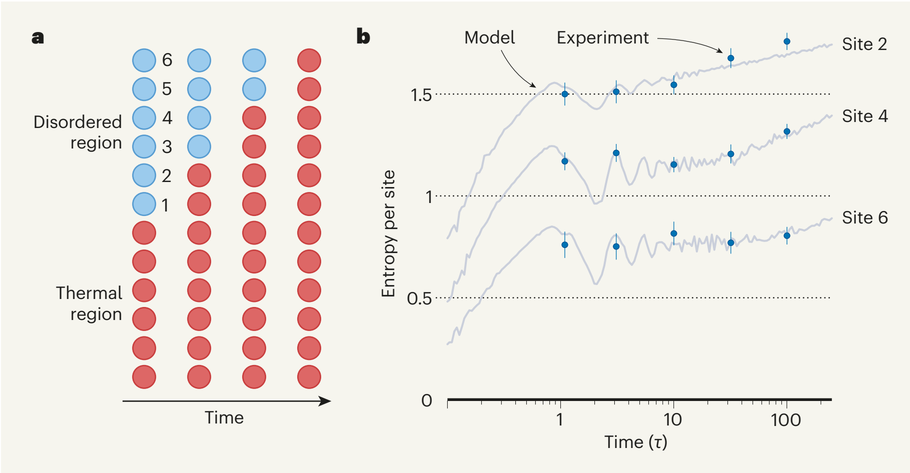

Figure 1 | Increasing entropy signals a 'quantum avalanche'. Interactions drive many-body quantum systems towards thermal equilibrium, but disorder could inhibit this thermalization process. Consensus that this holds in 1D systems with short-range interactions has been challenged by a process called a quantum avalanche, in which a small 'thermal' region can gradually lead to the thermalization of the whole system. **a**, Léonard *et al.*[8] demonstrated this phenomenon in a 1D system of atoms of the isotope rubidium-87, in which the thermal region initially contained six sites. **b**, They found that the entropy per site of the disordered region increased over time, with the sites closest to the interface between thermal and disordered regions increasing first, as shown for sites 2, 4 and 6. Eventually, the whole disordered region became thermalized. Time is measured in units of τ, a characteristic time constant for the system, which is 4.3 milliseconds, and entropy is dimensionless. (Adapted from Fig. 3 of ref. 8.)

referred to as a quantum avalanche.

Léonard and colleagues prepared a 1D system of atoms of the isotope rubidium-87 in a state that had a single atom per site. They then monitored each stage of the ensuing quantum avalanche. The atoms could hop between sites, and when more than one atom was on a site, they experienced repulsive interactions. The authors chose six neighbouring sites to form the disordered 'many-body localized' part of the system and kept either six sites or two sites free from disorder so that they represented the thermal region (Fig. 1a shows the first case). Quasiperiodic disorder in the disordered region was used to prevent nearby sites from accidentally having the same potential.

The authors found that the ensuing dynamics depended on the size of the thermal region. A quantum avalanche occurred when the thermal region contained six sites, but not for systems with a thermal region comprising just two sites. A possible explanation for this difference is that the region with only two disorder-free sites does not develop chaotic features, which are a prerequisite for an effective thermalizing system.

To detect whether one of the atoms moved between any two given sites, the authors measured the correlation between the density of atoms at those sites — a negative correlation indicating motion. For the system with six sites in the thermal region, negative correlations between all sites of the thermal region quickly built up, indicating delocalization, and the region rapidly reached thermal equilibrium. On longer timescales, negative correlations built up across the interface between the thermal and the disordered region, indicating the transport of atoms between the two regions.

The authors' experimental set-up enabled them to image each site in the system, allowing them to measure the probability distribution of the number of atoms at each site. They then used this to compute the entropy per site of the disordered region. For the system with the six-site thermal region, the entropy of the site closest to the interface was the first to increase, followed by that of successive neighbouring sites (Fig. 1b). This process reflects the progressive thermalization of the disordered region. By contrast, there was no increase in entropy for the system with a two-site thermal region.

Léonard and colleagues' results therefore challenge previous assumptions that many-body localization is stable in 1D systems. The findings also improve our understanding of the thermalization mechanism and of how quantum information spreads in many-body quantum systems that have short-range interactions. Future work could consider engineering the disorder in these systems to ensure the stability of the many-body localized phase[11]. A full understanding of this intriguing phenomenon will also require a thorough analysis of the way in which the thermalizing process in the disordered region depends, for example, on the size of the thermal region, the timescales and the initial states.

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Climate science

High variability under an Antarctic ice shelf

Craig McConnochie

Fixed moorings and underwater vehicles have uncovered varied patterns of melting and morphology under a West Antarctic glacier, offering insight into the potential for its collapse and highlighting key challenges for modelling. **See p.471 & p.479**

Ice loss from the West Antarctic Ice Sheet is one of the largest contributors to global sea-level rise. Indeed, the Thwaites Glacier in West Antarctica alone is responsible for around 4% of the total annual increase[1] — a contribution that has earned it the name the Doomsday Glacier because of its potential to cause rapid sea-level rise over the coming century. In two papers, Davis *et al.*[2] (page 479) and Schmidt *et al.*[3] (page 471) report observations of the melt rate, ocean conditions and ice shape deep beneath the Thwaites Glacier ice shelf — suggesting that complex interactions between the ice and the ocean will have a key role in the glacier's future.

The reason that the Thwaites Glacier poses such a threat for future sea-level rise involves both its size and its geography. Like many West Antarctic glaciers, Thwaites sits on bedrock that slopes upwards towards the coast. This geography makes such glaciers particularly susceptible to marine ice-sheet instabilities that could cause them to reach an unstable state, in which they continually and rapidly collapse into the ocean[4]. In the case of the Thwaites Glacier, this collapse would directly contribute more than 0.5 metres of sea-level rise over a few centuries and could destabilize neighbouring glaciers, which would contribute 3 m of sea-level rise over several thousands of years.

The two papers report observations of ocean properties and ice melt rate that were made several kilometres downstream of the grounding line — the location at which the glacier detaches from the ground and starts floating. Obtaining these data required that the authors drilled an access hole through around 587 m of ice. Although the region near the grounding line is crucial for the stability of the glacier, the technical challenge of accessing the region has previously prevented such measurements from being made.

Davis *et al.*[2] made observations from a fixed mooring that was positioned 1.5 m below the ice shelf to measure ocean temperature, salinity, velocity and melt rate over time. By contrast, Schmidt *et al.*[3] used an underwater vehicle to measure the same ocean properties, as well as the ice morphology (shape) over a wider region.

The mooring data show that, near the ice, the ocean velocities are low and the salt levels in the water are strongly stratified, owing to high meltwater concentrations (Fig. 1a). This stratification insulates the ice shelf and slows the rate of melting, even though ocean temperatures remain several degrees above the melting point. Davis and colleagues found that these conditions were reasonably consistent throughout the year, with a small shift between January and September caused by changes in the ocean conditions away from the coast. After September, the ocean freshened but remained at the same temperature — an intriguing trend indicating that fresh water is released at the grounding line. This subglacial discharge is known to have a pronounced impact on the melt rates of Greenland's glaciers[5], but is generally ignored in studies of Antarctic glaciers, owing to a lack of observations.

This information about temporal patterns near the grounding line is complemented by Schmidt and colleagues' underwater measurements, which offer information about spatial patterns. The authors' most striking observation was that of a highly variable ice morphology (Fig. 1b). On average, the undersides of ice shelves are very gently sloping and are often approximated as horizontal. However, at around 800 m from the grounding line, Schmidt *et al.* found that the ice base shows a series of terraces and channels, similar to those observed at nearby Pine Island Glacier[6]. The terraces have steep, near-vertical walls that measure more than 6 m, are separated by horizontal sections and are randomly oriented. The scale of these features grows with the distance from the grounding line, suggesting that they're reinforced by melt patterns.

Measurements from the underwater vehicle show that the stratified, low-velocity ocean conditions measured by the mooring are typical of the horizontal sections of the terraces, whereas steep sections are associated with higher flow velocities and weak stratification. Schmidt *et al.* estimated the melt rates in these steep sections on the basis of the temperature, salinity and flow speed that they measured, and found them to be up to 30 m per year – six times the average melt rate observed by fixed instruments.

Together, these two sets of observations show the complexity of ice–ocean interactions beneath Antarctic ice shelves. The future of Thwaites Glacier will depend on both the temporal and the spatial variability that was observed through these studies, as well as on broader changes in climate. The results highlight challenges for both modelling and observational attempts at understanding the present state of West Antarctica — and predicting its future.

From an observational perspective, long-term and widespread measurements are required to truly understand a region. Unfortunately, it is more common to extrapolate from short-term measurements or from those made at a single location. It is to be hoped that improving technical capabilities, particularly with respect to remote underwater vehicles, will help to shift this norm.

The impact of small-scale morphology and spatially varying ocean properties revealed by these studies presents a formidable challenge to modelling efforts. Current models lack the resolution to include the variability observed by the authors, and this will remain true for the foreseeable future. Small-scale processes that contribute to the stability of ice shelves will need to be modelled carefully to account for complex topography and the insulating effects of local stratification, and this will first require observations that provide sufficient data.

On a positive note, these studies set a standard to which future observational work should aspire. The authors' long-term and widespread observations have provided an unprecedented view near the grounding line of an important

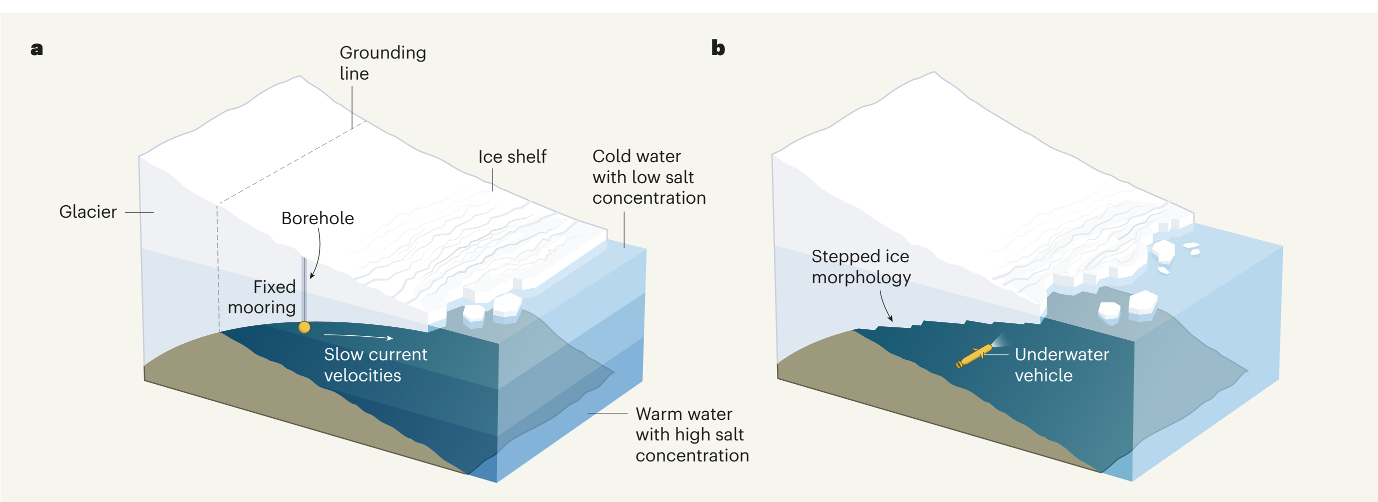

Figure 1 | Variability under Thwaites Glacier in West Antarctica. a, Davis *et al.*[2] used a fixed mooring under the West Antarctic ice shelf to take measurements showing that ocean velocities are low near the ice, and salt concentrations are stratified, which insulates the ice shelf and slows the rate of melting. **b**, Schmidt *et al.*[3] used an underwater vehicle to reveal a highly variable ice morphology. The undersides of ice shelves are usually almost horizontal, but the authors found a series of terraces and channels under the glacier, the scale of which grows with the distance from the grounding line (where the glacier detaches from the ground and starts floating). These findings suggest more-complex ice–ocean interactions than previously thought.

West Antarctic glacier. However, it is just a small region of a single glacier, and there is an urgent need to obtain a similar level of understanding of other Antarctic glaciers, each of which has its own unique features.

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Palaeontology

Fish fossil unfolds clues to vertebrate brain evolution

Hugo Dutel & Matteo Fabbri

A 319-million-year-old fossil provides the oldest known evidence of preserved vertebrate brain tissue. This specimen offers insights into the brain evolution of ray-finned fishes, the most diverse group of living vertebrates. **See p.486**

The diversity of modern animal forms that we might encounter in our day-to-day lives is only the latest chapter in hundreds of millions of years of evolution. Fossils are therefore pivotal in reconstructing the sequence and timing of the evolution of living animals' defining features. However, although mineralized tissues such as bone commonly fossilize, soft tissues, such as the brain and muscles, usually leave no trace. Therefore, our understanding of how living animals became how they are is incomplete. On page 486, Figueroa *et al.*[1] report the stunning discovery of a fossilized brain in an early ray-finned fish, presenting findings that overturn textbook narratives about the brain evolution of vertebrates.

Ray-finned fishes represent about half of all living vertebrates[2], and encompass most of the animals described as fish that we might encounter in everyday life, such as tuna and monkfish at the fishmongers. Their brain anatomy and the way in which the brain forms are among the most distinctive features of these animals[3]. In vertebrates, including our species, brain regions called the cerebral hemispheres are generally formed by a developmental process called evagination. The tip of a structure in the embryo called the neural tube bulges and folds inwards to form two cerebral hemispheres that enclose a hollow space called a ventricle (Fig. 1a).

However, the cerebral hemispheres of living ray-finned fishes are formed by a different process, known as eversion. In this case, the neural tube folds and extends outwards. Eversion results in solid cerebral hemispheres separated by a narrow ventricle, and this type of brain development was considered to have arisen when ray-finned fishes first appeared[3,4].

This evolutionary scenario was established on the basis of the study of living species only, but Figueroa and colleagues' examination of a small fossil of an extinct species named *Coccocephalus wildi* now turns this view on its head. The fossil, of a skull preserved in 3D, was discovered in rocks of the Carboniferous period (estimated to be 319 million years old) in north-west England, and first described around a century ago[5].

At first glance, *Coccocephalus* looks like a typical early ray-finned fish. It has a bulky skull, a short snout and large eye sockets, and other work[6] provides evidence consistent with the view that it is an early-diverging, distant cousin of all living ray-finned fishes. When studying its internal anatomy with X-ray scanning and 3D reconstruction techniques, Figueroa *et al.* found not only that the main regions of the brain and cranial nerves were fossilized in stunning detail, but also that the forebrain is evaginated – a feature previously unknown in ray-finned fishes (Fig. 1b).

Fossilized soft tissues in such ancient vertebrates are unusual, and this fossil is the oldest known fossilized vertebrate brain. Before this discovery, a slightly younger 3D fossilized brain was described in an extinct relative of ratfishes[7], and other fossilized organs have been described for fossil fishes called placoderms[8].

This discovery and the position of *Coccocephalus* in the vertebrate family tree have crucial implications for our understanding of brain evolution. The fact that *Coccocephalus* is unequivocally a ray-finned fish – but in a branch distinct from that of modern ray-finned fishes – means that an everted

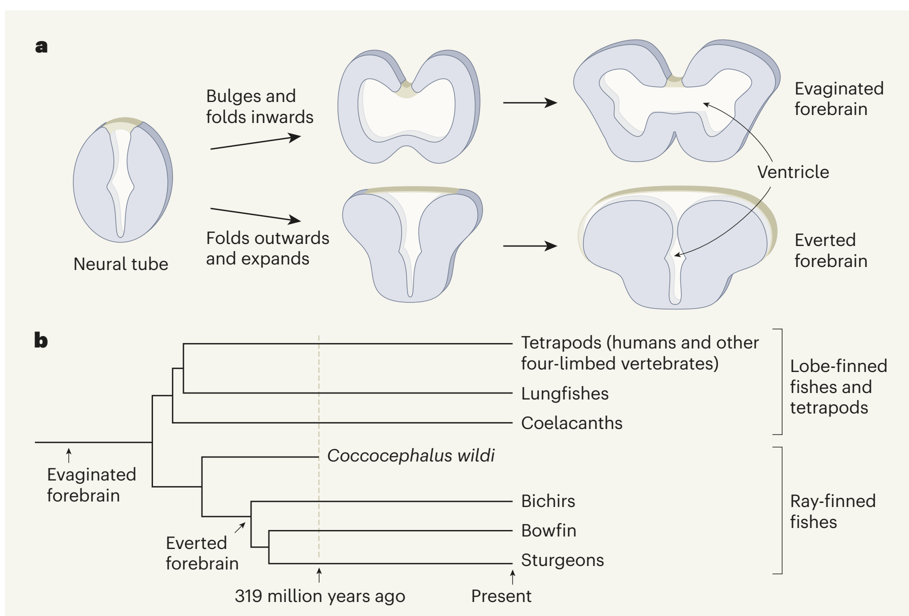

Figure 1 | Brain evolution. a, The vertebrate forebrain forms from the neural tube in the embryo. An evaginated forebrain, such as that of humans, consists of two cerebral hemispheres that enclose a hollow space called a ventricle. An everted forebrain consists of solid cerebral hemispheres that are separated by a narrow ventricle. **b**, Figueroa *et al.*[1] discovered brain tissue in a 319-million-year-old fossil specimen of the extinct ray-finned fish *Coccocephalus wildi*. The specimen has an evaginated forebrain. This is the oldest known vertebrate brain, and its forebrain anatomy contrasts with that of living ray-finned fishes, which have an everted forebrain. The finding offers a revised view of brain evolution for bony fishes (lobe-finned and ray-finned fishes).