

## Biogeology

## How old are bacteria from the Permian age?

**D**iscovery of bacteria that remain viable in a dormant state for lengthy periods is significant for understanding patterns of microbial diversity and evolution on Earth, as well as for assessing the possibility of life's interplanetary transport by impact processes. The isolation by Vreeland *et al.*<sup>1</sup> of viable 250-million-year-old bacteria is an extraordinary claim, based on meticulous extraction from evaporite deposits of the Delaware Basin. If valid, this discovery expands dramatically the maximum proposed age for microbial survivability. Here we argue that, although the Permian age of these well-documented deposits is not in question, the fluid inclusions and the viable bacterial spores contained in them may represent much more recent features. The age of these microbes must therefore remain uncertain.

Vreeland *et al.* describe commonly accepted primary evaporite textures and structures — fine-scale fluid inclusions and bedded halite, for example — that are suggestive of the original depositional environment. But these observations are not pertinent to the question at hand because bacterial samples were not obtained from halite displaying such primary features. Instead, bacterial spores were extracted from dissolution pipes of “coarse, clear halite with fewer, but larger, fluid inclusions”. The authors claim that these dissolution pipes are contemporaneous with primary halite, because the coarser crystal pipes “are overlaid by undisturbed (presumably primary) halite beds”: however, this observation is not sufficient to establish the age of the fluid inclusions.

The large, clear, single-crystal nature of the halite selected is not typical of primary halite deposition. Such coarse halite is more commonly associated with processes that occur after — sometimes long after — initial deposition. For example, evaporites of the Delaware Basin have large crystal-lined cavities, which almost certainly formed in a quiet, post-depositional subsurface environment<sup>2</sup>. Coarse halite with fluid inclusions may also form by the dissolution and recrystallization of primary halite. Such recrystallization can occur repeatedly in a salt body through interaction with new pulses of fluid, including bacteria-bearing groundwater from above or below.

Almost all bedded salt contains at least some healed fractures, not always readily visible even by optical microscopy, along which fluids have moved<sup>3</sup>. These moving fluids may produce pipe-like masses that crosscut many beds — features similar to the those described by Vreeland *et al.* —

and such dissolution and reprecipitation may take place much later than the primary deposit. Superposition of undisturbed salt beds is therefore insufficient to show that the bacteria-bearing halite dissolution pipes and their fluid inclusions are contemporaneous with primary depositional features.

Compositions of fluid inclusions from Delaware Basin evaporites also suggest multiple sources and ages, calling into question the supposed age of 250 million years. Petrographic studies and chemical analysis of large (about 1 mm) fluid inclusions in clear ‘recrystallized’ salt (as sampled by Vreeland *et al.*) show these fluids to be complex bitterns, which result from multiple diagenetic processes at unknown times<sup>3</sup>. This history is evident from the absolute concentrations as well as the ratios of halogen, alkali and alkaline-earth ions<sup>4,5</sup>. These compositions vary significantly in adjacent inclusions, often separated by less than 1 mm, and are almost always far from ion ratios obtainable by simple evaporation of sea water. Furthermore, isotope studies of such fluid inclusions from the Delaware Basin suggest that mixture with both ancient and modern meteoric waters has occurred<sup>6</sup>.

We conclude that, in the absence of primary growth features in the specific halite crystals studied, the age of those crystals and their fluids must remain in doubt.

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Vreeland *et al.* reply — Hazen and Roedder touch on several geological issues raised by our limited description of the Permian Salado Formation. In our study, we sampled coarse halite in dissolution pipes for testing for viable Permian-age bacteria.

A synsedimentary age of these dissolution pipes is shown by undisturbed overlying beds and by the development of pipes downward from surfaces exposed on desiccated salt pans<sup>1,2</sup>. Desiccation cracks, dish-shaped salt and clay laminae accumulated in salt polygons or saucers, and insoluble residues all indicate subaerial exposure<sup>2</sup>. Microkarst features (smaller, but similar to dissolution pipes) have been described in cores from the Permian San Andres Formation<sup>3</sup>, and the undisturbed overlying beds were considered to be evidence of syn-

depositional age of microkarst in Permian halite beds in the Palo Duro Basin, Texas<sup>3,4</sup>.

Dissolution pipes tend to reach a common depth below an exposure surface<sup>2</sup>. In some beds, macropores (10–30 cm across) filled with coarse halite developed at about that same depth. A common water (brine) table controlled macropores and pipes<sup>2–4</sup>. Coarse halite filling the synsedimentary dissolution pipes<sup>2</sup> and microkarst<sup>4</sup> shows crystal boundary relationships consistent with passive pore-filling cement growth. Some cloudy halite from fine fluid inclusions was found in Salado dissolution pipes<sup>1</sup>.

We see no brine conduits through the Salado and know no means of maintaining less than halite saturation in such a case. Permeability decreases quickly in halite beds as halite cements occlude porosity with near-surface crystallization<sup>4,5</sup>. Based on *in situ* experiments in Salado halite, the undisturbed permeability and hydraulic conductivity are about  $10^{-22}$  m<sup>2</sup> and  $10^{-15}$  m s<sup>-1</sup>, respectively<sup>6</sup>. With a hydraulic gradient of 0.01 and a porosity of 0.01, brine would take more than 30 million years to flow one metre. Brine chemistry commonly varies over centimetres, consistent with extremely limited permeability<sup>7</sup>. These characteristics weigh heavily against water flow through the Salado to dissolve and recrystallize halite and against post-Permian natural introduction of bacteria to the halite in the pipes.

We do not assume that sea water is trapped in these fluid inclusions. For example, marine and non-marine Salado beds can be distinguished<sup>8</sup>. Similar bromine concentrations in microkarst and primary halite in the Palo Duro study suggest penecontemporaneous formation from the same brine pool<sup>5</sup>. But differing compositions may not indicate greatly different ages. Variable exposure periods, marine inflows and continental fluid sources lead to complex chemistry, and stable isotopes may resemble mixes of meteoric and evaporated waters<sup>9</sup>, unless Permian rain and sea water were very different from now. Homogeneous fluid and mineral compositions may be better evidence for massive fluid movement through the evaporites.

Salado dissolution pipes are consistent with a synsedimentary origin and Permian age. Synsedimentary dissolution pipes should be useful in diagnosing exposure surfaces within evaporites. We anticipate renewed interest in these and similar deposits as a result of our study.

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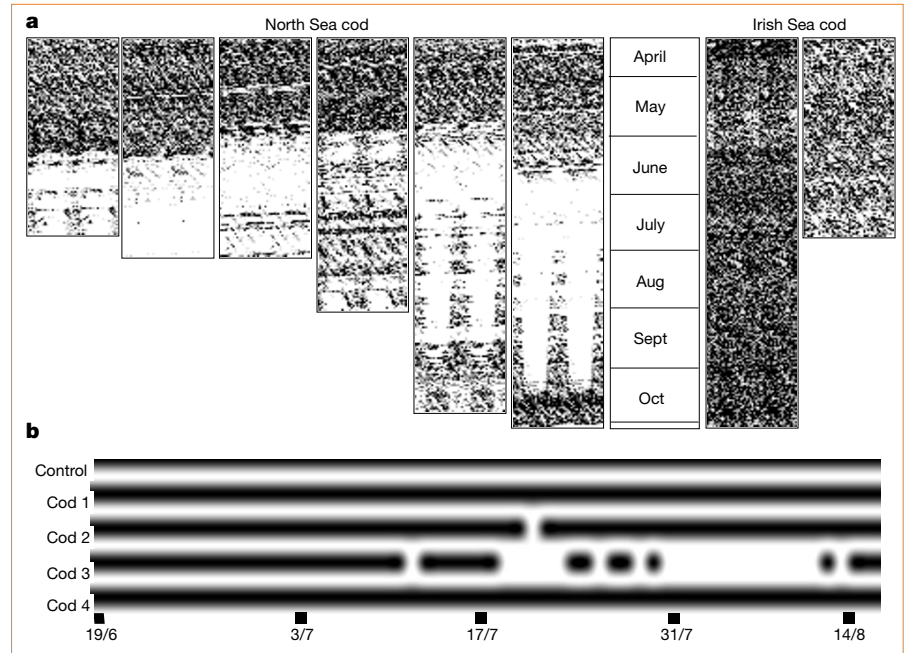
Fisheries

## Different behaviour of North and Irish Sea cod

Cod (*Gadus morhua*) are bottom-living, predatory fish of considerable commercial importance<sup>1</sup>, but surprisingly little is known of what cod do for most of their time because it is difficult and costly to study the behaviour of fish at sea<sup>2,3</sup>. Here we use electronic data-storage tags to investigate the behaviour of cod in the North Sea and in the Irish Sea and find that there are marked differences in the activity of fish in the two regions. This difference could be explained by dissimilar foraging ecology and may have implications for the future management of severely depleted cod stocks.

Evidence from acoustic<sup>4</sup> and fishing<sup>5</sup> surveys can be used to infer variations in behaviour patterns between different cod stocks, but behavioural data have never been collected simultaneously from individual fish from different stocks over timescales appropriate to fisheries management<sup>6</sup>. In March–April 1999, we tagged 78 cod (each over 50 cm long) with electronic data-storage devices: 58 were in the southern North Sea and 20 in the central Irish Sea. Twenty-two tags have so far been returned from fish caught in the North Sea, providing over 1,500 days of data, and four have been returned from the Irish Sea (over 750 days of data).

By using the depth record to estimate a cod's activity, we found that Irish Sea cod were extremely active at all times (dark regions in Fig. 1a), showing no discernible evidence of diurnal or seasonal patterns. North Sea cod were also very active during April and May, but in June all fish still at liberty (8 fish) showed a marked reduction in vertical movement, and in July they spent much or all of their time on the sea floor. Fish still free in August and September (5 fish) became active at night, and during October and November (2 fish) they returned to activity levels seen in the previous April and May (Fig. 1a). In a follow-up experiment in 2000, we monitored the position of North Sea cod implanted with



**Figure 1** Cod behaviour in the North Sea and Irish Sea. **a**, Activity between April and November 1999. Active and inactive states of each individual were determined from the depth (measured every 10 min) record of its tag (Lotek Marine Technologies LTD100). When an individual was 'inactive' on the seabed, its tag recorded only the smooth changes in pressure resulting from the rise and fall of the tide. Individuals were classed as 'active' when vertical movements were more rapid or irregular than could be accounted for by the tide alone. For each hour of the day, summed hourly activity held a value between zero (white; inactive) and six (black; most active). Each fish's activity record is shown as a double-plot actogram, with data in 48-h periods along the x-axis and days of the year along the y-axis. **b**, Residence on summer feeding grounds in the North Sea in 2000. A moored listening station continuously monitored the presence (bars) or absence (no bar) of four individuals implanted with individually coded acoustic tags. The listening station had a detection range of 500 m. The control tag was located within 200 m of the listening station for the duration of the experiment.

individually coded acoustic tags and demonstrated that their range of movement during the summer months (mid-June to mid-August) was less than 1 km (Fig. 1b).

The technology is not yet available to measure the feeding behaviour of fish directly in the field. However, our results indicate that North Sea cod reduce their foraging movements during the summer months. This observation challenges the explicit assumptions of multispecies management models<sup>7</sup> that cod are active and forage over substantial geographical areas. By contrast, Irish Sea cod appear to be active throughout the spring and summer. We propose that these differences in activity could be behavioural responses to variations in the distribution and abundance of prey species between sea basins, an idea we intend to test by using a tag equipped with a feeding sensor to investigate the feeding dynamics of free-ranging cod.

Low spawning-stock biomass, increased seawater temperatures and high fishing rates have put North Sea and Irish Sea cod stocks under great pressure<sup>8,9</sup>. Special technical conservation measures designed to provide protection for cod have been specified in recovery plans announced in 2000 for the Irish Sea<sup>10</sup> and recently for the North Sea<sup>11</sup>. A significant component of these plans involves closing particular areas of sea to fishing for short periods of time.

Our findings show that the activity of cod varies through the year, and that seasonal patterns of activity differ between stocks. To our knowledge, this is the first time that the activity patterns of cod from different stocks have been described over extended periods at such a fine temporal and spatial scale. This understanding will improve our ability to predict the effectiveness of fisheries management by closed areas in different regions.

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