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3D Reconstruction of Intricate Archean Microbial Structures Using Neutron Computed Tomography and Serial Sectioning

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Abstract

Three-dimensional visualization of intricate microbial structures in rocks is essential to understand the growth of ancient microbial communities. We have imaged and reconstructed the three-dimensional morphology of 2.5-2.6 billion year old intricate microbialites preserved in carbonate using both serial sectioning and neutron computed tomography (NCT). Reconstruction techniques vary with data type and sample preservation. NCT is a non-destructive technique for imaging organic-containing samples with sufficiently high hydrogen concentrations. The resolution of reconstruction is finer than 500 microns. We reconstructed microbialites preserved as organic inclusions in calcite using NCT. Reconstructions are interpreted using volume rendering, segmentation, and an interactive Matlab/visualization environment. Visualizations demonstrate the intricacy of the structures. Noise currently limits automatic growth surface extraction, but growth of structures can be qualitatively evaluated. One of the largest obstacles to date is efficient manipulation of large data sets. Our current visualization approach always renders the supplied data set at full resolution, which requires down-sampling of datasets larger than 256pixels3 (acquired volume data consists of up to 2048 pixels3) to isolate regions of interest and extract important features. We are exploring the use of multi-resolution techniques that store a data-set at different levels of detail and chose an appropriate resolution during user-interaction. Such an approach will allow us to visualize raw data at full resolution. Serial sectioning and scanning successive horizons provides reconstructions of samples lacking sufficient hydrogen for NCT. This technique destroys the sample and has a lower resolution than NCT. However, intricate networks of microbial laminae surrounded by cement-filled voids can be characterized using this technique. After microbial surfaces are manually interpreted on slices, the images lack noise, allowing clean, but less detailed reconstructions. Serial sectioning reconstructions results in high horizontal but low vertical resolution. Therefore, visualization and surface extraction techniques on a selective subset of the data are customized to accurately reconstruct the intricate structures. Results demonstrate that the ancient structures contain vertical connected planes that have the same scale and spacing as some modern microbial structures.

Project Goals

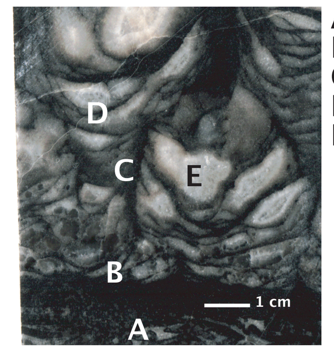
1. Evaluate destructive and nondestructive reconstruction techniques

2. Reconstruct 2.5 billion year microbial structures

3. Interpret growth mechanisms for ancient microbial communities

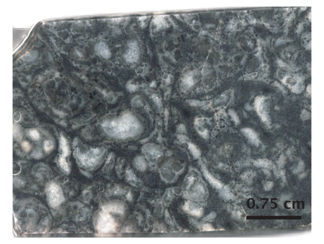
Background

Samples were collected from the 2.5 billion year old Gamohaan Formation, Transvaal Supergroup, South Africa. They contain structures created by ancient microbial communities (Sumner, 1997; 2000). The structures include fine, filmy laminae and wider, vertically oriented supports. The laminae and supports are composed of organic-rich inclusions. These structures grew in deep water (Sumner, 2000).



A. Rolled up laminae at base of microbialite
B. Small peaks of microbial laminae
C. Vertically oriented support
D. Draping laminae off support
E. Cement-filled voids between draping laminae

We focused the serial sectioning reconstruction on the microbial structure located at the base of the tall, vertically oriented supports.



In plan view, this structure is composed of a complicated network of microbial laminae. The laminae are dark colored due to organic-rich inclusions. They are surrounded by white, cement filled voids.

Methods

Neutron Computed Tomography

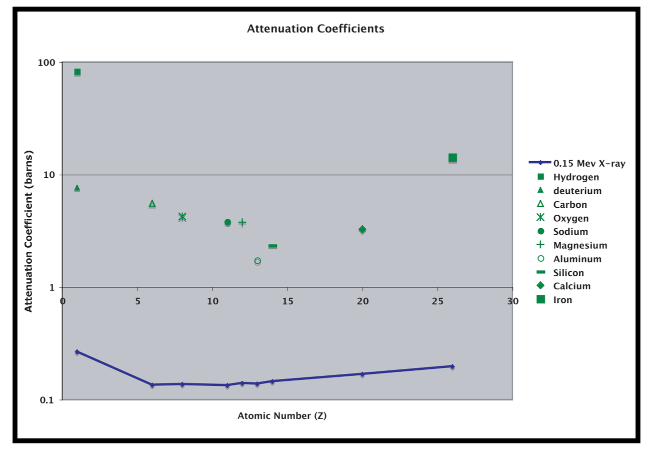
* Neutron Computed Tomography (N-CT) is a 3-D nondestructive imaging method that can be used to image geologic samples.

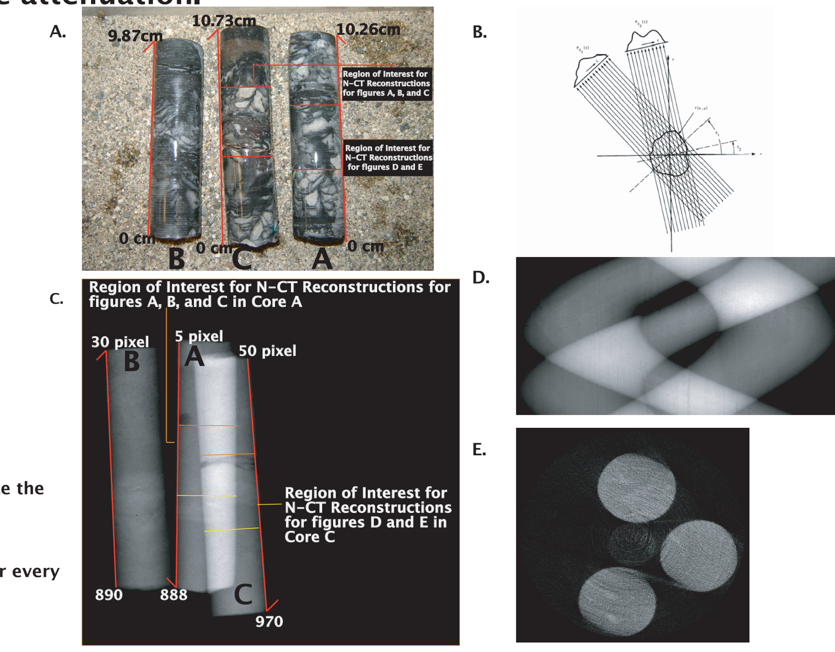
* N-CT is an attractive tool because neutrons are highly attenuated by hydrogen (organics) when compared to common mineral forming elements (i.e. calcite).

*The data-set is created by measuring the flux of neutrons transmitted through the sample, collecting an image on a CCD camera, and rotating the sample by 1 degree. This process is repeated over 180 degrees.

*The volume is reconstructed using a radon transform (Kak and Slaney, 2001).

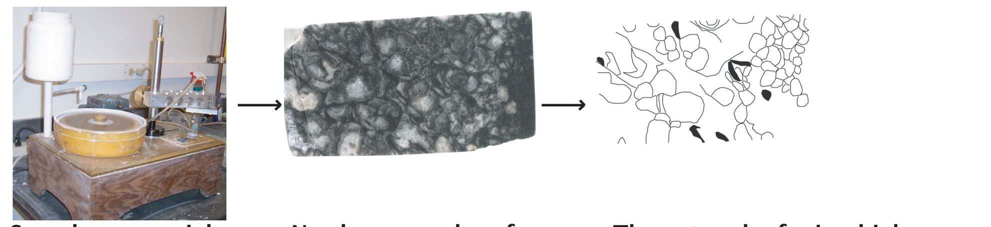
*Images show variations in transmission of neutrons by the sample. Attenuation is dominated by the interaction of nuclear energy states between neutrons and specific nuclei. The density of specific elements gives the average sample attenuation.





A. Photograph of the three rock cores used in this study. Arrows designate the up direction in each core.
B. Radiographic projection of neutrons through sample.
C. Neutron radiograph of sample cores.
D. Sinogram of radiographs which represent 1 pixel in the Y-direction for every angle (and number of radiographs) in the data-set.
E. Each sinogram is used to create a single slice which makes up the reconstructed volume.

Serial Sectioning



Sample was serial sectioned at 30 micron intervals.

Newly exposed surfaces were scanned at 1200 DPI.

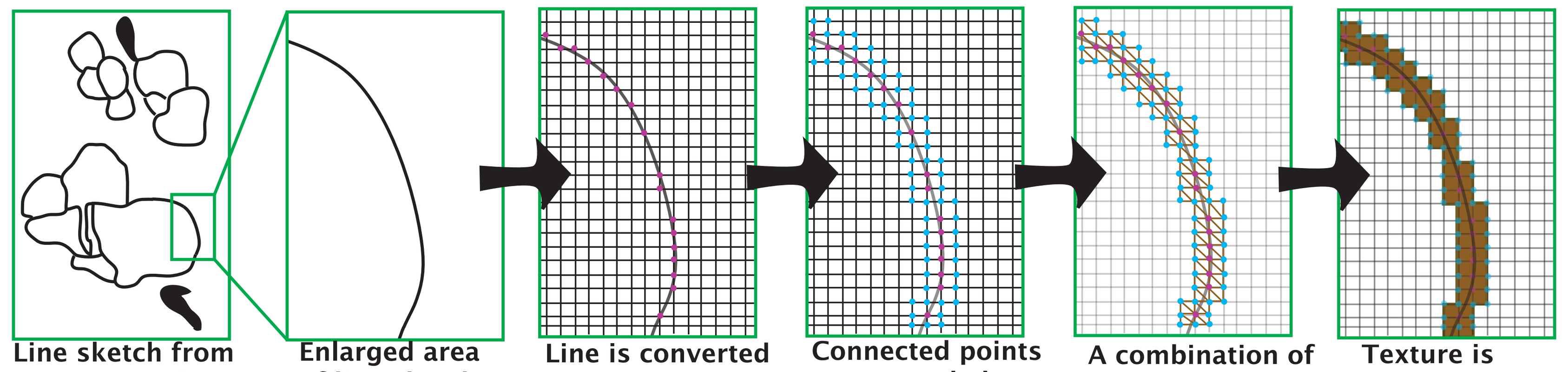
The network of microbial laminae was manually traced on each surface. The filled-in dark areas represent dense areas of organic-inclusion rich material within the network of laminae.

*Serial sectioning is a fabric destructive reconstruction technique.

*Structures must be manually interpreted on each slice.

*Images lack noise that is commonly associated with NCT.

*Reconstructions have high horizontal but low vertical resolution.



Line sketch from exposed surface on rock that highlights network of microbial laminae (black)

Enlarged area of line sketch

Line is converted to discrete set of points for each slice.

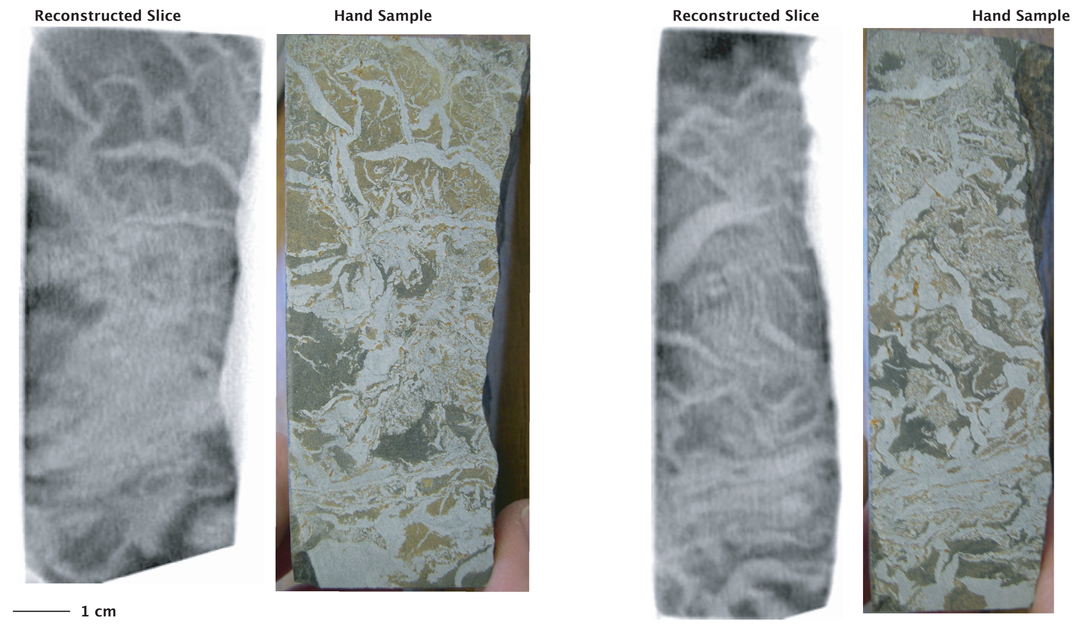
Connected points are expanded along each dimension independently to give thickness to surface.

A combination of immediate neighbors is used to create triangles. This displays the surface as a triangular mesh.

Texture is added to enhance surface visualization.

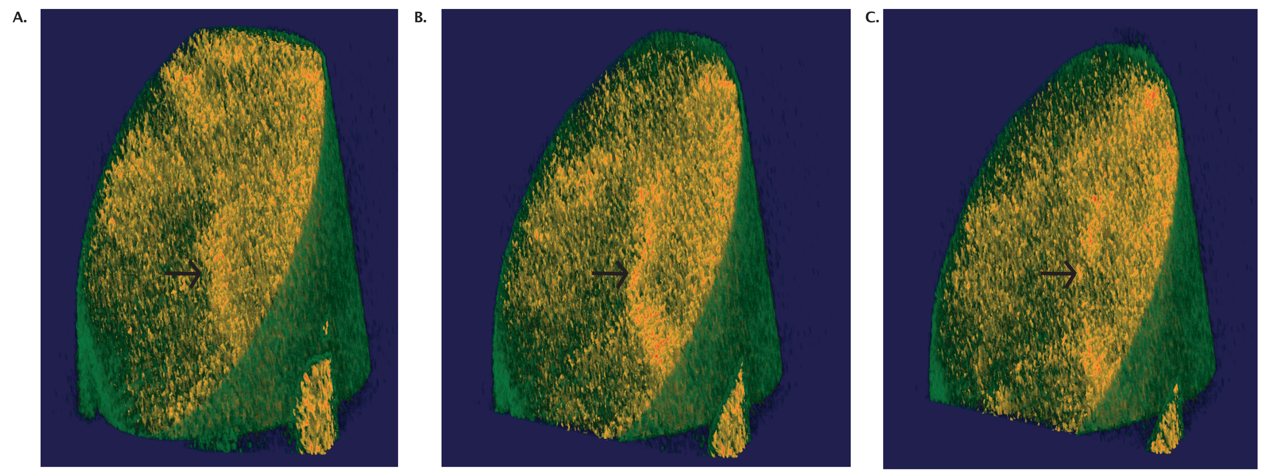
Neutron Computed Tomography Reconstructions

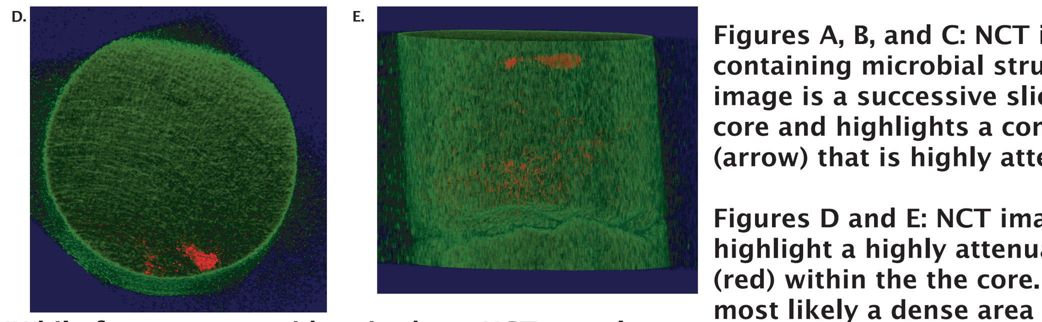
Simple Structures



Hand samples and reconstructed slices of rocks containing molar tooth structures from the 2.6 Ga Monteville Fm., Transvaal Supergroup, South Africa. These structures are syn-sedimentary veins that formed in shallow, subtidal muddy sediments (James et al., 1998). They are composed of pure calcite microspar (white) in a shale host rock. The H-bearing clay minerals in the shale attenuate neutrons more than the calcite. Therefore these structures can be imaged using NCT.

More Complex Structures





*While features are evident in these NCT samples, it is difficult to reconstruct microbial structures because the images are too noisy. This is a function of the reconstruction software and the imaging system.

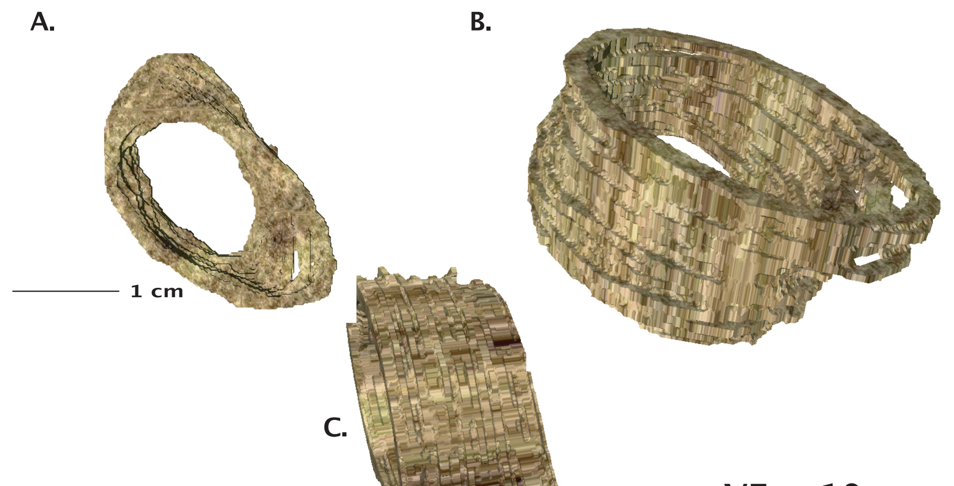
Figures A, B, and C: NCT images of core containing microbial structures. Each image is a successive slice through the core and highlights a complicated surface (arrow) that is highly attenuated.

Figures D and E: NCT images that highlight a highly attenuated structure (red) within the the core. This structure is most likely a dense area of organic-rich inclusions. A similar structure has also been identified through the serial sectioning reconstruction technique.

(Core diameter = 2.5 cm)

Serial Sectioning Reconstructions

Simple Structures



A. Plan view of 2.6 billion year old microbial tube structure from the Carawine Formation, Hamersley Basin, Western Australia.

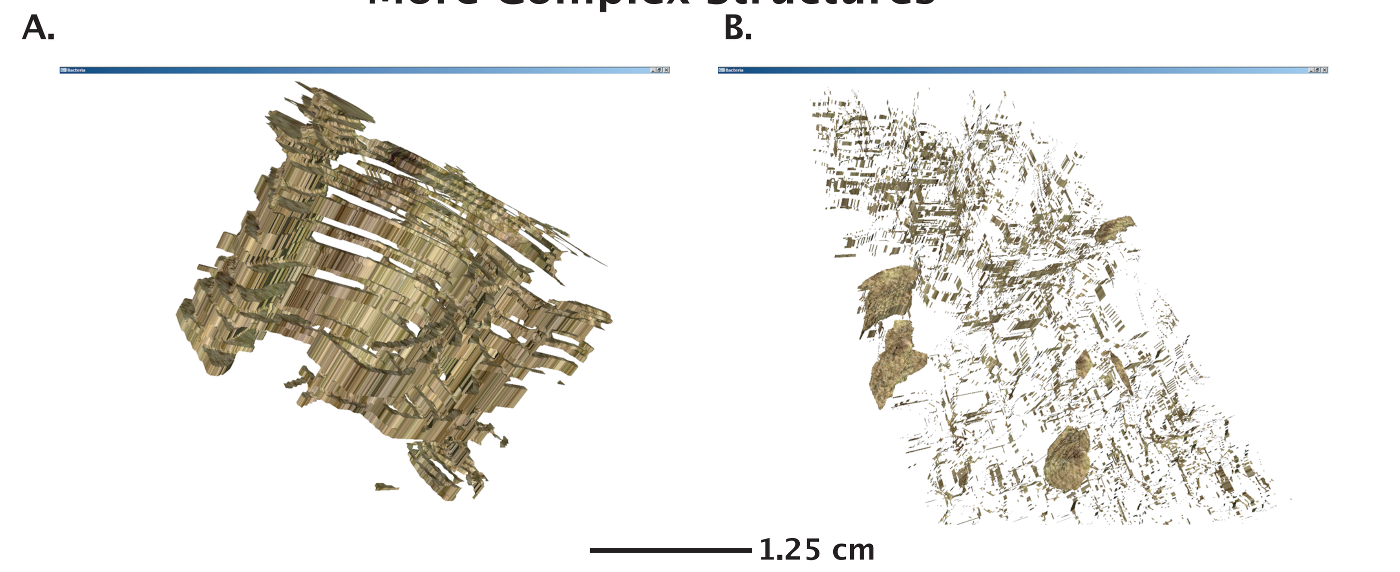
B. Cross sectional view of the same tube structure.

C. Side view of same tube structure.

Serial sectioning and growth surface reconstruction nicely recreate these simple, ancient microbial structures.

The tubes are defined by a 20-60 micron thick tube wall that is composed of organic-rich inclusions. The center of the tube was originally open to allow for deposition of ripped up pieces of microbial mat.

More Complex Structures



A. Reconstruction of an ancient network of microbial laminae using serial sectioning and a growth surface model. The image highlights vertical connected planes that comprise this intricate structure. 100 slices spaced 30 microns apart were used to create this image. This image represents a subset of the data as the full data-set is too large to render in the growth surface modeling program.

B. Outer layers of the reconstructed imaged were stripped away to highlight the connected layers that comprise the structure. Dark areas represent vertically continuous regions containing dense organic-rich inclusion areas. Similar structures were identified in the NCT reconstructions. This image represents the full data-set without the outer layers.

Conclusions

*NCT is a 3-D, nondestructive reconstruction technique that is useful for samples containing sufficient amounts of H.

*NCT can be used to reconstruct samples with simple structures (for example, molar tooth structures).

*Intricate networks of microbial laminae could not be imaged using NCT. However, areas of high and low attenuation can be imaged. These areas likely correspond to microbial structures.

*Interactive visualization allows one to see features that are not obvious in static images.

*Serial sectioning is a destructive reconstruction technique that is useful for samples containing low amounts of H.

*Serial sectioning and growth surface modeling were used to reconstruct simple 2.6 Ga microbial tube structures.

*Reconstructions of the network of microbial laminae appear complicated because the structure is intricate.

*Serial sectioning and growth surface modeling capture the peaks and ridges associated with the intricate network of microbial laminae preserved in 2.5 Ga rocks.

References

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