

Another is torque applied at the hip joints, making the forces on the feet vertical (see the figure, D).

One of the new robots described by Collins *et al.* (1), the Cornell biped, has been designed to work like the robot in part (C) of the figure. It has a torso, arms with shoulder joints but no elbows, and legs with hip joints, knees, and ankles. An electric motor in the ankle makes one foot push on the ground, just before the other lands. This is remarkably effective, giving a mechanical cost of transport of only 0.055. This cost is approximately equal to the human value, and far better than the estimated mechanical cost of 1.6 for the robot Asimo, in which all joints are motorized and controlled. The hip joints have no motors, but a passive linkage ensures that the torso bisects the angle between the two thighs, and so is kept upright. Other passive linkages make each arm swing in phase with the opposite leg. The knees have no motors, but latches

keep them straight while the foot is on the ground. Only the ankles are motorized. This astonishingly simple machine walks like a human and is remarkably economical with regard to energy expenditure.

The second of the new robots described by Collins and co-workers, the Delft biped, was not designed specifically for energy economy, but nevertheless achieves a mechanical cost of transport of only 0.08. It is powered by pneumatic actuators at the hips (see the figure, D). It has no other muscles but, like the Cornell biped, does have controlled latches at the knees. Clever ankle design, based on the principle of skateboard suspensions, improves lateral stability. The third new robot from the Massachusetts Institute of Technology group is based like the others on ramp-walking toys. It has motors only at the ankles. Its special feature is that it learns to control its own walking. Typically, the learning process takes about 10 min or 600 steps, and it can adapt to

uneven terrain and different surfaces.

These new robots are important for three reasons. They give us new insight into human walking. They point a possible way to the design of more lifelike artificial legs for amputees. And they bring renewed excitement to the design of humanoid robots. They show us that bipedal robots far simpler than their predecessors work as effectively and far more economically, and can even be designed to teach themselves to walk.

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## GEOLOGY

# The Calibration of Ediacaran Time

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More than a century ago, the last great geological period was formally ratified by an international committee. This was the final rocky step in the subdivision of deep time based on the evolutionary progression of animal fossils. However, recent years have seen the identification of an older and tumultuous new interval, the Ediacaran Period, during which Earth's earliest soft-bodied organisms emerged in the oceans. This interval was recently ratified (1), underscoring advances in the absolute dating (2–6) and worldwide correlation of geological strata that were deposited in isolated basins before true animals exploded onto the scene in the succeeding Cambrian Period.

On page 95 of this issue, Condon *et al.* (7) present precise age constraints for the Ediacaran Period. The authors have analyzed volcanic dust in two key depositional layers in the Doushantuo Formation of



**Early animals?** A pile of three-dimensionally preserved casts of the soft-bodied Ediacaran organism *Ermetta* from ~545 million-year-old sediments in the Nama Group of southern Namibia. The scale bar corresponds to 15 cm.

southern China. Their radiometric dates provide important insights into the rates of geological and evolutionary processes. The first layer, with an age of about 635 million years, is at the base of the new interval, whereas the second, at about 550 million years, may constrain the age of an environmental disaster (8–10) that is closely associated with the rapid diversification of the Ediacara biota (see the figure) that lend their name to the new Period.

Convention previously focused on the evolutionary first appearance of a specific fossil or assemblage to define the beginning of new geological periods. In contrast, the

beginning of the Ediacaran period is defined by the base of a marine carbonate rock, which formed in southern Australia in the aftermath of a distinctive and potentially global ice age (11, 12). Equivalent glacial rocks occur immediately beneath similar carbonates at the base of the Doushantuo Formation.

In the area studied by Condon *et al.*, the new ages constrain the Doushantuo Formation, which represents most of the Ediacaran Period, to some 85 million years—a remarkably long interval for only about 100 m of rock. This observation begs the question: How much time may be missing in Ediacaran strata from southern China?

In the absence of dates between the two radiometric tie points, one must consider two possibilities: Either the sediments accumulated continuously, albeit slowly (some two orders of magnitude more slowly than in similar environments of the same age), or there are breaks in time (hiatuses or unconformities) hidden within the poorly exposed layers. On the basis of limited physical data, Condon *et al.* suggest the presence of two such unconformities in their study area near the Yangtze Gorges. The duration of these stratigraphic breaks with respect to the environmental anomaly—reflecting a dramatic change in the cycling of carbon on Earth's surface—

and subsequent biological innovations form the cornerstone of their conclusions, and deserve closer examination.

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Spectacular fossil animal embryos (13, 14) of great evolutionary importance are found at Weng'an (some 375 km to the southwest of the authors' study area), where the Doushantuo Formation accumulated closer to the shoreline and records only a single surface of unconformity. In such nearshore environments, oceanic sediments are often exposed above sea level, resulting in the removal of underlying sediments and hence the erasure of some fraction of geological time. Which of the two hiatus surfaces from the deeper-water sections at the Yangtze Gorges correlates to the single unconformity at Weng'an? The data are more equivocal than presented by Condon *et al.*, and the choice carries important evolutionary consequences.

At the Yangtze Gorges, the extraordinary carbon cycle anomaly recorded in marine carbonates near the top of the Doushantuo Formation is truncated by the uppermost unconformity. Condon *et al.* suggest that there is little time missing across the surface, thereby preserving a causal relation between the environmental perturbation and the rapid diversification of Ediacara organisms and associated faunas around 550 million years ago. However, correlation of this surface and the intervening sediments back to Weng'an tells another story. At Weng'an, both the carbon cycle anomaly and the sediments typical of the uppermost Doushantuo Formation at the Yangtze Gorges are missing, implying a substantial hiatus.

Comparison of broadly equivalent strata in southern Australia and the western United States suggests a stratigraphic architecture similar to that in southern China, where similar carbon cycle anomalies are truncated by unconformities (15). In the western United States, the post-anomaly unconformity removes a minimum of 130 m of section, more than the entire thickness of the Doushantuo Formation. These observations suggest that the unconformity separating the Ediacaran faunas and the carbon cycle anomaly in southern China may, in fact, hide a lot of time, thereby decoupling the environmental and biological events that the authors wish to connect. This is not meant to detract from the important radiometric calibration that Condon *et al.* provide, but rather to note that the stratigraphic relations between these dates, and therefore their connection to evolutionary events, are far from straightforward.

According to Condon *et al.*, the rapid diversification of complex multicellular organisms in Ediacaran oceans forced the carbon cycle anomaly seen worldwide, but this seems possible only if there is no real time missing across the upper Doushantuo unconformity. If this is not the case, then this interpretation may be placing the cart before the horse. Alternative models suggest that environmental changes may have driven evolutionary transformations. In particular, atmospheric oxygen—long believed to be an external forcing factor to evolu-

tion—appears to have built up rapidly during the Ediacaran Period, not because of a discrete biological event but as a result of the tectonic forces that lift and erode mountain ranges (16).

Through precise radiometric clocks and clever stratigraphic connections, geoscientists can increasingly correlate Ediacaran sediments that are separated widely in space and time. These tools allow us to piece together a complex puzzle of unforgettable biological events against a background of repetitive climatic and environmental perturbations. However, even with exact dates, the cyclicity of these events and the specter of a fragmentary rock record add uncertainty to our picture of Ediacaran Earth history.

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## EVOLUTION

# Where We're Hot, They're Not

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**H**omologous recombination, the exchange of material between chromosome pairs during meiosis, plays several key roles in diploid organisms. It produces new combinations of alleles, greatly increasing the potential for adaptive diversity. It is required for the normal separation of the two members of a chromosome pair during meiosis. It is an essential step in recombination-mediated repair of double-strand breaks in DNA. Defects in this crucial repair process can give rise to inherited diseases such as familial breast cancer.

The measurement of recombination frequencies has been the keystone of long-standing efforts to map the chromosomal locations of genes. As Winckler *et al.* (1) now report on page 107 of this issue, map-

ping of recombination hotspots in the human and chimpanzee genomes reveals a surprising finding. Despite 99% identity between human and chimpanzee DNA sequences, there is virtually no overlap between these two species in the locations of their recombination hotspots.

Traditionally, gene mapping in humans has relied on the direct observation of recombination events in families (linkage analysis). This approach, while enormously successful, is limited by the small number of generations during which meiosis can be observed in humans. An alternative approach, based on the once-obscure concept of linkage disequilibrium (LD), has gained widespread attention during the past couple of decades. To understand LD, imagine that a disease-causing mutation has just occurred in a population. The chromosome on which this mutation occurred contains specific DNA variants (alleles) in

neighboring polymorphic (variable) loci. At first, the mutation will be observed only in conjunction with these alleles, so the association (or LD) between the mutation and the surrounding variants will be high. Through time, these associations will dissipate because of recombinations between the mutation and nearby loci, and LD will drop (see the figure, A). The closest loci will experience the fewest recombinations and hence retain higher levels of LD with the mutation. Thus, LD patterns can reveal the approximate locations of disease-causing mutations. LD analysis, in contrast to linkage analysis, reflects the effects of dozens or hundreds of past generations of recombination and may therefore confer improved resolution and statistical power to localize mutations. Although its merits are still debated (2), LD analysis may be especially useful in the detection of mutations that underlie complex diseases (3, 4), and it has yielded some recent successes (5, 6).

As with all explorations, gene hunting based on LD benefits from a good map. The principal goal of the much-discussed International Haplotype Map (HapMap)

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