Summary of results.
Re–Os molybdenite dating of copper and tungsten mineralisation in the Tennant Creek mineral field, and Hatches Creek and Mosquito Creek tungsten fields, Warramunga Province.

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SUMMARY

This Record details rhenium–osmium (Re–Os) geochronology for molybdenite from one copper–molybdenum prospect (Explorer 27), two tungsten deposits (Pioneer, Hill of Leaders) and one tungsten prospect (North Curtis) in the Warramunga Province of central Australia. Molybdenite was dated to determine absolute ages of mineralised quartz veins and to provide an indication of the timing of copper and tungsten mineralisation in the area.

Two samples of molybdenite associated with chalcopyrite in quartz veins were collected from the Explorer 27 prospect in the Tennant Creek mineral field. Sample TC18MVM001 yielded a Re–Os model age of 1711 ± 8 Ma, and sample TC18MVM002 yielded a Re–Os model age of 1719 ± 8 Ma. These ages are interpreted to record the timing of copper and molybdenum mineralisation at Explorer 27. The ages indicate an episode of copper mineralisation in the Tennant Creek mineral field younger than the reported age of most ironstone-related copper–gold deposits in the same mineral field. These results represent the first time that copper mineralisation of this age has been reported in the Tennant Creek mineral field.

One molybdenite sample (FR18MVM001), associated with scheelite and wolframite in a quartz vein, was collected from the Pioneer tungsten deposit in the Hatches Creek tungsten field. This sample yielded a Re–Os model age of 1714 ± 8 Ma. This new model age is interpreted as a direct age for tungsten mineralisation at the deposit. It is broadly consistent with previous Ar–Ar ages and is slightly older than Re–Os molybdenite ages from mineralisation elsewhere in the Hatches Creek tungsten field.

One molybdenite sample (BC18MVM003), associated with scheelite in a quartz vein at the Hill of Leaders tungsten deposit in the Mosquito Creek tungsten field, yielded an impossible Re–Os model age of 6713 ± 30 Ma. Analysis of this sample was repeated and yielded another geologically impossible age of 4940 ± 20 Ma.

One further molybdenite sample (BC18MVM006), from a quartz vein associated with tungsten mineralisation from the North Curtis tungsten prospect in the same tungsten field as Hill of Leaders, yielded a Re–Os model age of 1777 ± 9 Ma. This age is younger than the age of the Hill of Leaders Granite that hosts the mineralisation and is tentatively interpreted as a mineralisation age.

The new molybdenite ages reported in this study from the Tennant Creek and Hatches Creek fields are similar; they also share a similar timing to copper and tungsten mineralisation elsewhere in central Australia: for example, tungsten mineralisation at the Juggler prospect in the ca 1720 Ma Elkedra Granite in the Davenport Province, and further afield, granite-related copper and tungsten mineralisation in the eastern Aileron Province (eg Jervois mineral field, Bonya Hills area, Molyhil). Although further work is necessary, this similarity may suggest a widespread granite-related copper and tungsten mineralising episode at ca 1730–1680 Ma in the region.
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INTRODUCTION

This Record presents new Re–Os molybdenite geochronology results from four previously undated deposits and prospects in the Warramunga Province of central Australia: the Explorer 27 copper–molybdenum prospect in the Tennant Creek mineral field in TENNANT CREEK, the Pioneer tungsten deposit in the Hatches Creek tungsten field in FREW RIVER, and both the Hill of Leaders tungsten deposit and the North Curtis tungsten prospect in the Mosquito Creek tungsten field in BONNEY WELL. The Warramunga Province covers the area in and around Tennant Creek and is located approximately 375 km north of Alice Springs (Figure 1).

Copper–gold and tungsten mineralisation are widespread in the Warramunga Province; it occurs within the Tennant Creek mineral field, and the Hatches Creek, Waughope and Mosquito Creek tungsten fields (eg Ferenczi and Ahmad 1996, Fraser et al 2008, Donnellan 2013a, b; McGloin et al 2019). In many cases, the age of copper or tungsten mineralisation is relatively well understood (eg Compston and McDougall 1994, Warren et al 1995, Fraser et al 2008, Donnellan 2013a, 2013b). Other prospects and deposits have less certain, and in some cases, only inferred mineralisation ages (eg Wyborn et al 1998, McInnes et al 2008, Donnellan 2013a–b, Skirrow et al (in review), McGloin et al 2019). This study was conducted to constrain the timing of tungsten mineralisation in the Tennant Creek mineral field, and Hatches Creek and Mosquito Creek tungsten fields. It also provides an opportunity to test the validity of the Re–Os method for dating tungsten mineralising events in the region.

This Record documents the sampled locations, geological context, descriptions of the targeted molybdenite, and the relevant analytical data. The sampled locations are shown in Figure 1. Table 1 lists a summary of the results. A brief discussion and interpretation of the isotopic data is also included.

Re–Os MOLYBDENITE DATING

The Re–Os chronometer for dating molybdenite is a robust and reliable chronologic tool (Stein et al 2001, Norman et al 2004 and references therein). Re–Os is a closed isotopic system in molybdenite during high-grade metamorphism and deformation, even under granulite facies conditions (Bingen and Stein 2003). It is not commonly susceptible to chemical and thermal disturbances (Stein et al 2001). The Re–Os system appears particularly useful in terranes that have experienced multiple hydrothermal, magmatic and metamorphic episodes. This is because molybdenite typically is not complicated by overgrowths that are common in minerals like zircon, monazite and xenotime (Stein et al 2001; but see Aleinikoff et al 2012 for a counter example).

The Re–Os molybdenite system has produced lower closure temperatures in some examples (at least ~550°C; eg Suzuki et al 2001) compared to more traditional U–Pb mineral chronometers (~800–600°C; eg zircon, monazite, titanite, baddeleyite). However, closure temperatures are usually higher than many other chronometers (ie Rb–Sr, K–Ar, Ar–Ar; eg muscovite at ~350°C; Schaefer 2016). Other studies have demonstrated that closure temperatures for the molybdenite Re–Os system can be higher depending on the deposition system (~800°C; Bingen and Stein 2003, Selby et al 2004).

ANALYTICAL PROCEDURES

SAMPLE PREPARATION

Re–Os molybdenite dating was conducted at the University of Alberta in December 2018 and January 2019 on samples collected in the field in October 2018 by the Northern Territory Geological Survey. Molybdenite was separated by metal-free crushing, followed by gravity and magnetic concentration methods as described by Selby and Creaser (2004). Sample weights are reported in Table 2.

ANALYSIS

The methods used for molybdenite analysis are described in detail by Selby and Creaser (2004). The $^{187}$Re and $^{188}$Os concentrations in molybdenite were determined by isotope dilution mass spectrometry using Carius-tube, solvent extraction, anion chromatography and negative thermal ionization mass spectrometry (ID–NTIMS) techniques. A mixed double spike containing known amounts of isotopically enriched $^{187}$Re, $^{188}$Os, and $^{188}$Os was used (Markey et al 2007). Isotopic analysis was carried out on a ThermoScientific Triton mass spectrometer by Faraday collector. Total blanks for Re and Os are less than 3 picograms and 2 picograms respectively, which are insignificant for the Re and Os concentrations in molybdenite. The Reference Material 8599 Henderson molybdenite (Markey et al 2007) was used as an analysis standard. During the past year, this standard returned an average Re–Os date of 27.76 ± 0.08 Ma (n = 8), indistinguishable from the reference age value of 27.66 ± 0.1 Ma (Wise and Watters 2011). All uncertainties are quoted at 2σ level, and comprise all known analytical uncertainty, including uncertainty in the decay constant of $^{187}$Re.

---

1 Names of 1:100 000 and 1:250 000 mapsheets are shown in small and large capital letters, respectively, eg SHORT RANGE, TENNANT CREEK
Figure 1. Regional geological map of the Northern Territory showing location of molybdenite samples reported in this Record.
Table 1. Summary of molybdenite dating results. Re–Os model ages in bold are considered mineralisation ages; model ages in italics are considered geologically meaningless.

<table>
<thead>
<tr>
<th>Sample description</th>
<th>Prospect/deposit</th>
<th>Mineral field</th>
<th>Sample No</th>
<th>Target mineral</th>
<th>MGA94 zone</th>
<th>Easting (mE)</th>
<th>Northing (mN)</th>
<th>Re–Os model age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chalcopyrite-molybdenite-bearing quartz vein</td>
<td>Tennant Creek mineral field</td>
<td>TC18MVM001</td>
<td>molybdenite</td>
<td>53 K</td>
<td>378009</td>
<td>7864932</td>
<td>1711 ± 8</td>
</tr>
<tr>
<td></td>
<td>Chalcopyrite-molybdenite-bearing quartz vein</td>
<td>Tennant Creek mineral field</td>
<td>TC18MVM002</td>
<td>molybdenite</td>
<td>53 K</td>
<td>378009</td>
<td>7864932</td>
<td>1719 ± 8</td>
</tr>
<tr>
<td></td>
<td>Molybdenite-tungsten-bearing quartz vein</td>
<td>Hatches Creek mineral field</td>
<td>FR18MVM001</td>
<td>molybdenite</td>
<td>53 K</td>
<td>518579</td>
<td>7692107</td>
<td>1714 ± 8</td>
</tr>
<tr>
<td></td>
<td>Molybdenite-scheelite-bearing quartz vein</td>
<td>Mosquito Creek tungsten field</td>
<td>BW18MVM003</td>
<td>molybdenite</td>
<td>53 K</td>
<td>463087</td>
<td>7753693</td>
<td>6713 ± 30</td>
</tr>
<tr>
<td></td>
<td>Molybdenite-scheelite-wolframite-bearing quartz vein</td>
<td>Mosquito Creek tungsten field</td>
<td>BW18MVM006</td>
<td>molybdenite</td>
<td>53 K</td>
<td>462172</td>
<td>775467</td>
<td>1777 ± 9</td>
</tr>
</tbody>
</table>

Table 2. Summary of Re–Os age determinations. All uncertainties are quoted to 2σ uncertainties. Re–Os model ages in bold are considered mineralisation ages. ppb = parts per billion, ppm = parts per million.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample weight (mg)</th>
<th>Re (ppm)</th>
<th>± 2σ</th>
<th>²⁶⁷⁴⁸Re (ppm)</th>
<th>± 2σ</th>
<th>²⁶⁷⁴⁸Os (ppb)</th>
<th>± 2σ</th>
<th>Model age (Ma)</th>
<th>± 2σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC18MVM001</td>
<td>50</td>
<td>6.835</td>
<td>0.020</td>
<td>4.296</td>
<td>0.013</td>
<td>124.20</td>
<td>0.10</td>
<td>1711</td>
<td>8</td>
</tr>
<tr>
<td>TC18MVM002</td>
<td>9</td>
<td>1.303</td>
<td>0.004</td>
<td>0.819</td>
<td>0.002</td>
<td>23.80</td>
<td>0.03</td>
<td>1719</td>
<td>8</td>
</tr>
<tr>
<td>FR18MVM001</td>
<td>20</td>
<td>1.180</td>
<td>0.003</td>
<td>0.742</td>
<td>0.002</td>
<td>21.49</td>
<td>0.02</td>
<td>1714</td>
<td>8</td>
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<tr>
<td>FR18MVM001RPT</td>
<td>33</td>
<td>2.134</td>
<td>0.006</td>
<td>1.342</td>
<td>0.004</td>
<td>38.86</td>
<td>0.04</td>
<td>1714</td>
<td>8</td>
</tr>
<tr>
<td>BW18MVM003</td>
<td>20</td>
<td>1.616</td>
<td>0.005</td>
<td>1.015</td>
<td>0.003</td>
<td>120.20</td>
<td>0.10</td>
<td>6713</td>
<td>30</td>
</tr>
<tr>
<td>BW18MVM003RPT</td>
<td>60</td>
<td>2.194</td>
<td>0.006</td>
<td>1.379</td>
<td>0.004</td>
<td>118.30</td>
<td>0.30</td>
<td>4940</td>
<td>24</td>
</tr>
<tr>
<td>BW18MVM006</td>
<td>26</td>
<td>2.258</td>
<td>0.007</td>
<td>1.420</td>
<td>0.004</td>
<td>42.66</td>
<td>0.10</td>
<td>1777</td>
<td>9</td>
</tr>
</tbody>
</table>
SAMPLES ANALYSED

Chalcopyrite–molybdenite–pyrite-bearing quartz vein, Explorer 27 prospect (TC18MVM001)

Sample information

NTGS Sample ID: TC18MVM001
Collector: Matt McGloin
1:250 000 mapsheet: TENNANT CREEK (SE 53-14)
1:100 000 mapsheet: SHORT RANGE (5659)
Province: Warramunga Province
Grid reference: MGA94 Zone 53, 378009mE 7864932mN
Approximate position based on map of Tapp 1966
Drillhole: DDH1 (EXP027, Bureau of Mineral Resources)
Azimuth: 360°
Declination: -60°
Depth: 170.5 m (557')
Lithology: chalcopyrite–molybdenite–pyrite-bearing quartz vein
Geochronology target: molybdenite

Interpreted model age summary

1711 ± 8 Ma

Sample details and lithological characteristics

Molybdenite was sampled from diamond drillhole DDH1 at 170.5 m downhole depth. DDH1 intersected mineralisation at the Explorer 27 prospect in central eastern SHORT RANGE, Tennant Creek mineral field. The sampled molybdenite was hosted in a 2 cm-wide quartz vein along with chalcopyrite and pyrite (Figure 2). The quartz vein cuts a light grey to faint pink, foliated metamudstone rock. A thin selvedge of feldspar and chlorite occurs on the margins of the quartz vein. Molybdenite is fine-grained, typically 1–2 mm diameter and disseminated within the quartz vein. It is spatially associated, and commonly occurs in clusters, with chalcopyrite and pyrite.

DDH1 tested a gossanous limonite outcrop with anomalously high Cu and Mo surface geochemistry (Yeaman 1969). It was drilled to target mineralisation at depth after geochemical sampling over a geophysical anomaly at the Explorer 27 prospect yielded anomalous results for Cu (≤1500 ppm) and Mo (≤800 ppm; Yeaman 1969). At surface, exposures of limonite-bearing gossan represent oxidised sulfide mineralisation. Only minor amounts of chalcopyrite, pyrite and molybdenite in quartz veins were intersected during drilling, so the drill core was not assayed (Yeaman 1969).

The limonite gossans at Explorer 27 are now mapped as part of the Wundirgi Formation, a sequence of arenite, siltstone, shale and tuff within the Ooradidgee Group (Donnellan 2001, Donnellan et al 2001; Figure 3). The Wundirgi Formation is intruded by sills and small plutons of monzonite, quartz monzonite and quartz diorite (Donnellan 2001, Donnellan 2013a). SHRIMP U–Pb zircon dating of a sample of monzodiorite that intrudes the Wundirgi Formation near the Last Hope gold mine constrains a minimum depositional age of 1821 ± 8 Ma (Compston 1995) for the metasedimentary rocks that host mineralisation at Explorer 27.

The Explorer 27 prospect occurs close to vein-hosted, alluvial, and eluvial gold mineralisation (Figure 3). The Last Hope gold deposit is located ~3 km (Yeaman 1969), and the Bull Pup gold deposit, ~3.6 km southeast of Explorer 27 (Tapp 1966).

As the Explorer 27 prospect is located close to the margin of monzonite, quartz monzonite, and quartz diorite intrusions, it is possible that the copper–molybdenum mineralisation sampled in TC18MVM001 may have a similar age to the dated monzodiorite. Mineralisation at the prospect is hosted in quartz veins, unlike most copper mineralisation in the Tennant Creek mineral field, which is typically associated with ironstone bodies (Yeaman 1969, Donnellan 2013a and references therein). 40Ar/39Ar dating of coarse white mica associated with ironstone-hosted gold–copper–bismuth mineralisation at four deposits of the Tennant Creek mineral field has yielded re-calibrated 40Ar/39Ar ages ranging from 1851 ± 11 Ma to 1847 ± 11 Ma.
Figure 3. Geological map of the location of the Explorer 27 prospect (map adapted from Tapp 1966 and Donnellan 2001).

(Fraser et al. 2008, recalculated from Compston and McDougall 1994). These ages are broadly consistent with Pb model ages of ca 1855–1835 Ma from lead-bearing ironstone-hosted mineralisation (Warren et al. 1995). Dating of molybdenite at Explorer 27 was carried out to constrain the timing of this atypical style of Cu–Mo mineralisation.

Model result

ID–NTIMS analysis of molybdenite from sample TC18MVM001 yielded a model age of 1711 ± 8 Ma (2σ). The Re–Os isotopic data for this sample are reported in Table 2.

Interpretation of result

The ca 1711 Ma model age for sample TC18MVM001 (Table 2) is interpreted to record the timing of copper–molybdenum mineralisation at the Explorer 27 prospect. Further interpretation of this result is described after consideration of the results of sample TC18MVM002 from the same prospect (this Record).

Chalcopyrite–molybdenite–pyrite-bearing quartz vein, Explorer 27 prospect (TC18MVM002)

Sample information

NTGS Sample ID: TC18MVM002
Collector: Matt McGloin
1:250 000 mapsheet: TENNANT CREEK (SE 53-14)
1:100 000 mapsheet: SHORT RANGE (5659)
Province: Warramunga Province
Grid reference: MGA94 Zone 53, 378009mE 7864932mN (approximate position based on map of Tapp 1966)
Drillhole: DDH1 (EXP027, Bureau of Mineral Resources)
Azimuth: 360°
Declination: -60°
Depth: 175.3 m (571')
Lithology: chalcopyrite–molybdenite–pyrite-bearing quartz vein
Geochronology target: molybdenite

Interpreted model age summary

1719 ± 8 Ma

Sample details and lithological characteristics

Molybdenite was sampled from diamond drillhole DDH1 at 175.3 m downhole depth. DDH1 (Figure 3) intersected mineralisation at the Explorer 27 prospect in central eastern SHORT RANGE, Tennant Creek mineral field. DDH1 tested a gossanous limonite outcrop with anomalously high Cu and Mo surface geochemistry (Yeaman 1969). The sampled molybdenite was hosted in a 0.6 cm-wide quartz vein along with chalcopyrite, pyrite and minor hematite mineralisation (Figure 4). The quartz vein obliquely cuts a light grey to faint pink, compositionally layered metamudstone rock. A 0.1 cm-wide selvedge of feldspar occurs on the margins of quartz veins. Molybdenite is fine-grained, typically 1–2 mm diameter.
and disseminated within the quartz vein; it is commonly clustered with chalcopyrite and pyrite.

Details on drilling, geology, mineralisation and existing age constraints for sample TC18MVM002 are summarised in sample TC18MVM001 (this Record). Molybdenite sample TC18MVM002 was dated to confirm the timing of copper–molybdenum mineralisation at the Explorer 27 prospect, and to verify the reproducibility of the molybdenite dating technique at the prospect by comparison with sample TC18MVM001.

**Model result**

ID-NTIMS analysis of molybdenite from sample TC18MVM002 yielded a model age of 1719 ± 8 Ma (2σ). The Re–Os isotopic data for this sample are reported in Table 2.

**Interpretation of result**

The new ca 1719 Ma Re–Os model age for sample TC18MVM002 is within analytical uncertainty of the ca 1711 Ma model age from sample TC18MVM001 (this Record). Both samples were collected from similar copper–molybdenum-bearing quartz veins in DDH1 from Explorer 27. This suggests that both veins formed together during the same process.

A link between copper–molybdenum mineralisation and felsic intrusions at the Explorer 27 prospect is supported by the low Re concentrations (< 7 ppm) in the analysed molybdenite samples. These low Re concentrations are consistent with fluids sourced from relatively evolved granites or by dehydration of mid-crustal metamorphic rocks (Berzina et al 2005, Stein 2006). Low Re concentrations commonly indicate an evolved source (ie not an intermediate porphyry that might contain 50 ppm Re in the molybdenite; Berzina et al 2005).

The ca 1719–1711 Ma model ages are interpreted to constrain an absolute timing for copper–molybdenum mineralisation at Explorer 27. These results represent the first time that copper mineralisation of this age has been reported in the Tennant Creek mineral field.

The new molybdenite ages are also consistent with previously reported geochronology from other copper-bearing deposits in the Tennant Creek mineral field. A whole rock Re–Os isochron of high-grade copper sulfide (chalcopyrite) at the Gecko deposit yielded a model age of 1665 ± 66 Ma (McInnes et al 2008). However, the significance of this age remains unclear given the large uncertainty range (Donnellan 2013a). This chalcopyrite model age is within uncertainty of the new copper mineralisation ages from samples TC18MVM001 and TC18MVM002, which supports the possibility of a younger copper-related mineralising episode in the region. Furthermore, recent SHRIMP U–Pb dating of monazite associated with non-ironstone-related gold–copper–bismuth mineralisation at Navigator 6 and Orlando East yielded ages of ca 1660 Ma (Skirrow et al in review). Together with the results from this study, these ages provide evidence for previously unknown copper mineralising episodes in the Tennant Creek mineral field that are markedly younger than age estimates for ironstone related copper–gold–bismuth mineralisation (see Compston and McDougall 1994, Warren et al 1995, Fraser et al 2008, Donnellan 2013a). In addition, the new ages overlap with hydrothermal disturbances previously reported for the K–Ar system in hydrothermal muscovite and biotite at some ironstone-hosted copper-gold deposits (ca 1790–1710 Ma; see Compston and McDougall 1994). However, the magmatic source for this younger mineralisation and associated hydrothermal fluids is currently unrecognised in the area.

The new copper–molybdenum mineralisation ages from the Explorer 27 prospect are also within uncertainty of ages obtained for tungsten and copper mineralisation in the Davenport and Aileron provinces. This includes a new molybdenite model age from the Pioneer deposit in the Hatches Creek tungsten field (see sample FR18MVM001, this Record, for details and further discussion on a possible regional-scale mineralising event at this time).

![Figure 4](image.png)

**Figure 4.** Photograph of drill core from the Explorer 27 prospect showing a mineralised molybdenite-bearing quartz vein (sample TC18MVM002) cross-cutting metamudstone. Quartz vein is ~0.6 cm wide.
Molybdenite–scheelite–wolframite-bearing quartz vein, Pioneer deposit (FR18MVM001)

Sample information

NTGS Sample ID: FR18MVM001
Collector: Matt McGloin
NTGS Sample ID: FR18MVM001
Collector: Matt McGloin
1:250 000 mapsheet: FREW RIVER (SF 53-03)
1:100 000 mapsheet: HATCHES (5956)
Province: Warramunga Province
Grid reference: MGA94 Zone 53, 518579mE 7692107mN
Lithology: molybdenite–scheelite–wolframite-bearing quartz vein
Genechronology target: molybdenite

Interpreted model age summary

1714 ± 8 Ma

Sample details and lithological characteristics

A molybdenite–scheelite–wolframite-bearing quartz vein was collected from a mine dump in surface workings at the Dempsey and Jensen lodes in the western part of the Pioneer deposit, Hatches Creek tungsten field (Figure 5, 6a, b). The sample location is 10 m southwest of the orbital track that surrounds the former mine in south central HATCHES (Figure 5). Sample FR18MVM001 comprises coarse-grained molybdenite associated with scheelite and wolframite within a quartz vein (Figure 6c, d). Under ultraviolet light, the scheelite can be clearly distinguished from quartz by its strong fluorescence. The scheelite is intimately associated with molybdenite (Figure 6c, d). The quartz veins in the mine dump rocks cross-cut mafic amphibolite. Minor sulfides (chalcopyrite, pyrite, bornite) and malachite were also observed with the tungsten and molybdenum mineralisation. The quartz veins typically contained minor hematite and tourmaline with muscovite and K-feldspar selvedges commonly well-developed on vein margins. Figure 5 shows the mine dump and the location of the Dempsey and Jensen lodes to the northwest.

The Pioneer deposit is located in the north of the Hatches Creek tungsten field (Figure 7). The deposit covers an area of about 500 m trending southwest–northeast (Ryan 1961). En-echelon, south dipping mineralised quartz veins of ≤1 m width extend for 90–165 m, striking east–northeast (Ryan 1961). Typical ore minerals are wolframite and scheelite, along with bismuthite, chalcocite, azurite, malachite and limonite. In the primary zone, wolframite and scheelite are associated with molybdenite, native bismuth, bismuthinite, tetrahedrite, pyrite and chalcopyrite (Ryan 1961). The quartz veins are also associated with mica, K-feldspar and minor epidote and tourmaline alteration. These mineralised quartz veins intrude metasandstone and metamudstone of the Hatches Creek Group, as well as discrete blocks of mafic amphibolite from the informally named Pedlar gabbro (Ryan 1961; Donnellan in review). Minor hornfels alteration occurs on the margin of country rocks with the veins. The veins typically also have mica selvedges.

Figure 5. Map of the local area and geology of the Pioneer deposit showing the sampled location FR18MVM001 to the west of the deposit. Figure modified from Ryan (1961).
**Figure 6.** Photographs of sample and location for FR18MVM001 from the Pioneer deposit, Hatches Creek tungsten field. (a) Molybdenite and scheelite intergrown within a quartz vein. Sample is ~5 cm wide. (b) Same image under ultraviolet light where scheelite fluoresces in a light purple colour. (c) Mine dump at the Pioneer deposit where the sampled molybdenite was collected. Geopick for scale. (d) View of the Pioneer tungsten mine workings from a distant hill. Photograph looks northeast with various shafts and lodes indicated. Four-wheel drive for scale.

**Figure 7.** Geology of the Hatches Creek tungsten field showing location of the Pioneer deposit and other mineral occurrences. Modified from Kruse and Maier (2010).
No direct dating of mineralisation or host rocks has been undertaken at the Pioneer deposit. However, metasandstone hosting the deposit is interpreted as a correlative of the Warnes Sandstone Member (Kurinelli Sandstone), which has a SHRIMP U–Pb zircon maximum depositional age of 1837 ± 7 Ma (Claué-Long et al. 2008). The informally named Last Hope dolerite, a correlative of the Pedlar gabbro (Donnellan in review), has a SHRIMP U–Pb zircon age of 1811 ± 5 Ma, interpreted to record the timing of emplacement (Maidment et al. 2006). The interpreted ages of these host rocks suggests that tungsten mineralisation at the Pioneer deposit is likely younger than ca 1810 Ma.

Mineralisation in the Hatches Creek tungsten field has previously been related to felsic magmatism (eg Blake et al. 1987, Wyborn et al. 1998, Fraser et al. 2008); however, granite is not widely exposed in the tungsten field (Donnellan 2013a). Fraser et al. (2008) suggested a temporal and genetic link between regional tungsten mineralisation and the ca 1710 Ma Devils Suite based on Ar–Ar muscovite dating of tungsten-bearing quartz veins: coarse-grained muscovite selvedges on the edge of wolframite-bearing quartz veins at the Bonanza, Green Diamond and Copper Show prospects in the Hatches Creek tungsten field yielded \(^{40}\)Ar/\(^{39}\)Ar plateau ages of 1701 ± 7 Ma, 1703 ± 7 Ma and 1697 ± 7 Ma respectively. These ages are within uncertainty of each other, and are indistinguishable from muscovite sampled from the Devils Marble Granite, which yielded an \(^{40}\)Ar/\(^{39}\)Ar plateau age of 1699 ± 7 Ma. The Devils Marbles Granite also has a SHRIMP \(^{207}\)Pb/\(^{206}\)Pb zircon age of 1711 ± 11 Ma, interpreted to record the timing of magmatic crystallisation (Page 1996a).

Recent molybdenite dating in the Hatches Creek tungsten field at the Hit or Miss tungsten deposit, ~10 km south of the Pioneer deposit, yielded two Re–Os model ages of 1677 ± 10 Ma and 1602 ± 9 Ma from mineralised veins (McGloin et al. 2019). These ages were tentatively interpreted as mineralisation and/or remobilisation ages for molybdenum and tungsten, and the associated bismuth and copper mineralisation at the deposit. The older of the two Re–Os model ages is broadly consistent with the previously discussed ages determined for tungsten mineralisation and felsic intrusions in the Warramunga Province. The geological significance of the younger Re–Os molybdenite age is uncertain (McGloin et al. 2019).

Re–Os molybdenite dating at the Pioneer deposit provides an opportunity to directly constrain the timing of tungsten and sulfide mineralisation in the north of the Hatches Creek tungsten field. It also tests the validity of the Re–Os method for directly dating tungsten mineralising events in the region.

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**Model result**

An ID–NTIMS analysis of molybdenite from sample FR18MVM001 yielded a model age of 1714 ± 8 Ma (2σ). A repeat analysis of this sample (FR18MVM001RPT) yielded an identical model age of 1714 ± 8 Ma (2σ). The Re–Os isotopic data for these samples are reported in Table 2.

**Interpretation of result**

The Re–Os model age of 1714 Ma for the molybdenite (and genetically associated tungsten mineralisation) at the Pioneer deposit is broadly consistent with previously reported Ar–Ar ages, and slightly older than one Re–Os molybdenite age, for tungsten mineralisation in the Hatches Creek and the Wauchope tungsten fields (see Fraser et al. 2008, Donnellan 2013a,b; McGloin et al. 2019). The new age, along with these previous age constraints, support the interpretation of a direct mineralisation age for this deposit; it suggests a broadly consistent mineralising episode across the Hatches Creek tungsten field at ca 1720–1680 Ma. The low Re concentrations (~2 ppm) from the Pioneer deposit molybdenite are consistent with magmatic–hydrothermal fluids sourced from relatively evolved felsic intrusions (Berzina et al. 2005, Stein 2006).

Further afield, similar ages for copper and tungsten mineralisation associated with felsic magmatism are reported. The age of tungsten mineralisation in the Hatches Creek tungsten field is consistent with the new molybdenite Re–Os model ages for copper-molybdenum mineralisation at the Explorer 27 prospect in the Tennant Creek mineral field (see samples TC18MVM001 and TC18MVM002 in this Record). Similar ages for tungsten mineralisation are inferred at the Juggler prospect in the Davenport Province (Stidolph et al. 1988, Donnellan 2013b). The vein-hosted Juggler prospect occurs within the ca 1720 Ma Elkedra Granite (Page 1996b). The new molybdenite ages from the Pioneer deposit are also similar to ca 1730–1700 Ma ages reported for granite-related, epigenetic copper and tungsten mineralisation in the eastern Aileron Province at Molyhil, the Bonya Hills area and the Jervois mineral field (McGloin and Weisheit in review). This temporal and genetic link may suggest a widespread tungsten and copper mineralising episode across central Australia towards the end of the Paleoproterozoic. It hints at an exploration target from fertile crustal-scale magmatism in the southern part of the North Australian Craton during this period. Additional work is needed to test this hypothesis.
Molybdenite–scheelite-bearing quartz vein, Hill of Leaders deposit (BW18MVM003)

Sample information

NTGS Sample ID: BW18MVM003
Collector: Matt McGloin
1:250 000 mapsheet: BONNEY WELL (SF 53-02)
1:100 000 mapsheet: OORADIDGEE (5857)
Province: Warramunga Province
Grid reference: MGA94 Zone 53, 463087mE 7753693mN
Lithology: molybdenite–scheelite-bearing mineralised quartz vein
Geochronology target: molybdenite

Interpreted model age summary

No geologically meaningful age yielded.

Sample details and lithological characteristics

A molybdenite- and scheelite-bearing quartz vein was collected from a mine dump at surface workings at the Hill of Leaders deposit in the Mosquito Creek tungsten field. The sample site is located ~150 m west of a station track, about 22 km north of Kurundi Cattle Station in central OORADIDGEE (Figure 8).

The Mosquito Creek Tungsten field extends over about 2 km² and comprises several prospects containing scheelite and wolframite hosted in quartz veins ≤30 cm wide and ≤200 m long (Stewart et al. 1986, Donnellan 2013a). The quartz veins are typically hosted within north to north–west trending shear zones. Quartz–tourmaline–muscovite greisenised selvedges are commonly associated with the veins. Molybdenite sample BW18MVM003 (Figure 10a) was collected from the Hill of Leaders mine, where the majority of ore in the mineral field was mined.

Figure 8. Geological map of the Mosquito Creek tungsten field showing sample location sites at the Hill of Leaders deposit (BW18MVM003) and the North Curtis (BW18MVM006) prospect. Map modified from Wyche and Simons (1987).
In sample BW18VM003, coarse-grained molybdenite is associated with scheelite in a vug within a quartz vein (Figure 9a, b). Under ultraviolet light, scheelite (clearly distinguished from quartz by its strong fluorescence) occurs intimately associated with molybdenite (Figure 9c). Along with tungsten and molybdenum mineralisation, other ore minerals noted in quartz veins at the mine dump (Figure 9d) include sulfides (chalcopyrite, pyrite, bornite) and malachite (Figure 9e). Quartz veins typically contain minor hematite and tourmaline with muscovite and K-feldspar selvedges commonly well-developed on vein margins.

The tungsten workings are hosted within the Hill of Leaders Granite, a porphyritic plagioclase, muscovite-biotite granite (Figure 10a–b). The granite has been U–Pb zircon SHRIMP dated at 1846 ± 3 Ma (Maidment et al. 2006), which provides a maximum age for tungsten mineralisation at the workings. Some debate remains as to the timing of mineralisation in the Mosquito Creek tungsten field. Greisenisation observed in the granite may relate to late-stage evolved fluids exsolved from the Hills of Leaders Granite as it crystallised, suggesting that tungsten mineralisation formed during emplacement of this intrusion (Donnellan 2013a). Alternatively, the tungsten mineralisation may be associated with a poorly or non-exposed younger granite intrusion that exsolved ore-forming fluids that infiltrated pre-existing granite. Donnellan (2013a) reports geophysical data indicating a sub-circular gravity low coincident with the Mosquito Creek tungsten field that may be related to the younger ca 1710 Ma Devil’s Marbles Granite Suite. Furthermore, Maidment et al. (2006) report a lamprophyre dyke outcropping in the Mosquito Creek field with a SHRIMP U–Pb zircon age of 1711 ± 2 Ma. The ages of these felsic intrusions are purportedly similar in age to tungsten mineralisation elsewhere in the Warramunga Province (eg Wauchope tungsten field, Hatches Creek tungsten field; see Fraser et al. 2008 and Donnellan 2013).

![Figure 9](A18-505.ai)

**Figure 9.** Mineralisation and alteration at the Hill of Leaders deposit. (a) Quartz vein collected from the mine dump showing a vug containing molybdenite and scheelite (sample BW18VM003). Vein is ~0.6 cm wide. (b) Close-up of the same magnified using a hand lens. (c) Molybdenite sample BW18VM003 under ultraviolet light showing highly fluorescent scheelite associated with molybdenite. (d) The mine dump sampled for molybdenite next to a large trench and shaft. (e) Copper carbonate minerals including malachite associated with quartz veins. Hand sample is ~8 cm across (f) Example of highly muscovitised greisen granite in the mine workings that was altered during the tungsten mineralisation process. Hand sample is ~8 cm across.
Molybdenite sample BW18MVM003 was collected to constrain the timing of tungsten mineralisation at the Hill of Leaders tungsten deposit, and to help resolve which locally mapped (or currently unknown) felsic intrusive phase may be the likely source for the tungsten mineralisation.

Model result

An initial ID–NTIMS analysis of molybdenite from sample BC18MVM003 yielded a Re–Os model age of 6713 ± 30 Ma (2σ). This impossible age result warranted a repeat analysis (BC18MVM003RPT), which yielded another impossible and irreproducible Re–Os model age of 4940 ± 20 Ma (2σ). The Re–Os isotopic data for this sample are reported in Table 2.

Interpretation of result

The ages obtained from sample BC18MVM003 and repeat sample BC18MVM003RPT are geologically impossible and were not able to be reproduced. These ages are not considered to have any geological significance. The reason for the failed result is unclear. The samples contain anomalously high concentrations of radiogenic 187Os relative to the measured Re content. This suggests that the sampled molybdenite may have lost Re after formation. Alternatively the sampled coarse-grained molybdenite may have been strongly decoupled spatially with respect to Re and 187Os distribution.

Molybdenite–scheelite–wolframite-bearing quartz vein, North Curtis prospect (BM18MVM006)

Sample information

NTGS Sample ID: BW18MVM006
Collector: Matt McGloin
1:250 000 mapsheet: BONNEY WELL (SF 53-02)
1:100 000 mapsheet: OORADIDGEE (5857)
Province: Warramunga Province
Grid Reference: MGA94 Zone 53, 462172mE 7754674mN
Lithology: molybdenite–scheelite–wolframite-bearing quartz vein
Geochronology target: molybdenite

Interpreted model age summary

1777 ± 9 Ma

Sample details and lithological characteristics

Several small chips of molybdenite–scheelite–wolframite-bearing quartz vein were collected from a mine dump at surface workings at the North Curtis prospect in the Mosquito Creek tungsten field (Figure 8). The sample site is located ~55 m south of a station track, about 22 km north of Kurundi Cattle Station in central OORADIDGEE.

In the sample, coarse-grained molybdenite is associated with minor wolframite, scheelite, pyrite and chalcopyrite, as well as oxidised tungstite and secondary copper carbonate minerals including malachite (Figure 11a). Under ultraviolet light, scheelite is distinguished from quartz by its strong fluorescence (Figure 11b). Tourmaline, muscovite and biotite are common alteration minerals associated with the quartz veins. The sampled mine dump (Figure 11c) is located 6 m north from a small working and shaft on a 50 cm wide vertical quartz vein (Figure 11d–e). This shaft is at least 7 m deep. The quartz vein is hosted in greisenised Hill of Leaders Granite (Figure 11f–g). Several other small pits and workings occur close to the sample site.

Details on the geology, mineralisation and existing age constraints for sample BW18MVM006 and the wider Mosquito Creek tungsten field are summarised for sample BW18MVM003 (this Record). Molybdenite sample BW18MVM006 was dated to confirm the timing of tungsten mineralisation at the North Curtis prospect.

Model result

ID–NTIMS analysis of molybdenite from sample BW18MVM006 yielded a Re–Os model age of 1777 ± 9 Ma (2σ). The Re–Os isotopic data for this sample is reported in Table 2.
Figure 11. Mineralisation and geology from the North Curtis prospect, Mosquito Creek tungsten field. (a) Molybdenite and scheelite-bearing quartz chips sampled for BW18MVM006 (vein fragments are ~1 cm across). (b) Same quartz chips under ultraviolet light showing highly fluorescent scheelite. (c) Mine dump of mineralised quartz where sample BW18MVM006 was collected (rucksack for scale). (d) View of working and mine dump at North Curtis. (e) View of small shaft with vertical-trending quartz vein exploited for tungsten. (f) View of North Curtis site from southerly hill outcrop of Hill of Leaders Granite (four wheel drive for scale). (g) Close-up of Hill of Leaders Granite showing a megacrystic K-feldspar, porphyritic, two mica composition (hammer for scale).

Interpretation of result

The ca 1777 Ma model age for molybdenite from sample BW18MVM006 is tentatively interpreted to record the timing of tungsten mineralisation at the North Curtis prospect in the Mosquito Creek tungsten field. The low Re concentration in the analysed molybdenite (≤2 ppm) is consistent with an evolved felsic magmatic source, supporting a link with granite intrusions (Berzina et al. 2005, Stein 2006). However, this new age is significantly younger than that of the ca 1846 Ma Hill of Leaders Granite, which the mineralised quartz vein cross-cuts. Thus, these
new data permit two possible interpretations of the Re–Os molybdenite age. First, the ca 1777 age records the timing of tungsten mineralisation associated with a period of felsic magmatism not currently recognised in the Mosquito Creek tungsten field. Second, the age may reflect remobilisation if molybdenite was dissolved and precipitated by hydrothermal fluids during metamorphism and/or fluid flow, a process that could reset or decouple the Re–Os ratios in the molybdenite. However, the high closure temperature of Re–Os in molybdenite (≥550–800°C; Selby et al 2004) makes the second scenario unlikely.

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REFERENCES

Berzina AN, Sotnikov VI, Economou-Eliopoulos M and Eliopoulos DG, 2005. Distribution of rhenium in molybdenite from porphyry Cu–Mo and Mo–Cu deposits of Russia (Siberia) and Mongolia. Ore Geology Reviews 26, 91–113.


Page RW, 1996b. *GA sample 84497022 (Elkedra Granite)*.
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