

## DIVERSIFICATION IN THE ARCHEAN BIOSPHERE: Insights from NanoSIMS of Microstructures in the Farrel Quartzite of Australia.

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**Introduction:** The nature of early life on Earth is difficult to assess because potential Early Archean biosignatures are commonly poorly preserved. Interpretations of such materials have been contested, and abiotic or epigenetic derivations have been proposed (summarized in [1]). Yet, an understanding of Archean life is of astrobiological importance, as knowledge of early evolutionary processes on Earth could provide insight to development of life on other planets.

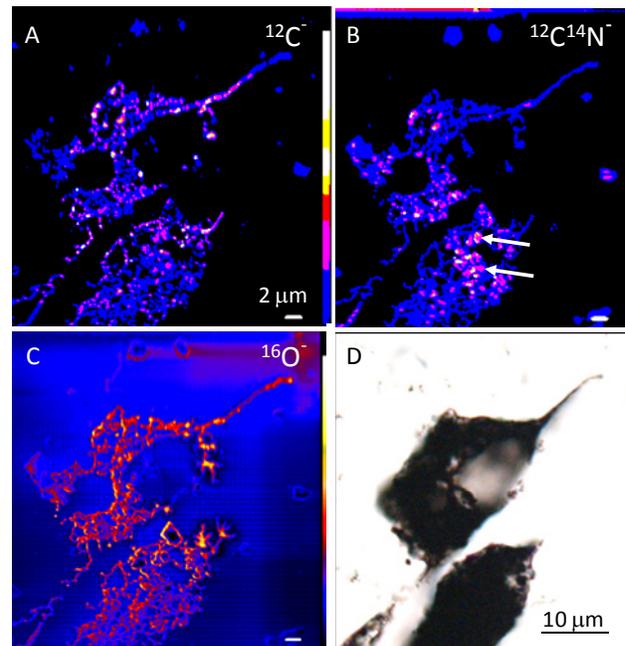
A recently-discovered assemblage of organic microstructures in ~3 Ga cherts of the Farrel Quartzite (FQ) of Australia [2-4] includes unusual spindle-like forms and a variety of spheroids. If biogenicity and syngeneity of these forms could be substantiated, the FQ assemblage would provide a new view of Archean life.

Our work uses NanoSIMS to further assess the biogenicity and syngeneity of FQ microstructures. In prior NanoSIMS studies [5-6], we gained an understanding of nano-scale elemental distributions in undisputed microfossils from the Neoproterozoic Bitter Springs Formation of Australia. Those results provide a new tool with which to evaluate poorly preserved materials that we might find in Archean sediments and possibly in extraterrestrial materials. We have applied this tool to the FQ forms.

**Results:** NanoSIMS analyses of the FQ microstructures show that small and large spheroids and spindle-shaped forms (Figs. 1-3) have parallel carbon (C<sup>-</sup>), nitrogen (measured as CN<sup>-</sup>), and sulfur (S<sup>-</sup>) distributions, a one-to-one correspondence of C<sup>-</sup> and CN<sup>-</sup> to microstructures imaged by optical microscopy, and calculated N/C atomic ratios (from measured CN<sup>-</sup>/C<sup>-</sup>) that are similar to N/C ratios of younger Precambrian microfossils of undisputed biological derivation. These features suggest that the FQ forms are biogenic [5].

The FQ microstructures also have silicon (Si<sup>-</sup>) and oxygen (O<sup>-</sup>) distributions that mimic C<sup>-</sup> and CN<sup>-</sup> distributions suggesting an intimate association between organic matter and silica. Such an association suggests that the organic matter was present at the time of silicification and thus that the FQ structures are syngenetic and the same age as the enclosing cherts [6].

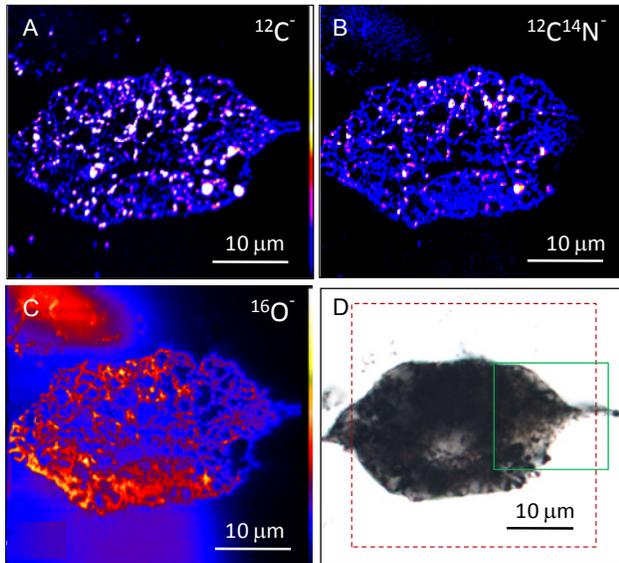
NanoSIMS element maps of the spindles also demonstrate their complexity. Some spindles contain vacuole-like cavities (Fig. 1). Adjacent to these cavities are patches with unusually high CN<sup>-</sup> (Fig. 1B) and S<sup>-</sup>,



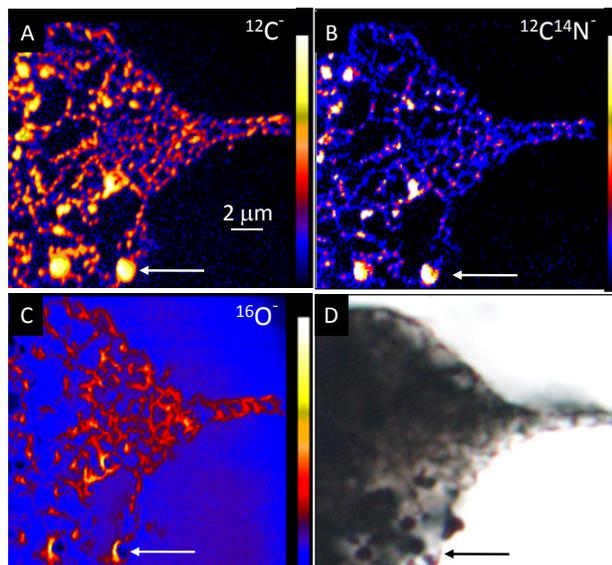
**Fig. 1.** NanoSIMS element maps (A-C) and an optical photomicrograph (D) of spindles in the Farrel Quartzite. Color bars on (A-C) indicate intensity of response, with blue being lowest and white being highest. Upper spindle has vacuole-like cavities. Arrows in (B) point to patches with unusually high CN<sup>-</sup> ion response.

perhaps reflecting release of nitrogen- and sulfur-bearing compounds from the cavities during early diagenesis. NanoSIMS results also demonstrate an intricate internal network of carbonaceous material that appears to fill the body and appendages of some spindles (Figs. 2-3).

**Discussion:** The spindles (Figs. 1-3) are the most enigmatic forms in this assemblage. Similar spindle-like forms have only been reported from Eo to Meso Archean deposits [7]. Their large size and complexity of organization seem surprising for Archean organisms. The apparent robustness of these microfossils might support a derivation from a spore-like structure adapted for resistance to extreme UV, desiccation, or perhaps, as suggested by Walsh [7], to nearly planet-sterilizing heat associated with impacts on the early Earth. The reticulate internal network may represent an architecture that developed during an early evolutionary phase of morphological experimentation.



**Fig. 2.** NanoSIMS element maps (A-C) and an optical photomicrograph (D) of a spindle in the Farrel Quartzite. Color bars on (A-C) indicate intensity of response, with blue being lowest and white being highest. Red dashed rectangle in (D) is area of (A-C). Green rectangle in (D) is area of panels in Fig. 3.



**Fig. 3.** NanoSIMS element maps (A-C) and optical photomicrograph (D) showing area of green rectangle in Fig. 2D. Color bars on (A-C) indicate intensity of response, with blue being lowest and white being highest. Arrows point to granules with intense C and CN ion response.

While the ~3 Ga age of the spindles might suggest prokaryotic affinities, their large sizes are more typical of eukaryotic microbes [8], even though some prokaryotic spores can reach relatively large sizes [7]. Certainly the organizational complexity of the spindles attests to a relatively advanced morphology. Since recent biomarker studies [9] have concluded that biochemical innovation in the Archean laid the

groundwork for all three Domains of life, it is even conceivable that the spindles could be early representatives of the Domain Eukaryota. At a minimum, our results support the existence of a diverse microbiota at 3 Ga, with spindle-shaped components that exhibit advanced levels of structural organization.

**Conclusions and Implications:** NanoSIMS element distributions suggest that organic spheroids and spindles in the FQ are *bona fide* microfossils of ~ 3 Ga microorganisms. This assemblage, then, joins other examples of *bona fide*, organically-preserved microfossils of Archean age (summarized in [10-11]). And these microbiotas join Early Archean stromatolites and a host of geochemical, electron microscopic, and spectroscopic studies of kerogens > 3 Ga in age suggesting that the Archean biosphere was multifaceted and diverse [9-27].

The spindle-like forms are robust and abundant. They are of interest because of their large size and complexity - with flanges, appendages, vacuole-like cavities, and an internal carbonaceous network. They may represent resistant spores that developed on a hostile young planet, a life-cycle stage, or perhaps a form that is extinct with no modern analog; they might even be early representatives of the Domain Eukaryota.

Our conclusions align with those of Waldbauer *et al.* [9] suggesting that the Archean was a time of evolutionary innovation and diversification. This view of early terrestrial evolution may increase the likelihood that primitive life on other planets could survive and adapt to adverse or unusual conditions by ready development of diversity in form and biochemistry.

**References:** [1] Oehler D. *et al.* (in press). *Astrobiology* [2] Sugitani K. *et al.* (2007) *Prec. Res.* 158, 228-262 (2007). [3] Sugitani K. *et al.* (in press) *Astrobiology*. [4] Sugitani K. *et al.*, (2009) *Prec. Res.* 173, 50-59. [5] Oehler D. *et al.* (2006) *Astrobiology* 6, 838-850. [6] Oehler D. *et al.* (2009) *Prec. Res.* 173, 70-78. [7] Walsh, M. (1992) *Prec. Res.* 54, 271-293. [8] Schopf J.W. (1992) Ch. 5.4 in *The Proterozoic Biosphere* (eds. J.W. Schopf & C. Klein, Cambridge Univ. Press. [9] Waldbauer J. *et al.* (2009) *Prec. Res.* 169, 28-47. [10] Schopf J.W. (2006) *Ph. Trans. R. Soc. Lond. B.* 361, 869-885. [11] Schopf J.W. *et al.* (2007) *Prec. Res.* 158, 141-155. [12] Walter M.R. *et al.* (1980) *Nature* 284, 443-445. [13] Schopf J.W. (1993) *Science* 260, 640-646. [14] Hofmann H.J. *et al.* (1999) *GSA Bull.* 111, 1256-1262. [15] Altermann W. & Kazmierczak J. (2003) *Res. Microbiol.* 154, 611-617. [16] Allwood A. *et al.* (2006) *Nature* 441, 714-718. [17] Allwood A. *et al.* (2009) *PNAS* 106, 9548-9555. [18] Schopf J.W. & Walter M.R. (2007) *Prec. Res.* 158, 139-140. [19] Rasmussen B. (2000) *Nature* 405, 676-679. [20] Rasmussen B. *et al.* (2009) *Geology* 37, 423-426. [21] Eigenbrode J. & Freeman K. (2006) *PNAS* 103, 15759-15764. [22] De Gregorio B. & Sharp T. (2007) *GSA Abs. Prog.* 39 #166-3. [23] Duck L. *et al.* (2007) *Prec. Res.* 154, 205-220. [24] Marshall C. *et al.* (2007) *Prec. Res.* 155, 1-23. [25] Van Zuilen M. *et al.* (2007) *GCA* 71, 655-669. [26] Derenne S. *et al.* (2008) *EPSL* 272, 476-480. [27] De Gregorio B. *et al.* (2009) *Geology* 37, 631-634.