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Chemostratigraphy, Geochronology & Provenance of the Late Neoproterozoic & Early Cambrian Sediments in Oman

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ABSTRACT

The Nafun and Ara Groups are late Neoproterozoic and early Cambrian sedimentary successions that are key exploration and development targets in Oman. The age, lithological diversity and, occasionally, structural complexity of these groups makes regional stratigraphic correlations challenging using many conventional stratigraphic techniques. Presented here are the results of an integrated multidisciplinary inorganic geochemical, mineralogical and radiometric study on outcrop and well sections to produce a regional surface to subsurface chemostratigraphic framework of the Nafun and Ara Groups.

Through a detailed examination of the inorganic geochemical dataset, the key elements employed to produce the chemostratigraphic framework are Si, Al, Ca, Mg, Ti, Zr, Y, Th, Mo and U. These elements have been paired to form geochemical ratios, from which seven chemostratigraphic sequences are defined: five within the rock assigned to the Nafun Group and two within the rock assigned to the lower part of the Ara Group. The key element ratios are interpreted to reflect mineralogical temporal variations in felspars, dolomite and heavy minerals that are used to infer stratigraphic changes in environment, redox and sediment provenance throughout the Late Neoproterozoic and early Cambrian. The geochemical signatures are traced through multiple lithologies with a high degree of confidence and the mineralogical interpretations are supported by supplementary whole-rock and heavy mineralogical data.

Zircon geochronology performed upon selected samples highlights variable contributions of detritus from rocks of the Palaeozoic Angudan Orogeny, Neoproterozoic basement, as well as Palaeoproterozoic and Archean sources that are not currently known from the Arabian Plate. The recognition of Angudan-aged zircons (c.540Ma) facilitates the definition of maximum depositional ages of rocks that have no other form of chronostratigraphic control.
The results of this study demonstrate the efficacy of an integrated geochemical and mineralogical approach to defining a robust and age-constrained stratigraphic scheme for the late Neoproterozoic sedimentary succession of Oman that allows for clear correlations to be produced between outcrop and subsurface.

INTRODUCTION

The Nafun and Ara Groups are late Neoproterozoic and early Cambrian sedimentary successions that are key exploration and development targets in Oman. The age, lithological diversity and, occasionally, structural complexity of these groups makes regional stratigraphic correlations challenging using many conventional stratigraphic techniques. Compounding the issue is the fact that formation names for the same sedimentary successions are different depending on whether they are encountered in north, or central Oman (Glennie et al., 1974; Rabu et al., 1993; Forbes et al., 2010). The Nafun and Ara Groups contain multiple lithologies (clastics, carbonates, silicilytes, evaporites and volcanics/volcaniclastics) that were deposited in a marine environment during the final convergence of east and west Gondwana.

Detailed work has been carried out on the late Neoproterozoic and early Cambrian outcrops at Wadi Bani Awf and at Saih Hatat and proprietary work carried out on the lateral equivalents encountered in the subsurface (McCabe, et al, 2022). The primary objective of the study is to understand whether there are marked stratigraphic variations in element and/or element ratio abundances that can be employed to produce a regional chemostratigraphic framework of the rocks assigned lithostratigraphically to the Nafun and Ara Groups. Further objectives focus on understanding the geological interpretation of key elements and element ratios, which provide detailed insights on depositional environment and sediment provenance.

Analytical methodologies (inorganic geochemistry, Raman spectroscopy and zircon geochronology)

In this study, inorganic geochemistry is employed on outcrop and well sections to produce a regional surface-to-subsurface chemostratigraphic framework of the Nafun and Ara Groups. All samples have been analysed by inductively-coupled plasma optical emission spectroscopy (ICP-OES), and inductively-coupled plasma mass spectrometry (ICP-MS) instruments, using the lithium metaborate (alkali) fusion procedure advocated by Jarvis & Jarvis (1992a and 1992b). Data is acquired for 10 major elements and 38 trace elements, including 14 rare earth elements (REEs - La to Lu)

Heavy mineral analysis by Raman spectroscopy and whole-rock XRD analysis were performed on a subset of outcrop samples to improve understanding of the mineralogical controls on the key elements and element ratios and to refine provenance interpretations. Seventeen minerals are identified in the combined datasets, of which the minerals supporting the chemostratigraphic framework are dolomite, calcite, plagioclase, monazite, apatite, rutile and zircon. The redox-sensitive minerals uraninite is also highly important to the study but is not reported by XRD or Raman spectroscopy.

Zircons were separated from the heavy mineral populations and subjected to La-ICP-MS geochronological analysis to understand the source areas shedding detritus into the basins during the Late Neoproterozoic and early Cambrian. Recognition of the first appearance of zircons associated with the Angudan Orogeny (c.540 ma) permits maximum depositional age for the sedimentary rocks to be determined and defines the Nafun-Ara Boundary at outcrop and in the subsurface.

Chemostratigraphic Characterisation and Correlation

The key elements identified within the dataset have been paired to form geochemical ratios, which are associated with mineralogical affinities associated with various different factors (lithology, environment, provenance, weathering) (Table 1)

Element / Ratio	Mineralogical interpretation	Geological Control
Si/Al	Quartz abundance relative to clay minerals & Al-silicates	Depositional environment
Mg/Al	Dolomite abundance	Depositional environment
CaO	Ca-carbonate & sulphate abundance	Depositional environment
U/Al	Uraninite abundance	Depositional environment
Ti	Rutile abundance	Provenance
Na/Al	Plagioclase abundance	Provenance and chemical weathering
Ti/Zr	Rutile abundance relative to zircon	Provenance

Table 1: Key element and element ratios, their associated mineral affinity and geological control.

Using these parameters, the study interval is divided into seven chemostratigraphic sequences (from bottom to top) QN-E1 – QN-E5, QA-E1 and QA-E2 (Table 2 and Figure 1). The elemental signatures used to define the various chemostratigraphic sequences clearly reflect temporal changes in depositional environment and provenance during the late Neoproterozoic Era that largely occur independently of lithology. By observing more subtle variations in the same key elements and element ratios, many of the chemostratigraphic sequences are divided into higher resolution chemostratigraphic packages (seven in total throughout the study interval), most of which are correlative between the outcrop at Wadi Bani Awf and that at Saih Hatat, and between the outcrop and the subsurface.

Chemo. Megasequence	Equivalent Lithostratigraphic Group	Chemo.Sequence	Equivalent Lithostratigraphic Formation (Outcrop)	Equivalent Lithostratigraphic Formation (Subsurface)	Matrix table highlighting the geochemical characteristics of each chemostratigraphic zone					
					Mg/Al	CaO	U/Al	Ti	Na/Al	Ti/Zr
QAE	Ara	QA-E2		Birba						
		QA-E1	Fara	Birba Clastics	red	orange	red	red	orange	red
QNE	Nafun	QN-E5	Fara	Upper Buah	red	orange	green	red	orange	red
		QN-E4	Kharus	Lower Buah	red	green	green	red	orange	green
		QN-E3	Mu'aydin	Shuram	green	red	red	orange	red	green
		QN-E2	Haijr	Khufai	red	green	green	red	orange	red
		QN-E1	Mistal	Masirah Bay/Hadesh	red	red	red	green	orange	red

Table 2: summary of chemostratigraphic zonation, key geochemical characteristics and equivalent lithostratigraphic formation. In the matrix table, red indicates relatively low values, orange indicated moderate values and green indicates high values being used to characterise a chemostratigraphic sequence.

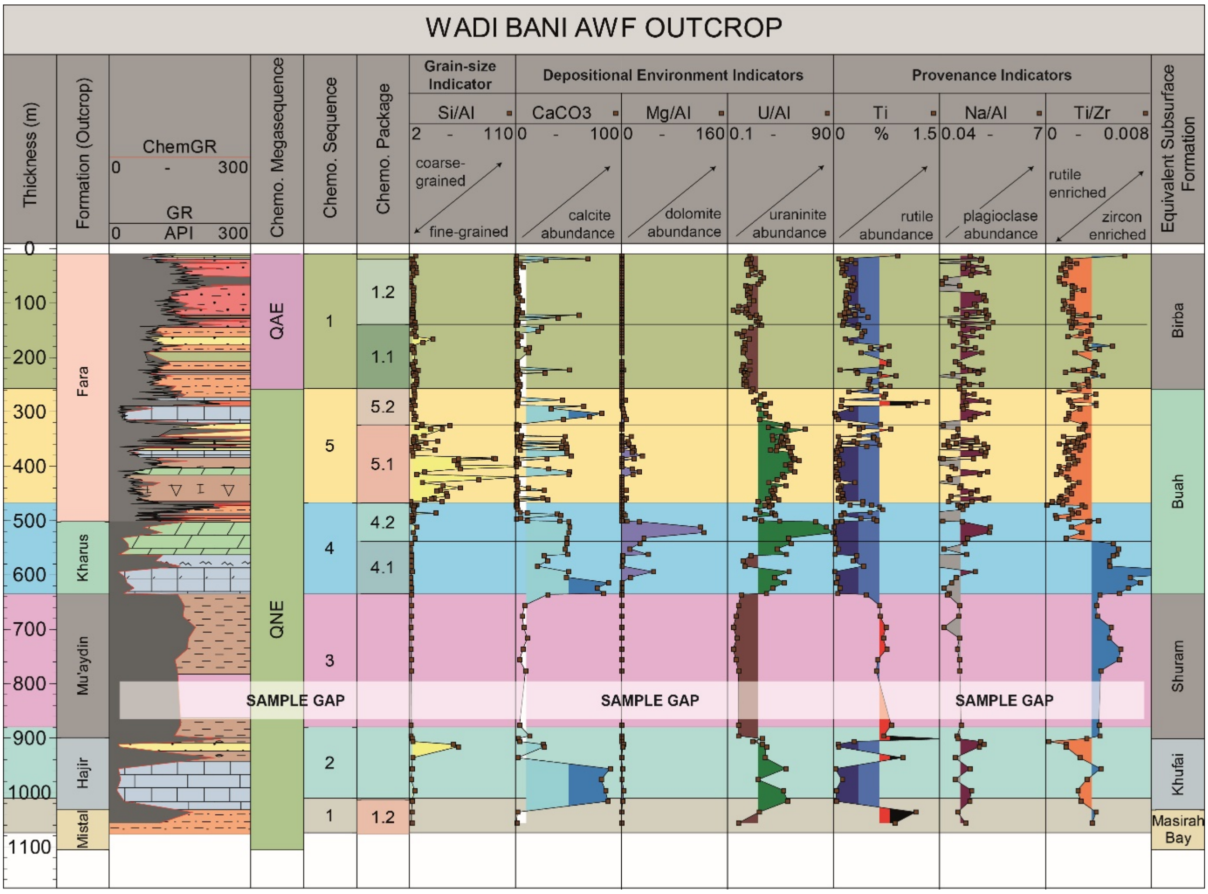

Figure 1: characterisation of the chemostratigraphic sequences and packages encountered in the late Neoproterozoic sedimentary succession at outcrop in northern Oman. Formation (Outcrop) as determined by Glennie et al., 1974; Rabu et al., 1993)

Zircon geochronology on selected samples highlights variable contributions of detritus from rocks of the Palaeozoic Angudan Orogeny, Neoproterozoic basement, as well as Palaeoproterozoic and Archean sources that are not currently known from the Arabian Plate. The recognition of Angudan-aged zircons (c.540Ma) facilitates the definition of maximum depositional ages of rocks that have no other form of chronostratigraphic control (Figure 2).

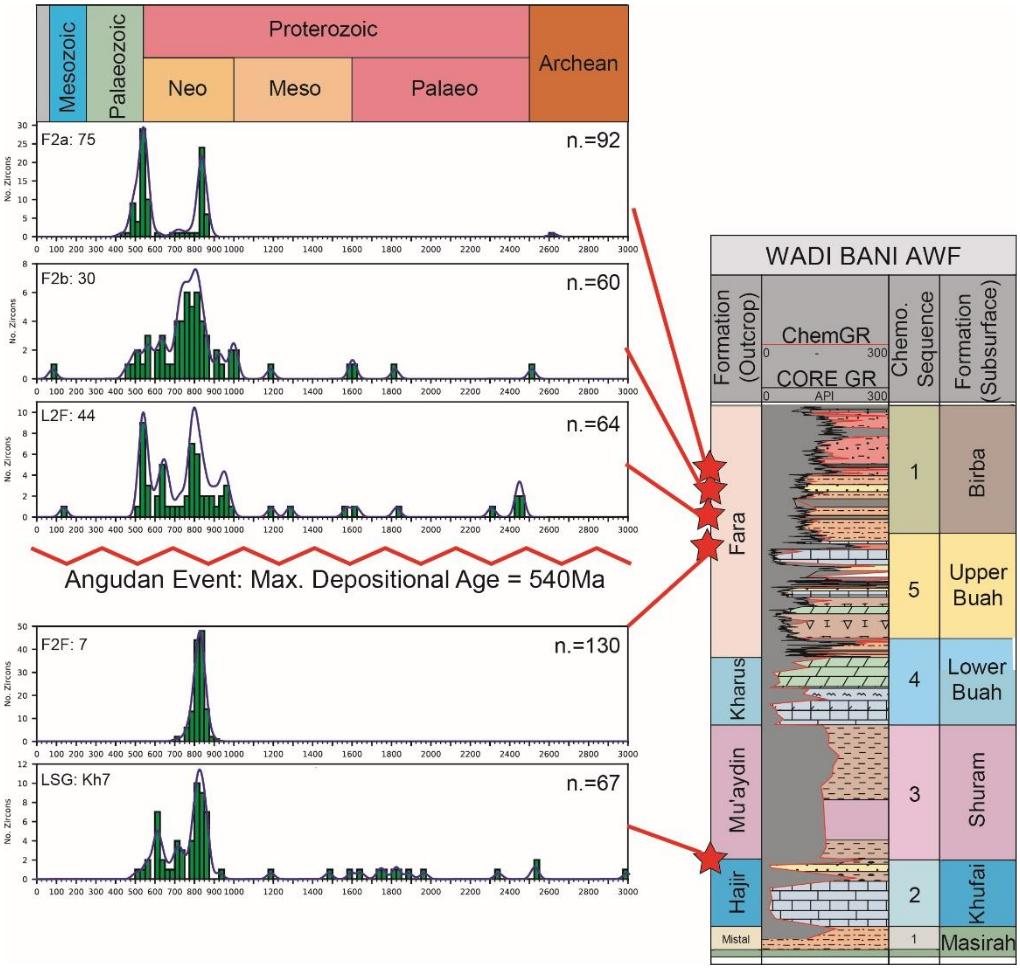

Figure 2: zircon geochronology histograms for five samples from Wadi Bani Awf

Conclusions

The results of this study demonstrate the efficacy of an integrated geochemical and mineralogical approach to defining a robust and age-constrained stratigraphic scheme for the late Neoproterozoic sedimentary succession of Oman that allows for clear correlations to be produced between outcrop and subsurface. The key elements and element ratios employed reflect changes in depositional environment and sediment provenance though time, the signatures of which can be traced through multiple lithologies with a high degree of confidence. Using a single chemostratigraphic nomenclature to define the sedimentary successions allows for clear correlations to be produced between outcrop and subsurface. Some of these units do not follow present lithostratigraphic boundaries from type sections in central Oman to the subsurface of south Oman. Integration of elemental data with other datasets (sedimentology, sequence stratigraphy, log data and stable isotope data) is ongoing to better understand the relationship between these sections.

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