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Biogeology

How old are bacteria from the Permian age?

Discovery 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.*[1] 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[2]. 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[3]. 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[3]. This history is evident from the absolute concentrations as well as the ratios of halogen, alkali and alkaline-earth ions[4,5]. 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[6].

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[1,2]. Desiccation cracks, dish-shaped salt and clay laminae accumulated in salt polygons or saucers, and insoluble residues all indicate subaerial exposure[2]. Microkarst features (smaller, but similar to dissolution pipes) have been described in cores from the Permian San Andres Formation[3], 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[3,4].

Dissolution pipes tend to reach a common depth below an exposure surface[2]. 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[2–4]. Coarse halite filling the synsedimentary dissolution pipes[2] and microkarst[4] shows crystal boundary relationships consistent with passive pore-filling cement growth. Some cloudy halite from fine fluid inclusions was found in Salado dissolution pipes[1].

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[4,5]. Based on *in situ* experiments in Salado halite, the undisturbed permeability and hydraulic conductivity are about 10^{-22} m^2 and 10^{-15} m s^{-1}, respectively[6]. 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[7]. 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[8]. Similar bromine concentrations in microkarst and primary halite in the Palo Duro study suggest penecontemporaneous formation from the same brine pool[5]. 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[9], 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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