Iron oxides from Modern to Archean – nm-scale balls... nannobacteria or not?

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Among many hundreds of SEMs of iron oxides taken over many years and from a great many localities, certain similarities stand out. When studied at 50,000x or more, they are seen to consist of small balls in the 30-150 nm range, previously identified in carbonates, clay minerals, etc. as cells of dwarf bacteria (nannobacteria). In Fe oxide samples, are these small balls also nannobacterial cells or are they just the way that IN-organic Fe oxide precipitates? A simple trick helps to answer this question: iron oxides dissolve when hit with HCl (at different rates depending upon which iron oxide mineral is involved), but organic cells will resist solution (see Folk and Carlin, 2006). In this survey from modern, living iron bacteria to rocks from Greenland over 3 billion years old, interesting similarities are revealed. Nanocells of the same size are present the whole way through. If these tiny cells are not nannobacteria, then someone needs to come up with a viable alternative.

Fig. 1 is an iron sludge from a water well in Iowa; Collector Lee Potter. Fig. 1A shows twisted ribbons resembling **Gallionella**, the strands totally covered with 25 nm balls. There are also clumps of 0.3 micron spheroids, some clearly elliptical. Fig. 1B shows a pipe-like strand, probably **Leptothrix**, covered with 50 nm balls. Many strands from disintegrating **Gallionella** stems are visible, as well as clumps of 0.2-0.3 micron spheroids. This is a real zoo of diverse objects...different "taxa" of bacteria?

Fig. 2 is an iron crust on a pebble from a spring in Arkansas; Collector Eloise Doherty. Fig. 2A shows abundant 30-50 nm balls forming chains and a nice group of 0.2-0.3 micron cells, some deformed from contact with neighbors. This is the "squashed orange" effect, indicating elasticity typical of living cells. Fig. 2B shows two distinct types, a swarm of 30 nm balls aggregating into blades, plus a colony of tiny worm-like objects (25 x 150 nm) in the top left.

Fig. 3, a stereopair, is from Kane Cave, Wyoming; Collector Annette Summers Engel. Some **Leptothrix** "pipes" are covered with small balls, others are nearly smooth. The smooth one has a group of 100 nm balls tethered by a strand to the **Leptothrix**; the cluster of balls appears to be floating free, like balloons on a string.

This raises the question: 1) does **Leptothrix** precipitate iron oxide through its own metabolism or 2) are symbiotic or parasitic nannobacteria the ones who do the actual work of precipitation?

Fig. 4. Rusted piece of iron from Port O'Connor, Texas; Collector Marjorie Thomas Folk. Acidized; remaining insoluble cells are 20-40 nm covering the surface. Several chains of nannobacteria favor an organic interpretation.

Fig. 5. Iron oxides and calcite precipitated in spring runoff, Bagno Vignone, Toscana, Italy; Collected with Dr. Brenda Kirkland. This sample is etched; Fig. 5A shows a mass of 100-150 nm balls (formerly Fe-coated?) in calcite crystals. Fig. 5B shows chains and colonies of 150-200 nm balls in calcite, and Fig. 5C shows a helical bacterium (possibly **Spirulina**) encased in calcite.

Fig. 6, 7, and 8 are from a Pleistocene travertine in Belem, New Mexico; collected with H. S. Chafetz and S. Cather. The sample is from a thick vein in the travertine filled with calcite, large prisms of aragonite (2 x 10 mm), and brown Fe oxide layers and stains. The SEM's here are from a 2 mm thick layer of calcite densely crowded with helical threads of Fe-bacteria; Fig. 6A is a stereopair of a thin section showing the light brown (probably "limonitic") threads. The remaining SEM's are from a sample lightly etched with HCl, which takes the calcite more readily than the Fe oxide. Fig. 6B is a stereo view of the threads. Fig. 6C shows straight "pipes" of probable **Leptothrix** as well as helical threads of **Gallionella** or **Spirulina**.

Fig. 7 shows successive enlargements of the bacterial threads. In Fig. 7B, a cross-section shows that the threads have a crude radial structure, but higher magnification in Fig. 7C shows a central region that is a chaotic mass of 25-40 nm balls, while in the outer part they line up into radial chains. In Fig. 7D, the exterior surface of the bacterial threads is made up of chains or blades of 25 nm balls, very similar to the chain-like features found in the Martian meteorite ALH84001. On both Mars and Earth, these are interpreted as nannobacteria (Folk and Taylor, 2002). Balls line up into chains and chains into either sheets or blades.

Fig. 8A reveals a few blades seen face-on; Fig. 8B is a stereo view. Fig. 8C, at higher magnification, clearly shows the individual 30 nm balls.

Going deeper into time, Fig. 9A shows the "Diaspro di Barga" (collected with L. S. Land and F. L. Lynch), in the Jurassic of northern Toscana and used to wonderful effect as meter-wide red and white slabs in the Medici Chapel, church of San Lorenzo in Florence. This was etched in NaOH and reveals common elliptical spheroids of 60-100 nm verging into tiny sausages -- good bacterial shapes. Fig. 9B is even older red jasper from the Devonian Caballos novaculite in trans-Pecos Texas (Folk and McBride, 1977). This was etched in HCl and 35-60 nm balls were revealed.

Now we hurtle way back into the Proterozoic Banded Iron Formations (BIF). For a century there has been controversy over the problem of iron precipitation: was it INorganic or the product of bacterial activity? But nobody previously has looked for NANNObacteria! Fig. 10A, a BIF from Minnesota, shows straight threads of Fe oxide resembling **Leptothrix**. Fig. 10B and 10C are SEMs from a hematite crystals in the center of a hematite ooid, etched 30 minutes in concentrated HCl. Elliptical spheroids of 100-250 nm are common. Fig. 10C shows several chains of beads -- nice evidence for biology.

Fig. 11 is from a BIF in Hammersley, Australia; a red quartz and hematite jasper. This was etched in concentrated HF, which partially dissolved the hematite "goo" cementing the less soluble quartz crystals. The stereo pair (Fig. 11A) shows abundant small cells coating the angular quartz grains and within the glue-like hematite. Fig. 11B shows tightly packed balls of 25-90 nm. Fig. 11C shows filaments as well as balls -- the larger 0.1-0.3 micron objects may or may not be organic. We never go out on limbs!

Fig. 12 and 13 are from the oldest known sedimentary rocks on Earth: about 3.7 billion years old from the Archean Isua series of the western coast of Greenland; sample collected by Frances Westall (Westall and Folk, 2003). If my idea is correct, this is Earth's earliest known life. The rock consists of layers of magnetite and pyroxene. The magnetite required a very strong etch to reveal its insides, getting away from any potential surface contamination. It was etched 24 hours in 10% HCl at 60°C. Fig. 12A shows a dense clump of 30-60 nm balls (some grouped into chains) as well as some larger bacteriform bodies about 0.5 micron long -- long enough to be considered as "normal" bacteria (compare similar larger bodies on the Martian meteorite, Folk and Taylor, 2002). Fig. 12B shows a discrete clump of 25-50 nm balls, contrasting with a smooth, ball-free background. Fig. 12C is a side view of a larger (0.3 micron) balls exhumed by the etching. Fig. 12D shows two bacteria copulating or dividing -- the world's oldest known example of reproduction! Fig. 13A reveals a filament 0.1 micron wide with pinch-and-swell structure, clearly organic. In Fig 13B there are insoluble threads emerging from holes in the magnetite, showing that both are co-eval and the filaments are not some later contamination. Fig. 13C is a most remarkable photo, a normal-sized bacterial cell showing (a) an empty area corresponding to the nuclear region of living bacteria, (b) cytoplasm filled up with a swarm of 50 nm balls (were they feeding on moribund bacterial cells?), (c) raised rim, probably representing the more resistant original cell wall, and (d) a remarkable surrounding halo, probably representing a polysaccharide coating on the cells. Pretty nice preservation for the world's oldest life.

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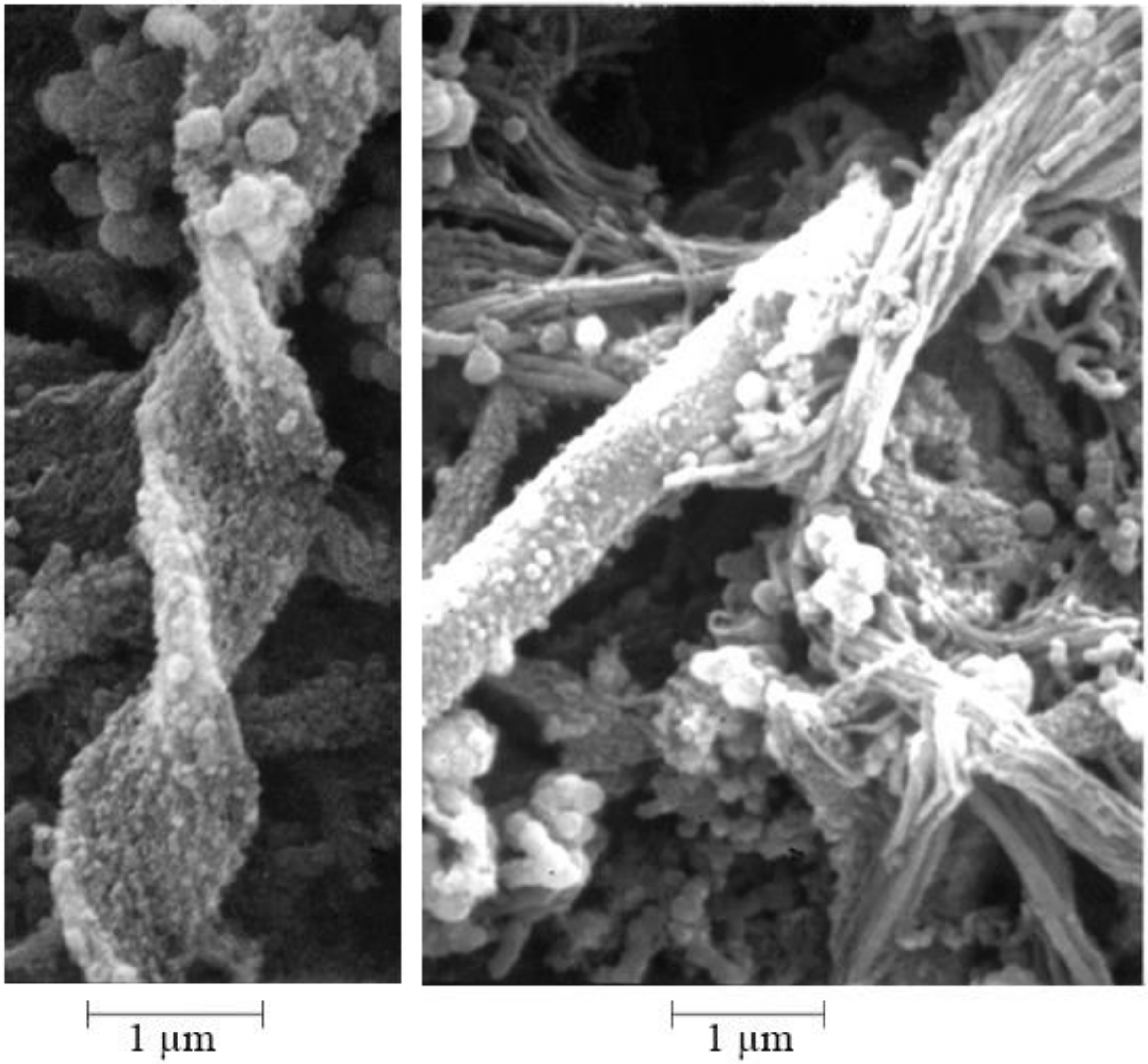
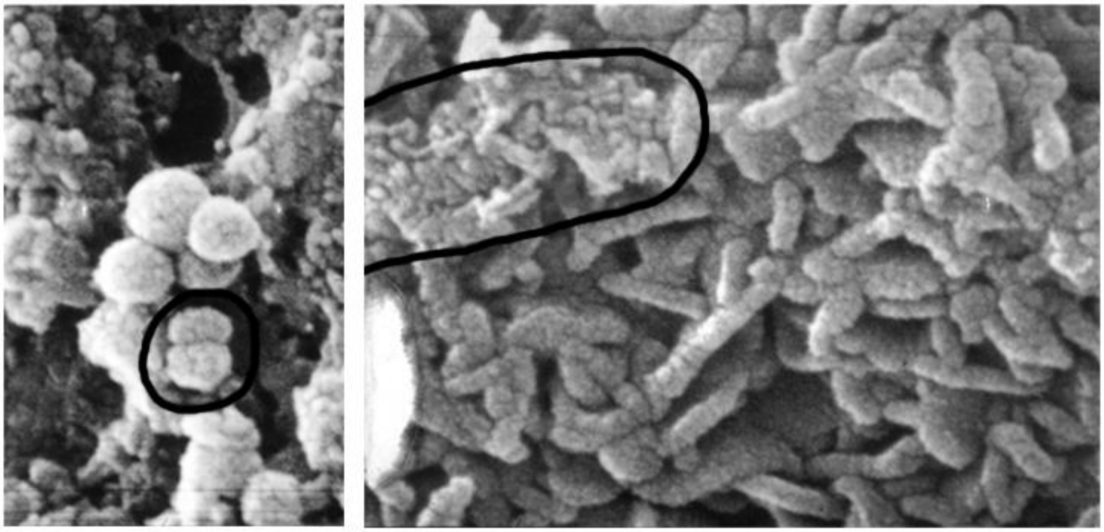
1A 1B



2A 2B



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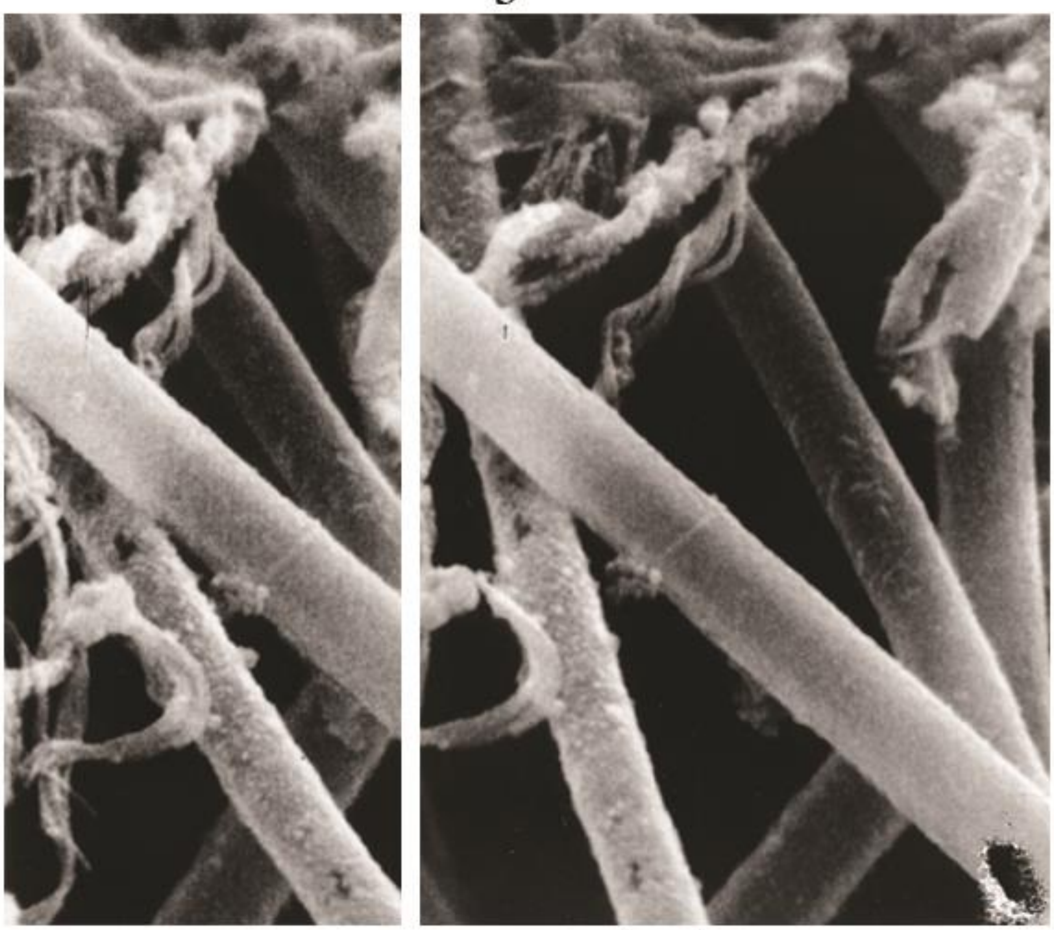
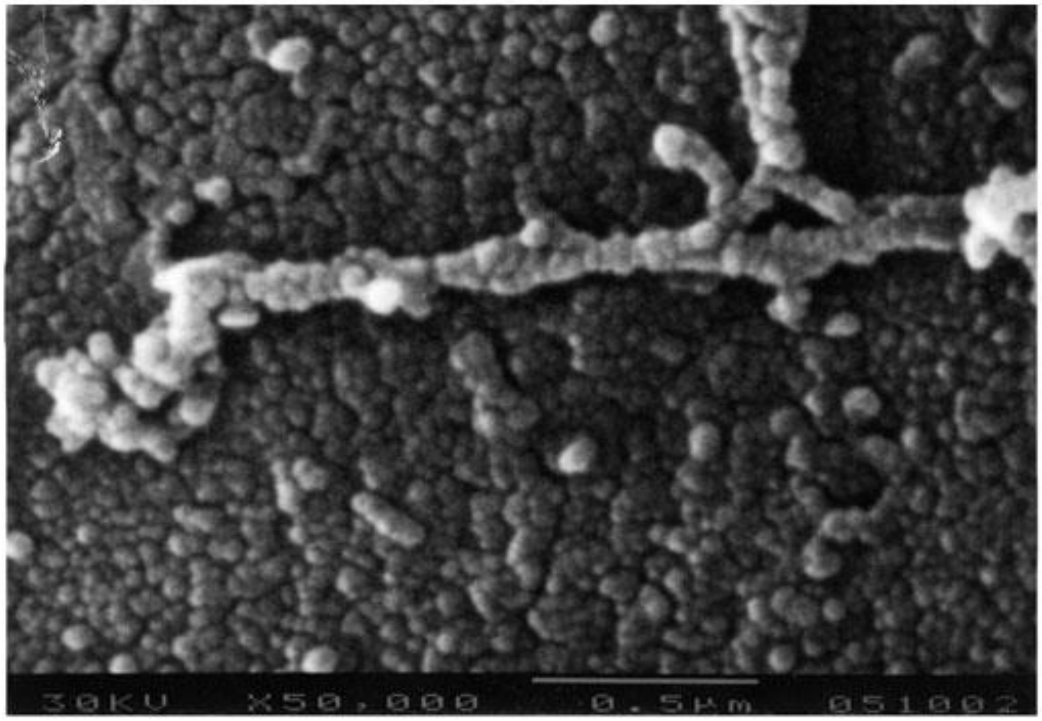
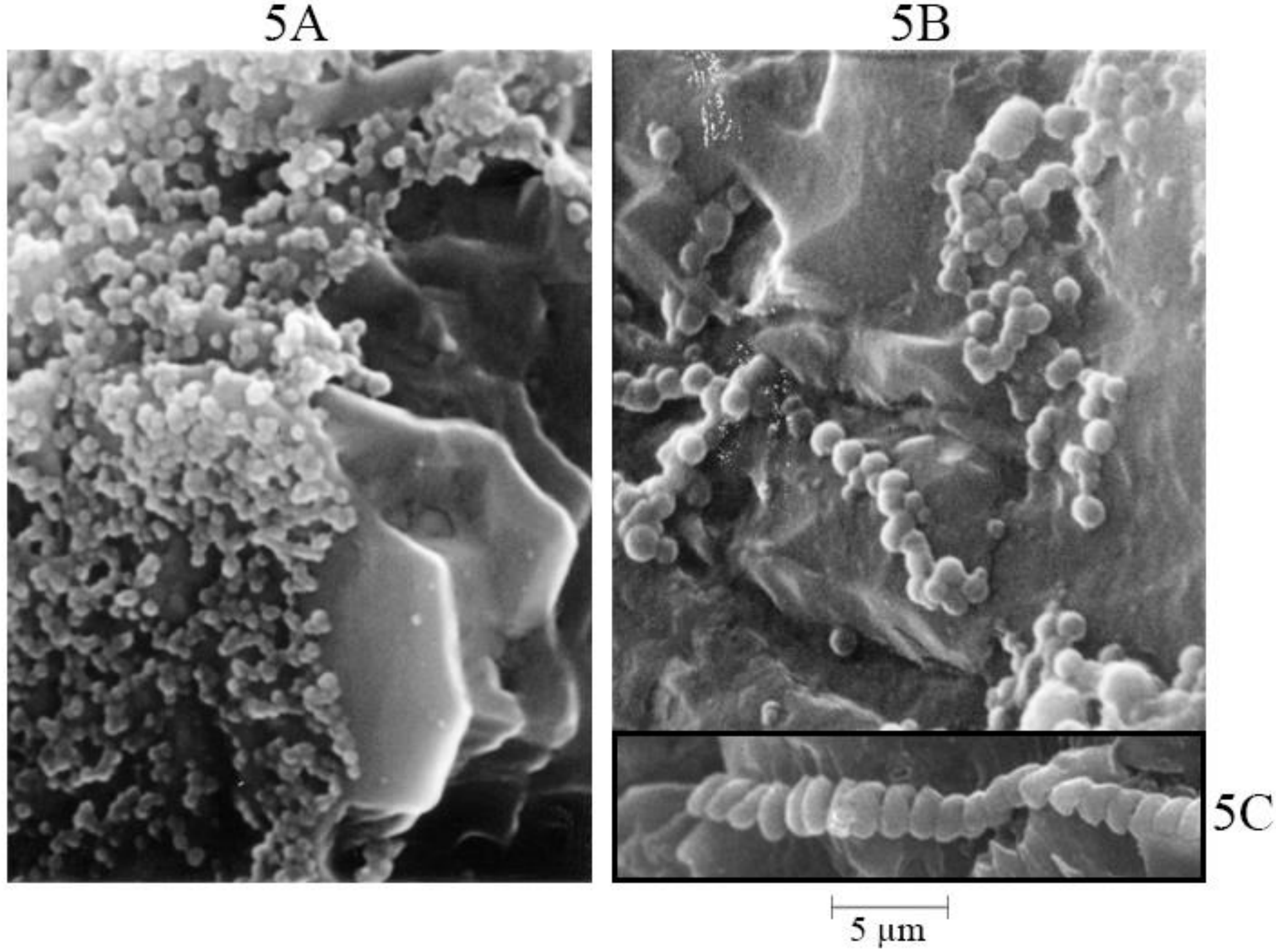
3



1 µm

4




5A
5B
5C
5 µm

6A

10 µm

6B

10 µm

6C

7A

1 µm

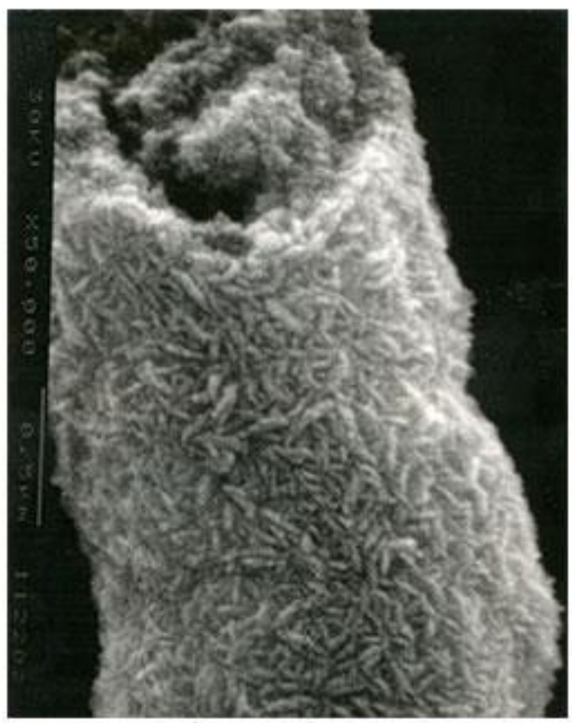
7B

1 µm

7C

0.5 µm

7D



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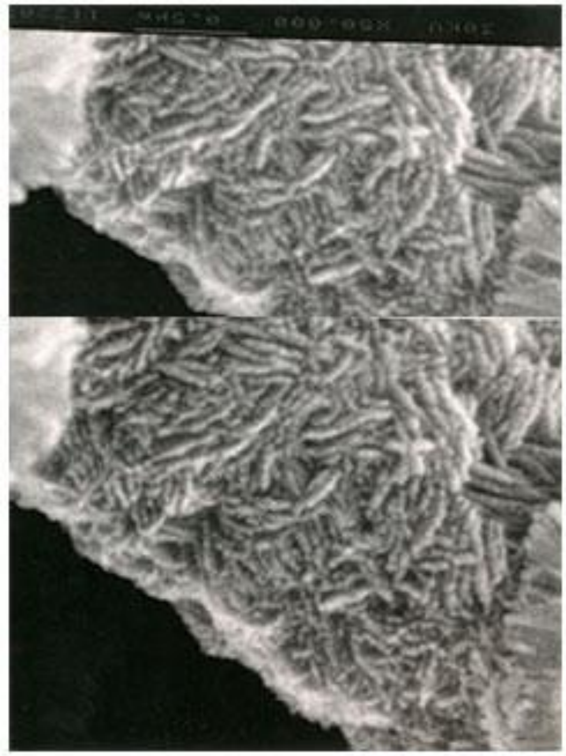
8A

0.5 µm

8B



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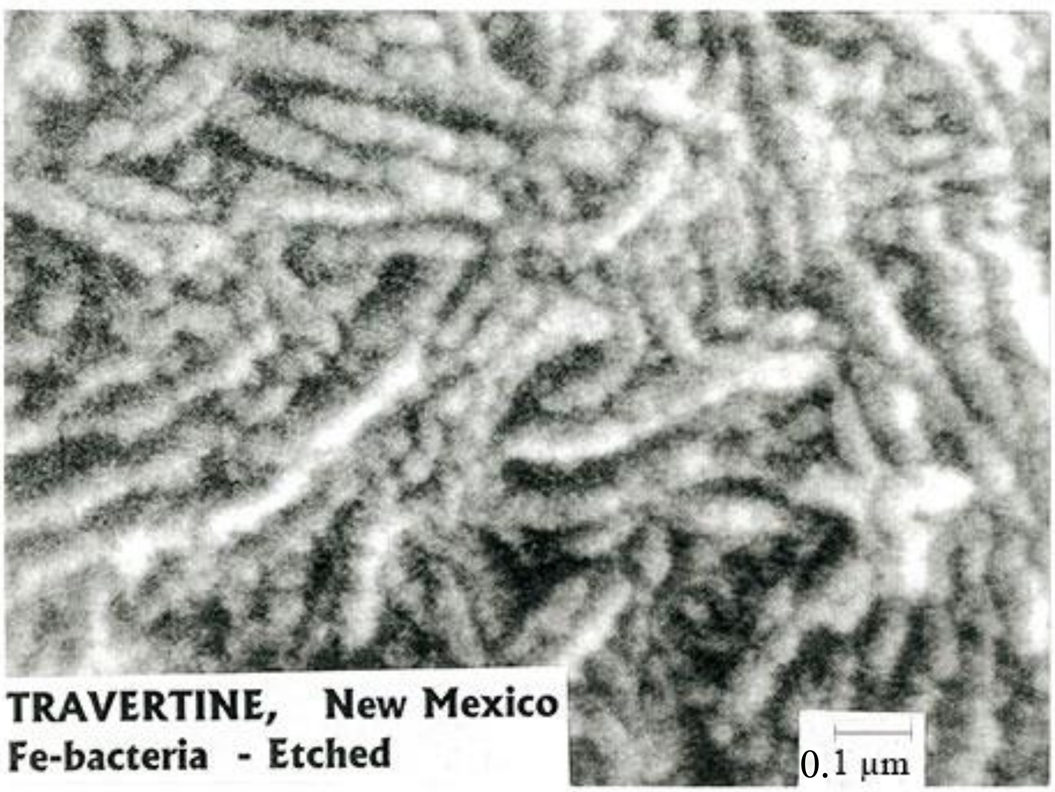
8C

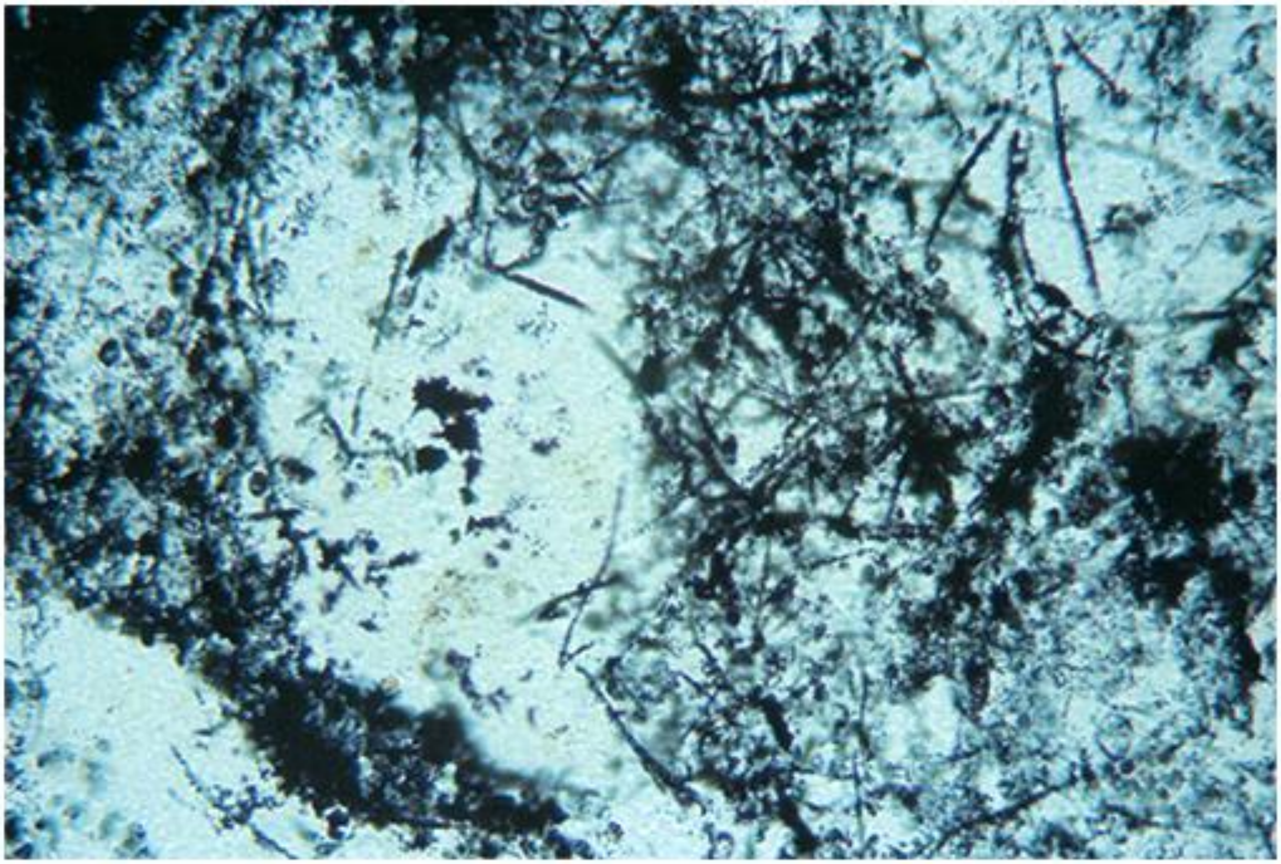


9A

0.5 µm

9B

10A



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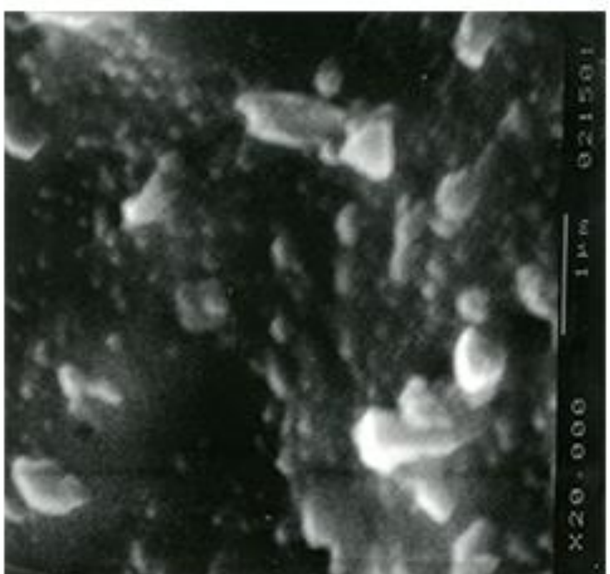

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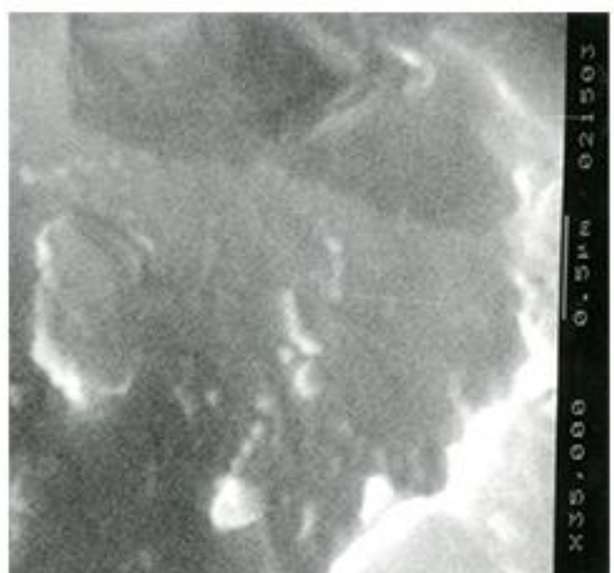

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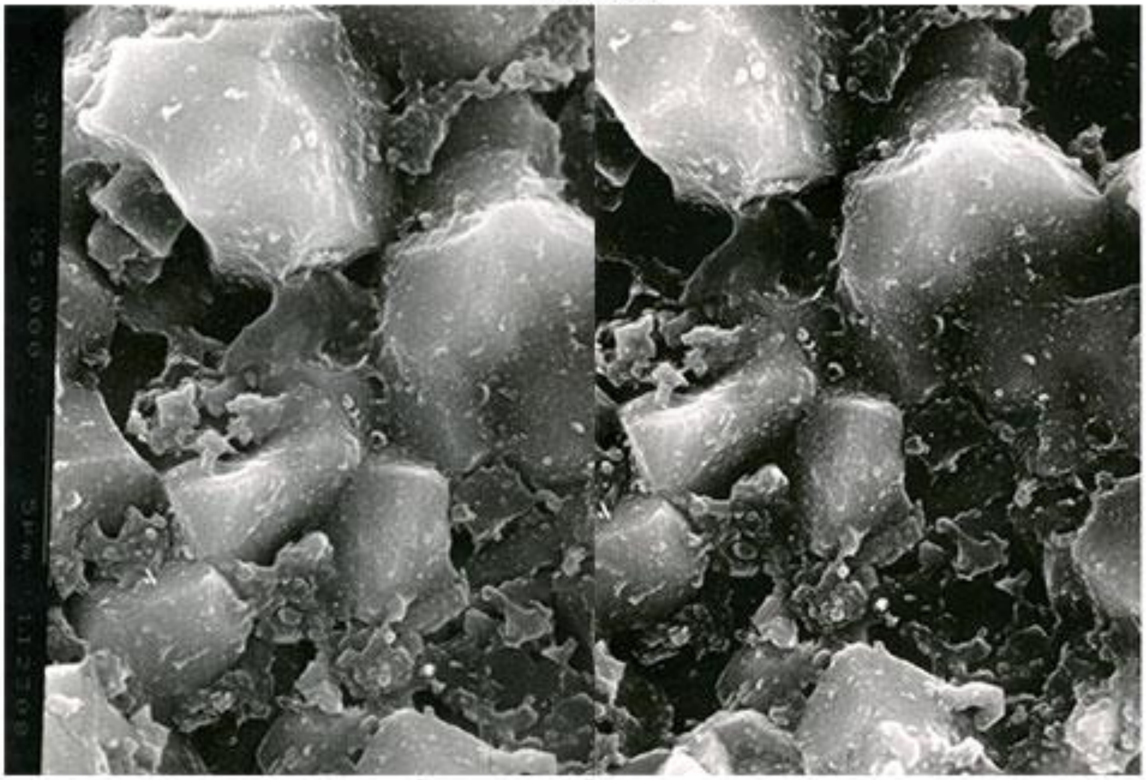
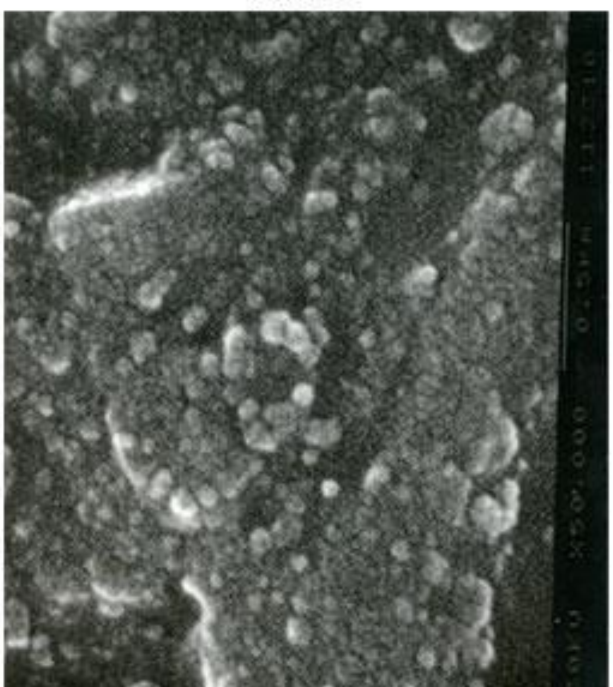


5 µm

11B



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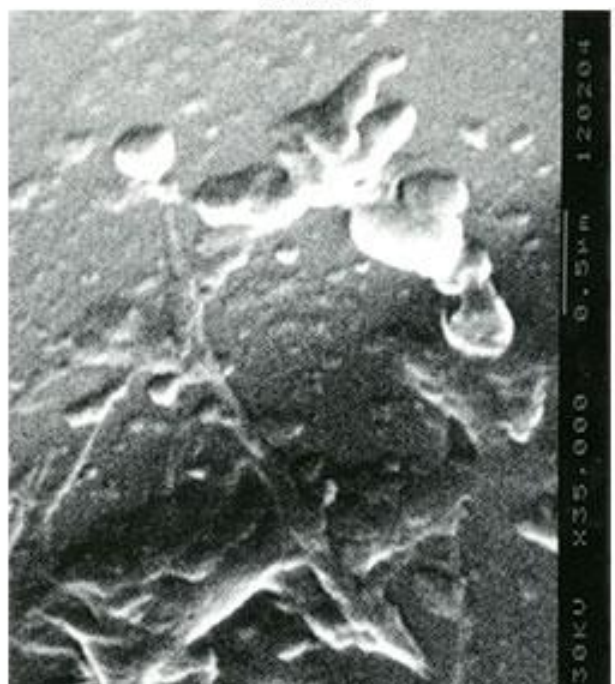
11C



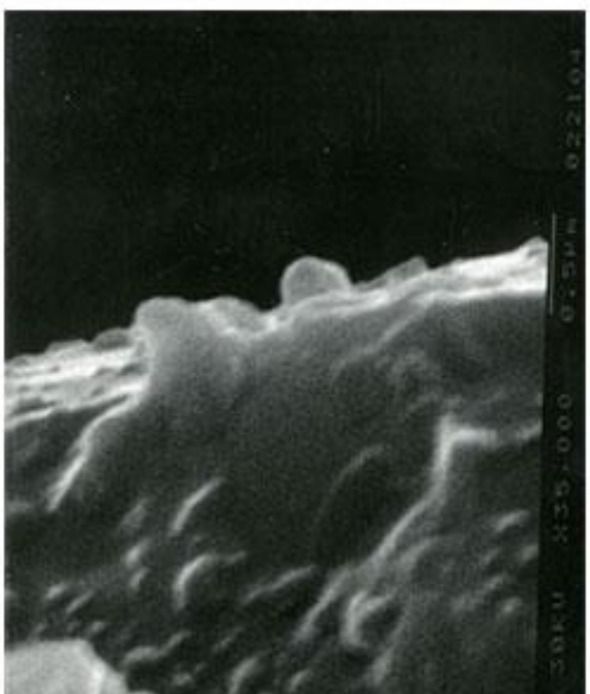
12A

0.5 µm

12B

0.1 µm

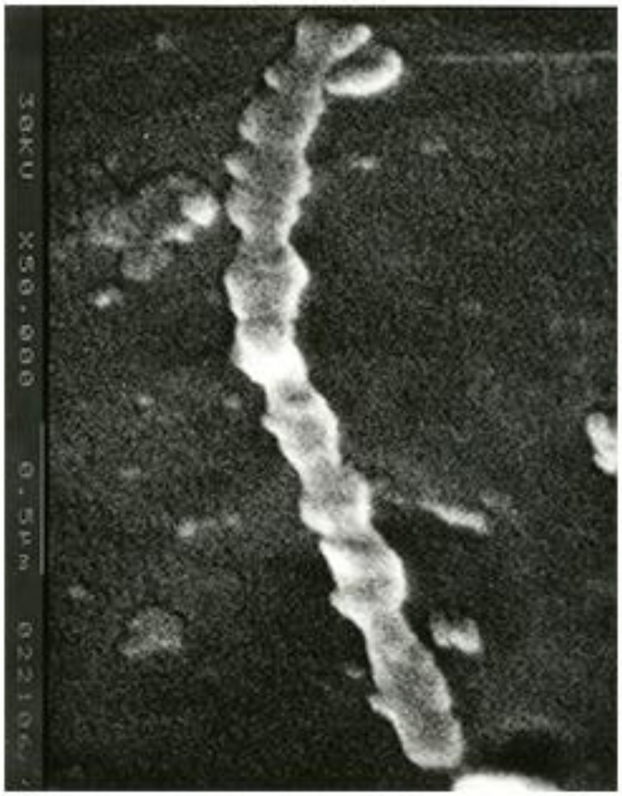
12C



0.5 µm

12D

13A



13B

13C