

ensemble that incorporates all of these conserved quantities. Each conserved quantity is associated with its own temperature; a 5000-particle system might require 5000 different temperatures to specify the distribution function.

Our harmonic oscillator example for 5 and 500 particles, where each oscillator separately conserves energy, shows two central points (see the figure, panel C). First, these distributions look nothing like the standard Maxwell-Boltzmann distribution (pink); second, the distributions depend on the system's initial conditions, with peaks set (as in panel A) by the initial energy of each particle. If the per-particle energy had been distributed differently between particles, then the distribution would be peaked at different points. This initial state effect was first observed in a 1D Bose gas (5) in which an atomic "Newton's cradle" was created.

"...cold-atom experiments can be used to study the thermodynamics of systems with internal constraints and can provide the understanding required to predict the outcome of an experiment."

The physical origin of these conservation laws is simple and depends on the central assumption that each microstate is occupied with equal probability. Usually, physicists argue that collisions between particles are effective in moving the system among all allowed microstates. For 1D systems with binary, local, and elastic collisions (such as between billiard balls), this assumption fails. If we consider just two particles with momentum p_1 and p_2 colliding at some position x , then there are only two possible outcomes that conserve energy and momentum: Either the dynamics continues unchanged ($p_1 \rightarrow p_1$ and $p_2 \rightarrow p_2$), or it continues with the roles of the particles swapped ($p_1 \rightarrow p_2$ and $p_2 \rightarrow p_1$). In either case, the distribution function is unaltered by the collisions.

Langen *et al.* first prepared individual ultracold 1D Bose gases with about 5000 atoms and split these into two parallel decoupled 1D systems, mapping each atom into a coherent superposition of being in the left and the right system. As a result, each of these 1D subsystems was initialized

very far from equilibrium. The quantum mechanical phase difference was then observed along the length of the split system as it approached equilibrium. Langen *et al.* found that after some time the split system reached an equilibrium state, but not one predicted by a standard thermodynamic ensemble.

To identify the details of their experiment's underlying ensemble, the authors made a comparison with the higher-order correlations of the measured phase difference (essentially asking how the phase differences at various points are related) up to 10th order. These distributions were found to be qualitatively different from those predicted by standard thermodynamics. Instead, Langen *et al.* considered the resulting quasi-equilibrium in terms of the predictions of the GGE and found that two separate temperatures were required before the ensemble was consistent with their experimental data within the technical noise.

According to the eigenstate thermalization hypothesis (4), many-particle quantum systems generically evolve to distribution functions resembling the microcanonical ensemble for local observables, such as the spatial distribution functions discussed here. It requires special effort, such as in Langen *et al.*'s experiment, to find initial states going beyond this.

Langen *et al.* have shown that cold-atom experiments can be used to study the thermodynamics of systems with internal constraints and can provide the understanding required to predict the outcome of an experiment. One might have expected some 5000 constraints to be required to reconcile experiment and theory; experimentally one was insufficient, but two sufficed. In light of the eigenstate thermalization hypothesis, can the impact of all of these constraints ever be felt, or is a small subset always sufficient to describe the outcome of realistic experiments? ■

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GEOLOGY

An early start for the Panama land bridge

The land bridge between North and South America formed 10 million years earlier than previously thought

By Carina Hoorn and Suzette Flantua

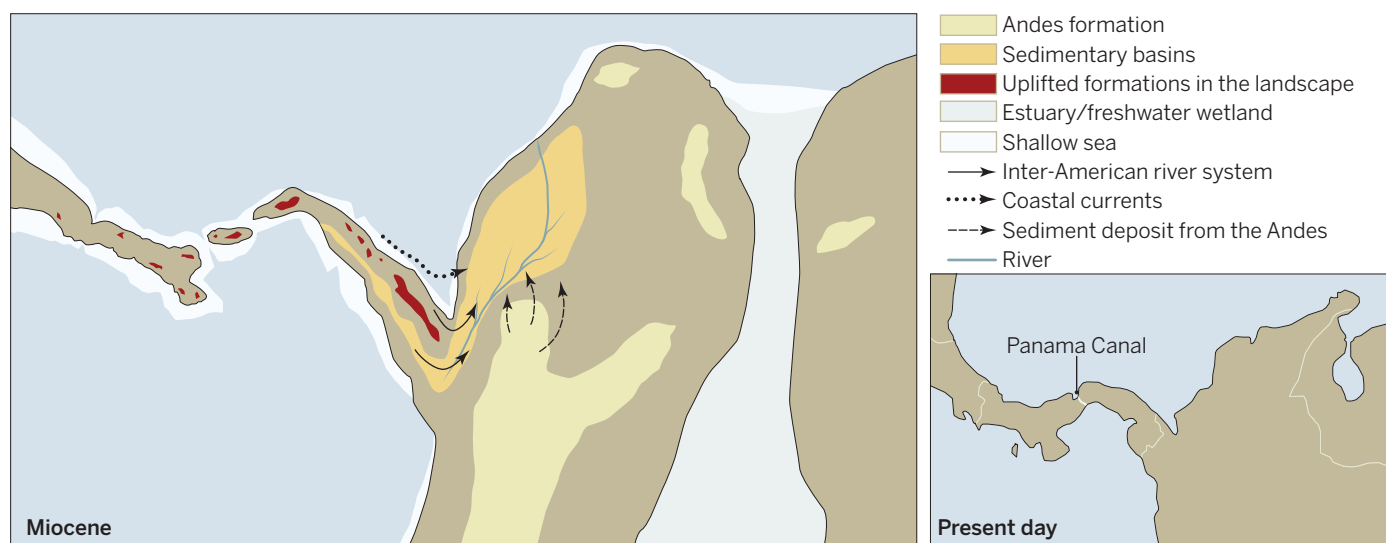
The birth of the Panama land bridge, which connects the Americas, has been associated with one of the biggest biological exchanges in Earth history as numerous species migrated from one continent to the other (1). Nevertheless, the timing of formation of the land bridge is still much debated (2). On page 226 of this issue, Montes *et al.* (3) propose that the Central American Seaway, which separated South and North America, closed about 15 to 13 million years ago, more than 10 million years earlier than previously thought (4), with important implications for ocean circulation, climate, and biotic exchange.

The authors studied ancient river deposits found in northern Colombia. Through a combination of geochronological analysis and geological mapping, they determined the age, origin, and pathway of this river. They show that the river system began to flow about 15 to 13 million years ago and could not have originated in any other place than the volcanic arc of Panama. This means that a terrestrial connection must have existed between northern Colombia and the river's source area at this time. A marine connection, the authors state, could only have consisted of transient shallow channels west of today's Panama Canal (see the figure). With this, they contest alternative scenarios (4), which suggest that a deep-sea strait separated the Americas until 3 million years ago, preventing massive biotic exchange before this time.

Montes and colleagues first questioned the generally accepted young age of the seaway closure in 2012 (5). Before this, however, some geologists and biologists had already

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Connecting the Americas



Panama then and now. According to Montes *et al.* (3), a Panama land bridge with an “Inter-American” river system formed during the Miocene (15 to 10 million years ago). Support for this land bridge comes from fossils of herald animals that crossed the land bridge in either direction well before 3 million years ago (6). (Inset) Map of Central America today.

suspected that the land bridge might have emerged earlier than presumed. Paleontologists found that an array of “herald animals” such as camels, peccaries, horses, beardedogs, and rhinoceroses were at the bridge by 15 million years ago and that giant sloths, terror birds, and plants (among others) passed the bridge in the northern direction well before 3 million years ago (6). Bacon *et al.* have also inferred early exchange of plants between the continents from dated molecular phylogenies (7).

Various scenarios were invoked to explain these observations, but none of them were conclusive. A crucial point of controversy has been whether early biotic exchange reflects a terrestrial connection or was a result of random long-distance dispersals (7) or perhaps climatic cooling (8). With excavations well on their way for renewal of the Panama Canal, a wealth of new paleontological data (2) and comparative molecular analyses (7) is enforcing the idea of an early land bridge.

Other evidence for an early emergence of the land bridge comes from the magmatic rocks in Panama and northern South America. Changes in the geochronological composition of the Panama volcanic arc at about

24 million years ago mark its collision with the South American island continent (9). This collision represented the end of a 2- to 3-thousand-km oceanic voyage of the Caribbean plate on which embryonic Panama was situated (10) and formed the prelude to complex deformation at the triple junction of the Caribbean, South American, and Nazca plates. In essence, subduction processes built the fundamentals of Panama and ultimately determined the pace of its emergence (10).

The formation of the Panama land bridge was not an isolated event. As the Caribbean plate scraped along South America, it reconfigured the northern South American landscape (9), resulting in the characteristic trifurcate shape of the northern Andes. Shoaling of the Central American Seaway also coincided with large changes in the South American lowlands corresponding to today’s Amazonia, where a mainly fluvial landscape changed into a vast wetland that developed as a consequence of deep subsurface processes, the rising Andes, and related climate change (11). Wetland formation, contemporary marine influence in Amazonia, and an extended inland coastline (12) are all related to the Caribbean collision and closure of the Central American Seaway.

Pushing back the age of the Panama land bridge by more than 10 million years is noteworthy. However, an early terrestrial connection reconciles an array of seemingly odd results, such as the early dispersal of freshwater fishes between South and Central America (13) and shoaling, changes in oceanic currents, and deep-water exchange between the Pacific and Atlantic between 12 and 7 million years ago (6, 14, 15). These events are difficult to explain if the Central

American Seaway did not close until about 3 million years ago.

The geological evidence presented by Montes *et al.* lends support to the idea that the Great American Biological Interchange (GABI) between the Americas started millions of years earlier than commonly assumed. But why did many organisms wait before migrating around 3 million years ago? Molnar (8) has suggested that the peak in biological exchange about 3 million years ago was a result of climatic cooling and the formation of savannas suitable for herbivore migration. A full understanding of the dynamics of the GABI will require better knowledge of the early land bridge and its environments. Data are also needed on the existence and duration of any intermittent transoceanic connections elsewhere along the narrow strip of land that separates the Atlantic and the Pacific. ■

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Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, 1090 GE Amsterdam, Netherlands.
E-mail: m.c.hoorn@uva.nl



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Carina Hoorn and Suzette Flantua

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