Project Report for Eukaryotic Evolution in Heterogeneous Proterozoic Seas prepared for the Lewis and Clark Fund for Exploration and Field Research in Astrobiology

Earth's oceans were anoxic for much of their history. Biogeochemical models and the rock record indicate that following an initial increase in atmospheric oxygen (~2.4 Ga), temporally and spatially variable shallow-water euxinia (sulfidic anoxia) and deep-water ferruginous anoxia co-existed beneath an at-least-moderately oxygenated surface layer until the Neoproterozoic. Although the oldest unambiguous eukaryotic fossils date from this period of heterogeneous oceans, these oceanic conditions are hypothesized to have acted as a throttle on eukaryotic diversity and abundance. Recent ecological studies, however, illustrate great eukaryotic diversity in modern euxinic and ferruginous waters, suggesting these conditions (and perhaps Paleoproterozoic oceans) may not have been poisonous environments as once supposed.

With the study funded here I am working to combine paleontological and geochemical records of the earliest eukaryotes and their habitats, focusing on late Paleoproterozoic through Mesoproterozoic rocks (~1.73-1.4 Ga) to address the paleoecological question of eukaryotic distribution with regards to water redox state. With this project I am focused on refining our understanding of the co-evolution of early eukaryotes and Earth's ocean chemistry, and testing the assumption that eukaryotic diversity and abundance were tightly restricted by oxygen availability and could increase only after substantial growth in atmospheric and oceanic oxygen levels.

The Lewis and Clark Fund for Exploration and Field Research in Astrobiology funded travel for sampling as well as travel for geochemical analyses portions of this research project. Travel to Darwin, Australia for sample collection occurred 15-26 July 2019 and resulted in collection of 428 siliciclastic samples from 8 drillcores that penetrated Paleoproterozoic and Mesoproterozoic units in the McArthur and Birrindudu basins of northern Australia (Fig 1). Travel to the Ogilvie Mountains in the Yukon Territory, Canada (Fig. 2) occurred June 19-July 13, 2022 and resulted in collection of samples as well as advances in mapping of Mesoproterozoic through Tonian units of the Wernecke Supergroup and Pinguicula and Fifteenmile groups.

Paleontological and geochemical study of new samples collected in June-July 2022 will begin upon receipt of the shipped samples, but analyses are nearing completion for materials collected in 2019. We found that fossiliferous samples occur throughout both successions, occasionally recording only prokaryotic taxa such as the smooth-walled *Leiosphaeridia* spp. and simple filaments or cell aggregates like *Siphonophycus* spp. and *Synsphaeridium* spp., respectively, but often also preserving likely eukaryotes such as Satka favosa, *Valeria lophostriata*, *Tappania plana* and new, unnamed taxa (Fig. 3). Both paleontological and iron speciation data (a proxy for water column anoxia) are available for 88 samples across the 8 cores; there are 41 oxic samples, 23 ferruginous and one anoxic and sulphidic (euxinic) and 23 equivocal samples for which the redox state cannot yet be resolved. Most fossil specimens (70%) come from oxic samples, whereas only 1% from ferruginous samples and 28% of fossils come from equivocal samples, the only euxinic sample was barren. Eukaryotes are even more likely to be found in oxic samples—91% of eukaryote specimens occur in oxic samples, 3% in ferruginous samples and 6% in equivocal samples.

The Paleoproterozoic and Mesoproterozoic McArthur and Birrindudu Basins are richly fossiliferous, preserving named and new taxa, indicating reasonably high diversity by this time in eukaryotic evolution and boding well for future study. We find a greater stratigraphic range for several taxa, pushing back the age of the oldest evidence of eukaryotes. Additionally, discovery of a new operculate taxon indicates that early eukaryotes possessed a sophisticated cytoskeleton and complex life cycle by the end of the Paleoproterozoic.

By pairing our paleontological and redox data we see that eukaryotic fossils predominantly occur in samples interpreted to record oxic, shallow marine deposition, indicating that these early eukaryotes indeed lived in and favored oxygenated habitats, and were perhaps aerobic. Further, our paired data suggest that individual taxa such as *Satka favosa*, with its strong preference for oxic settings, may have potential as fossil redox proxies where geochemical data are unavailable.

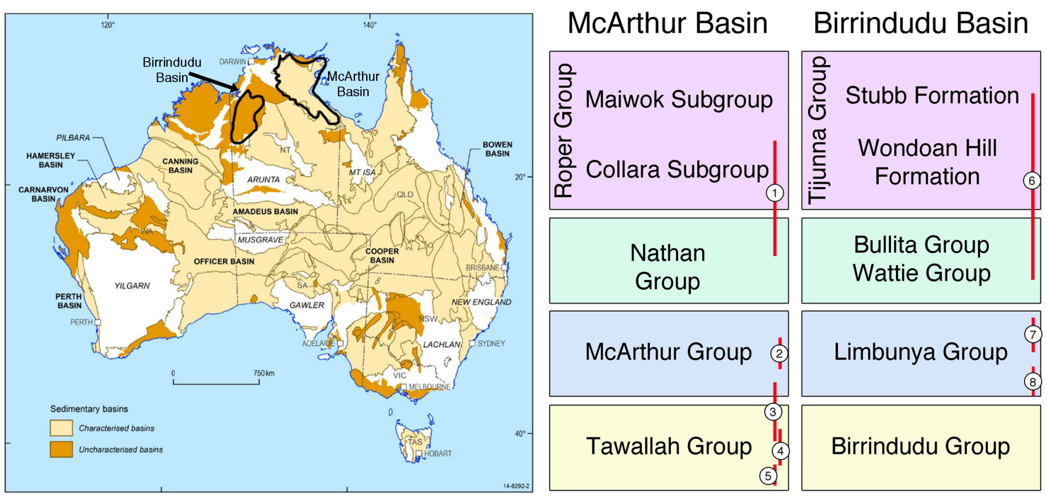

Fig. 1 Map indicating location of Birrindudu and McArthur basins; correlated stratigraphic columns indicating sampling extent in each core. 1)Broughton-1, 2) McA5, 3) MCDD0005, 4) MCDD0003, 5) GSD7, 6) 99VRNTGSDD2, 7) DD90VRB1, 8) DD90VRB2.

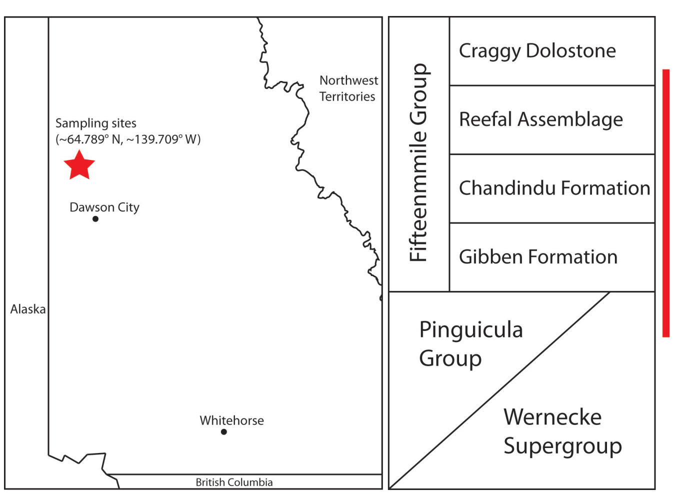

Figure 2. Map indicating sampling locations in Ogilvie Mountains, Yukon and stratigraphic column with red line indicating extent of sampling.

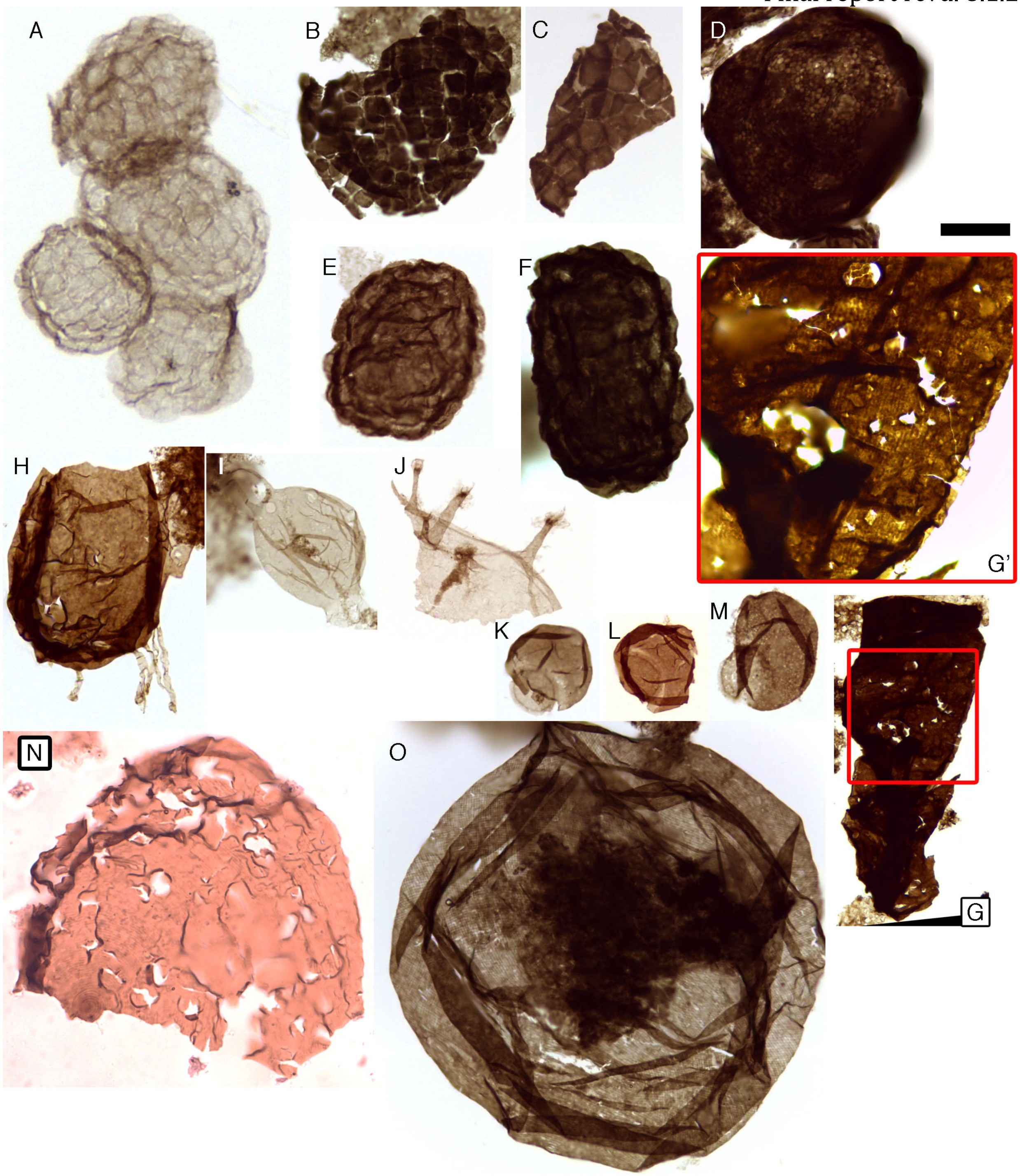

Fig. 3. **Organic-walled microfossils (A-C)** *Satka favosa*, **(D)** *Dictyosphaera macroreticulata*, **(E-F)** *Squamosphaera colonialica*, **(G, G')***Jixiania lineata*, **(H-J)** *Tappania plana*, (H), **(K-M)** New operculate taxon,. **(N-O)** *Valeria lophostriata*. Scale bar near D is 20μm for all except G, for which it is 50μm.

Final report rcvd. 8.1.22

Supplemental Figure. The author during drillcore sampling at Northern Territories Geological Survey Drill Core Facilities in Darwin, NT Australia, July 2019. Paleoproterozoic drillcore MCDD0003 in the background.