Mineralogy variations in the Mamadawerre Sandstone, Kombolgie Subgroup at Angularli Uranium Prospect: Applications to exploration in other areas

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There is little publically available information on mineralogy variations in the Kombolgie Subgroup sandstones. This is important as mineralogy variations may result from alteration associated with mineralisation. Visual logging is the main tool in assessing alteration associated with mineralisation. However, visual logging is subjective and introduces variation by using different company generated logging templates or logging by multiple geologists. This hinders the ability to map alteration between drillholes. Recent HyLogging of drillcore around the Angularli prospect has identified mineralogy zonation and cross-cutting mineral relationships (mineral paragenesis) in the sandstones and conglomerates of the Kombolgie Subgroup. These results have increased understanding on differentiating diagenetic from hydrothermal mineralogy in sandstones. This information may be applied by explorers in other areas to assist in prioritising exploration targets.

Unconformity-style uranium mineralisation alteration

The Alligator Rivers Uranium Field, located in west Arnhem Land hosts a number of unconformity-style uranium deposits, including; Ranger 1 and 3, Koongarra, Nabarlek and Jabiluka 1 (**Figure 1**). Uranium deposits in this area are economically significant, with a combined estimated uranium endowment of 360 000 t U_3O_8 (Lally and Bajwah 2006). Key features of this style of mineralisation are well documented (Lally and Bajwah 2006 and references herein). These features include mineralisation within the basement rocks immediately below the unconformity, and an association with structural traps (fault or breccia zone). Palaeoproterozoic basement rocks of the Nimbuwah Domain (Pine Creek Orogen) comprise metamorphosed sedimentary rocks of the Cahill Formation and Nourlangie Schist and mafic amphibolite (Hollis and Glass 2012). A spatial association between Neoarchean granitic gneisses and uranium mineralisation is also been documented (Hollis and Glass 2012 and reference therein). Sandstones of the Kombolgie Subgroup, McArthur Basin unconformably overlie the Neoarchean and Palaeoproterozoic basement rocks (**Figure 2**). The Oenpelli Dolerite intrudes both the sandstones and the basement metamorphic rocks. Mg-Al-rich chlorite accompanied uranium deposition in and around ore in some deposits (eg Jabiluka, Figure 1: Gustafson and Curtis 1983; Ranger 1#3: Potma *et al* 2012). However, at Nabarlek (**Figure 1**) uraninite mineralisation was not coeval with chlorite, but precipitated with illite and hematite (Polito *et al* 2004). This demonstrates that alteration varies between deposits and can increase the difficulty in exploring for these deposits. Exploration success is further hampered by the surface expression of thick sequences of Kombolgie Subgroup sandstones masking mineralisation.

Fluid flow through the sandstones of the Kombolgie Subgroup is considered a key factor in the development of unconformity-style uranium mineralisation (Hollis and Glass 2012). Sandstone mineralogy is not affected by variations in protolith composition or overprinting metamorphism, so mineralogy changes are likely to be due to diagenesis and/or hydrothermal alteration. Diagenetic mineralogy that has not been overprinted by later-stage hydrothermal fluid flow would be expected to have a consistent composition and crystallinity within a thick interval and/or over a large area. The ability to distinguish diagenetic minerals from hydrothermal minerals would be useful in identifying fluid pathways and prioritising exploration targets.

Previous studies

Previous studies have focussed on characterising alteration within the underlying Cahill Formation or Nourlangie Schist host rocks at uranium deposits. Beaufort *et al* (2005) analysed 230 samples from seven sites, while other studies focussed on Nabarlek (Wilde and Wall 1987, Polito *et al* 2004), Ranger (Potma *et al* 2012), and Jabiluka deposits (Gustafson and Curtis 1983, Nutt 1989). Methods of analysis include x-ray diffraction (XRD), x-ray fluorescence (XRF), petrography, electron microprobe, isotope measurements and microthermometry, and hyperspectral analysis (at 0.5–1 m spacings). The hyperspectral analyses collected spectra from the visible and near infrared (VNIR) and shortwave infrared (SWIR) wavelength ranges (350–2500 nm) from basement lithologies below the unconformity at Ranger 1#3 (Potma *et al* 2012).

There is little publically available information on mineralogy variations in the Kombolgie Subgroup sandstones above the unconformity. Quirt (1998) characterised the Kombolgie Subgroup sandstones in the Deaf Adder Project area, noting diagenetic features and hydrothermal alteration. This study developed a rating scheme attempting to differentiate diagenetic features from diagenetic-hydrothermal features to be used in prioritising targets in mineral exploration.

Angularli prospect

Angularli is an unconformity-style uranium prospect located in western Arnhem Land, about 50 km north of Oenpelli in the COBOURG PENINSULA[3] map area (**Figure 1**). It is located below a cover of Cretaceous Bathurst Island Formation sedimentary rocks, and a 250 m thick succession of Mamadawerre Sandstone of the Kombolgie Subgroup above the unconformity-style uranium mineralisation. The Angularli prospect was discovered from an offset in TEMPEST airborne electromagnetic data that coincides with a NW-trending magnetic feature (King

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[3] Names of 1:250 000 and 1:100 000 mapsheets are shown in large and small capital letters respectively, eg COBOURG PENINSULA, OENPELLI

2012). The mineralisation is described as being primarily in the hanging wall of a structural zone (Angularli fault zone) extending from the basement into the overlying sandstone. Intense silica-sericite-clay pyrite alteration surrounds the primary mineralisation. The alteration halo and sandstone mineralogy is not described (King 2012).

HyLogger results

A summary of the mineralogy results for the Mamadawerre Sandstone around the Angularli prospect is presented here. It is part of a collaborative project between NTGS and Joint Venture partners Cameco Australia Pty Ltd and Rio Tinto Exploration Pty Ltd (Smith and Sinclair in prep), which also documents the mineralogy of the Cahill Formation within the geological context of the Angularli prospect. The aim of this summary is to document the mineralogy changes in the sandstone and highlight implications for uranium exploration in other areas.

Seventeen drillholes in this study were scanned by HyLogger 3-7 in Darwin, with 15 of the drillholes remaining the property of the Rio Tinto / Cameco Joint Venture (JV). Two of the drillholes (WRDD0134 and WRDD0136) were drilled as part of the NTGS Geophysics and Drilling Collaborations Programme (Round 9; 2016). Any drill core interval that recorded a reading of >500 ppm eU_3O_8 and intervals within the same core tray were not scanned. Thus mineralisation and immediately adjacent intervals are excluded from this study. Lithological and stratigraphic logs were provided by Cameco on behalf of the JV and give context to the HyLogger results. To validate the HyLogger response, a small number of samples were analysed by XRD.

Key findings from this study of sandstone mineralogy include the following observations.

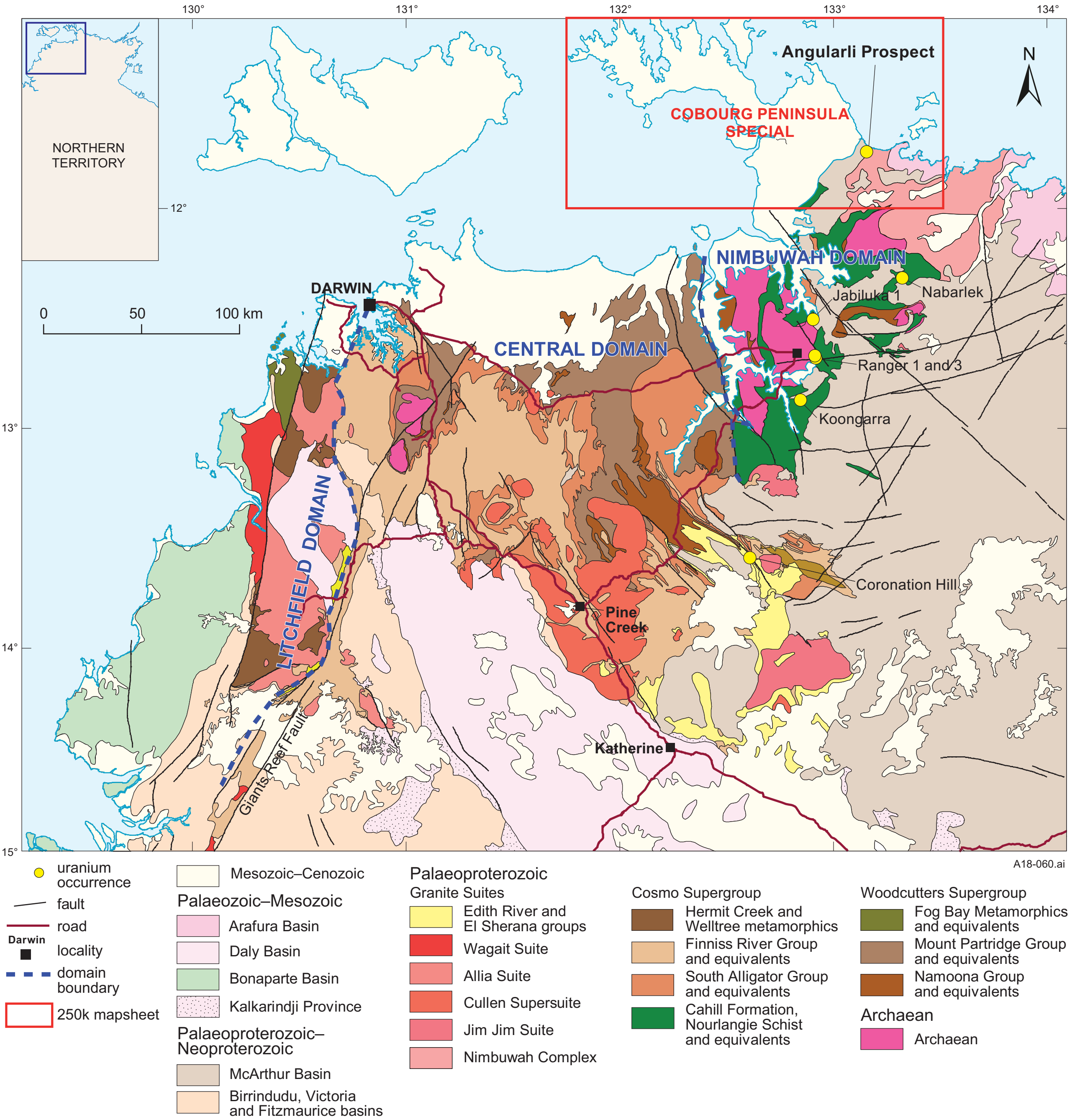

Figure 1. Regional geology of the Pine Creek Orogen showing the location of the Angularli prospect and major uranium deposits.

i) Quartz is the dominant mineral. No feldspars were identified in any of the sandstones.
ii) Most of the matrix around the quartz occurs as a mixture of minerals. For example, kaolinite may be in a mineral mixture with white mica +/- dickite +/- pyrophyllite +/- diaspore.
iii) White micas (short wavelength, muscovitic white micas) and well-crystalline kaolinites are the most common matrix minerals around quartz. White micas and kaolinite are found both proximal and distal to mineralisation.
iv) White micas distal to mineralisation are more likely to have a consistent wavelength and crystallinity (eg in drillhole WRDD0136).
v) Well-crystalline kaolinite most commonly occurs as a matrix mineral with hematite. Less commonly, kaolinite with goethite is found in fractures or in weathered sandstone. In a mineralised hole at Angularli (WRD0084), kaolinite is found with goethite between two zones of (unscanned) sandstone-hosted mineralisation.
vi) There is a north-south zonation of some minerals at Angularli prospect:
   a. White mica intervals become thinner with increasing crystallinity moving from north to south.
   b. Kaolinite is more common in holes to the north, with less kaolinite in holes to the south.
   c. Dickite and pyrophyllite increase in quantity and interval thickness moving further south. Sporadic pyrophyllite and dickite associated with fractures are found both in holes to the north at Angularli prospect, and distal to Angularli prospect.
vii) There is a zonation of mineralogy with depth in some holes:
   a. 'Pure' kaolinite occurs for thicknesses of around 110–140 m extending from 70 m uphole of the unconformity in drillholes over a mineralised cross-section of the Angularli prospect (MGA 8701450 N).
   b. Thick intervals of dickite may be mixed with well-crystalline kaolinite at shallower depths and at transitions to dickite mixed with pyrophyllite closer to the unconformity.
   c. Thick intervals of pyrophyllite are found in the lower portions of the sandstone and adjacent to intervals that contain sandstone-hosted mineralisation.
   d. Matrix-hosted Mg chlorite is found in limited intervals in the upper part of the sandstone to the north at Angularli prospect. There is no matrix chlorite in sandstones further south at Angularli. Chlorite (when present) in other holes is usually associated with alteration around intrusives (eg Oenpelli Dolerite) or along fractures.
viii) Pyrophyllite is either absent or minor in holes away from Angularli mineralisation.
ix) Matrix pyrophyllite (when present) is found in sandstones with varying grain size and textures.
x) Diaspore is found in the Angularli fault zone and/or adjacent to the (unscanned) mineralised zones. It is not found away from the Angularli fault zone or distal to mineralisation.
xi) Tourmaline is not common, but is found proximal to mapped mineralisation, especially within the sandstone matrix. Tourmaline is either extremely minor or absent away from mineralisation.

As well as mineralogy zonation, there is evidence for several phases of minerals based on cross-cutting relationships. White mica, kaolinite, dickite and pyrophyllite occur as thick intervals within the matrix of the quartzose

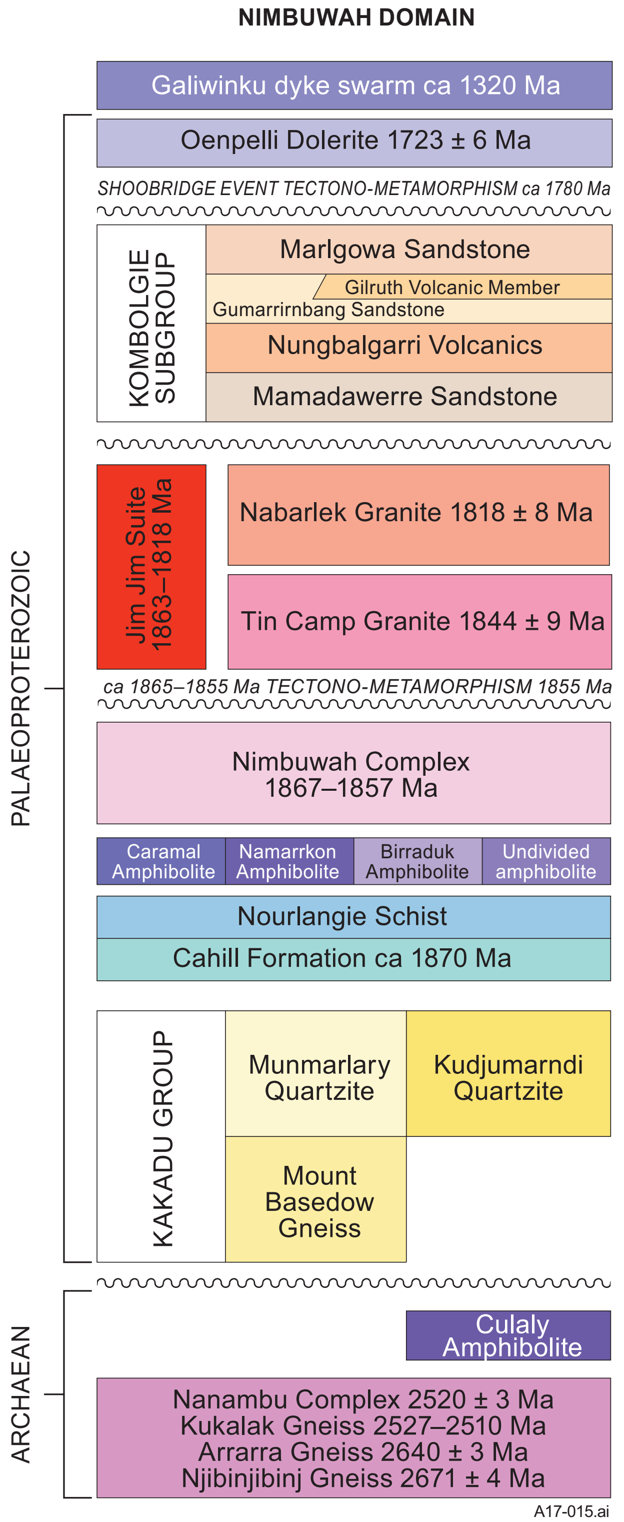

Figure 2. Simplified stratigraphic column of the Nimbuwah Domain, Pine Creek Orogen. Modified from Hollis and Glass (2012).

sandstone. These minerals are also found as later-stage fracture linings cross-cutting the matrix minerals. Dickite and pyrophyllite are absent from the alteration selvedge around dolerite intrusions. This would imply that the dickite and pyrophyllite predated the dolerite intrusives.

Kaolinite and white mica are common diagenetic minerals that can form at shallow depths in warm wet conditions. Dickite is a high temperature kaolin polymorph and can be a common indicator of burial depth (3–4.5km burial depth, with temperatures of 90–130°C; Worden and Morad 2003). Diagenetic dickite would perhaps be expected to be regionally pervasive, especially in areas with no textural evidence of alteration, such as around faults. At Angularli prospect, the dickite is zoned along the Angularli fault zone, increasing to the south. Fracture-hosted dickite is also found in holes distal to Angularli prospect (WRDD0136).

Pyrophyllite is rarely documented in sandstones; it is usually found in aluminium-rich metamorphic rocks, or as a hydrothermal alteration product in siliceous rocks (Deer *et al* 2013). Pyrophyllite can form from kaolinite in the presence of quartz-rich fluids at around 345°C and 2 Kbars water pressure (Eberl and Howie 1974). The zoned pyrophyllite distribution at Angularli, along with the lack of evidence of overprinting metamorphism in the sandstones, would indicate pyrophyllite emplacement is from localised high temperature hydrothermal alteration of kaolinite, rather than as a diagenetic effect.

Diaspore also forms at high temperatures (275°C; Ervin and Osborn 1951) and can form from the desilicification of kaolinite or pyrophyllite (Essene *et al* 1994). This process of desilicification liberates quartz and water into the system. As with pyrophyllite formation, the presence of diaspore and its location within faults and near mineralisation would indicate hydrothermal emplacement.

Tourmaline is found within fractures and breccias or as patchy matrix infill in the sandstones proximal to the Angularli mineralisation. It is not detrital tourmaline. Tourmaline (specifically dravite) is well-documented in alteration haloes around uranium mineralisation in the Athabasca Basin (Hoeve and Sibbald 1978).

Application to exploration

As noted above, visual logging is subjective and introduces variation from the use of different logging templates or from logging by multiple geologists. The use of hyperspectral instruments such as HyLogger, objectively logs mineralogy and allows for comparisons between drillholes.

This study has generated more than 360 000 mineralogy results from the Mamadawerre Sandstone. Previous studies focussing on sandstone mineralogy were based on tens or hundreds of samples. The higher number of samples in this study has highlighted the mineralogical zoning in the sandstone. This contrasts with the findings in previous work (eg Beaufort et al 2005) which categorised the sandstones as containing illite and/or kaolinite, but did not describe spatial relationships of the mineralogy. Being able to recognise mineralogical zonation and overprinting will assist in determining fluid pathways within the sandstone and rating the prospectivity of the sandstone.

This study has indicated that collecting spectra with imagery from both the sandstone matrix and fractures may be used to determine cross-cutting mineralogy and mineral paragenesis. Handheld field hyperspectral instruments (Terraspec, ASD, PIMA etc) could be used in lieu of a HyLogger to map mineralogy, especially when used in conjunction with photographing textures. The standard practice of routinely collecting one metre-spaced spectral data of sandstone matrix is more useful when additional measurements of fractured or 'bleached' material are also collected. Cross-referencing the spectral data with texture photos can be done in the field to enhance understanding of cross-cutting mineralogy.

When collecting or assessing spectral data from sandstones, it is useful to note the following issues and observations.

i) White mica crystallinity and composition should be filtered for samples containing 'pure' white mica only (not in a mineral mix with other Al-rich minerals such as kaolinite or pyrophyllite). The presence of these other Al-rich minerals gives a spurious result which will impact on geological interpretation.
ii) Presence or absence of variation in sandstone mineralogy. A monotonous sequence of white mica with no change in composition or crystallinity has probably not been in contact with post-diagenetic fluid flow (diagenetic aquitard).
iii) Presence of chlorite, tourmaline and diaspore in sandstone, with textural context (in matrix, or along fractures/faults).
iv) Minerals with overlapping spectral features (such as pyrophyllite and kaolinite) may not give accurate mineral matches within the TSG software. This may affect the interpretation of geological history of the sandstone. Minerals such as kaolinite and pyrophyllite can be distinguished by using scalars based on the diagnostic reflectance features in other wavelength ranges, or confirmed with other methods (such as XRD). Assays may be useful (eg; in confirming tourmaline by using boron assays).
v) Mineralogical and textural information integrated with other known geological information (location of intrusives, distance from major faults, and proximity to unconformity). For example, is the change in mineralogy explained by the presence of post-mineralisation intrusives (which could downgrade the significance of the mineral change)?
vi) Integrate the mineralogical information with external information. If assay results are available, there should be a change in the K:Al ratio in kaolinitic sandstones compared with white mica-rich sandstones. This could be used to confirm large-scale mineralogy changes. Petrography can illustrate the quantity of quartz cement (from diagenesis, which could impair fluid flow). Deformed quartz grains and styolites could indicate significant burial depth during diagenesis. This information could be used to determine whether dickite is more likely to be diagenetic rather result from hydrothermal fluids. Integrating surface hyperspectral results (ie HyMap) with drillcore could identify mineralogical zonations on

a regional scale. Beckitt (2003) presented results from integrating HyMap with PIMA results at King River.

The mineralogy in Kombolgie Subgroup sandstones may vary between depocentres / sub-basins due to differences in diagenetic conditions. For example, a closed sub-basin may favour widespread diagenetic white mica formation over kaolinite. A sub-basin that underwent deeper burial than another depocentre may have a higher quartz cement content that affected permeability during diagenesis. A deeper burial in one sub-basin may favour the development of diagenetic dickite. Comparing the diagenetic mineralogy between areas may not be useful if the areas are in different sub-basins.

There are also variations in alteration minerals around uranium mineralisation between deposits. Chlorite is associated with uranium mineralisation at Jabiluka, which contrasts with the illite–hematite alteration at Nabarlek. These mineralogical differences demonstrate that there is no prescriptive list of minerals that may indicate uranium mineralisation. The textural context is also important. For example, sandstone-hosted chlorite near the unconformity is related to mineralisation at Jabiluka, but sandstone-hosted chlorite may also be in an alteration selvedge around Oenpelli Dolerite (as noted in this study). Chlorite may also suggest fluid flow along a fault zone, as interpreted by the presence of chlorite in breccia zones within the sandstone at the Angularli prospect.

Integrating carefully processed spectral data (either from HyLogger or handheld field ASD instruments) with photographs and other ancillary data can aid in differentiating diagenetic minerals from hydrothermal minerals, which can then be used to prioritise exploration areas.

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