Global Positioning System (GPS) data combined with a tiltmeter record of deformation on the only rock outcropping among the glaciers that cover the volcano. Radar measurements and photographs were also used to constrain the height of the eruption column, which varied over the course of the eruption. Hreinsdóttir *et al.* were able to infer the changing eruption rate by making use of theory and observations that show that eruption rate scales with column height[9]. The estimated eruption rate and the GPS measurements of deformation correlate remarkably well. The GPS data not only record the overall decline of the eruption, but also track shorter-term fluctuations in eruption rate in fine detail.

The constant proportionality between the eruption rate and GPS measurements, and hence essentially constant compressibility, has important implications. Firstly, it argues against significant changes in the volcanic plumbing system during the eruption. Secondly, it indicates that any additional bubble formation must have been modest. Decreasing magma chamber pressure causes volatile species (principally water) to separate from the melt, enlarging bubbles. It has also been postulated that crystallization could accelerate the escape of volatiles[2]. Finally, the data suggest that there was little or no influx of new magma into the chamber during the eruption because this would have resulted in relatively more erupted material and less deformation. Any of these processes would make forecasting more difficult, so the relative simplicity of the behaviour at Grímsvötn in 2011 is encouraging.

By combining deformation and eruption flux measurements with physics-based models of eruptions, important properties of volcanic systems, including magma chamber volume and compressibility, can be constrained[10]. Such an approach could potentially be extended to forecast the future eruptive behaviour of a volcano[7]. Whether such forecasts prove useful will depend on the accuracy of our conceptual and mathematical models. However, if we are to transition from empirical forecasting to approaches based on physical–chemical models of magmatic systems, it will be vital to combine deformation data with eruption-rate measurements of the sort recorded at Grímsvötn Volcano.

Hreinsdóttir and colleagues[1] demonstrate that ground deformation preceded the May 2011 eruption of Grímsvötn Volcano, Iceland — and, during the eruption, was correlated with observations of volcanic plume height. The study shows that near-real-time ground deformation data can be used to provide timely warnings of imminent eruptions and, coupled with eruption-rate data, can potentially be used to forecast future eruptive behaviour. Such information could be vital for aviation safety. ❒

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EARLY EARTH

Closing the gap

The age of the oldest Jack Hills zircons — Earth's oldest minerals — is contentious. Atomic-scale mapping of the distribution of radiogenic isotopes within a Jack Hills zircon confirms that the oldest known continental crust formed just after the Earth–Moon system.

Samuel Bowring

Our understanding of Earth's early evolutionary timeline is mostly inferred from geochemical data from meteorites and the oldest preserved crust. The first megascopic objects in the Solar System formed about 4.567 billion years ago[1]. However, the Earth–Moon system — probably created during a giant impact — is far younger, and dates back to between about 4.5 and 4.4 billion years ago[2,3]. The oldest preserved crust was previously thought to have formed around 3.8 billion years ago, 600 million years after the Earth–Moon system formed[4], but over the past few decades older remnants of crust have been identified, both in outcrop and as grains of the mineral zircon[5–8]. However, the accuracy of the oldest zircon dates has been called into question[4,9–11]. Writing in *Nature Geoscience*, Valley *et al.*[12] use high-spatial-resolution analytical methods to confirm the antiquity of the oldest known remnant of Earth's continental crust, a single grain of zircon, at 4.374 ± 0.006 billion years — closing the gap in time between the Moon-forming impact and the creation of Earth's first continental crust.

During the Hadean eon — between Earth's formation and 4 billion years ago — the Earth differentiated into a core, mantle and crust. The planet was also resurfaced by bombardment of planetesimals and asteroids, as well as some form of plate tectonics. As a result, few rocks of Hadean age remain. Every scrap of material older than 4 billion years is therefore of great interest, whether it is the oldest rock dated by zircon, the 4.03-billion-year-old Acasta Gneiss[7], or grains of zircon eroded from older crust that is no longer exposed.
In the Jack Hills of Western Australia, a sandstone contains abundant grains older than 4.0 billion years[5,6], and analysis of more than 100,000 grains has yielded two

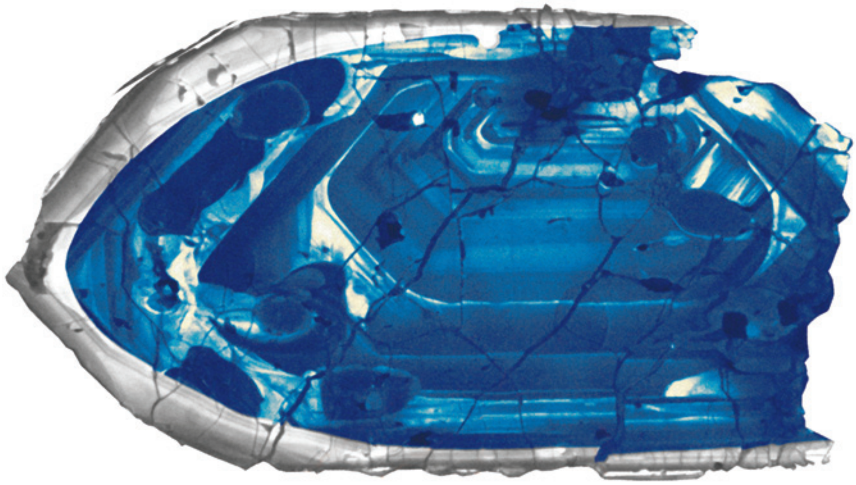

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Figure 1 | Jack Hills zircon. A zircon from the Jack Hills in Western Australia was claimed to be 4.4 billion years old[13], but the age has proven contentious and is thought to reflect post-crystallization modification. Valley *et al.*[12] use atom-probe tomography to map the distribution of radiogenic lead isotopes at a nanometre scale. They show that although the lead isotopes can be mobile and form discrete clusters within the mineral grain, the heterogeneity occurs on such a small scale that it will not affect current dating techniques. The analyses confirm that the oldest known zircon on Earth 4.374 ± 0.006 billion years old. The grain is probably less than 100 million years younger than the Earth–Moon system and is likely to be a remnant of the oldest continental crust.

that are older than 4.35 billion years[6]. These grains are thought to be derived from continental crust, some of which could be more than 4.37 billion years old. The Nuvvuagittuq greenstone belt rocks in Hudson Bay, Canada, are inferred to be up to 4.4 billion years old, based on isotopic analyses[8]. It is no surprise that zircon is the oldest known mineral on Earth, as it is highly resistant to modification and can survive multiple cycles of weathering, transport and re-deposition, and so provides one of the most reliable ways to date crustal rocks.

Zircons are typically dated using the uranium-lead (U-Pb) radio-isotopic method. Isotopes of uranium decay to isotopes of lead over time, so the age of a grain is calculated by measuring the amounts of the parent uranium isotopes compared to the daughter lead isotopes. However, the age is robust only if the system was closed, that is, if no uranium or lead was added to or escaped from the grain. Although zircons are largely resistant to modification, the decay of uranium isotopes to lead isotopes within the zircon crystal emits alpha particles that distort the crystal lattice. As a result, some of the radiogenic isotopes may move around within the grain, diffusing along small defects in the crystal structure[13]. Since only a small part of the grain is used in a single analysis to measure the amounts of uranium and lead isotopes, the radioisotope mobility could lead to the calculation of erroneously old ages. The age of the oldest Jack Hills zircons, originally posited as 4.4 billion years[13], have therefore been controversial since their discovery[4,9–11]. Whether a grain is 4.3 or 4.4 billion years old, and whether this reflects a primary age, is not a trivial matter — in the context of the 4.4–4.5-billion-year age of the Earth, a difference in age of 0.1 or 0.2 billion years is enormous in terms of modelling the geochemical evolution of Earth and the formation and recycling of the first continental crust.

Valley *et al.*[12] address this issue by using atom-probe tomography to map the distribution of lead isotopes within the oldest known terrestrial zircon from Jack Hills (Fig. 1), with unprecedented nanometre-spatial resolution. They find that the radiogenic lead atoms form regularly spaced clusters that accumulate in isolated damaged zones in the crystal just a few nanometres in diameter. So although the radiogenic lead had been mobilized, the redistribution occurred over very small length scales. Such heterogeneity will be averaged out during a typical ion microprobe measurement that analyses a grain volume of about 20 micrometres diameter by 1–5 micometres depth. This study provides a more accurate and precise estimate of the age of one of the oldest Jacks Hills zircons at 4.374 ± 0.006 billion years.

The results show that single grains of ancient zircon can yield a rich history, the implications of which date back to the very earliest history of our planet. Our understanding of the Earth–Moon system continues to evolve. Over the past decade, estimates for the age of the Moon have been lowered, and ages for the oldest continental crust have increased. These ages can be used to inform models for the origin of the Earth and Moon, the timescales of their internal differentiation, and their thermal and chemical evolution. For example, the Jack Hills zircons were probably derived from typical continental granitic crust, formed from a hydrated mantle that interacted with some primordial crust at relatively cool surface temperatures[13,14]. Thus, the gap in time between Earth's formation and the initiation of processes that produce more evolved rock types, such as granites and typical continental crust, rather than a primordial crust, is now firmly fixed at 100 million years or less.

Valley and colleagues[12] close the time gap between the formation of the Earth–Moon system and the generation of Earth's first continental crust at about 100 million years, by mapping the distribution of radiogenic isotopes within a single zircon grain with unprecedented precision. Although incredibly laborious, their analytical technique can be applied to not only additional terrestrial zircons but also to zircons from meteorites and lunar samples, to perhaps tease out a detailed thermal history of magmatism and impacts[14,15]. ❐

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