of the continents by repeated astronomical positioning, because only recently this method furnished the first real proof of the present-day displacement of Greenland—predicted by drift theory—and because it constitutes a quantitative corroboration."[7] From repeated longitude measurements Wegener inferred that Greenland had drifted 1610 ± 285 m from Europe between 1827 and 1907, a rate of 19 ± 3 m/yr. This result agreed with longtitude observations performed elsewhere on Greenland between 1860 and 1921. Wegener dismissed the possibility—now known to be true—that gradual improvement of the measurement precision, rather than drift of Greenland, accounted for the longitude changes: "This accumulation of similar results which do not stand in opposition to any others makes it highly improbable that it is all just a matter of unfortunate combination of extreme errors of observation."[7] Today, Wegener stands at once vindicated and discredited. Greenland is indeed drifting away from Europe, but at a velocity now measured to be 1.9 ± 1.0 cm/yr, one-thousandth Wegener's proffered rate.

It is ironic that plate tectonics enjoyed such widespread acceptance before this crucial confirmation, whereas evolution—read from the same geologic and fossil record—remains controversial. Our response to scientific advances appears to be bound more closely to how we view ourselves than it is to how we view the science. One cannot help but wonder whether confirmation of evolution, such as contemporary observation of speciation by natural selection, would encourage the reluctant 53% to acknowledge their simian floor rather than plowing through it, followed in 1963. Until now, neither species evolution nor continental motion could be observed during a human lifetime, but plate tectonics is no longer a matter of geologic conjecture: During the past four years the movement of the Earth's dozen plates has been measured, centimeter by centimeter, across four continents and three oceans.

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The space and terrestrial observations yield a stunning result: the plate rates measured during the past few years are—within the measurement uncertainty—identical to those deduced for the past several million years from the geologic record. This discovery attests to the fidelity of the geologic record of our planet's past. More important, it means that the gravitational forces that drive the plates and the viscous forces that resist their motion must stay balanced over millions of years. The jerk of occasional great earthquakes at plate edges, and the perhaps million year cycle of transient convection—eddies of flowing rock beneath the plates—may thus leave the plates unperturbed.

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Dynamics of the Upper Ocean

The atmosphere presents an almost constantly changing heat flux and wind stress to the surface of the sea. Recent field and theoretical studies have given a greatly improved description of the upper ocean's response to this surface forcing, and here we note some advances in understanding the effects of heating by solar insolation.[1]

Much of the recent progress can be traced directly to new measurement techniques which have yielded field data sets with expanded duration and resolution. Notably, recent turbulence measurements from the equatorial Pacific Ocean show a pronounced diurnal cycle of upper ocean turbulence.[2–4] The immediate effect of solar heating is to produce a warm layer adjacent to the sea surface. The static stability of this layer inhibits the downward penetration of turbulent vertical mixing so that the surface flux of heat and momentum will be trapped near the sea surface during mid-day. After the sun sets, sea surface cooling by evaporation and infrared radiation produces an unstable heat flux, and the resulting free convection and turbulent mixing by the wind then penetrates to surprisingly large depths, up to about 100 m. This great penetration of nocturnal mixing may be connected with the presence along the equator of strong, highly sheared mean currents which at some depths flow against the prevailing wind, but other hypotheses involving internal wave generation and re-absorption at depth appear equally plausible.[5]

Field observations from mid-latitude sites show that this solar heating-induced variation in mixing depth imposes a diurnal pulse on the wind-driven velocity. During mid-day the momentum flux supplied by wind stress is absorbed within the warm surface layer which then accelerates downwind as a diurnal jet. The Coriolis acceleration due to the Earth's rotation turns the diurnal jet clockwise during the day (northern hemisphere) and by sunset the jet may be turned counter to the wind. During the remainder of the night the adverse wind stress together with the increased vertical mixing will often erase completely the diurnal jet generated during the preceding day. The long-term average of this diurnally pulsing current has a spiral shape.[6] These solar heating plays by modulating the penetration depth of vertical mixing.

Satellite-derived infrared views of the sea surface reveal the large scale patterns of diurnal warming. In many cases there is a remarkably clear signature of the overlying surface heat flux and wind stress. For example, large amplitude diurnal warming of up to 3 C occurs along the axis of marine high pressure systems where there is a coincidence of clear sky and light winds.[7] In the future it may be possible to exploit this new knowledge of the effects of solar heating to infer meteorological data in remote oceanic regions which are inaccessible to direct observations.

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High-Pressure Experiments and the Earth's Deep Interior

What is the nature of the Earth's core? How high is the temperature at the center of our planet? Advances in high-pressure experimental techniques are yielding new insights about the deep interior, revealing that the core is an unusual alloy of iron with a peak temperature exceeding that of the sun's surface.[1,2]

The experimental breakthroughs allow materials to be examined in detail at the extreme conditions of the core: pressures ranging from 136 GPa (billion Pascals) at the core-mantle boundary to 364 GPa at the center (1.36 to 3.64 million times atmospheric pressure) and temperatures above 3500 K. The most recent developments involve a laser-heated diamond cell, in which less than one microgram of sample is squeezed between the points of two gem-quality diamonds. Pressures in excess of 500 GPa have beeen achieved by this technique.[3,4] To simulate deep-Earth temperatures a laser beam is focused through the diamonds and into the sample area, thus producing temperatures of 1000–7000 K.[5,6] During the experiments the sample is directly observed through the diamond anvils (or more properly in this context, the diamond windows) by techniques ranging from x-ray diffraction to visible and infrared spectroscopy. In particular, temperature is determined by spectroradiometry. Complementing the diamond cell, in which high temperatures and pressures can be sustained for hour-long periods, are the well-established shock-wave experiments