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# Velkerri Formation Depositional Model - Beetaloo Sub-basin, Northern Territory, Australia : Biostratigraphy and Organic Enrichment

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## Introduction

The Velkerri Formation is the oldest proven petroleum source rock in the Beetaloo Sub-basin (McArthur Basin), with the best source rocks mid-formation, readily detected from gamma ray and resistivity logs, and confidently correlatable over 100s of kilometres (Warren et al., 1998). Whether source-rock deposition was in deep or shallow water has environmental implications for both species and organic-rich rock distribution. The sub-basin lay in the tropics during deposition of the Velkerri Formation based on palaeomagnetism (Idnurm, 2004), and Re-Os dating of the Middle Velkerri Formation in Urapunga-4 of 1361 +/-21 Ma (Creaser & Kendall, 2007).

## Previous interpretations

There have been various interpretations of the depositional environment of the Mesoproterozoic Velkerri Formation and Moroak Sandstone. Summons et al. (1988) favoured an outer shelf marine setting and Jackson et al. (1988, fig. 4) identified distal turbidites. By contrast, Donnelly and Crick (1988) inferred deposition in a large lake or barred bay from a study of Urapunga-3. However, detailed facies analysis by Jackson and Raiswell (1991), based on Urapunga-3 and Urapunga-4, indicated that the middle Velkerri Formation was deposited in a variety of environments on an epicratonic marine shelf, mostly beyond the effects of normal wave and tidal current activity, and noted that glauconite, widespread throughout the formation, is incompatible with a lacustrine-barred-bay setting. Warren et al. (1998) interpreted the Velkerri Formation as predominantly glauconitic marine shale deposited in restricted to anoxic conditions in a deep-water pro-delta slope to basin environment. These interpretations were based mainly on wells and outcrops in the northern Beetaloo Sub-basin. This study has incorporated wells from the southern Beetaloo Sub-basin including the recently drilled Shenandoah-1/1A (logs courtesy of Falcon Oil & Gas), allowing construction of a roughly south to north geological cross-section datumed on a readily correlatable combination of well log characteristics.

More recently, Silverman et al. (2007) noted that upward shoaling into the Moroak Sandstone (interpreted as a lateral

equivalent of the upper Velkerri Formation shales) in Elliott-1, the southernmost well, reflected a basin-wide deltaic progradation and an up-section increase in depositional environmental energy 'likely the result of some basin-filling event such as regional deltaic progradation'. Shenandoah-1/1A added significantly to understanding deposition in the southern sub-basin, supporting the Silverman et al. model.

Jackson et al. (1988, fig. 4) indicated high energy, very shallow water environments for the Moroak Sandstone. Powell et al. (1987) noted that the 'Broadmere Sandstone Member' in Amoco drill hole 1982/1 consisted of 4 upward-fining cycles (each c. 40 m thick), of fine-grained kaolinitic sandstone and minor siltstone that is commonly scoured and incorporated in the overlying sandstone, suggesting alternating traction currents and slack water. Outcrops south of Amoco 1982/1 contain very large scale cross-bedded pebbly sandstone with persistent northerly-directed palaeocurrents (Powell et al., 1987). The electric log for Shenandoah-1/1A shows a generally coarsening upward profile, reminiscent of a prograding complex in the section identified as Moroak Sandstone. Elliott-1 shows a similar profile although no contact was logged with the Velkerri Formation. NW progradation in the southern basin suggests a southeast provenance for the Moroak Sandstone, possibly from the Helen Springs High.

## New model

Our depositional model, based on log correlation, core inspection and mineralogy suggests uplift to the 'south' and a developing foredeep to the 'north' and depths that shallow up a ramp margin. Coarse clastics, derived from rising mountains, were shed into the foredeep, ranging from coarser proximally to finer-grained more distally. Mesoproterozoic rocks are unlikely to have any terrestrial organic input. All organic matter originated in the marine environment and deposition of organic matter would be greater in quieter distal waters. Least dilution of organic matter and consequently the thickest source rock development would be expected on the ramp in relatively shallow water.

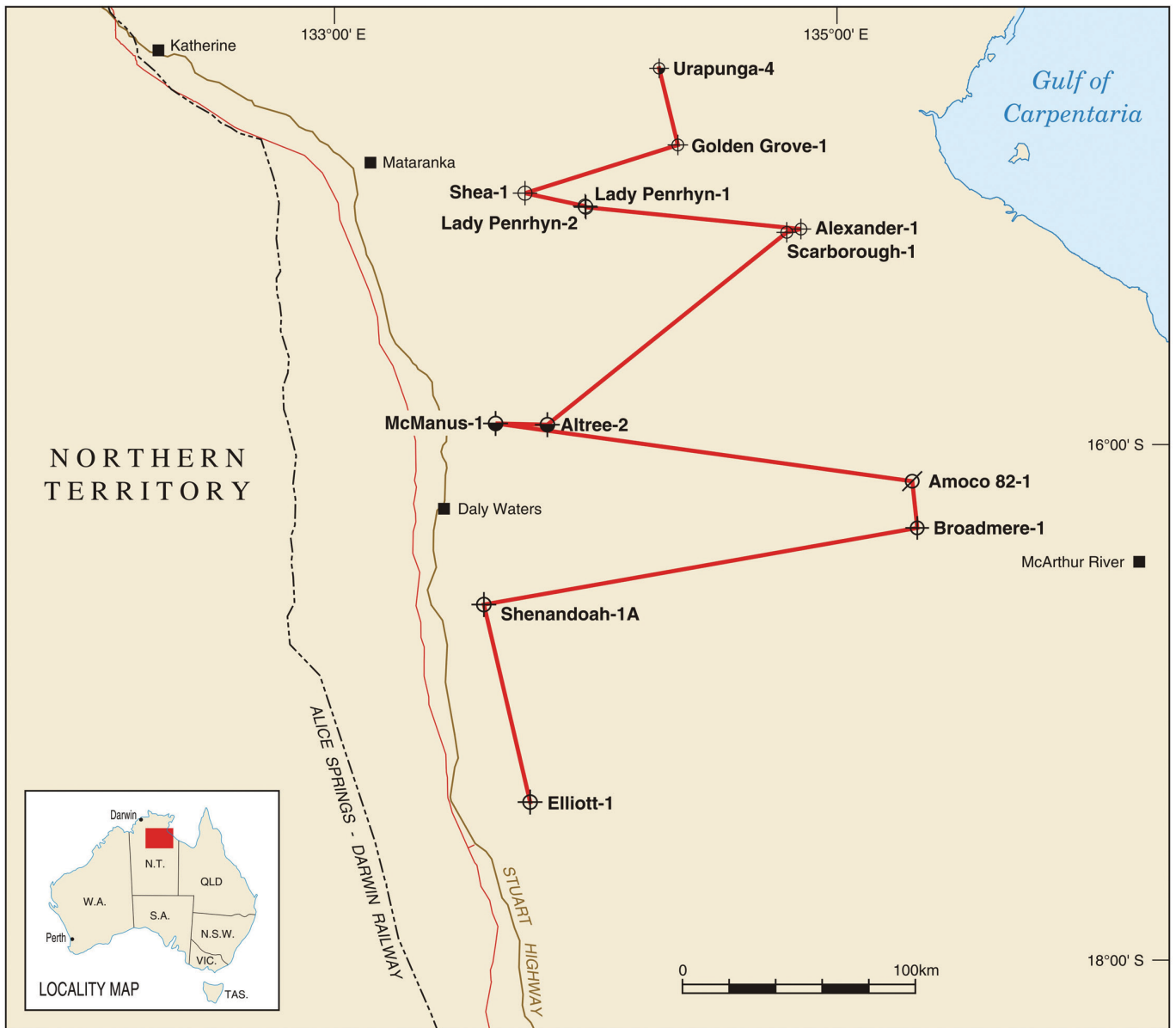
## Palynology and mineralogy

Shale samples from the Velkerri Formation from cores in Aintree-2 and McManus-1 were prepared by palynological techniques. A part of each of the shale sample was thin-sectioned and examined under the microscope to determine the mineralogy and petrographic fabric. Each sample also had the total organic carbon content (TOC) measured and was analysed by pyrolytic techniques to determine the geochemical parameters of the contained organic matter (see Table).

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Locality map

These analyses show that the dark coloured argillite in the Middle Velkerri Formation is organic-rich, determined at present day maturity levels as Type II/III kerogen in the upper part of the middle Velkerri, and Type III kerogen in the lower part of the Middle Velkerri where carbonate minerals are more abundant. In the Upper and Lower Velkerri the organic content is much reduced and the occurrence of glauconite, chamosite and carbonate porphyroblasts suggests a nearer shore depositional environment. Organic matter in the Middle and Lower Velkerri Formation is very poorly preserved and there are hardly any identifiable palynomorphs.

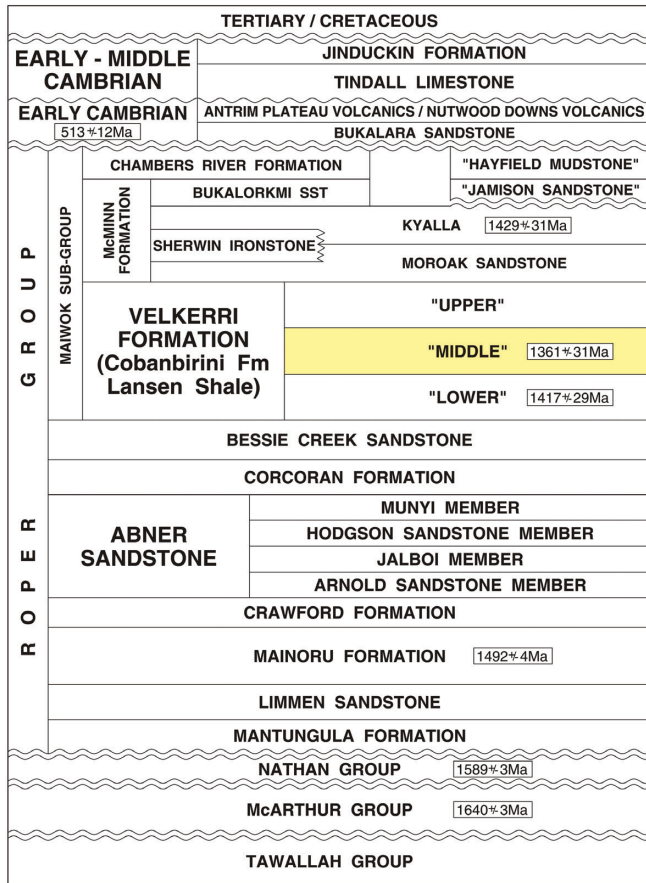
By contrast, the Upper Velkerri Formation contains well preserved palynomorphs, mostly of simple leiospheres, but including some clusters of spheres and other morphological types. From preliminary work, it looks as if the ratio of filaments to acritarchs will be useful for indicating the distance from shore throughout the succession, but further study is needed to confirm this. The highest proportion of filaments is in the Upper Velkerri Formation suggesting that this unit represents the shallowest

deposits of the formation, in agreement with the progradational character deduced from the well logs as shown in the cross-section. The poor preservation and low number of samples from the Lower Velkerri Formation precludes an assessment of water depths based on the palynological assemblage.

This study has shown that palynological information can assist in determining the organic facies and thermal maturity of Mesoproterozoic strata in the Velkerri Formation. In addition, further analysis may prove the biostratigraphic potential of certain palynomorphs for inter and intra-basin correlations.

### Organic enrichment

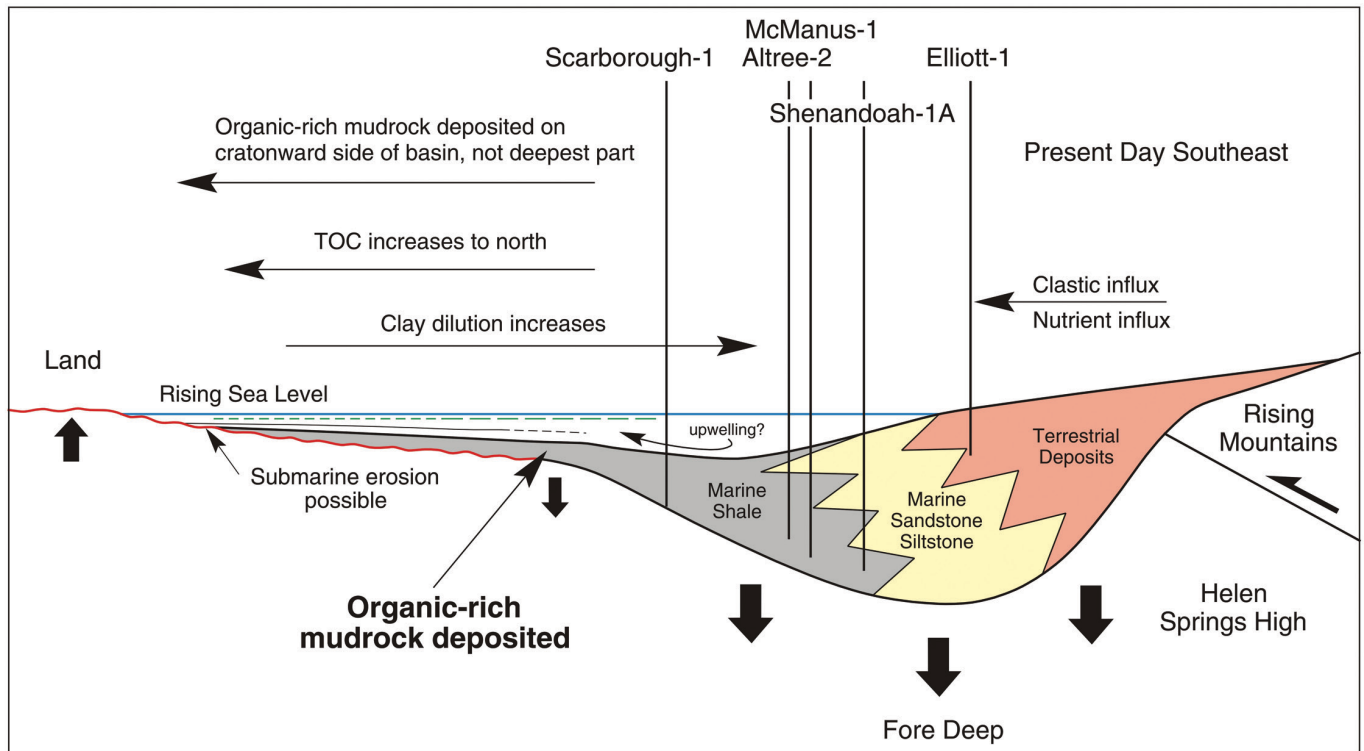
Three regionally extensive zones of organic enrichment are apparent in the Middle Velkerri Formation and can be correlated regionally by means of geophysical logs from boreholes. All the organic-rich zones are marked by high radioactivity and resistivity



Simplified Stratigraphy and Absolute Ages

anomalies, the occurrence of abundant amorphous organic matter, the upper two enrichment zones appearing at the base of shoaling cycles with which they have a gradational upward contact. By contrast, the lower organic-rich zone appears to have a relatively sharp contact, marked by chert, with the overlying coarser grained clastics. Additionally, the base of the organic-rich zone in the middle source interval is gradational downward into the top of the lower shoal cycle whereas both the upper and lower organic-rich zones have relatively sharp bases. According to Warren et al. (1998), high organic content reflects changes in organic productivity vs. sediment supply rates, rather than fluctuating oxygen levels in the bottom waters or changes in water depth. However, these differences are regionally consistent and suggest a depositional environment control - perhaps tectonic or eustatic.

Two measures of the thermal maturity of the organic matter in the enriched zones in the Middle Velkerri Formation, Rock-Eval pyrolysis Tmax values and the thermal alteration of organic material (TAI of Traverse, 1988) indicate, on the one hand, based on well-established Phanerozoic measurements of organic maturity, that the Middle Velkerri organic matter is in the early to middle oil generation zone in McManus-1 and Atree-2, whereas the TAI values of 4+ in the same unit indicates over mature source beds. TAI is determined from pre-oxidation macerate slides, based on spore colouration is a rough guide only, especially as Precambrian organic material has not so far been adequately calibrated with Phanerozoic material. Based on the TAI encountered in Atree-2 and McManus-1 (4- to 4+) in the Velkerri Formation, the organic material contained within these rocks has attained a vitrinite reflectivity equivalence of over 2% to 2.5% and is now in the dry gas-generative zone (Traverse, 1988). Summons et al. (1994, fig. 3) showed that the Tmax values of extracted rock samples from

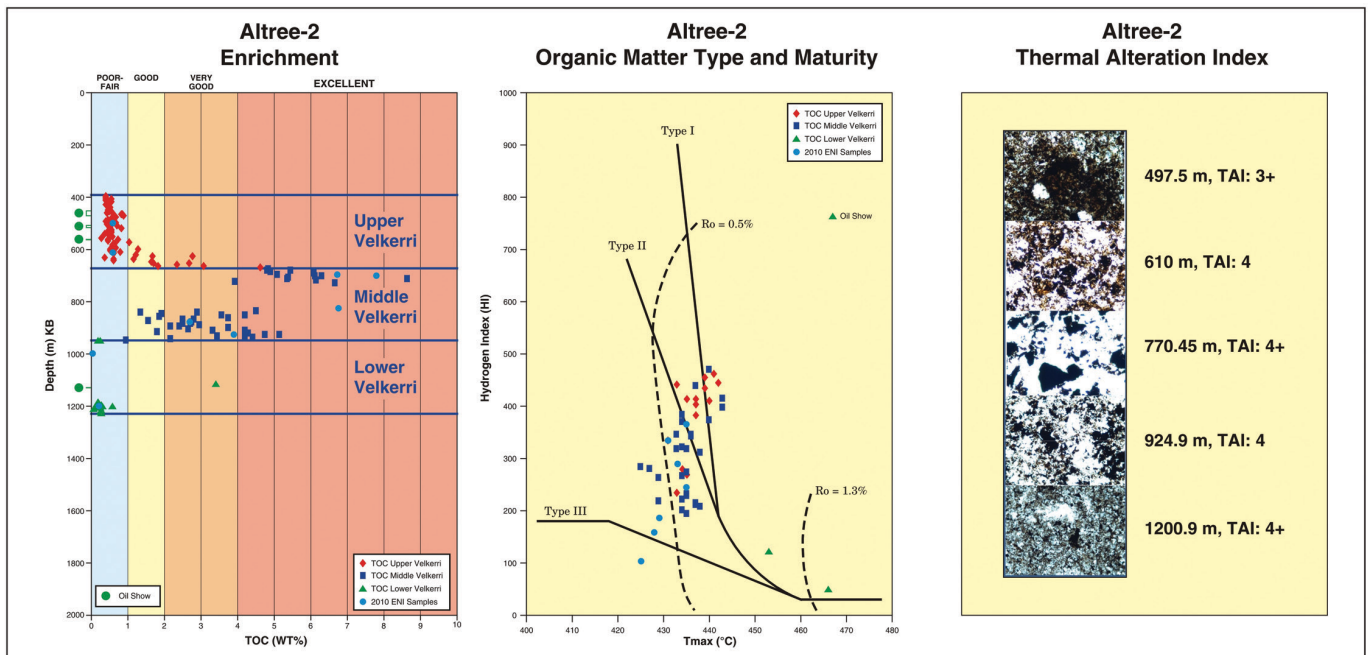


Depositional model

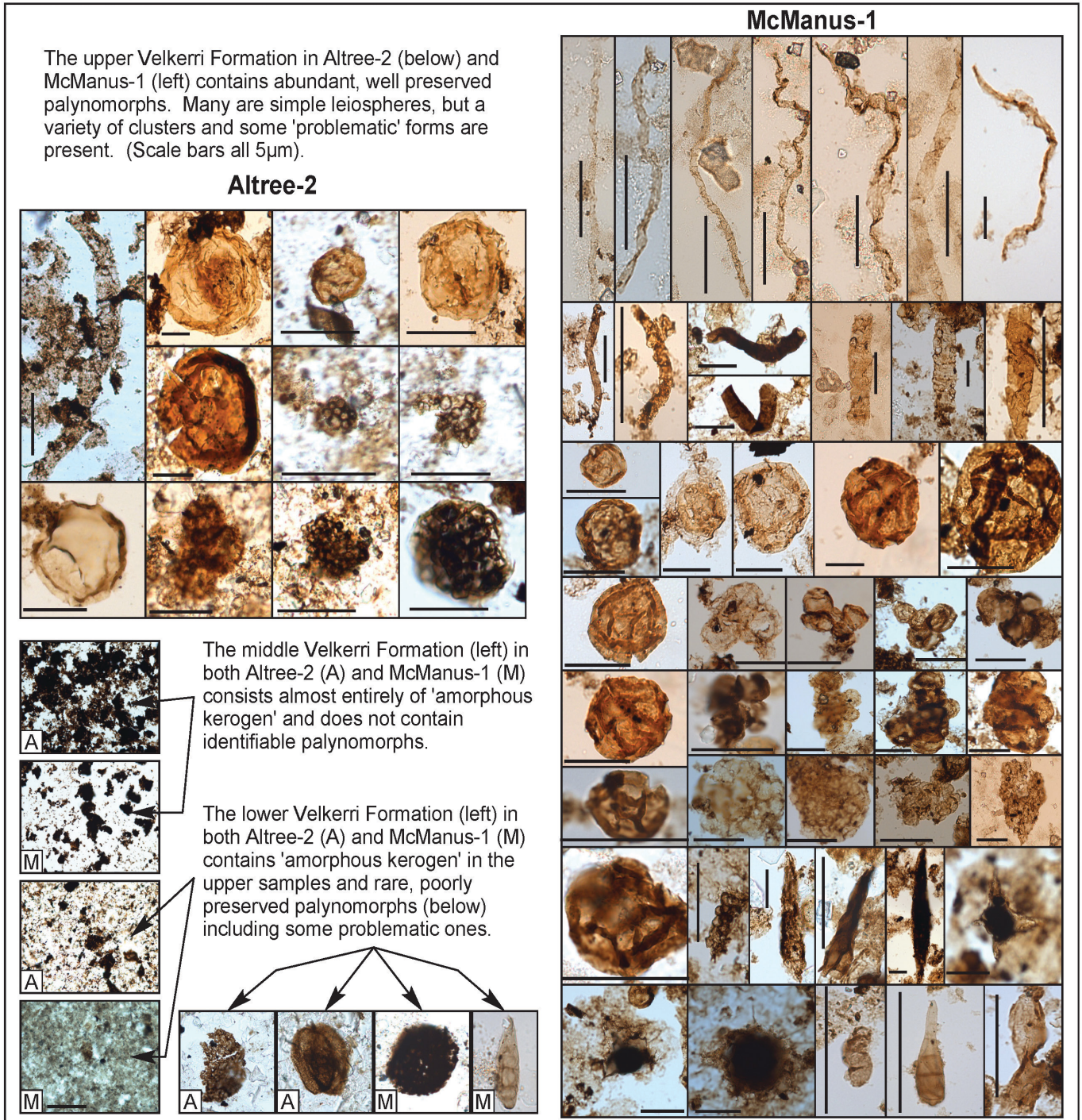
# Palaeolatitude of Beetaloo area during mid Velkerri deposition (Idnurm, 2004)



Palaeolatitudes



Altre-2 Enrichment, Organic Matter Type and Maturity



**Representative microfossils**

the lower part of the Middle Velkerri Formation in Atree-2 were elevated compared to the un-extracted rocks samples supporting the TAI-derived maturity observed here.

The expectation that Middle Proterozoic organic matter would be dominated or exclusively composed of algal and bacterial remains constituting a Type I kerogen mix is at odds with the Type II/III kerogen mix indicated by the Hydrogen Index. This observation can be explained by thermal maturation of the original

Type I organic material and migration from the source rocks of hydrocarbons resulting in the apparent retention of low HI kerogen and the suppression of the Tmax values. The relatively high Production Index observed in these analyses, especially from the lower part of the Middle Velkerri Formation supports the presence of migrated hydrocarbons retained in the sediments, as does the occurrence of oil and gas shows in the cores of the more permeable Upper Velkerri Formation in both McManus-1 and Atree-2.

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Note: Geochemical data used in this study are archived either at the Geoscience Australia website, through the Northern Territory Geological Survey, or in released well completion reports. The geochemical analyses used for the Warren et al. (1998) paper are apparently not archived and requests for the information in 2010 proved unsuccessful.