reported for different physical systems, what is lacking is a way of storing and releasing at some later time a true single photon, including its shape and structure [5–7]. Constructing this basic element of quantum memory has been a major challenge.

A group at the Key Laboratory of Quantum Information, Chinese Academy of Science, at the University of Science and Technology of China finally resolved this problem [8]. They reported on the first experimental realization of a true single-photon-carrying OAM stored via electromagnetically induced transparency (EIT) in a cold atomic ensemble (Fig. 2). With such a suitable candidate, this work indicates a means of constructing high-dimensional quantum memory. After this, similar results were reported by Laurat's group at Laboratoire Kastler Brossel, at Université Pierre et Marie Curie in France [9], where an extremely weak laser at single-photon level carrying OAM was also stored via EIT in a cold atomic ensemble. Ding *et al.* [8] first prepared two cold $^{85}$Rb atomic clouds in two magnetic-optical traps (MOT) using laser cooling and trapping techniques. They generated non-classical correlated photon pairs using spontaneous four-wave mixing in an atomic cloud. One photon of each pair was used as a trigger; the other mapped and stored in a second atomic cloud via EIT. Each photon to be stored carried one OAM unit. After a programed storage time, the photon was retrieved. What they achieved during storage included (1) proof that the non-classical correlation between the trigger photon and the retrieved photon is retained by demonstrating a strong violation of the Cauchy–Schwarz inequality, (2) a demonstration that the single-photon property of the signal photon is maintained by performing the Hanbury–Brown and Twiss experiment on the trigger photon, (3) proof that the spatial structure of the photon is also very well preserved by showing a high similarity between input and output, and (4) evidence, gathered by Sagnac interferometry, that the coherence of a single photon is also preserved.

This is a significant breakthrough towards the realization of a quantum internet and, potentially, quantum computing. This work addresses the ability to generate, store, retrieve on demand an arbitrary single-photon-level photonic state encoded in OAM space. It signifies an important step in the development of practical quantum-enabled technologies, opens up the possibility for realizing high-dimensional quantum memories based on this degree of freedom of light, and will have a large impact in a broad physical community, especially in the quantum information and quantum optics communities. The *Technology Review* website of MIT comments on their work very positively with an article entitled 'First Quantum Memory That Records the Shape of a Single Photon Unveiled in China'. Further, *Nature Photonics* selected this work as a research highlight.

Clearly, memory that can preserve the spatial structure of photons will make the internet far more flexible and capable. Of course, there are still many basic problems remaining that need to be solved to build the future quantum internet, one of which is the construction of quantum memory exploiting entanglement. This derives from the fact that a quantum network needs the distribution of quantum-entangled photons over channels between different nodes [10]. A high-dimensional quantum internet needs to store OAM-entangled states and perform entanglement swapping to efficiently extend the achievable communication distances. While Ding *et al.* [8] reported the storage of light with OAM at the single-photon level, the photon was, however, still encoded in a 2D space. Therefore, whether it is possible to construct a high-dimensional quantum memory remains an open issue that needs to be investigated further.

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GEOSCIENCES

# Defining the discipline of geobiology

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One of the fundamental questions in science, but also for any intelligent person, is 'What is the difference between life and non-life?' Philosophers have debated this for centuries, and alchemists and novelists have explored remarkable ways to create life. As Mary Shelley wrote in her masterpiece 'Frankenstein', 'Life and death appeared to me ideal bounds, which I should first break through, and pour a torrent of light into our dark world' [1].

These aspects of life and the physical Earth did not concern delegates at the recent Third International Conference of Geobiology, held at China University of Geosciences at Wuhan from 16 to 18 June 2014 (www.geobiology.net.cn). There, 350 delegates met to explore a diverse range of topics—geology, geography, ecology, biology, environmental sciences, chemistry, astronomy, physics. Key themes included the origin of life on Earth, stages in the evolution of Earth's atmosphere, growing complexity of life, earth–life interaction, mass extinctions and recoveries, life on other planets, extremes of life, and microbial impacts today and in the past.

## WHAT IS GEOBIOLOGY?

Geophysics and geochemistry are well-established disciplines, some featuring in the names of academic departments, in the titles of degrees, and of numerous journals and textbooks. Geobiology is newer.

Geobiology was defined as 'an interdisciplinary study of life sciences and earth sciences' by Yin Hongfu and colleagues, in their 2008 review [2]. This was elaborated by the same authors more recently [3], who say that 'Geobiology aims to study the interaction and coevolution between life and Earth environments, or between the biosphere and the geosphere, focusing not only on the environmental effects on organisms but also on the biotic impacts on the ambient environments'.

## ORIGIN AND EARLY EVOLUTION OF LIFE

The origin of life is hard to study because the transition to life did not instantly alter the Earth. Atmospheres continued largely anoxic, and current levels of oxygen were achieved only over the span of the Precambrian and in several steps. Phylogenomic and protein engineering approaches were presented by José Sanchez-Ruiz and Joanne Hobbs, who showed how individual proteins in modern microbes can be engineered backwards to produce their Precambrian precursors: a common finding of such studies is that these earliest protein variants were generally adapted to high temperatures [4]. This chimes with phylogenetic evidence that the most basal microbes were thermophiles, and has been taken as evidence that life originated in hot, perhaps chemically concentrated settings.

The subsequent mid-Proterozoic, from 1.8 to 0.8 Myr ago, was termed the 'boring billion' by Timothy Lyons and colleagues at the meeting, because this was a time of remarkable stability in the carbon cycle [5].

In a 'Workshop on Ediacaran and Cryogenian Stratigraphy', 30 speakers addressed issues concerning life and earth processes from a span of 850–540 Myr ago, immediately preceding the Cambrian explosion. The Cryogenian was the time of Snowball Earth, several major glaciation events when the Earth was entirely enveloped in ice, according to many, or icy slush, according to others.

The succeeding Ediacaran is most notable for the extraordinary organisms found first in Australia, and subsequently worldwide. Most researchers identify the Ediacaran organisms, a mix of frond-like, circular, and worm-like structures as early animals, probably unrelated to modern groups, living in marine sediments. At the meeting, Greg Retallack championed his heterodox view [6] that the Ediacaran organisms are in fact lichens and the sediments not shallow marine, but terrestrial palaeosols. Indeed, at the meeting Retallack presented further evidence that other Precambrian fossil sites were palaeosols; his presentations led to some lively debates, and highlight the difficulty of identifying such ancient organisms.

The remarkably preserved Doushantuo fossils are equally controversial. Early reports described microfossils interpreted as embryos of animals [7], a view supported by Yin Zongjun and colleagues at the meeting, arguing that a new fossil represents a sponge-grade organism and another has features resembling an acoelomorph flatworm. Other Doushantuo fossils have, alternatively, been interpreted as encysting protists [8], a view reinforced by Yin Chongyu and colleagues at the meeting.

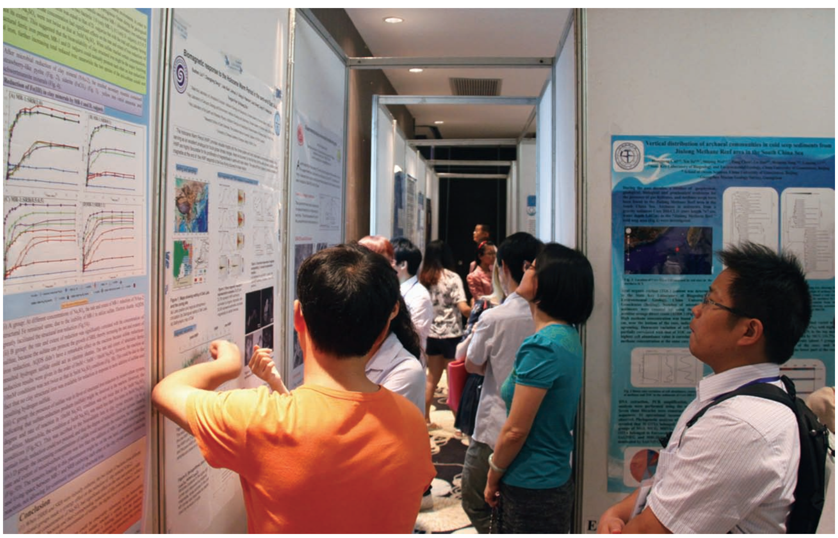

**Figure 1.** Students discuss their posters on microbial activity, ancient and modern. (*Courtesy of Jun Hu, China University of Geosciences*)

## EARTH CHANGES

There have been many mass extinctions, the most extreme at the end of the Permian, 252 Myr ago. Massive volcanic eruptions led to perturbations of land, atmosphere and oceans, and the loss of perhaps 95% of species. Numerous papers addressed aspects of the environmental crisis, its source, dating, and impact on life. Unusual microbial facies marked early phases of the recovery, and there were several sharp episodes of global warming in the Early Triassic that continued to perturb life and its recovery [9].

In studies of life through deep time, biomarkers, sometimes called 'chemical fossils', are key fingerprints used to

**Figure 2.** Line-up of the award winners for the best talks by young scientists (left-hand row), awarded by more senior scientist (right-hand row), and applauded by Professor Yin Hongfu (far left), the inspiration behind the international geobiology programme. (*Courtesy of Xiaohui Zhang, China University of Geosciences*)

identify ancient organisms and their associated environmental conditions. In particular, microbes in ancient times are hard to preserve in rocks or difficult to identify by morphological investigations, so biomarkers diagnostic of a microbial taxon (e.g. cyanobacteria), a microbial functional group (e.g. sulphate-reducing bacteria, methanotrophs) or even a domain (e.g. bacteria, Archaea) can be critical records.

At the meeting, microbial tetraethers, together with the deuterium content in lipid biomarkers derived from higher plants, were presented as important proxies of past climatic and environmental changes, with a focus on limnoterrestrial and marine sediments. Some also document significant biogeochemical processes in the deep biosphere and extreme environments. Kai-Uwe Hinrichs presented a direct, extraction-free stratigraphic analysis of tetraether lipids in nanogram-scale core samples, which will enable the establishment of high-resolution molecular stratigraphy.

## EXTREMOPHILES AND ASTROBIOLOGY

Organisms, particularly microbes termed 'extremophiles' ('extreme-lovers'), can live in punishing situations, such as at depths of over 1 km in the crust, in the boiling water of geysers and, as Alison Murray described at the meeting, in the supersaturated icy brines of Lake Vida, covered with 20 m of ice [10]. Other authors reviewed numerous attempts to detect life on other planets, and how this field (astrobiology, exobiology) depends on understanding of Earth-bound extremophiles.

From Mars to the deep ocean, and from the origin of the Universe to the present day, geobiology encompasses a wide range of current themes in modern earth and environmental sciences.

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