



Australian Journal of Earth Sciences

An International Geoscience Journal of the Geological Society of Australia

ISSN: 0812-0099 (Print) 1440-0952 (Online) Journal homepage: www.tandfonline.com/journals/taje20

Zircon U–Pb emplacement ages of intrusions in the Mary Kathleen Domain, Mount Isa Inlier, Australia

H. A. Cocker, I. Sanislav, P. Dirks & A. McCoy-West

To cite this article: H. A. Cocker, I. Sanislav, P. Dirks & A. McCoy-West (2025) Zircon U–Pb emplacement ages of intrusions in the Mary Kathleen Domain, Mount Isa Inlier, Australia, Australian Journal of Earth Sciences, 72:4, 503–527, DOI: [10.1080/08120099.2025.2527816](https://doi.org/10.1080/08120099.2025.2527816)

To link to this article: <https://doi.org/10.1080/08120099.2025.2527816>



© 2025 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.



[View supplementary material](#)



Published online: 21 Jul 2025.



[Submit your article to this journal](#)



Article views: 902



[View related articles](#)



[View Crossmark data](#)



Citing articles: 3 [View citing articles](#)

Zircon U–Pb emplacement ages of intrusions in the Mary Kathleen Domain, Mount Isa Inlier, Australia

H. A. Cocker^{a,b} , I. Sanislav^{a,b} , P. Dirks^{a,b}  and A. McCoy-West^{a,b} 

^aEconomic Geology Research Centre (EGRU), James Cook University, Townsville, QLD, Australia; ^bEarth and Environmental Science, College of Science and Engineering, James Cook University, Townsville, QLD, Australia

ABSTRACT

The Mary Kathleen Domain (MKD), within the Mount Isa Inlier, Queensland, hosts numerous occurrences of Cu ± Au mineralisation, which are spatially associated with igneous intrusions. However, the temporal relationships between the emplacement (crystallisation) ages of these intrusions and important mineralisation events remain ambiguous in most cases. This is further complicated by secondary overprinting of primary magmatic rocks (and mineralisation) during later metamorphic or hydrothermal events, which can potentially reset datable mineral archives. Here we present 29 new U–Pb zircon ages for magmatic intrusions from across the MKD, which are all interpreted as emplacement ages. Our results, combined with previous data, show that most intrusions in the MKD were emplaced during at least four discrete periods of magmatic activity between ca 1880 Ma and ca 1500 Ma; these are the Kalkadoon–Leichhardt Igneous Province (ca 1860 Ma), Argylia Igneous Province (ca 1780 Ma), Wonga–Burstall Igneous Province (ca 1760–1710 Ma) and Williams Igneous Province (ca 1550–1500 Ma). Available geochronology data on ore mineralisation associated with intrusions within the MKD suggest that most mineralisation formed coeval with the emplacement of the Williams Igneous Province; however, intrusions of this province are only exposed in the northern portion of the MKD. Therefore, in other areas where reported ore mineralisation ages (i.e. ca 1500 Ma) are much younger than the spatially related magmatic emplacement ages of intrusions, mineralisation is probably the result of remobilisation of older mineralisation temporally linked to the surrounding intrusions. These results also highlight the need for detailed mapping of the field relationships between different magmatic phases and the surrounding country rock to resolve ambiguities in the geological history and stratigraphic succession observed within some areas of the MKD.

KEY POINTS

1. New U–Pb zircon ages are reported for 29 magmatic intrusions across the Mary Kathleen Domain, Mount Isa Inlier.
2. Ages demonstrate that most intrusions in the Mary Kathleen Domain were emplaced during four discrete periods of magmatic activity.
3. Ambiguities remain in the geological history and stratigraphic succession in some areas of the MKD, especially the timing of mineralisation.

ARTICLE HISTORY

Received 2 December

2024

Accepted 24 June 2025

KEYWORDS

Mary Kathleen Domain; Mount Isa Inlier; intrusions; emplacement age; geochronology; igneous province

Introduction

To examine the link between magmatism and ore mineralisation, it is important to know the timing of magmatic and mineralisation events. Many types of hydrothermal ore deposits are related to magmatic events, with the magmas providing a source of heat, fluids and/or metals for the ore-forming system (Andersen & Weis, 2020; Audétat & Edmonds, 2020; Burnham, 1997; Halter & Webster, 2004; Hedenquist & Lowenstern, 1994). The Mount Isa Inlier, located in northwest Queensland, Australia, hosts a diverse range of ore deposit types, including some that are spatially and/or temporally linked to magmatic events (e.g. Mark *et al.*, 2006; Williams, 1998). Despite being

geologically well-exposed and extensively studied, the region remains poorly understood owing to evidence of multiple phases of regional-scale metamorphism, deformation and hydrothermal alteration (e.g. Cave *et al.*, 2024; Le *et al.*, 2021b; Oliver, 1995; Spence *et al.*, 2021, 2022). These events have affected large parts of the inlier, creating a complex arrangement of rock units in which original features are commonly obscured (e.g. Spence *et al.*, 2021) and the geochronology of primary events can be overprinted by later resetting (e.g. Burnham *et al.*, 2024; Spandler *et al.*, 2016).

The Mary Kathleen Domain (MKD) is a north–south-trending terrane in the central part of the mineralised Mount Isa Inlier

CONTACT H. A. Cocker  helen.mccoywest@jcu.edu.au  Economic Geology Research Centre (EGRU), James Cook University, 1 James Cook Drive, Townsville, QLD 4814, Australia

 Supplemental data for this article can be accessed online at <https://doi.org/10.1080/08120099.2025.2527816>.

Editorial handling: Anita Andrew

© 2025 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.

This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited, and is not altered, transformed, or built upon in any way. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

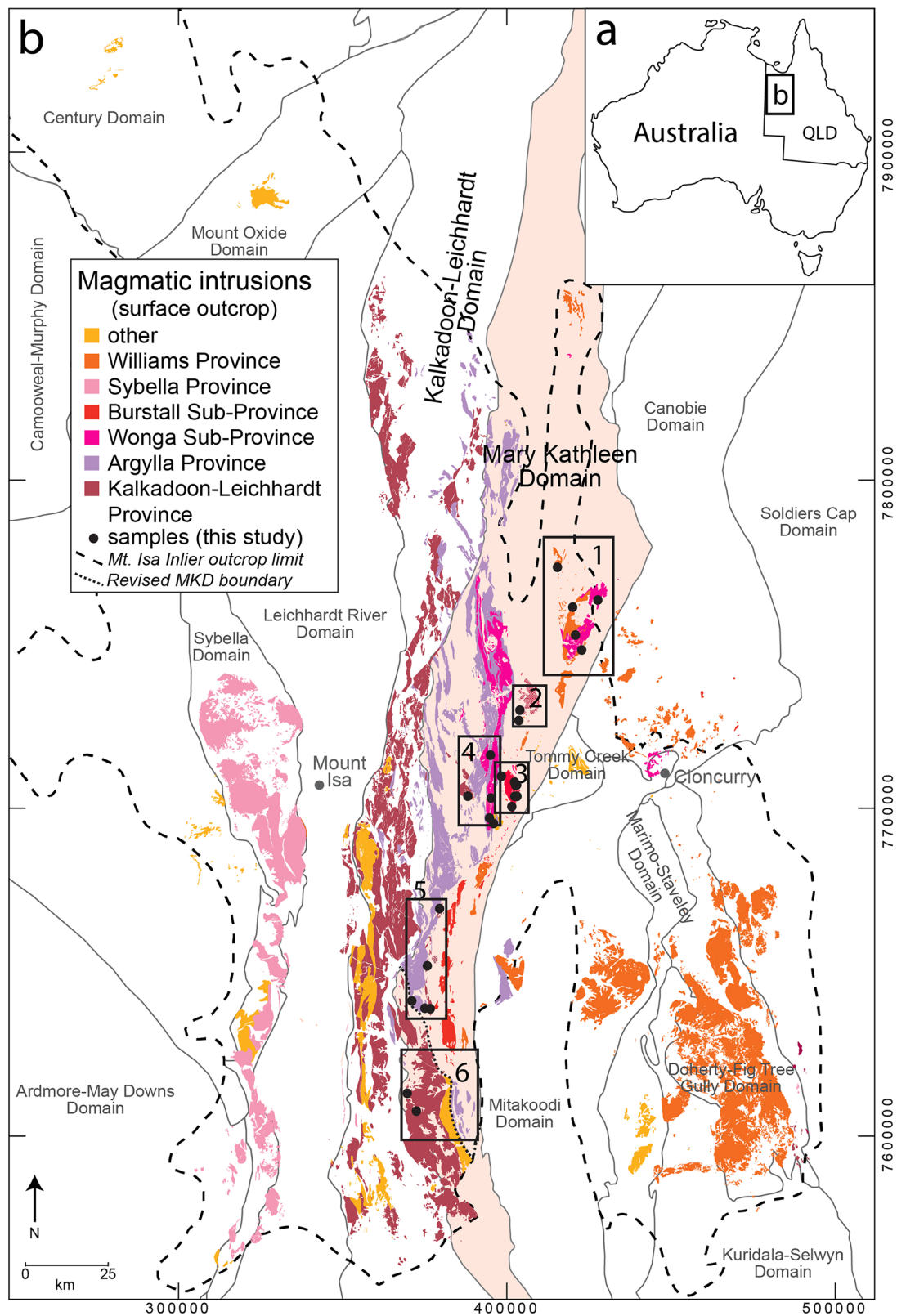


Figure 1. Map of the outcropping Mount Isa Inlier (dashed line) with domain boundaries and the Mary Kathleen Domain shaded pink (with revised southern boundary shown as dotted line across box 5; Bultitude *et al.*, 2021). Intrusions of the Kalkadoon–Leichhardt Igneous Province, Argylla Igneous Province, Wonga Igneous Sub-province, Burstall Igneous Sub-province, Sybella Igneous Province, Williams Igneous Province and ‘other’ intrusions (belonging to other smaller igneous provinces or their association is unknown) outcropping across the Inlier are shown (modified after Queensland Department of Resources, 2018, 2022). Sample locations for this study are shown as black circles. Boxes labelled 1–6 are study areas for this paper.

(Figure 1a). Multiple igneous intrusions and complexes are emplaced in the MKD throughout the Paleoproterozoic to Mesoproterozoic. In some cases, intrusions are clearly spatially associated with Cu $\pm$ Au mineralisation (e.g. Mount Colin Cu $\pm$ Au deposit and Burstall Granite; Duchess and Ivanhoe deposits and Mt Erle Igneous Complex; Cave *et al.*, 2024; Geological Survey of Queensland, 2017; Williams, 1998), a pattern also observed in other domains of the Mount Isa Inlier to the east of the MKD (e.g. Hutton *et al.*, 2012). However, the exact nature of the genetic relationship between magmatism and ore mineralisation remains ambiguous for many occurrences of mineralisation in the MKD. Most rocks in the MKD were overprinted by regional deformation and metamorphism during the mid-Paleoproterozoic to early Mesoproterozoic (ca 1870–1500 Ma; Bultitude *et al.*, 2021; Spence *et al.*, 2021, 2022), which has obscured the timing of the magmatic events relative to the formation of ore mineralisation. Most mineralisation in the area was deposited during the later stages of the Isan Orogeny (ca 1530–1500 Ma; Abu Sharib & Sanislav, 2013; Blake, 1987; O'Dea *et al.*, 1997) and coincided with the emplacement of intrusions of the Williams Igneous Province (ca 1550–1500 Ma; Burnham *et al.*, 2024; Cave *et al.*, 2024; Hutton *et al.*, 2012; Le *et al.*, 2021a, 2021b; Mark *et al.*, 2006; Oliver *et al.*, 2004; Perkins & Wyborn, 1998; Spandler *et al.*, 2016), although not all deposits can be directly related to intrusions of this age range (e.g. Duncan *et al.*, 2011). Therefore, it is critical to obtain emplacement (crystallisation) ages for all intrusions and clearly differentiate the timing of emplacement from any subsequent metamorphic or hydrothermal events. Consequently, the genesis and deposition of mineralisation can be better constrained when the emplacement ages of intrusions that are spatially related to that mineralisation are known.

The closure temperature of Pb diffusion varies between minerals; for example, zircon has a Pb closure temperature of >900 °C (Cherniak & Watson, 2001; Lee *et al.*, 1997), titanite of 600–700 °C (Cherniak, 1993; Scott & St-Onge, 1995) and apatite of 375–600 °C (Cochrane *et al.*, 2014; Schoene & Bowring, 2007). The higher closure temperature for zircon relative to other datable minerals like titanite and apatite means that zircons are less likely to have their U–Pb ages isotopically reset by later thermal events (e.g. metamorphism or hydrothermal activity). Therefore, the preferred mineral to determine emplacement ages of intrusions is zircon, because of its higher closure temperature and increased resistance to alteration/overprinting during subsequent events. In the Mount Isa Inlier, including the MKD, peak metamorphism during the early Isan Orogeny (ca 1600–1580 Ma; Betts *et al.*, 2006; Giles *et al.*, 2006) reached greenschist to upper-amphibolite facies, with maximum *P*–*T* conditions in some parts of the inlier estimated at 400–500 MPa and >650 °C (Foster & Rubenach, 2006; Le *et al.*, 2024). These *P*–*T* conditions are near to, or above, the Pb closure temperatures in titanite and apatite.

The intrusions of the MKD (and the Mount Isa Inlier) have been grouped into various igneous provinces, previously referred to as igneous suites (e.g. compare Budd *et al.*, 2001 with Bultitude *et al.*, 2021). Here we adopt the province and subprovince terminology used by Bultitude *et al.* (2021; see supplemental data, Table A1). Initially intrusions were grouped based on

the physical characteristics of the rocks; however, many intrusions in the MKD appear similar in outcrop (e.g. Bultitude *et al.*, 2021). Recent geochronological work on the intrusions and other units of the MKD has begun to better constrain the emplacement ages of the intrusions and has necessitated reassignment of some intrusions to different igneous provinces (Bodorkos *et al.*, 2020; Bultitude *et al.*, 2021; Carson *et al.*, 2011; Kositcin *et al.*, 2019, 2021; Le *et al.*, 2021a; Spence *et al.*, 2021, 2022).

The work presented in this study was done in collaboration with the Geological Survey of Queensland (GSQ) as part of a project investigating the mineralisation potential of the MKD (Bultitude *et al.*, 2021). Results from Bultitude *et al.* (2021), other GSQ projects, and published and unpublished studies in the MKD have been utilised and incorporated in a revised geological map of the MKD (Queensland Department of Resources, 2022), and throughout this paper, the 2022 revised map unit names are used. In addition, Bultitude *et al.* (2021) revised the southern boundary of the MKD (Figure 1), based on a range of published and unpublished geochronological studies. We also adopt the nomenclature used by Bultitude *et al.* (2021) for the groupings of the igneous units. The principal aim of this study was to obtain emplacement ages for a range of intrusions in the MKD and constrain the timing of plutonic magmatic events in the region. A secondary objective is to determine areas within the MKD that host intrusions with emplacement ages ca 1550–1500 Ma (i.e. Williams Igneous Province related), which is potentially the age most of mineralisation in the region, and therefore may provide a direct link between magmatism and mineralisation at this time period. Synthesis of this new geochronological data with published data shows that the intrusions of the MKD were emplaced during several discrete periods of magmatic activity between ca 1870 and 1500 Ma.

Geological setting

The outcropping rocks of the Mount Isa Inlier are mostly Paleoproterozoic to Mesoproterozoic in age and comprise sedimentary sequences, volcanic units and intrusions, many of which have been metamorphosed and/or hydrothermally altered (Blake, 1987; Blake & Stewart, 1992; Withnall & Hutton, 2013). The Mount Isa Inlier has been divided into three broad tectonic belts, the Eastern Fold Belt (Eastern Succession or Eastern Province), Kalkadoon–Leichhardt Belt, and the Western Fold Belt (Western Succession or Western Province; Day *et al.*, 1983; Withnall & Hutton, 2013). The Eastern and Western fold belts were later further subdivided into several domains based on their geological and geophysical characteristics (Geological Survey of Queensland, 2011; Withnall & Hutton, 2013; Figure 1b). The basement units (>1870 Ma) of the Mount Isa Inlier, mainly found in the Kalkadoon–Leichhardt Domain, were affected by the Barramundi Orogeny (ca 1870–1850 Ma; Betts *et al.*, 2006; Blake & Stewart, 1992; Etheridge *et al.*, 1987; Page & Williams, 1988). The subsequent Proterozoic units comprise three successive basinal sequences that were deposited on top of the basement: the Leichhardt (ca 1790–1750 Ma), Calvert (ca

1730–1670 Ma) and Isa (*ca* 1640–1575 Ma; Betts *et al.*, 2006; Foster & Austin, 2008; Gibson *et al.*, 2016; Withnall & Hutton, 2013) superbasins. Later deformation and metamorphism during the Wonga (*ca* 1750–1710 Ma; Spence *et al.*, 2022) and Isan Orogenies (*ca* 1600–1500 Ma; Abu Sharib & Sanislav, 2013; Betts *et al.*, 2006; Foster & Rubenach, 2006; Giles *et al.*, 2006) have variably impacted the basin sequences and associated intrusions. Rocks associated with major igneous events, predominantly spanning *ca* 1870–1500 Ma, crop out throughout these domains, intruding the basement and superbasin sequences (Figure 2). The igneous rocks include both volcanic and plutonic units with a bimodal mafic–felsic compositional distribution (Blake, 1987; Bultitude *et al.*, 2021). The reader is referred to Withnall and Hutton (2013), Gibson *et al.* (2016) and

Withnall (2019) for more detailed information on the geology and geochronology of the Mount Isa Inlier, as well as the recent publications of Spence *et al.* (2021, 2022) and Cave *et al.* (2024) for more detailed geological overviews of the MKD.

The MKD is located along the western margin of the Eastern Fold Belt, adjoining the eastern margin of the Kalkadoon–Leichhardt Domain (Figure 1b). Within the MKD, sediments deposited during the Leichhardt Superbasin formed the Mary Kathleen Group, which includes the Ballara Quartzite and Corella Formation (Jackson *et al.*, 1990; 2000). Sediments of the Calvert Superbasin are predominantly expressed within the MKD as the Mount Albert Group, which were deposited unconformably above the Mary Kathleen Group units (Loosveld & Schreurs, 1987; Stewart, 1989). Outcropping geology in the MKD is mostly metasedimentary and metavolcanic packages of the Mary Kathleen and Mount Albert groups and intrusions of various ages. Most of these intrusions have been assigned to the Kalkadoon–Leichhardt (*ca* 1870–1850 Ma), Argylia (*ca* 1780–1775 Ma), Wonga (*ca* 1760–1730 Ma), Burstall (1750–1710 Ma) or Williams (*ca* 1550–1500 Ma) igneous provinces (Figures 1b and 2; Bultitude *et al.*, 2021; Withnall, 2019). The rocks of the MKD were variably deformed, with a major belt of significant deformation, the Wonga Belt, forming a north–south-trending high strain zone that developed during the Wonga Orogeny (*ca* 1750–1710 Ma; Spence *et al.*, 2021, 2022). The Isan Orogeny (*ca* 1600–1500 Ma; Abu Sharib & Sanislav, 2013; Withnall, 2019) left an additional imprint of high-temperature metamorphism across much of the Mount Isa Inlier. In the MKD, peak metamorphic conditions during the Isan Orogeny reached mid- to upper-amphibolite facies (400–500 MPa at >650 °C; Foster & Rubenach, 2006; Gibson *et al.*, 2020; Oliver *et al.*, 1991; Reinhardt, 1992). Cenozoic aged sediments cover many of the older units in the northern part of the domain (Blake, 1987; Bultitude *et al.*, 2021). In the southern part of the MKD, Bultitude *et al.* (2021) revised the domain boundary, based on their results in conjunction with a range of other recent geochronology studies (*e.g.* Kositcin *et al.*, 2021; Le *et al.*, 2021a). The new boundary separates the Birds Well Granite and most of the other intrusions of the Kalkadoon–Leichhardt Igneous Province to the south and west from the adjacent intrusions of the Argylia Igneous Province and younger units in the north and east of the domain (Figure 1b). The MKD hosts most of the intrusions of the Argylia Igneous Province and Wonga and Burstall igneous subprovinces and a small number of intrusions belonging to the Kalkadoon–Leichhardt and Williams Igneous provinces. Intrusions in the MKD are predominantly intermediate to felsic in composition, and they range from monzodiorite to granite. In some locations, there are gabbroic intrusions that appear to be coeval with the adjacent granitoid rocks, with field occurrences that show mingling between mafic and felsic magmas (*e.g.* Blake, 1987). A summary table that details the various intrusions and igneous provinces of the MKD is included in the supplemental data (Table A1). There are several significant mineral deposits within the MKD, including the Dugald River Zn–Pb–Ag, Mary Kathleen U–REE and Tick Hill Au deposits (Le *et al.*, 2021b; Page, 1983; Xu, 1996). There are also several Cu ± Au deposits that are spatially associated with intermediate–felsic intrusions throughout

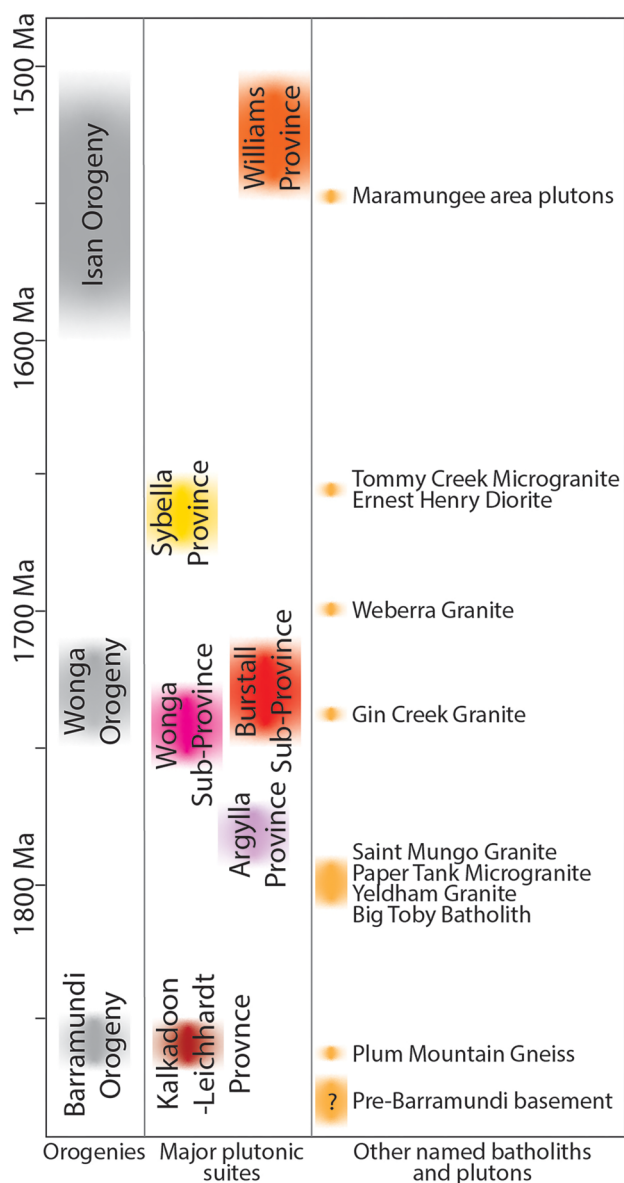


Figure 2. Diagram illustrating approximate timing of orogenic events and plutonic magmatism across the Mount Isa Inlier. Note that emplacement of the Kalkadoon–Leichhardt, Wonga, Burstall and Williams igneous provinces overlaps with interpreted ages of orogenic events. After Withnall (2019), Le *et al.* (2021a), Bultitude *et al.* (2021), Spence *et al.* (2021, 2022) and this study.

the domain, including mineralisation associated with the Burstall Granite and the Mount Erle Igneous Complex (Austin *et al.*, 2016; Cave *et al.*, 2024; Williams, 1998).

Sampling selection and analytical methods

Intrusive units were sampled during several field campaigns in the areas shown as boxes 1–6 in Figure 1b. The samples selected for geochronology are mainly from a larger selection of samples from the MKD analysed for geochemistry, details of which are beyond the scope of this study. The samples are predominantly granites, with some granodiorite, quartz monzonite, monzonite, gabbrodiorite and one felsic porphyry, based on a TAS diagram where geochemical data were available (Table 1). The granites are metaluminous to peraluminous with some mild A-type granite geochemical affinities that plot on both sides of the I/S/M and A-type fields near the boundary in various discrimination diagrams of Whalen *et al.* (1987). These petrological and geochemical observations are consistent with those of previous studies of intrusions in this region (*e.g.* Budd *et al.*, 2001; Bultitude *et al.*, 2021; Wyborn *et al.*, 1988). The intrusions of the Wonga and Burstall igneous subprovinces were the main focus of this work. Table 1 provides sample information and brief petrological details. Figures 3–8 show more detailed geological maps with sample locations, summary geochronology and locations of samples from other studies. Additional details of each sampling area and petrographic descriptions are provided in the supplemental data (Figure A1). Fresh samples of each intrusion were selected where possible; however, in one case, intensive and pervasive alteration was unavoidable (sample MK2020-45; see supplemental data for more details). Samples were crushed and zircon grains separated using standard mineral separation techniques (see supplemental data for more details on sample preparation and analytical techniques).

Zircon geochronology

Zircon grains were analysed in the Advanced Analytical Centre, James Cook University, for cathodoluminescence (CL) and laser-ablation inductively coupled mass spectrometry (LA-ICP-MS). The zircons were imaged using a Jeol JSM5410LV with attached CL detector to identify zoning within zircon grains. Suitable zircons were analysed for U–Th and Pb isotopes (along with Si, Ti, Fe and Zr) with a GeoLas 200 Excimer Laser Ablation System in a He ablation atmosphere, coupled to a Thermo Scientific iCAP RQ ICP-MS. The zircon standard GJ1 (ID-TIMS $^{207}\text{Pb}/^{206}\text{Pb}$ age = 608.5 ± 0.4 Ma; Jackson *et al.*, 2004; LA-ICP-MS $^{206}\text{Pb}/^{238}\text{U}$ age of 601.95 ± 0.4 Ma; Horstwood *et al.*, 2016) was used as the primary standard, and three other zircon standards were used for quality control, including zircon 91500 ($^{207}\text{Pb}/^{206}\text{Pb}$ age = 1065 ± 0.3 Ma; Wiedenbeck *et al.*, 1995), Temora 2 (ID-TIMS $^{206}\text{Pb}/^{238}\text{U}$ age = 416.78 ± 0.33 Ma; Black *et al.*, 2004) and Plešovice (ID-TIMS $^{206}\text{Pb}/^{238}\text{U}$ age = 337.13 ± 0.37 Ma; Sláma *et al.*, 2008). Propagated uncertainties on the final weighted mean ages given throughout this paper include the population uncertainty on the weighted mean of zircons from

the sample, the uncertainty on the primary GJ-1 standard (0.12%), and the uncertainty on the decay constants (^{235}U 0.07% and ^{238}U 0.05%; Jaffey *et al.*, 1971). Data were processed using Iolite 4 (U–Pb geochronology DRS; Paton *et al.*, 2011) and weighted mean ages and concordia diagrams were plotted using IsoplotR (Vermeesch, 2018). $^{207}\text{Pb}/^{206}\text{Pb}$ weighted mean ages were calculated in Isoplot. Analyses showing discordance of greater than 5%, based on $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ ages, were excluded from age calculations.

Zircon U–Pb ages

Zircons were typically pale purple-grey to brown in colour, tabular to prismatic and euhedral to subhedral in shape. The CL images of the zircon grains show zonation patterns that range from simple concentric zoning to complex patterns with zones that appear metamict (Figure 9). Magmatic emplacement ages of the intrusions based on weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ ages are summarised in Table 2. Owing to the complex nature of the region many of the zircon analyses were discordant ($n=647/2309$ zircons with $\leq 5\%$ discordance; Table A2). Of 42 samples analysed, 21 samples had only a small population (<10) of concordant analyses, and three samples had no concordant analyses at all (supplemental data, Table A3). Based on the concordia diagrams, most of the discordant grains have been affected by Pb loss, with common Pb contamination and U loss rarer. The concordia diagrams also showed that some samples yielded multiple populations of concordant analyses, which we interpret as either zircon inheritance or growth/overprinting from younger events (*e.g.* metamorphism), depending on the concordia diagram pattern for each sample. A combination of concordia and discordia patterns, along with ranked $^{207}\text{Pb}/^{206}\text{Pb}$ ages (*i.e.* to identify outliers from the plateau in the weighted mean diagrams; Figures 10–14; supplemental data, Figure A2) were used to determine the analyses included in the final weighted mean magmatic emplacement age (Figures 10–14). The limited number of concordant zircon analyses, and the complexity of the age patterns, made interpretation of some of the zircon populations challenging. However, this is consistent with the long and complex geological history of the MKD. Age results are presented below for 29 samples, with some additional sample results included in the supplemental data. The reader is advised to exercise caution in comparison of the uncertainties reported here with those from other studies owing to differences in the calculation methods applied.

Northern MKD

Granitoids from the northern section of the MKD (Box 1 in Figure 1b; Figure 3) typically yield younger ages than from other parts of the MKD. Samples QB2, QB3 and QB5 yield zircon ages of 1517 ± 19 , 1505 ± 19 , 1503 ± 46 and 1504 ± 32 Ma, respectively (Figure 10). Zircons from sample QB6 yielded an age of 1750 ± 9 Ma (Figure 10), significantly older than the other QB samples. QB2 is an unnamed granitic intrusion, and the age here is within uncertainty of a previously reported age from the same location (1511 ± 4 Ma; Bodorkos *et al.*, 2020). Sample QB3

Table 1. Sample locations and summary petrology of the Mary Kathleen Domain samples from this study. Coordinates are MGA-zone 54.

Sample	Easting	Northing	Intrusion unit name/comments	Rock type ^a	Major mineral assemblage/description summary
Williams Igneous Province					
QB2	416008	7774561	Unnamed granite	Granite	Medium-grained, comprising quartz, K-feldspar, plagioclase, hornblende
QB3	420671	7762420	Mavis Granodiorite	Quartz monzonite	Medium-grained, comprising quartz, K-feldspar, plagioclase, biotite
QB5	423328	7749354	Mavis Granodiorite	Granite	Medium-grained, comprising quartz, K-feldspar, plagioclase, hornblende
Burstall Igneous Subprovince					
MGK18-001	403790	7726405	Mount Godkin Granite/m	Quartz monzonite	Medium-grained, comprising quartz, plagioclase, K-feldspar, hornblende
MGK18-002	403665	7726673	Mount Godkin Granite/d	Monzonite	Medium-grained, comprising quartz, plagioclase, K-feldspar, hornblende
MGK18-017	403924	7729408	Mount Godkin Granite/g	Granite	Fine to medium-grained, with quartz, plagioclase, K-feldspar, hornblende
BST18-001	399023	7710890	Burstall Granite/l (leucogranite)	Granite	Coarse-grained with quartz, plagioclase, K-feldspar, biotite, hornblende
BST18-008	403696	7708296	Lunch Creek Gabbro	Gabbrodiorite	Medium-grained, comprising plagioclase, biotite, clinopyroxene
BST18-010	402986	7709157	Burstall Granite	Granite	Medium-grained, weakly foliated, with plagioclase, K-feldspar, quartz, hornblende, biotite
MK2020-01	402159	7701037	Felsic dyke (Burstall area)	Granite	Medium-grained, weakly foliated, with quartz, plagioclase, K-feldspar, hornblende
MK2020-03	403774	7704820	Burstall Granite	Granite	Coarse-grained, foliated, with quartz, K-feldspar, plagioclase, hornblende, minor biotite
MK2020-05	403107	7704809	Lunch Creek Gabbro	Gabbrodiorite	Medium-grained, comprising plagioclase, biotite, amphibole, clinopyroxene
MK2020-20	403355	7708181	Burstall Granite	Quartz monzonite	Coarse-grained, foliated, with quartz, K-feldspar, plagioclase, hornblende, minor biotite
Wonga Igneous Subprovince					
WG18-001	395539	7697950	Greens Creek Quartz Monzonite (previously Wonga Granite/3a)	Granodiorite/quartz monzonite	Medium to coarse-grained, weakly foliated, with quartz, plagioclase, K-feldspar, biotite, amphibole
WG18-007	395881	7704314	Natalie Granite (previously Wonga Granite/5a)	Granite	Fine to medium-grained, foliated, with quartz, plagioclase, K-feldspar, minor biotite
WG18-011	395735	7717378	Natalie Granite (previously Wonga Granite)	Granite	Medium to coarse-grained, weakly foliated, with quartz, plagioclase, K-feldspar, biotite, hornblende
Argylla Igneous Province					
M13	379907	7669427	Mapped as Bushy Park Gneiss	Granitic gneiss ^b	Foliated sample, predominantly coarse-grained quartz and K-feldspar
M14	379460	7669750	Porphyry intruding Magna Lynn Metabasalt	Felsic porphyry ^b	Foliated felsic porphyry
M11	375555	7651540	Argylla Formation	Felsic porphyry ^b	Medium-grained, porphyritic, foliated with coarse quartz and feldspar with asymmetric tails in a fine-grained matrix of mainly felsic material
M02	375530	7639965	Mairindi Creek Granite (foliated)	Granitic gneiss ^b	Foliated coarse-grained gneiss
M06	371382	7641338	Mairindi Creek Granite (undeformed)	Granite ^b	Undeformed coarse-grained granite
M08	370920	7640802	Argylla Formation	Felsic porphyry ^b	Intensely deformed felsic porphyry with coarse feldspar and a finer-grained matrix of quartz, feldspar and mica
Kalkadoon Igneous Province or older					
GC2	396545	7696170	Greens Creek area (now mapped as Undaunted Metamorphics)	Granodiorite	Medium-grained, weakly foliated, with quartz, plagioclase, K-feldspar, biotite, hornblende
MK2020-45	369919	7614053	Birds Well Granite?	Granite ^c	Coarse-grained, foliated, intensely and pervasively altered, with quartz and minor altered K-feldspar
M16	387822	7703519	Hardway Granite	Granite ^b	Coarse-grained foliated granitic rock with quartz, K-feldspar and biotite
M10	375304	7651229	Bushy Park Gneiss	Granitic gneiss ^b	Deformed coarse-grained granitic gneiss
M05	376347	7638509	Bushy Park Gneiss	Granitic gneiss ^b	Foliated coarse-grained gneiss
Unassigned to an igneous province – likely Burstall or Wonga Igneous Subprovince					
QB6	421468	7753890	Unnamed granite	Granite	Medium-grained, comprising quartz, plagioclase, K-feldspar, minor chlorite (altered from biotite or hornblende)
MK2020-33	395060	7697698	Felsic dyke (Greens Creek area)	Granite	Fine-grained, foliated, with quartz, K-feldspar, plagioclase and minor biotite

^aRock type based on the TAS diagram of Middlemost (1994) for most samples.^bNo geochemical data, rock type based on field description.^cAltered sample, however, still places in this field but has much lower alkalis than other samples in this group.

returned only three concordant data points; however, the discordia line through most of the discordant analyses generated an upper intercept age of 1494 ± 29 Ma (Figure 10), suggesting that the calculated mean age has geological significance. Sample

QB3 is from an area mapped as Mavis Granodiorite, and the crystallisation age herein of 1505 ± 19 Ma is within uncertainty to a previous age (1501 ± 6 Ma; Page & Sun, 1998) for the Mavis Granodiorite further to the south (Figure 3). Similarly, the age of

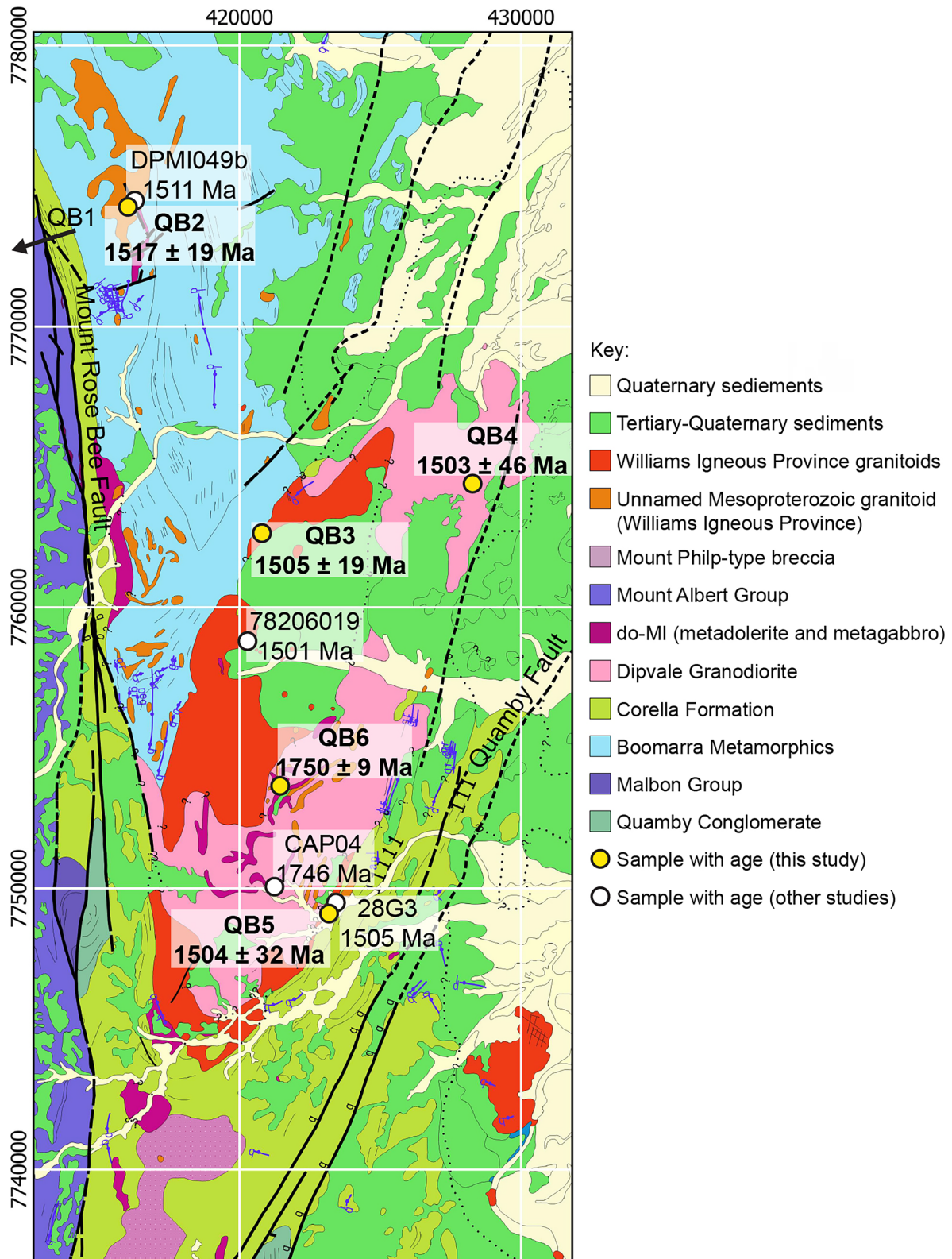


Figure 3. Geology map of northern study area of the Mary Kathleen Domain, Mount Isa Inlier (Figure 1, box 1). Sample numbers in bold with yellow circles are from this study. Sample numbers with white circles are ages of granitoid samples from other studies: (north to south) DPMI049b (unnamed granite; Bodorkos *et al.*, 2020); 78206019 (Mavis Granodiorite; Page & Sun, 1998); CAP04 and 28G3 (Dipvale Granodiorite and Mavis Granodiorite, respectively; Davis *et al.*, 2001). Approximately 80 km north of QB2 is the location of sample DPMI013 of an unnamed granite with an emplacement age of 1500 Ma (Bodorkos *et al.*, 2020). Geology modified after Queensland Department of Resources (2018, 2022).

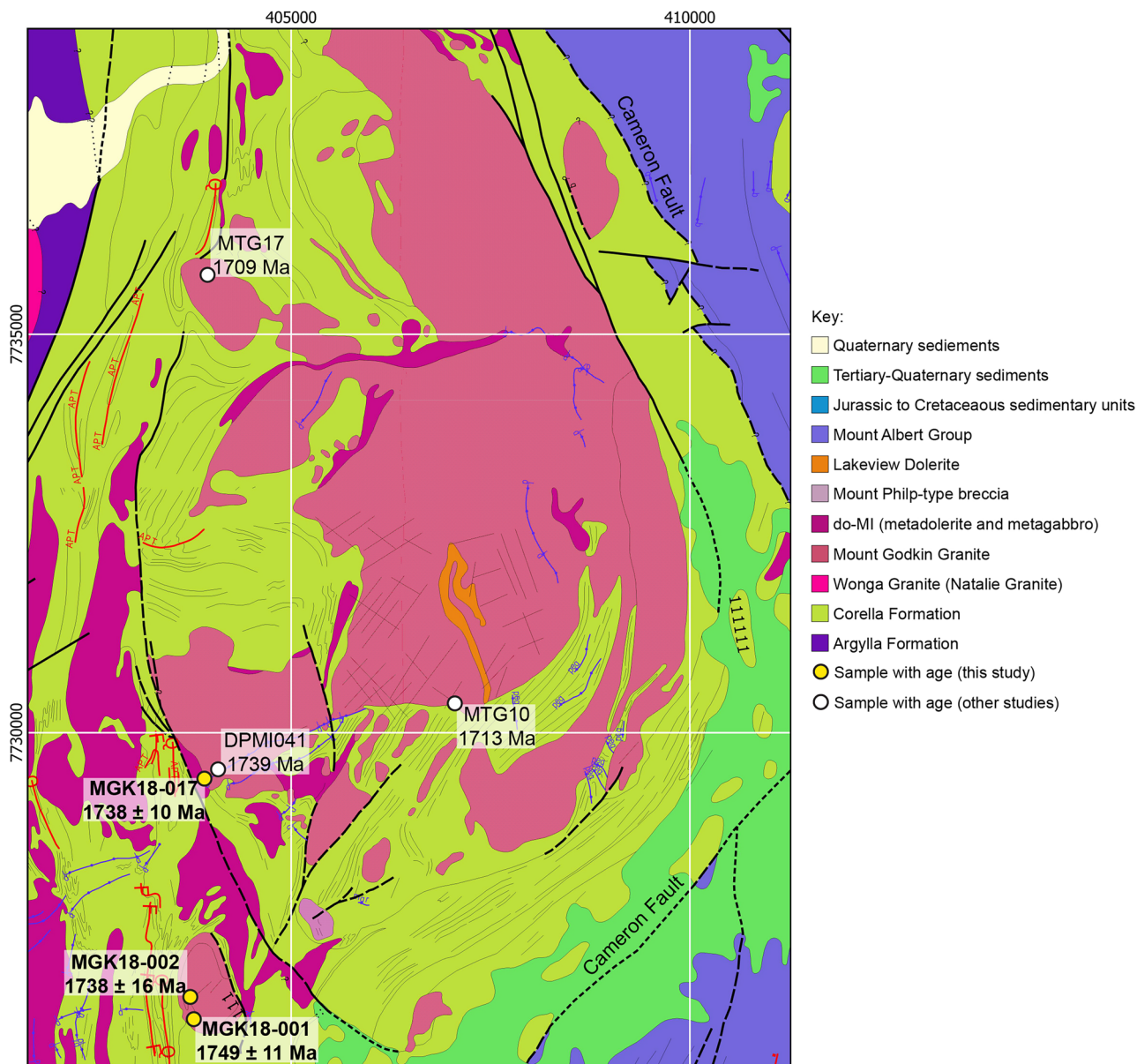


Figure 4. Geology map of the Mount Godkin study area in the Mary Kathleen Domain, Mount Isa Inlier (Figure 1, box 2). Sample numbers in bold with yellow circles are from this study. Sample numbers with white circles are ages of granitoid samples from other studies: (north to south) MTG17 and MTG10 (Spence *et al.*, 2021); DPMI041 (Bodorkos *et al.*, 2020). Geology modified after Queensland Department of Resources (2018, 2022).

sample QB5 (1504 ± 32 Ma), mapped as a separate outcrop of Mavis Granodiorite, is comparable with the reported age for another sample of the same unit (1505 ± 7 Ma; Davis *et al.*, 2001).

The Dipvale Granodiorite is mapped as two discrete outcropping magmatic bodies (Figure 3). Sample QB6 (1750 ± 9 Ma), an unnamed intrusion within the southern body of the Dipvale Granodiorite, produced an age within uncertainty of a previously dated sample from the southern section of Dipvale Granodiorite (1746 ± 7 Ma; Davis *et al.*, 2001). Sample QB4 was collected from the northern body of the Dipvale Granodiorite. Although the age result for this sample is not as well constrained (1503 ± 46 Ma; Figure A2a), the result does suggest that the northern body of the Dipvale Granodiorite is not the same unit as the southern body, or that younger intrusions are present in the northern body that were not recognised during fieldwork.

Mount Godkin Igneous Complex

Three samples from the Mount Godkin Igneous Complex yielded zircon ages of 1749 ± 11 Ma (MGK18-001), 1738 ± 16 Ma (MGK18-002) and 1738 ± 10 Ma (MGK18-017; Figure 11). MGK18-001 and MGK18-002 are from a small intrusive complex located southwest of the main Mount Godkin Granite body (Figure 4). MGK18-017 is from the southwestern part of the main Mount Godkin Granite body. A sample of the main granite body from a similar location to MGK18-017 has an age of 1739 ± 3 Ma (Bodorkos *et al.*, 2020), which is within uncertainty in the age of MGK18-017 (Figure 4). Interestingly, emplacement ages for the Mount Godkin Igneous Complex from other areas of the main granite body are 25–30 Ma younger than the southwestern samples (Figure 4; Spence *et al.*, 2021). This suggests that the

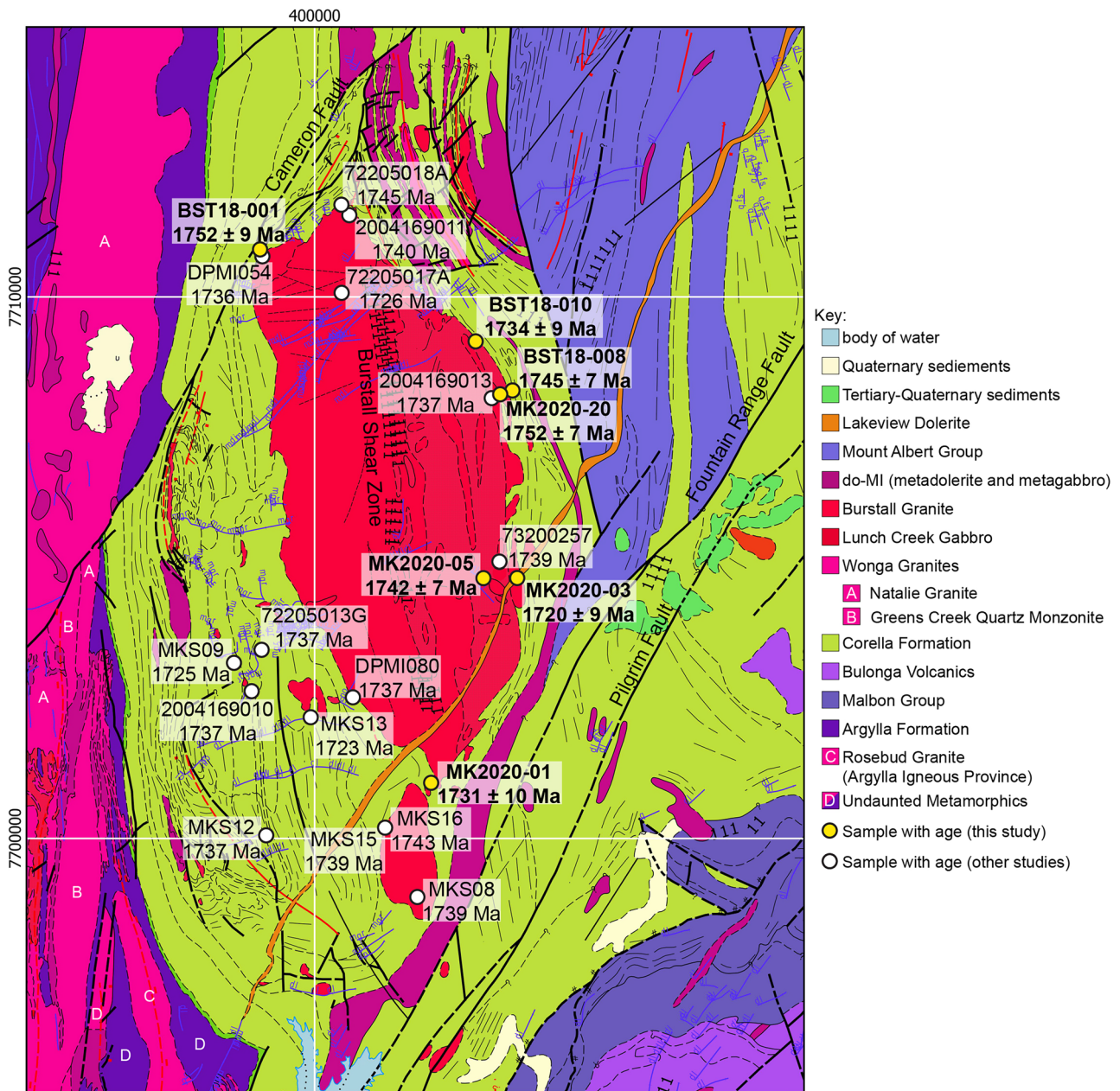


Figure 5. Geology map of the Burstall–Lunch Creek Gabbro study area in the Mary Kathleen Domain, Mount Isa Inlier (Figure 1, box 3). Sample numbers in bold with yellow circles are from this study. Sample numbers with white circles are ages of granitoid samples from other studies: (north to south) 72205018A (Burstall Granite; Page, 1983); 2004169011 (Burstall Granite; Neumann *et al.*, 2009); DPMI054 (Burstall Granite/I; Bodorkos *et al.*, 2020); 72205017A (Burstall Granite; Page, 1983); 2004169013 (Burstall Granite; Neumann *et al.*, 2009); 73200257 (Lunch Creek Gabbro; Page, 1983); 72205013 G (Burstall Granite; Page, 1983); MKS09 (Granitic intrusion in Corella Formation; Spence *et al.*, 2021); 2004169010 (Burstall Granite; Neumann *et al.*, 2009); DPMI080 (unnamed leucogranite from drillcore; Bodorkos *et al.*, 2020); MKS13 and MKS12 (granitic intrusions in Corella Formation; Spence *et al.*, 2021); MKS16 and MKS08 (Burstall Granite; Spence *et al.*, 2021); MKS15 (dolerite porphyry; Spence *et al.*, 2021). Additional intrusions of the Burstall Igneous Subprovince to the south of this map return emplacement ages of 1740 and 1736 Ma for the Overlander Granite (samples BB5904 and D16; Bodorkos *et al.*, 2020; Spence *et al.*, 2022), 1741–1722 Ma for the Revenue Granite (samples FBMI5605, 95208071 and D34B; Bierlein *et al.*, 2011; Jones *et al.*, 2018; Spence *et al.*, 2022), 1727 and 1723 Ma for the Muybee Igneous Complex (samples BB5966 and D45; Bodorkos *et al.*, 2020; Spence *et al.*, 2022) and 1735 and 1718 Ma for the Mount Erle Igneous Complex (samples BB5933 and FBMI5601; Bierlein *et al.*, 2011; Kositsin *et al.*, 2019). In addition, there are other intrusions in the Corella Formation near these intrusions with ages of 1740–1737 Ma (Jones *et al.*, 2018; Kositsin *et al.*, 2019). Geology modified after Queensland Department of Resources (2018, 2022).

main granite body could represent at least two episodes of magmatic activity.

Burstall Granite and Lunch Creek Gabbro

Zircon ages were calculated for seven samples from this area, with results ranging from 1752 ± 9 to 1720 ± 9 Ma (Figures 11

and 12). Sample BST18-001, from the leucocratic meta-granite (mapped as Burstall Granite/I) at the northwest end of the main Burstall Granite intrusion, has an age of 1752 ± 10 Ma. Emplacement ages for two Lunch Creek Gabbro samples, BST18-008 and MK2020-05, are 1745 ± 7 Ma and 1742 ± 7 Ma, respectively. One sample of the Burstall Granite returned an age of 1752 ± 7 Ma (MK2020-20). Two other granitic intrusions and

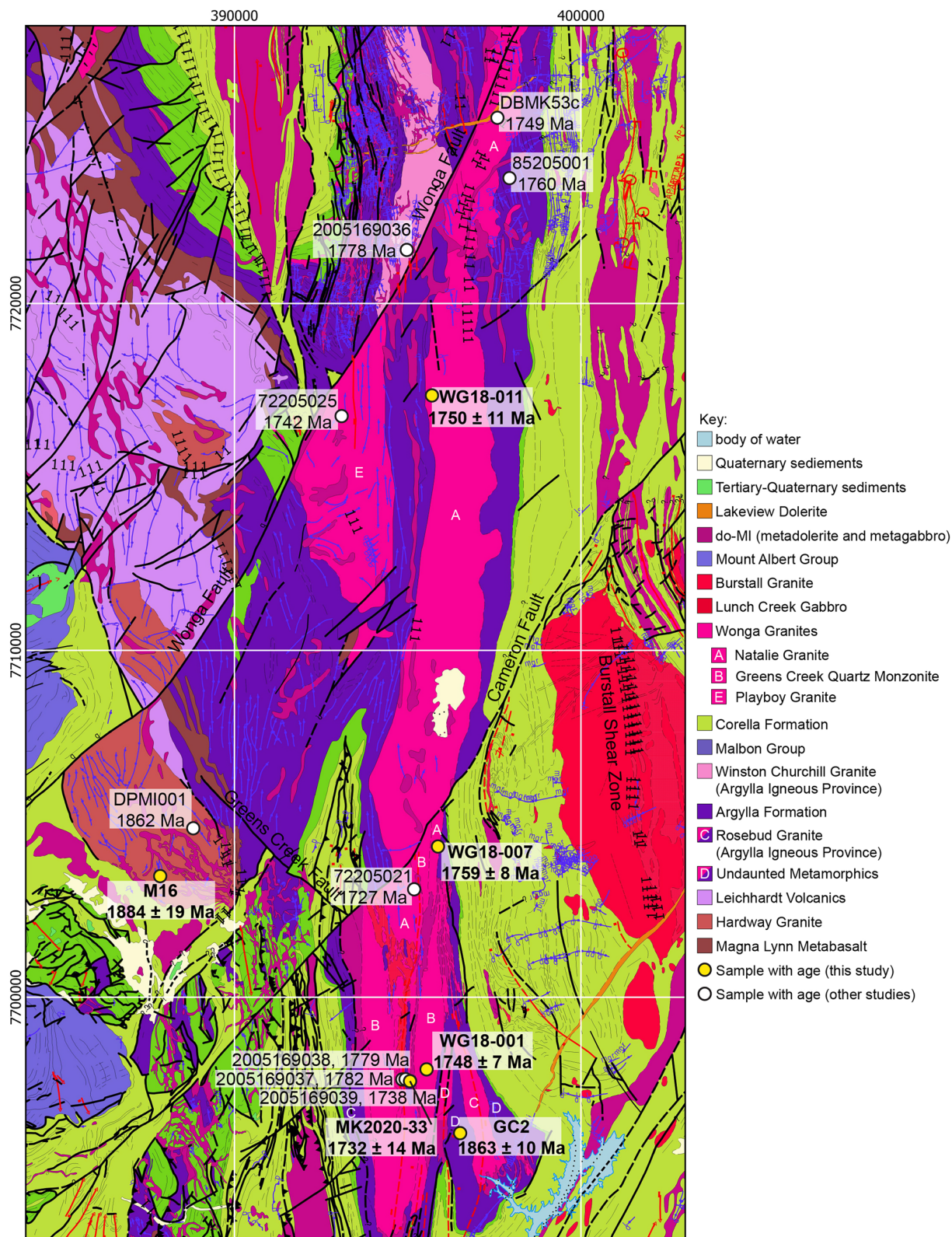


Figure 6. Geology map of the Wonga study area in the Mary Kathleen Domain, Mount Isa Inlier (Figure 1, box 4). Sample numbers in bold with yellow circles are from this study. Sample numbers with white circles are ages of granitoid samples from other studies: (north to south) DBMK53 (Natalie Granite; Kositsin *et al.*, 2019); 85205001 (Natalie Granite(?) intrusion in Argylla Formation; Pearson *et al.*, 1992; Withnall, 2019); 2005169036 (Winston Churchill Granite; Bultitude *et al.*, 2021; Neumann *et al.*, 2009); 72205025 (Playboy Granite; Pearson *et al.*, 1992); DPMI001 (Hardway Granite; Kositsin *et al.*, 2019); 72205021 (Natalie Granite; Pearson *et al.*, 1992; Withnall, 2019). Further north of this map is a sample of the Mount Maggie Granite with an emplacement age of 1729 Ma (DPMI129; Kositsin *et al.*, 2021) and an unnamed quartz diorite adjacent to the Mount Maggie Granite with an emplacement age of 1730 Ma (DPMI056; Kositsin *et al.*, 2019). Geology modified after Queensland Department of Resources (2018, 2022).

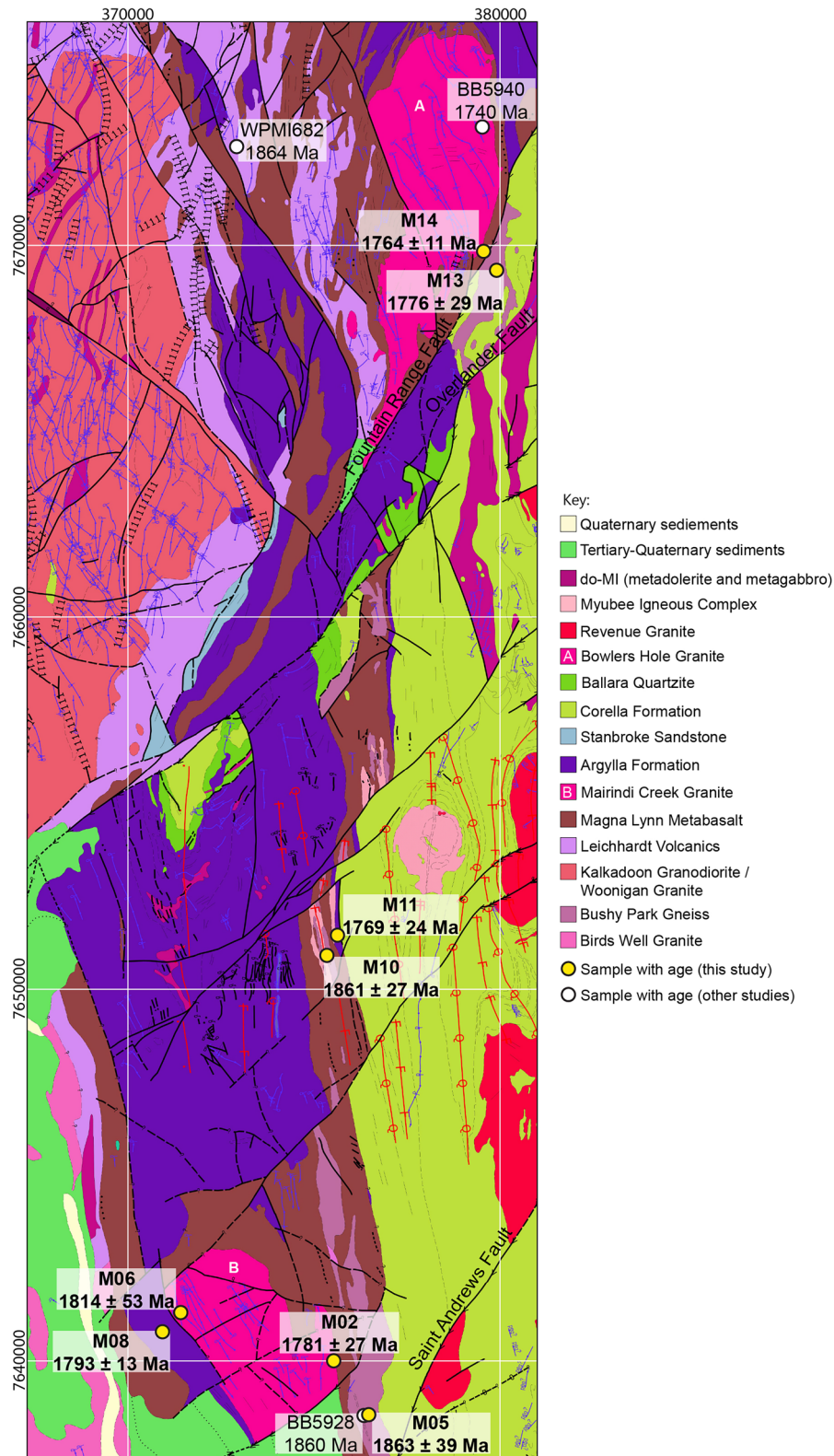


Figure 7. Geology map of the study area around the Mairindi Creek Granite and Bushy Park Gneiss in the western part of the Mary Kathleen Domain, Mount Isa Inlier (Figure 1, box 5). Sample numbers in bold with yellow circles are from this study. Sample numbers with white circles are ages from other studies: BB5940 (Bowlers Hole Granite; Kositsin *et al.*, 2019); WPML682 (Leichhardt Volcanics; Carson *et al.*, 2009); BB5928 (Bushy Park Gneiss; Kositsin *et al.*, 2021). The Myubee Igneous Complex and Revenue Granite on the eastern part of this map belong to the Burstall Igneous Province and have ages of ca 1735–1717 Ma (Bierlein *et al.*, 2011; Bodorkos *et al.*, 2020; Jones *et al.*, 2018; Spence *et al.*, 2022). Geology modified after Queensland Department of Resources (2018, 2022).

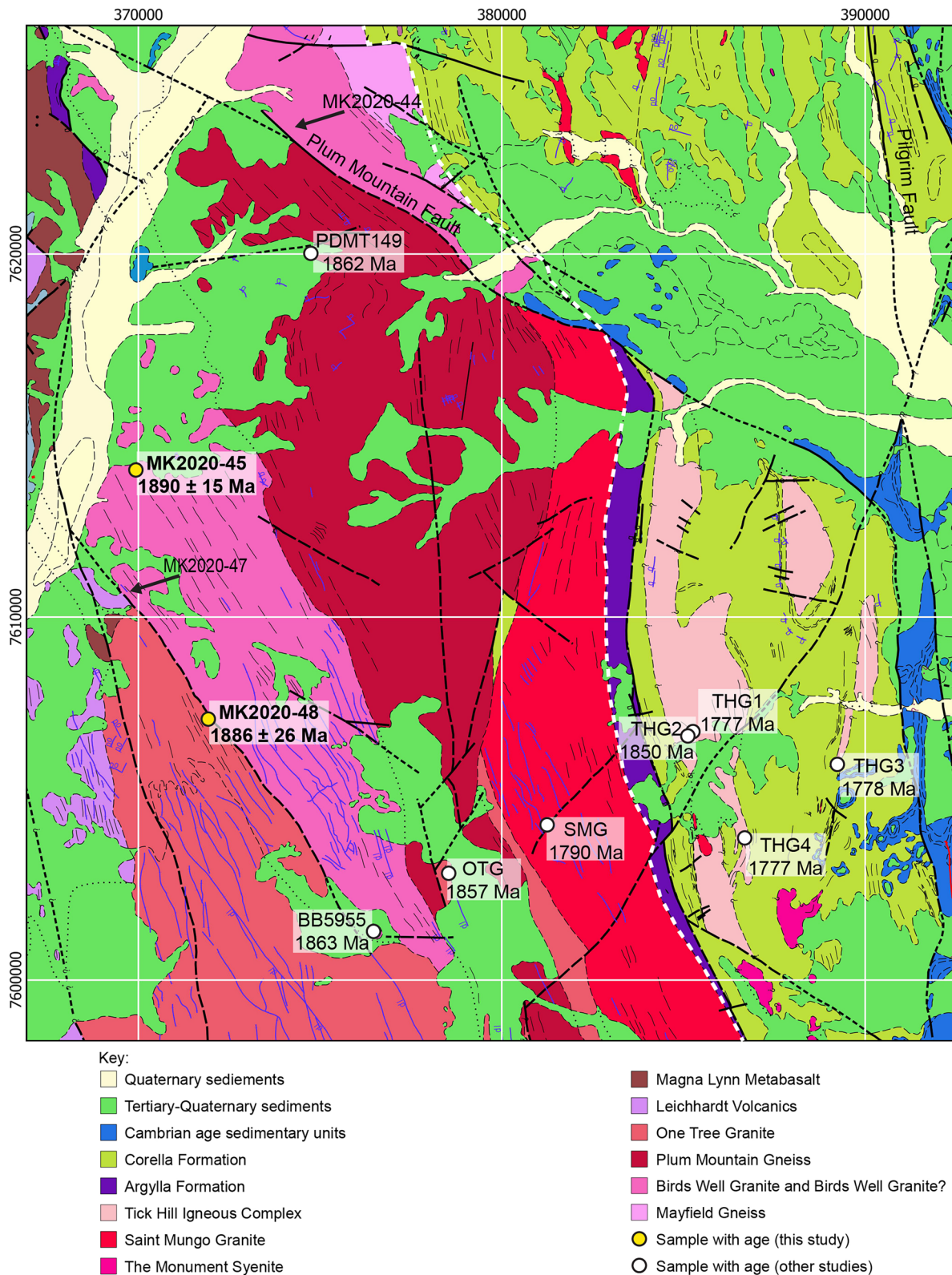


Figure 8. Geology map of the study area south of the Plum Mountain Fault in and to the west of the southern part of the Mary Kathleen Domain, Mount Isa Inlier (Figure 1, box 6). The white dashed line represents the recently revised southern boundary of the Mary Kathleen Domain (Bultitude *et al.*, 2021). Sample numbers in bold with yellow circles are from this study. Sample numbers with white circles are ages from other studies: PDMT149 (Plum Mountain Gneiss; Carson *et al.*, 2011); OTG (One Tree Granite/d; Le *et al.*, 2021a); SMG (Saint Mungo Granite; Le *et al.*, 2021a); THG1 (granitic dyke crosscutting THG2); THG3, THG4 (Tick Hill Igneous Complex; Le *et al.*, 2021a); THG2; maps as Tick Hill Complex but is an older granitic gneiss; Le *et al.*, 2021a); BB5955 (maps as Birds Well Granite?; Kositsin *et al.*, 2021). Geology modified after Queensland Department of Resources (2018, 2022).

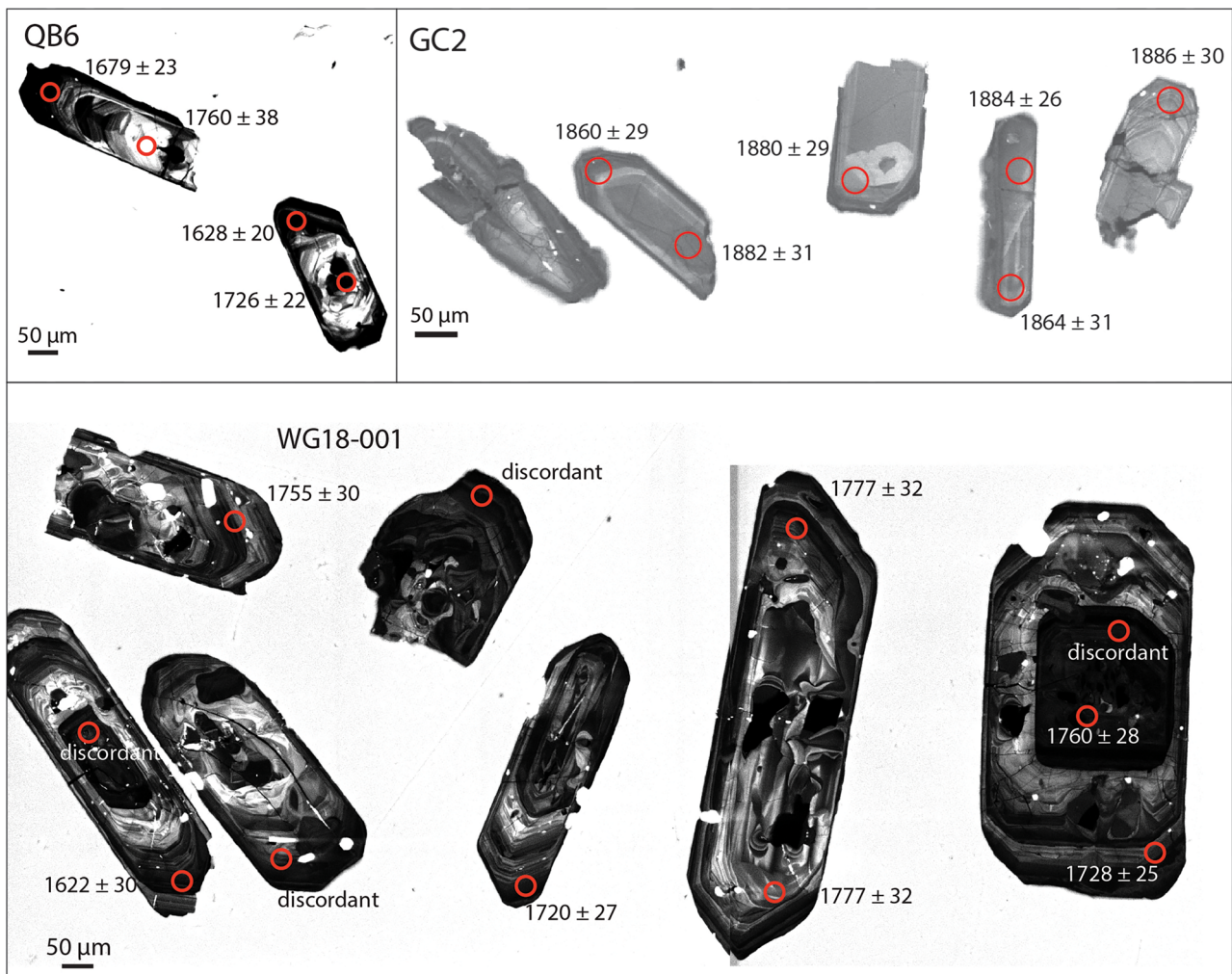


Figure 9. Cathodoluminescence images of a number of zircons from selected samples with $^{207}\text{Pb}/^{206}\text{Pb}$ age data for individual analyses shown. Images show zoning in many of the zircons with some grains showing clear cores with concentric rim zoning. Uncertainties are 2SE.

a felsic dyke in the area returned younger ages of 1734 ± 9 Ma (BST18-010), 1731 ± 10 Ma (MK2020-01) and 1720 ± 9 Ma (MK2020-03), respectively. These new ages agree with emplacement ages for other igneous intrusions in this area, which range from 1745 to 1723 Ma (Figure 5; $n = 15$; Neumann *et al.*, 2009; Page, 1983; Spence *et al.*, 2021). The large age spread (*ca* 32 Ma) for intrusions mapped as the Burstall Granite can be explained by field evidence of multiple phases of intrusion emplacement, including many cross-cutting dyke structures, within the Burstall Granite–Lunch Creek Gabbro area.

Wonga, Greens Creek and Hardway granites

Three samples of granite from the Wonga Igneous Subprovince returned ages that were within uncertainty of each other (Figure 13): 1748 ± 7 Ma for the Greens Creek Quartz Monzonite (WG18-001); 1759 ± 8 Ma for the Natalie Granite east of the Burstall Granite and the Cameron Fault (WG18-007); and 1750 ± 11 Ma for the Natalie Granite northeast of the Burstall Granite and west of the Cameron Fault (WG18-011). Previous studies of granites from the Wonga Igneous Subprovince have yielded ages

ranging from 1749 to 1727 Ma, with the Natalie Granite spanning this entire range (Figure 6; Kositsin *et al.*, 2019, 2021; Neumann *et al.*, 2009; Pearson *et al.*, 1992; Withnall, 2019). Another sample to the northwest of WG18-011 is attributed to the Natalie Granite and was dated at 1760 ± 12 Ma (Pearson *et al.*, 1992; Withnall, 2019). The location of this sample maps as Argylia Formation, but the sample represents a microgranite that is one of the younger units at the sample site, based on field relationships (Pearson *et al.*, 1992). The large age range for samples from the Natalie Granite suggests that the granite comprises multiple phases of plutonism during the Wonga Orogeny.

Zircons from sample GC2, which was previously mapped as Argylia Formation (Queensland Department of Resources, 2018), yield an age of 1863 ± 10 Ma (Figure 13). This age is significantly older than intrusions of the Argylia Igneous Province (*ca* 1780 Ma) and is instead similar to the ages of intrusions in the Kalkadoon–Leichhardt Igneous Province (*ca* 1870–1850 Ma). We interpret this intrusion to be a granitic lens belonging to the Kalkadoon–Leichhardt Igneous Province within the recently remapped Undaunted Metamorphics (Queensland Department of Resources, 2022). Emplacement ages for intrusions in contact

Table 2. Summary of zircon $^{207}\text{Pb}/^{206}\text{Pb}$ age data from Mary Kathleen Domain samples of this study.

			²⁰⁷ Pb/ ²⁰⁶ Pb	Uncertainty	Combined		
Sample	Intrusion unit name/comments	Map figure	weighted mean (Ma)	2SE	uncertainty ^a 2SE	MSWD	n
Williams Igneous Province							
QB2	Unnamed granite	Figure 3	1517	11	19 ^b	2.8	7
QB3	Mavis Granodiorite	Figure 3	1505	18	19	1	3
QB5	Mavis Granodiorite	Figure 3	1504	14	32 ^b	5.1	5
Burstall Igneous Subprovince							
MGK18-001	Mount Godkin Granite/m	Figure 4	1749	10	11	1.6	4
MGK18-002	Mount Godkin Granite/d	Figure 4	1738	15	16	2	2
MGK18-017	Mount Godkin Granite/g	Figure 4	1738	7	10	0.83	12
BST18-001	Burstall Granite/l (leucogranite)	Figure 5	1752	7	9	1.7	11
BST18-008	Lunch Creek Gabbro	Figure 5	1745	3	7	0.93	44
BST18-010	Burstall Granite	Figure 5	1734	7	9	1.1	15
MK2020-01	Felsic dyke (Burstall area)	Figure 5	1731	8	10	1.1	12
MK2020-03	Burstall Granite	Figure 5	1720	4	9 ^b	2.8	27
MK2020-05	Lunch Creek Gabbro	Figure 5	1742	3	7	0.94	53
MK2020-20	Burstall Granite	Figure 5	1752	4	7	0.94	30
Wonga Igneous Subprovince							
WG18-001	Greens Creek Quartz Monzonite (previously Wonga Granite/3a)	Figure 6	1748	3	7	1.2	68
WG18-007	Natalie Granite (previously Wonga Granite/5a)	Figure 6	1759	5	8	1.3	22
WG18-011	Natalie Granite (previously Wonga Granite)	Figure 6	1750	9	11	0.9	5
Argylla Igneous Province							
M13	Mapped as Bushy Park Gneiss	Figure 7	1776	18	29 ^b	2.6	6
M14	Porphyry intruding Magna Lynn Metabasalt	Figure 7	1764	9	11	1.1	23
M11	Argylla Formation	Figure 7	1769	20	24	0.75	20
M02	Mairindi Creek Granite (foliated)	Figure 7	1781	23	27	0.81	15
M06	Mairindi Creek Granite (undeformed)	Figure 7	1814	51	53	0.67	3
M08	Argylla Formation	Figure 7	1793	12	13	0.86	18
Kalkadoon Igneous Province or older							
GC2	Greens Creek area (now mapped as Undaunted Metamorphics)	Figure 6	1863	5	10 ^b	2.3	34
MK2020-45	Birds Well Granite?	Figure 8	1890	14	15	1.8	4
M16	Hardway Granite	Figure 6	1884	18	19	1.1	6
M10	Bushy Park Gneiss	Figure 7	1861	24	27	0.97	14
M05	Bushy Park Gneiss	Figure 7	1863	22	39 ^b	3	4
Unassigned to an igneous province – likely Burstall or Wonga Igneous Subprovince							
QB6	Unnamed granite	Figure 3	1750	5	9 ^b	1.8	36
MK2020-33	Felsic dyke (Greens Creek area)	Figure 6	1732	12	14	1.8	4

^aTotal uncertainty includes the propagated external uncertainty from IsoplotR (for overdispersion if relevant) plus the uncertainty on the primary reference material.

^bIncludes additional uncertainty for overdispersion.

with this unit could not be determined. Other outcrops of intrusions and gneisses in Greens Creek to the northwest of the location of GC2 yielded ages of 1738 ± 3 Ma, 1782 ± 3 Ma and 1779 ± 3 Ma (Neumann *et al.*, 2009), and have been mapped as part of the Wonga and Argylla igneous provinces (Figure 6). Sample MK2020-33, a felsic dyke that cross-cuts the 1738 Ma Greens Creek intrusion (Neumann *et al.*, 2009), returned a younger age of 1732 ± 14 Ma. Sample GC2 represents one of the most northerly and easterly outcrops of an intrusion of this age (*i.e.* >1850 Ma) within the MKD.

A sample of the Hardway Granite (M16) produced an age of 1884 ± 19 Ma (Figure 13). At the sampling location, the granite is strongly deformed and contains a well-developed, steeply dipping, gneissic foliation striking 065. This age is older than the age currently reported for the Hardway Granite (1862 ± 3 Ma; Kositcin *et al.*, 2019), from a sample, described as mildly deformed, approximately 1.8 km northeast of sample M16. During fieldwork, it was noted that amphibolite with foliation-trending 065 was cut by undeformed granite near the outcrop associated with sample DPIM001. However, around the sampling site of M16, amphibolite with foliation bearing 300 occurs in granite with foliation bearing 065. An east–west-trending strongly deformed granite occurs 190 m to

the southwest of sample M16. These observations indicate that the Hardway Granite may contain intrusive phases of different ages. On the geological maps, the Hardway Granite is surrounded by rocks assigned to the much younger Argylla and Corella formations. The field relationships between the Hardway Granite and these rocks were not investigated during this study, but the map pattern suggests a possible intrusive relationship. Further work is recommended to clarify the field relationships, since this may have direct implications for the stratigraphic succession in the area.

Western MKD intrusions of the Kalkadoon–Leichhardt and Argylla igneous provinces

Eight of 10 samples from this region (Box 5 of Figure 1; Figure 7) returned ages based on multiple concordant zircon analyses. Samples from units mapped as Bushy Park Gneiss, an intrusive unit assigned to the Kalkadoon–Leichhardt Igneous Province, yielded ages of 1863 ± 39 Ma (M05), 1861 ± 27 Ma (M10) and 1776 ± 29 Ma (M13; Figure 14). Of these results, only samples M05 and M10 returned ages associated with the Kalkadoon–Leichhardt Igneous Province, suggesting that sample M13 is

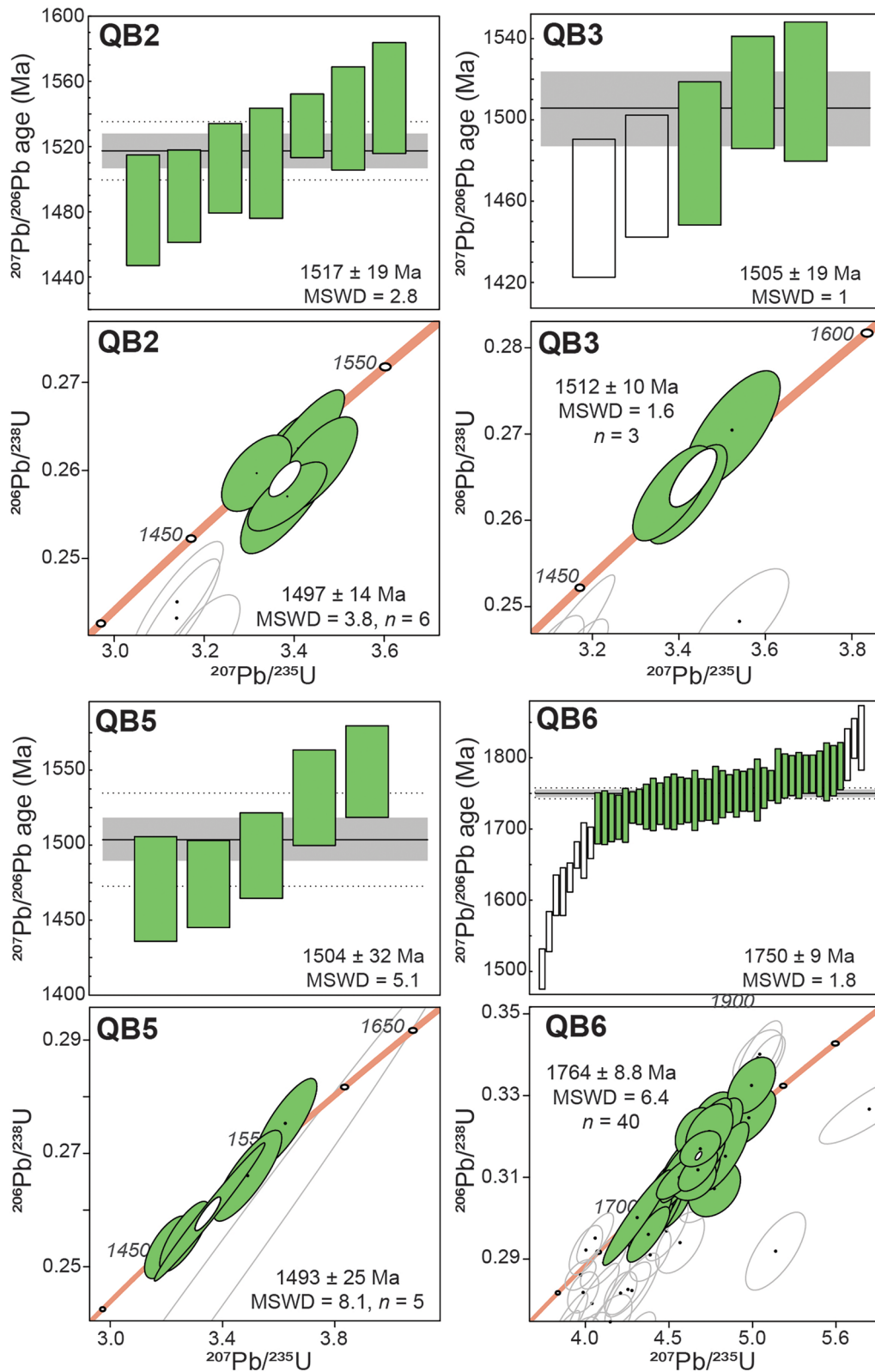


Figure 10. Weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age and Wetherill concordia plots for samples of the Williams Igneous Province and sample QB6. Uncertainties shown are 2SE propagated uncertainty for concordia plots and combined propagated uncertainty for weighted mean ages. Weighted mean ages and concordia diagrams were calculated and plotted in IsoplotR, with MSWD shown for concordance plus equivalence for the concordia diagrams.

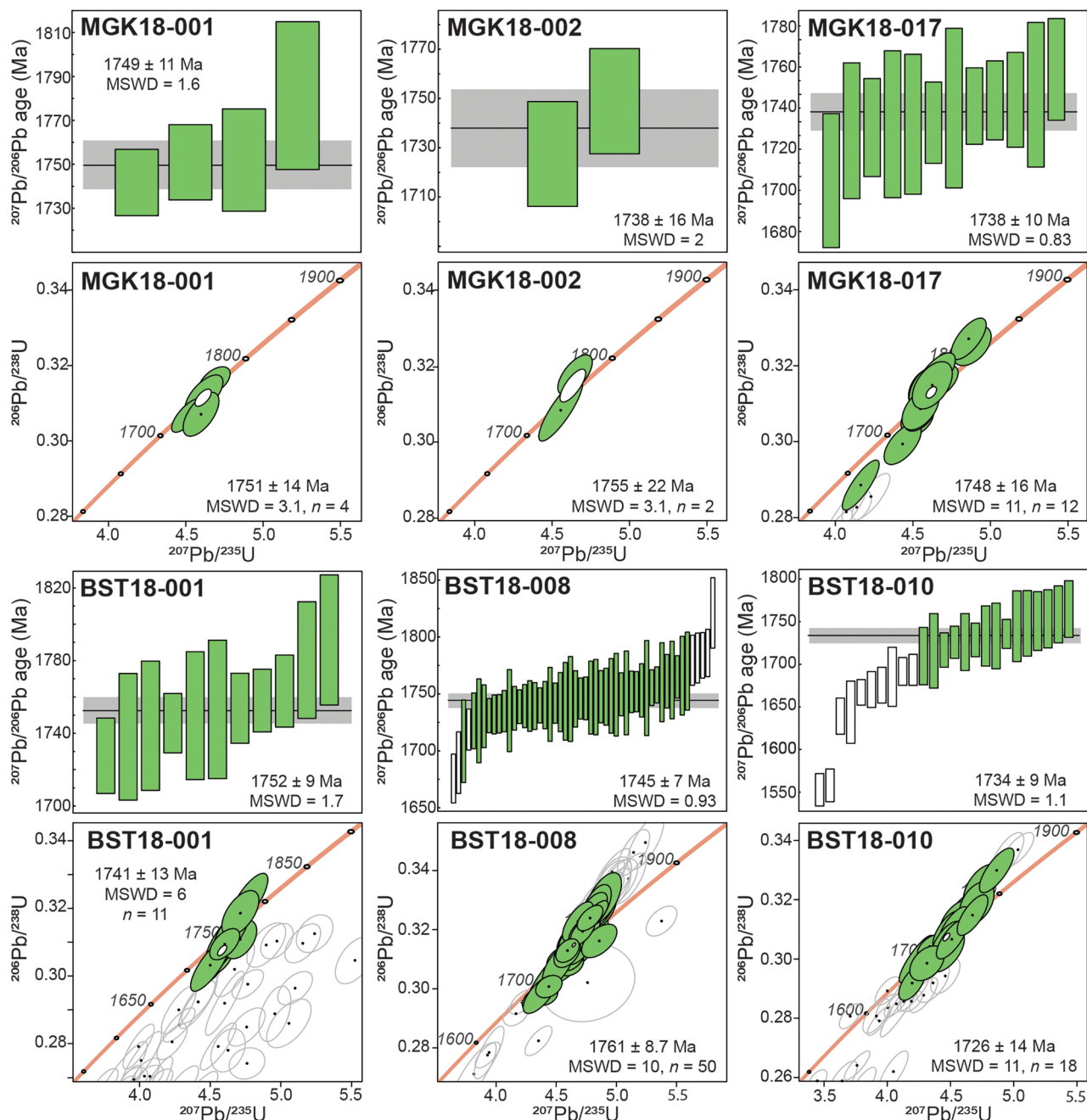


Figure 11. Weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age and Wetherill concordia plots for samples of the Mount Godkin Igneous Complex and from the Burstall Granite–Lunch Creek Gabbro area (Burstall Igneous Subprovince). Uncertainties shown are 2SE propagated uncertainty for concordia plots and combined propagated uncertainty for weighted mean ages. Weighted mean ages and concordia diagrams were calculated and plotted in IsoplotR, with MSWD shown for concordance plus uncertainty for the concordia diagrams.

from a younger intrusion more likely related to the Argylla Igneous Province. Sample M05 is from a similar location to that of another study that produced a similar age of 1860 ± 5 Ma (Kositcin *et al.*, 2021).

Samples M02, from the eastern side, and M06, from the western side, of the Mairindi Creek Granite returned ages of 1781 ± 27 Ma and 1814 ± 53 Ma, respectively (Figure 14). Although the ages are within error, it is noted that sample M02 is porphyritic and foliated, while M06 is undeformed. Samples of units mapped as the Argylla Formation produced ages of

1793 ± 13 Ma (M08) and 1769 ± 24 Ma (M11; Figure 14). Sample M14, from a porphyry intruding the Magna Lynn Metabasalt, yielded an age of 1764 ± 11 Ma (Figure 14), providing a minimum age for the Magna Lynn Metabasalt, which has not been previously dated (Bultitude *et al.*, 2021).

Area south of the Plum Mountain Fault

Many of the samples from intrusions in the area south of the Plum Mountain Fault are intensely and pervasively altered

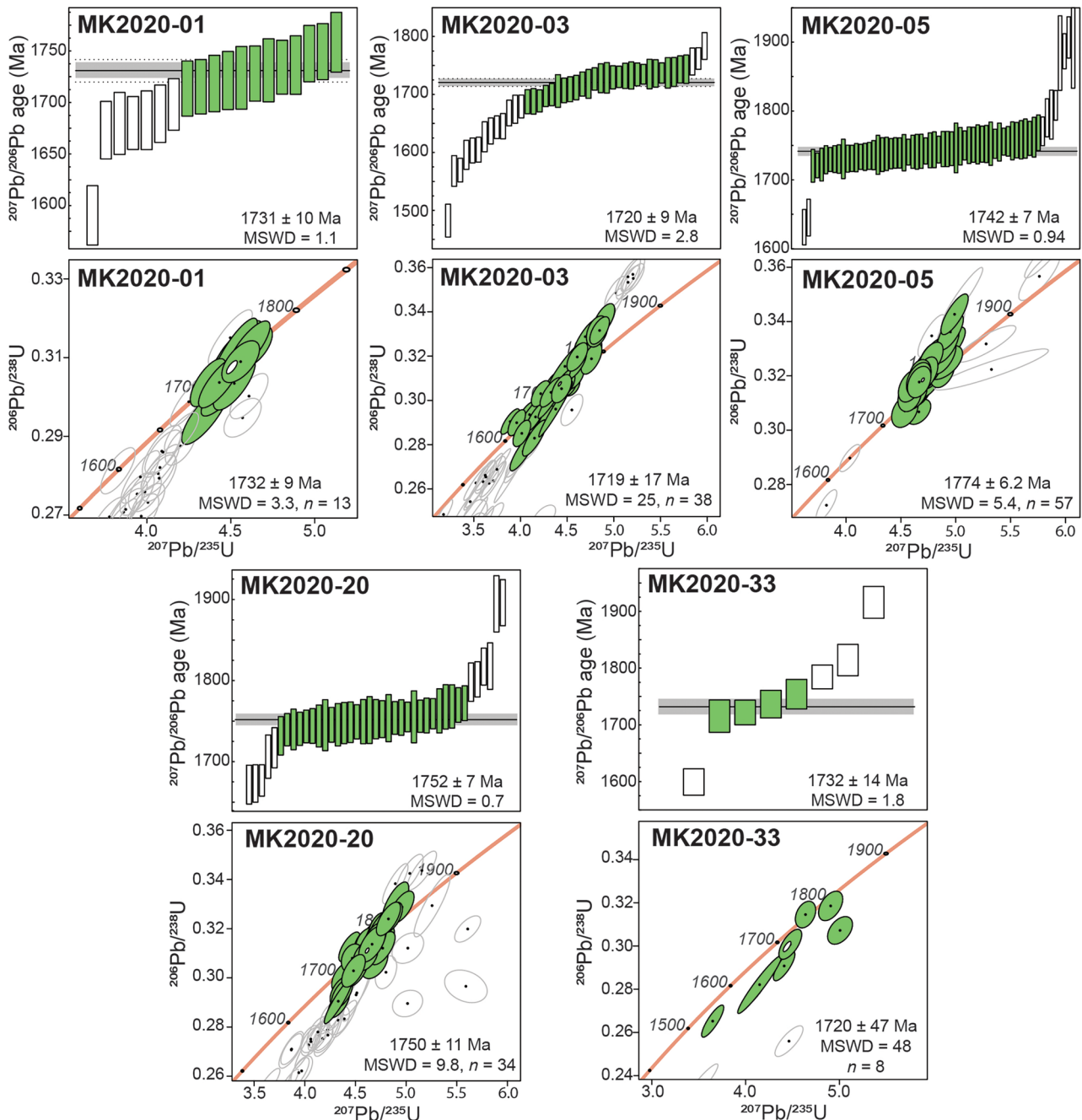


Figure 12. Weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age and Wetherill concordia plots for samples from the Burstall Granite–Lunch Creek Gabbro area (Burstall Igneous Subprovince). Uncertainties shown are 2SE propagated uncertainty for concordia plots and combined propagated uncertainty for weighted mean ages. Weighted mean ages and concordia diagrams were calculated and plotted in IsoplotR, with MSWD shown for concordance plus equivalence for the concordia diagrams.

(e.g. supplemental data, Figure A1f). Only one of five samples collected from this area in this study yielded concordant results from several zircon grains (MK2020-45), generating a weighted mean age of 1890 ± 15 Ma (Figure 13; the limited age information for the other samples from this area is included in the supplemental data, Table A3). This age is older than the age range for the Kalkadoon–Leichhardt Igneous Province, to which this unit has been reassigned (Bultitude *et al.*, 2021), and could be interpreted as having been

emplaced early during, or even before, the Barramundi Orogeny (*ca* 1870–1850 Ma; Betts *et al.*, 2006; de Vries *et al.*, 2008; O’Dea *et al.*, 1997). Other ages of intrusions in this region correspond to the Kalkadoon–Leichhardt Igneous Province (e.g. Plum Mountain Gneiss at 1862 ± 3 Ma, Carson *et al.*, 2011; Birds Well Granite? at 1863 ± 6 Ma, Kositcin *et al.*, 2021; One Tree Granite at 1857 ± 5 Ma, Le *et al.*, 2021a) and the Argylla Igneous Province (e.g. Tick Hill Granite at *ca* 1777 Ma, Le *et al.*, 2021a; Figure 8).

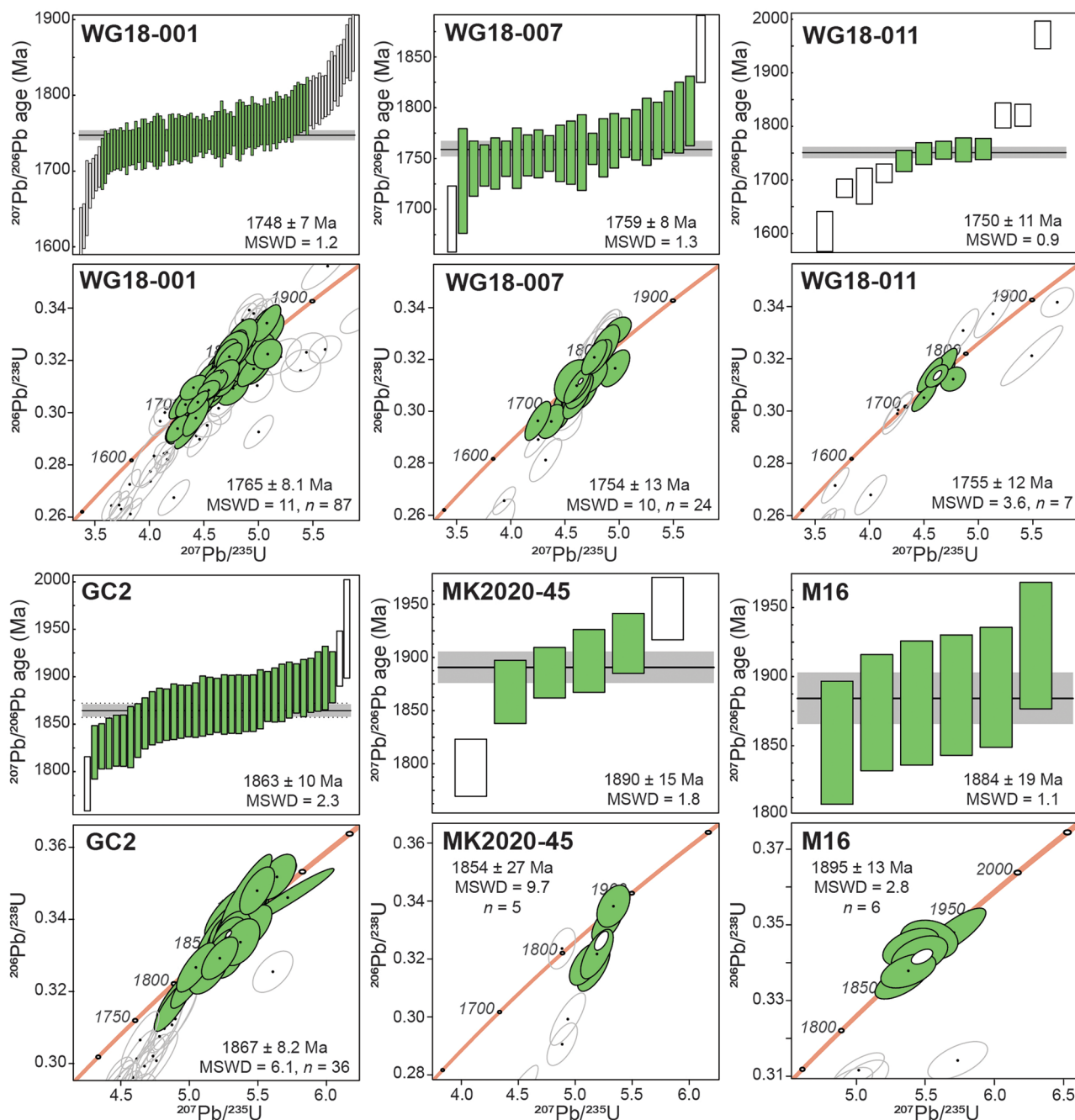


Figure 13. Weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age and Wetherill concordia plots for samples of the Wonga Igneous Subprovince and Kalkadoon–Leichhardt Igneous Province. Uncertainties shown are 2SE propagated uncertainty for concordia plots and combined propagated uncertainty for weighted mean ages. Weighted mean ages and concordia diagrams were calculated and plotted in IsoplotR, with MSWD shown for concordance plus equivalence for the concordia diagrams.

Discussion

Division of intrusions into igneous provinces

A variety of nomenclatures have been used to refer to groups of intrusions, and in some cases also volcanic units, of the Mount Isa Inlier. These include references to igneous or magmatic events (e.g. Neumann *et al.*, 2009; Withnall, 2019), batholith (e.g. Betts *et al.*, 2006; Blake, 1987; Blake & Stewart, 1992; Budd *et al.*, 2001; Davis *et al.*, 2001; Mark, 1999; Withnall, 2019; Withnall & Hutton, 2013; Wyborn, 1998; Wyborn *et al.*, 1988), suite/

supersuite (e.g. Budd *et al.*, 2001; Geoscience Australia & Australian Stratigraphy Commission, 2025; Pollard *et al.*, 1998; Withnall, 2019; Withnall & Hutton, 2013) and association (e.g. Budd *et al.*, 2001; Wyborn *et al.*, 1988). Some of these terms are not very well defined in the literature, or the usage of the terms varies among different sources. Here the term ‘province’ is adopted following Bultitude *et al.* (2021). We interpret a province to include all igneous units (both plutonic and volcanic) within the spatial extent of the Mount Isa Inlier that formed within the time period constrained by geochronology for each

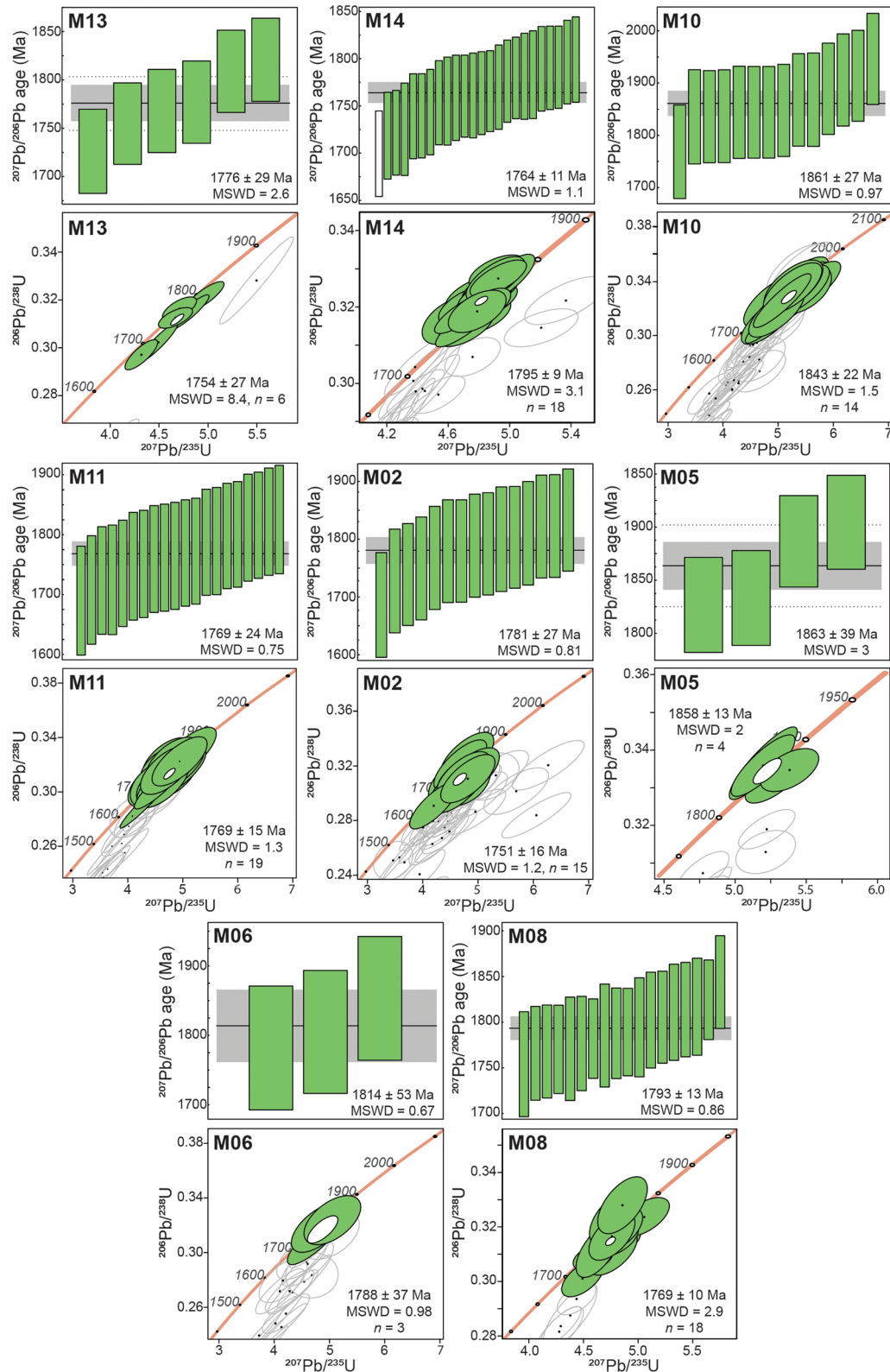


Figure 14. Weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age and Wetherill concordia plots for samples of the Argylla and Kalkadoon–Leichhardt igneous provinces. Uncertainties shown are 2SE propagated uncertainty for concordia plots and combined propagated uncertainty for weighted mean ages. Weighted mean ages and concordia diagrams were calculated and plotted in IsoplotR, with MSWD shown for concordance plus equivalence for the concordia diagrams.

province (e.g. ca 1550–1500 Ma for the Williams Igneous Province). In this study, we focussed on the intrusive units of the MKD, which predominantly belong to the Kalkadoon–Leichhardt, Argylla and Williams igneous provinces, and the Wonga and Burstall igneous subprovinces. The Kalkadoon–Leichhardt and Williams igneous provinces and Wonga and Burstall igneous subprovinces are comparable with the suites and supersuite groupings referred to in previous works (e.g. Budd *et al.*, 2001; Geoscience Australia & Australian Stratigraphy Commission, 2025), with some minor revisions based on updated geochronology (supplemental data, Table A1; Bultitude *et al.*, 2021). The Argylla Igneous Province is a new grouping of igneous units that mainly incorporates the Argylla Formation along with older intrusions previously mistakenly assigned to the Wonga Suite (supplemental data, Table A1; Bultitude *et al.*, 2021; this study).

Budd *et al.* (2001) and Withnall (2019) recognised the need to test which intrusions in the Mount Isa Inlier were comagmatic and revised how the intrusions were grouped together accordingly. This was particularly relevant for the Wonga Igneous Subprovince, which previously comprised intrusions with emplacement ages overlapping with those of the Argylla and Burstall provinces. We agree with the newly revised igneous provinces of the MKD, as outlined in Bultitude *et al.* (2021), summarised in the supplemental data (Table A1; with data from this study included). Most noteworthy is that intrusions of the previously named Wonga Suite (e.g. Budd *et al.*, 2001) have now been separated into the Argylla and Wonga provinces based on their emplacement ages (Bultitude *et al.*, 2021).

There is significant overlap in the emplacement ages of intrusions of the Wonga and Burstall igneous subprovinces (1760–1727 Ma and 1755–1709 Ma, respectively; Figures 15 and 16), and these were originally grouped together as the Wonga Batholith (Blake, 1987; Wyborn *et al.*, 1988). The Wonga Batholith was separated into (a) more intensely deformed intrusions interpreted to have been emplaced at deeper levels in the crust, which were later termed the Wonga Suite (e.g. Budd *et al.*, 2001; Neumann *et al.*, 2009), and (b) those of the Burstall Suite (e.g. Budd *et al.*, 2001; Neumann *et al.*, 2009), which were interpreted to have been emplaced at higher crustal levels, with intrusions of both suites emplaced during extensional shearing (e.g. Holcombe *et al.*, 1991; Oliver *et al.*, 1991; Pearson *et al.*, 1992). However, recent work by Spence *et al.* (2021, 2022) indicates that the intrusions of both provinces were instead emplaced into high- and low-strain domains of the same stratigraphic sequence during compressional deformation of the Wonga Orogeny (ca 1750–1710 Ma).

Figures 15 and 16 demonstrate how the emplacement ages of most of the intrusions within the MKD fall into discrete time periods spanning the Paleoproterozoic to Mesoproterozoic. These form the basis for the division of intrusions into the various igneous provinces and can be extended across the Mount Isa Inlier (e.g. Neumann *et al.*, 2006; Page, 1988; Withnall, 2019; Wyborn *et al.*, 1988). Within the MKD, there is a general trend of younger emplacement ages towards the north and

east of the MKD, with older intrusions towards the west and south (Figure 15). This pattern is partially related to the position of the MKD boundary and the overall domain shape. For example, units of the Argylla Igneous Province extend from the MKD north into the northeastern part of the Kalkadoon–Leichhardt Domain (Figure 15). The broad trend of older units to the west and younger to the east in the MKD possibly relates to the orientation of convergent tectonics during orogenic events and assembly of the North Australian Craton (e.g. Spence *et al.*, 2021). The broad trend of younger units to the north and older units to the south also follows an emerging pattern observed with the metasedimentary host units. For example, the host sediments of the Tick Hill deposit in the southern part of the MKD are mapped as the Corella Formation (ca 1760–1740 Ma); however, geochronology shows these sediments to be older than 1760 Ma (Kositcin *et al.*, 2021; Le *et al.*, 2021a). Field relationships and geochronology of units mapped as the Corella Formation further north in the MKD indicate a younger age (ca 1752–1737 Ma; Kositcin *et al.*, 2019, 2021; Withnall, 2019).

Intrusions older than 1780 Ma in the MKD

Many of the oldest intrusions within the former MKD boundary (Geological Survey of Queensland, 2011; Withnall & Hutton, 2013), which were interpreted as basement in the eastern part of the Mount Isa Inlier, have now been excluded from the current MKD, following a revision by Bultitude *et al.* (2021). The former MKD boundary, along with other domain boundaries of the Mount Isa Inlier, was based on structural, basinal, metamorphic and geochronological features (Withnall & Hutton, 2013). The southern boundary of the MKD has been changed because several intrusions near and south of the Plum Mountain Fault have yielded radiometric ages that were significantly older than expected for the mapped units of the igneous provinces they were assigned to (e.g. Bushy Park Gneiss, Birds Well Granite?, and Saint Mungo Granite; Bultitude *et al.*, 2021; Kositcin *et al.*, 2019, 2021; Le *et al.*, 2021a). The revised MKD boundary in the southwestern part of the domain now represents a division between the Leichhardt Volcanics and the Magna Lynn Metabasalt/Argylla Formation (Bultitude *et al.*, 2021). However, some intrusions of the Kalkadoon–Leichhardt Igneous Province remain within the revised MKD, for example the Hardway Granite on the western side of the MKD and the Bushy Park Gneiss close to the revised southern boundary. This study identified an additional outcrop of a similarly aged basement, sample GC2 with an emplacement age of 1864 ± 9 Ma, situated approximately 9.5 km southeast of the Hardway Granite (Figure 6). This intrusion is therefore one of the more northerly and the most easterly outcrops of an intrusion correlating to the age of the exposed basement in the MKD (Figure 15). The presence of outcropping units of the Kalkadoon–Leichhardt Igneous Province or units of similar ages indicates that the MKD may reflect a transitional domain between the Kalkadoon–Leichhardt Domain and the rest of the Eastern Fold Belt.

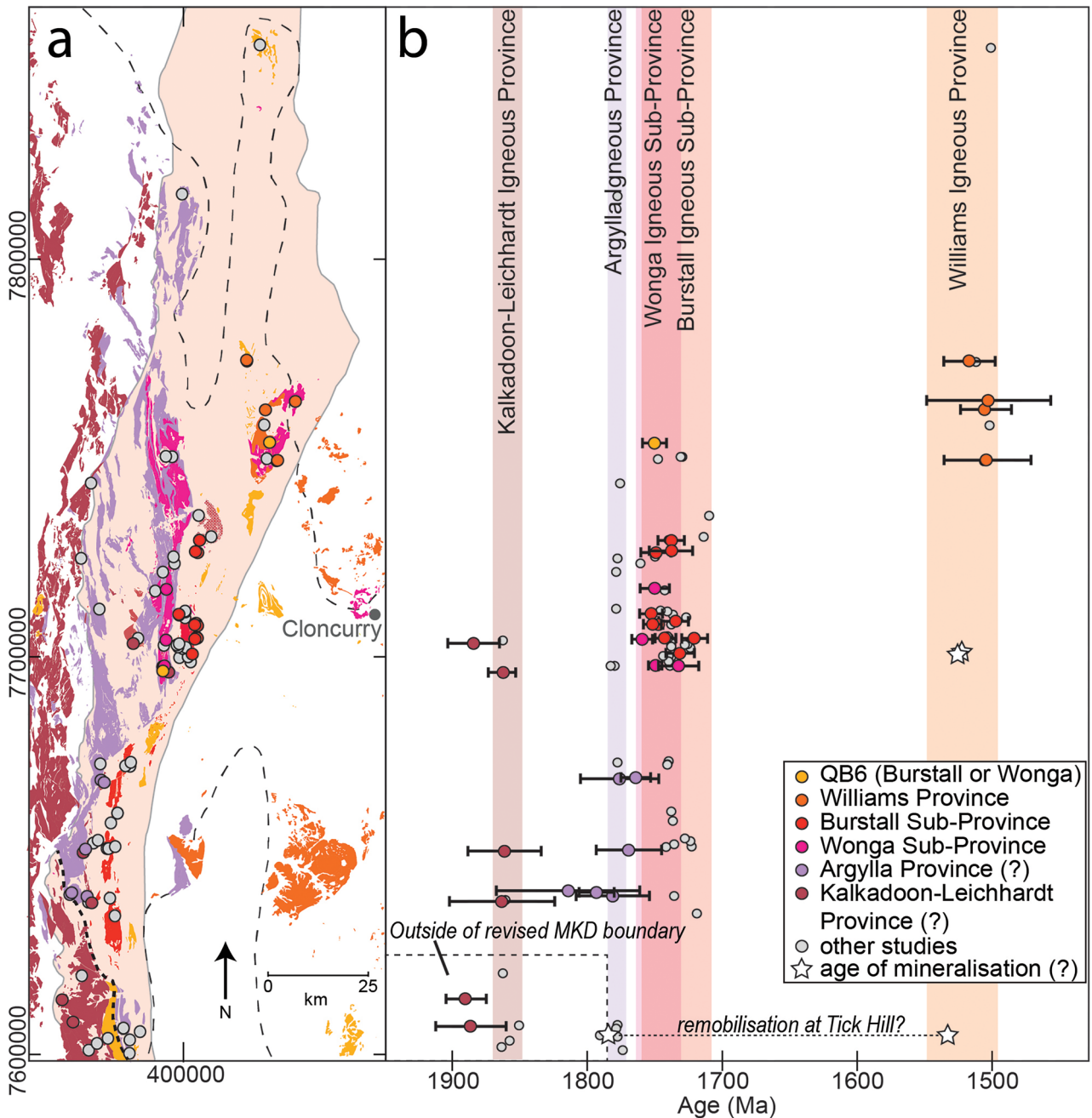


Figure 15. (a) Map from Figure 1 with location of samples of intrusions with U–Pb ages from this study and other studies. (b) Interpreted magmatic emplacement age data for intrusions in the Mary Kathleen Domain sampled in this study (with 2SE error bars) shown as northing (MGA zone 54) plotted against age. Also shown are data from other studies of intrusions in the Mary Kathleen Domain, including those outside the revised southern boundary (Bierlein *et al.*, 2011; Bodorkos *et al.*, 2020; Carson *et al.*, 2011; Davis *et al.*, 2001; Jones *et al.*, 2018; Kositsin *et al.*, 2019, 2021; Le *et al.*, 2021a; Neumann *et al.*, 2009; Page, 1983; Page & Sun, 1998; Pearson *et al.*, 1992; Spence *et al.*, 2021, 2022; Withnall, 2019). In addition, ages interpreted to represent mineralisation ages are shown for Tick Hill (Le *et al.*, 2021a, 2021b), Mount Colin (Cave *et al.*, 2024), and Elaine Dorothy (Spandler *et al.*, 2016).

Timing of magmatism, tectonism and mineralisation

The emplacement ages of intrusions from this study, combined with previous work, show that magmatism in the MKD occurred periodically throughout the Paleoproterozoic to Mesoproterozoic. Many of the emplacement age ranges of each igneous province also coincide with broader orogenic events: the Kalkadoon–Leichhardt Igneous Province with the Barramundi Orogeny (*ca* 1870 Ma; Bierlein *et al.*, 2008); the Wonga–Burstall Igneous

Province with the Wonga Orogeny (*ca* 1750–1710 Ma; Spence *et al.*, 2021, 2022) and the Williams Igneous Province with the end of the Isa Orogeny (*ca* 1530–1500 Ma; Withnall, 2019; Figure 2). Emplacement of these batholiths in long parallel N–S belts (Figure 1b) contemporaneously with specific orogenic events can be indicative of substantial periods of convergent tectonics throughout the Proterozoic (Winton, 2014). The orientation of these belts is sub-parallel to major sutures associated with the formation of the North Australian Craton (Spence *et al.*, 2021).

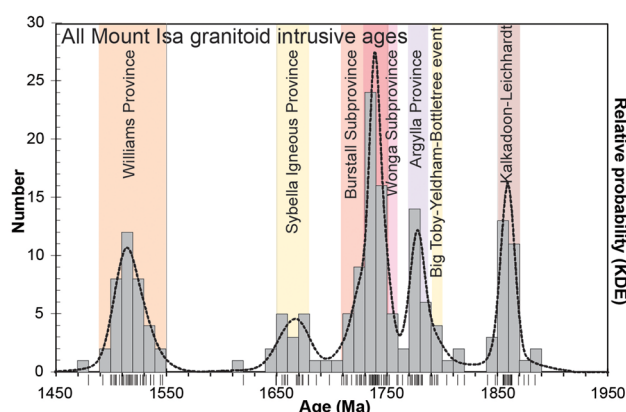


Figure 16. Histogram and probability density plot of U–Pb ages for intrusions of the Mount Isa Inlier. Note that for some intrusions, more than one emplacement age has been determined in separate studies. Data from Bierlein *et al.* (2008, 2011), Bodorkos *et al.* (2020), Carson *et al.* (2009, 2011), Coleborn (1999), Connors and Page (1995), Davis *et al.* (2001), Jones *et al.* (2018), Kositsin *et al.* (2019, 2021), Le *et al.* (2021a), Magee *et al.* (2012), Neumann *et al.* (2006, 2009), Page (1983), Page and Bell (1986), Page and Sun (1998), Pearson *et al.* (1992), Rubenach *et al.* (2008), Spence *et al.* (2021, 2022), Withnall (2019), Wyborn *et al.* (1988) and this study.

While the emplacement of intrusions in the MKD occurred episodically over a protracted *ca* 400 Ma time span, most known Cu–Au mineralisation and associated alteration in the Mount Isa Inlier has been interpreted to have formed in a restricted period from *ca* 1550 to 1500 Ma, coinciding with the emplacement of intrusions of the Williams Igneous Province (Burnham *et al.*, 2024; Cave *et al.*, 2024; Mark *et al.*, 2006; Oliver *et al.*, 2004; Perkins & Wyborn, 1998; Spandler *et al.*, 2016; Wyborn, 1998). In this study, we found intrusions of the Williams Igneous Province only in the northern parts of the MKD (Figure 15), with the Mount Philp Breccia the only other magmatic related body with possibly a similar age (Bultitude *et al.*, 2021). Therefore, there is uncertainty around the age of the initial mineralisation events because of the possibility of remobilisation of that mineralisation, which would result in younger mineralisation ages and create doubt in interpretation of the geochronology of mineralisation events. Remobilisation of mineralisation has been interpreted at several mineral deposits within the MKD, with regional metamorphic or hydrothermal activity as likely causes. For example, petrographic, structural and geochronological evidence indicates that gold in the Tick Hill deposit was first deposited at *ca* 1790–1770 Ma during metamorphism and was later remobilised during metasomatism at *ca* 1525–1520 Ma (Figure 15; Le *et al.*, 2021a, 2021b). Similarly, Page (1983), Spandler *et al.* (2016) and Cave *et al.* (2024) also interpreted geochronology of various minerals as suggesting remobilisation of mineralisation in the region around the Burstall Granite (Figure 15). Given that most Cu–Au mineralisation within the MKD has not been definitively dated, this implies that if the mineralisation were sourced from the older magmatic intrusions by magmatic–hydrothermal fluids, then in many cases that mineralisation had been remobilised by later events. Further work to directly constrain the sources and ages of mineralisation within the

MKD is required to determine if this pattern is prevalent throughout this region.

Conclusions

We obtained 29 emplacement (crystallisation) ages for various intrusions of the MKD in the Mount Isa Inlier, including for one intrusion to the south of the revised southern MKD boundary. The ages of intrusions from this study span the range of igneous provinces that crop out in the MKD: 1884–1861 Ma for intrusions of the Kalkadoon–Leichhardt Igneous Province or older, 1759–1748 Ma for granites belonging to the Wonga Igneous Subprovince, 1752–1720 Ma for intrusions of the Burstall Igneous Subprovince and 1517–1503 Ma for intrusions of the Williams Igneous Province. Comparison with other available data shows that some granitic bodies (e.g. Mount Godkin Granite, Burstall Granite) have emplacement ages that span large time periods, and further study in some areas is required to determine if these ages truly represent multiple pulses of magmatic activity, which phases may be comagmatic and the relationships between different magmatic phases as well as with the surrounding stratigraphy. Additionally, better constraints of the timing of mineralisation associated with these intrusions are now required to generate mineralisation histories and deposit formation models across the MKD.

Acknowledgements

We would like to thank the staff (former and current) of the GSQ, in particular Helen Degeling, Vladimir Lisitsin, David Purdy, Bob Bultitude and Dominic Brown for their assistance with this project. We also thank Peter Betts and David Murphy for constructive reviews that improved the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

Funding for this project was provided by GSQ as part of the Strategic Resources Exploration Program. This study was supported by Queensland Government Department of Resources.

ORCID

H. A. Cocker  <http://orcid.org/0000-0002-5543-5701>

I. Sanislav  <http://orcid.org/0000-0002-3680-3740>

P. Dirks  <http://orcid.org/0000-0002-1582-1405>

A. McCoy-West  <http://orcid.org/0000-0003-4171-9276>

Data availability statement

McCoy-West, H., Sanislav, I., & Dirks, P. (2024). Zircon U–Pb geochronology data of intrusions from the Mary Kathleen Domain. James Cook University. <https://doi.org/10.25903/gdpt-9f04>. CC BY 4.): Attribution 4.0 International.

References

- Abu Sharib, A. S. A. A., & Sanislav, I. V. (2013). Polymetamorphism accompanied switching in horizontal shortening during Isan Orogeny: Example from the Eastern Fold Belt, Mount Isa Inlier, Australia. *Tectonophysics*, 587, 146–167. <https://doi.org/10.1016/j.tecto.2012.06.051>
- Andersen, C., & Weis, P. (2020). Heat transfer from convecting magma reservoirs to hydrothermal fluid flow systems constrained by coupled numerical modelling. *Geophysical Research Letters*, 47(23), e2020GL089463. <https://doi.org/10.1029/2020GL089463>
- Audétat, A., & Edmonds, M. (2020). Magmatic-hydrothermal fluids. *Elements*, 16(6), 401–406. <https://doi.org/10.2138/gselements.16.6.401>
- Austin, J., Hawkins, S., Gazley, M., Patterson, B., leGras, M., & Walshe, J. (2016). *The Mount Colin Au–Cu deposit: integrated petrophysical and geochemical analyses*. CSIRO, North Ryde. <https://doi.org/10.4225/08/585820d2990d3>
- Betts, P. G., Giles, D., Mark, G., Lister, G. S., Goleby, B. R., & Aillères, L. (2006). Synthesis of the Proterozoic evolution of the Mt Isa Inlier. *Australian Journal of Earth Sciences*, 53(1), 187–211. <https://doi.org/10.1080/08120090500434625>
- Bierlein, F. P., Black, L. P., Hergt, J., & Mark, G. (2008). Evolution of Pre-1.8 Ga basement rocks in the western Mt Isa Inlier, northeastern Australia – Insights from SHRIMP U–Pb dating and in-situ Lu–Hf analysis of zircons. *Precambrian Research*, 163(1–2), 159–173. <https://doi.org/10.1016/j.precamres.2007.08.017>
- Bierlein, F. P., Maas, R., & Woodhead, J. (2011). Pre-1.8 Ga tectono-magmatic evolution of the Kalkadoon–Leichhardt Belt: Implications for the crustal architecture and metallogeny of the Mount Isa Inlier, northwest Queensland, Australia. *Australian Journal of Earth Sciences*, 58(8), 887–915. <https://doi.org/10.1080/08120099.2011.571286>
- Black, L. P., Kamo, S. L., Allen, C. M., Davis, D. W., Aleinikoff, J. N., Valley, J. W., Mundil, R., Campbell, I. H., Korsch, R. J., Williams, I. S., & Foudoulis, C. (2004). Improved $^{206}\text{Pb}/^{238}\text{U}$ microprobe geochronology by the monitoring of a trace-element-related matrix effect; SHRIMP, ID–TIMS, ELA–ICP–MS and oxygen isotope documentation for a series of zircon standards. *Chemical Geology*, 205(1–2), 115–140. <https://doi.org/10.1016/j.chemgeo.2004.01.003>
- Blake, D. H. (1987). *Geology of the Mount Isa Inlier and environs, Queensland and Northern Territory*. Bureau of Mineral Resources, Geology and Geophysics Bulletin 225. Department of Resources and Energy.
- Blake, D. H., & Stewart, A. J. (1992). Stratigraphic and tectonic framework, Mount Isa Inlier. In A. J. Stewart & D. H. Blake (Eds.), *Detailed studies of the Mount Isa Inlier* (pp. 1–11). Australian Geological Survey Organisation Bulletin 243. Australian Government Publishing Service.
- Bodorkos, S., Purdy, D. J., Bultitude, R. J., Lewis, C. J., Jones, S. L., Brown, D. D., Hoy, D. (2020). *Summary of results. Joint GSQ–GA Geochronology Project: Mary Kathleen Domain and Environs, Mount Isa Inlier, 2018–2020*. Queensland Geological Record 2020/04. Geological Survey of Queensland.
- Budd, A. R., Wyborn, L. A. I., Bastrakova, I. A. (2001). *The metallogenic potential of Australian Proterozoic granites*. Geoscience Australia Record 2001/12.
- Bultitude, R. J., Purdy, D. J., Brown, D. D., Hoy, D. (2021). *Igneous geology of the Mary Kathleen Domain (MKD)*. Queensland Geological Record 2021/02. Geological Survey of Queensland.
- Burnham, C. W. (1997). Magmas and hydrothermal fluids. In H. L. Barnes (Ed.), *Geochemistry of hydrothermal ore deposits* (pp. 63–124). John Wiley and Sons.
- Burnham, A. D., Chandler, R., Amelin, Y., & Mavrogenes, J. (2024). Allanite geochronology in the Mount Isa Inlier. *Australian Journal of Earth Sciences*, 71(8), 1156–1169. <https://doi.org/10.1080/08120099.2023.2291514>
- Carson, C. J., Hutton, L. J., Withnall, I. W., & Perkins, W. G. (2009). *Joint GSQ–GANGA geochronology project, Mount Isa region, 2007–2008*. Queensland Geological Record 2008/05. Geological Survey of Queensland.
- Carson, C. J., Hutton, L. J., Withnall, I. W., Perkins, W. G., Donchak, P. L. T., Parsons, A., Blake, P. R., Sweet, I. P., Neumann, N. L., & Lambeck, A. (2011). *Summary of results: Joint GSQ–GA geochronology project, Mount Isa region, 2009–2010*. Queensland Geological Record 2011/03. Geological Survey of Queensland.
- Cave, B., Healy, M., Overall, D., & Lilly, R. (2024). Genesis of the Mount Colin Cu–Au deposit, NW Queensland: Evidence from geology, multi-mineral U–Pb geochronology, S-, O- and C-isotope constraints. *Journal of Geochemical Exploration*, 256, 107350. <https://doi.org/10.1016/j.jgeexp-10.2023.107350>
- Cherniak, D. J. (1993). Lead diffusion in titanite and preliminary results on the effects of radiation damage on Pb transport. *Chemical Geology*, 110(1–3), 177–194. [https://doi.org/10.1016/0009-2541\(93\)90253-F](https://doi.org/10.1016/0009-2541(93)90253-F)
- Cherniak, D. J., & Watson, E. B. (2001). Pb diffusion in zircon. *Chemical Geology*, 172(1–2), 5–24. [https://doi.org/10.1016/S0009-2541\(00\)00233-3](https://doi.org/10.1016/S0009-2541(00)00233-3)
- Cochrane, R., Spikings, R. A., Chew, D., Wotzlaw, J-F., Chiaradia, M., Tyrrell, S., Schaltegger, U., & Van der Lelij, R. (2014). High temperature (>350 °C) thermochronology and mechanisms of Pb loss in apatite. *Geochimica et Cosmochimica Acta*, 127, 39–56. <https://doi.org/10.1016/j.gca.2013.11.028>
- Coleborn, D. (1999). *Geophysical analysis of the Sybella Batholith, Mount Isa Inlier, NW Queensland* [unpublished BSc (Hons.) thesis]. James Cook University.
- Connors, K. A., & Page, R. W. (1995). Relationships between magmatism, metamorphism and deformation in the western Mount Isa Inlier, Australia. *Precambrian Research*, 71(1–4), 131–153. [https://doi.org/10.1016/0301-9268\(94\)00059-Z](https://doi.org/10.1016/0301-9268(94)00059-Z)
- Davis, B. K., Pollard, P. J., Lally, J. H., McNaughton, N. J., Blake, K., & Williams, P. J. (2001). Deformation history of the Naraku Batholith, Mt Isa Inlier, Australia: Implications for pluton ages and geometries from structural study of the Dipvale Granodiorite and Levian Granite. *Australian Journal of Earth Sciences*, 48(1), 113–129. <https://doi.org/10.1046/j.1440-0952.2001.00848.x>
- Day, R. W., Whitaker, W. G., Murray, C. G., Wilson, I. H., & Grimes, K. G. (1983). *Queensland Geology: A companion volume to the 1:2500000 scale geological map (1975)*. Publications of the Geological Survey of Queensland, 383.
- de Vries, S. T., Pryer, L. L., & Fry, N. (2008). Evolution of Neoproterozoic and Proterozoic basins of Australia. *Precambrian Research*, 166(1–4), 39–53. <https://doi.org/10.1016/j.precamres.2008.01.005>
- Duncan, R. J., Stein, H. J., Evans, K. A., Hitzman, M. W., Nelson, E. P., & Kirwin, D. J. (2011). A new geochronological framework for mineralization and alteration in the Selwyn–Mount Dore corridor, Eastern Fold Belt, Mount Isa Inlier, Australia: Genetic implications for iron oxide copper–gold deposits. *Economic Geology*, 106(2), 169–192. <https://doi.org/10.2113/econgeo.106.2.169>
- Etheridge, M. A., Rutland, R. W., & Wyborn, L. A. I. (1987). Orogenesis and tectonic process in the Early to Middle Proterozoic of northern Australia. In A. Kröner (Ed.), *Proterozoic Lithospheric Evolution* (pp. 131–147). American Geophysical Union.
- Foster, D. R. W., & Austin, J. R. (2008). The 1800–1610 Ma stratigraphic and magmatic history of the Eastern Succession, Mount Isa Inlier, and correlations with adjacent Paleoproterozoic terranes. *Precambrian Research*, 163(1–2), 7–30. <https://doi.org/10.1016/j.precamres.2007.08.010>
- Foster, D. R. W., & Rubenach, M. J. (2006). Isograd pattern and regional low-pressure, high-temperature metamorphism of pelitic, mafic and calc-silicate rocks along an east – west section through the Mt Isa Inlier. *Australian Journal of Earth Sciences*, 53(1), 167–186. <https://doi.org/10.1080/08120090500434617>
- Geological Survey of Queensland. (2011). *North-west Queensland Mineral and Energy Report*. Queensland Department of Employment, Economic Development and Innovation.
- Geological Survey of Queensland. (2017). *Mineral occurrence database MINOCC and the Queensland major minerals data QMIN*. Version April 2017. <https://geoscience.data.qld.gov.au/data/dataset/ds000004>

- Geoscience Australia and Australian Stratigraphy Commission. (2025). *Australian Stratigraphic Units Database*. <https://asud.ga.gov.au/>
- Gibson, G. M., Champion, D. C., Huston, D. L., & Withnall, I. W. (2020). Orogenesis in Paleo–Mesoproterozoic Eastern Australia: A response to arc–continent and continent–continent collision during assembly of the Nuna supercontinent. *Tectonics*, 39(2), e2019TC005717. <https://doi.org/10.1029/2019TC005717>
- Gibson, G. M., Meixner, A. J., Withnall, I. W., Korsch, R. J., Hutton, L. J., Jones, L. E. A., Holzschuh, J., Costelloe, R. D., Henson, P. A., & Saygin, E. (2016). Basin architecture and evolution in the Mount Isa mineral province, northern Australia: Constraints from deep seismic reflection profiling and implications for ore genesis. *Ore Geology Reviews*, 76l, 414–441. <https://doi.org/10.1016/j.oregeorev.2015.07.013>
- Giles, D., Betts, P. G., Aillères, L., Hulscher, B., Hough, M., & Lister, G. S. (2006). Evolution of the Isan Orogeny at the southeastern margin of the Mt Isa Inlier. *Australian Journal of Earth Sciences*, 53(1), 91–108. <https://doi.org/10.1080/08120090500432470>
- Halter, W. E., & Webster, J. D. (2004). The magmatic to hydrothermal transition and its bearing on ore-forming systems. *Chemical Geology*, 210(1–4), 1–6. <https://doi.org/10.1016/j.chemgeo.2004.06.001>
- Hedenquist, J. W., & Lowenstern, J. B. (1994). The role of magmas in the formation of hydrothermal ore deposits. *Nature*, 370(6490), 519–527. <https://doi.org/10.1038/370519a0>
- Holcombe, R. J., Pearson, P. J., & Oliver, N. H. S. (1991). Geometry of a Middle Proterozoic extensional decollement in northeastern Australia. *Tectonophysics*, 191(3–4), 255–274. [https://doi.org/10.1016/0040-1951\(91\)90061-V](https://doi.org/10.1016/0040-1951(91)90061-V)
- Horstwood, M. S. A., Košler, J., Gehrels, G., Jackson, S. E., McLean, N. M., Paton, C., Pearson, N. J., Sircombe, K., Sylvester, P., Vermeesch, P., Bowring, J. F., Condon, D. J., & Schoene, B. (2016). Community-derived standards for LA-ICP-MS U–(Th–)Pb geochronology – Uncertainty propagation, age interpretation and data reporting. *Geostandards and Geoanalytical Research*, 40(3), 311–332. <https://doi.org/10.1111/j.1751-908X.2016.00379.x>
- Hutton, L. J., Denaro, T. J., Dharam, C., & Derrick, G. M. (2012). Mineral systems in the Mount Isa Inlier. *Episodes*, 35(1), 120–130. <https://doi.org/10.18814/epiugs/2012/v35i1/011>
- Jackson, S. E., Pearson, N. J., Griffin, W. L., & Belousova, E. A. (2004). The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. *Chemical Geology*, 211(1–2), 47–69. <https://doi.org/10.1016/j.chemgeo.2004.06.017>
- Jackson, M. J., Scott, D. L., & Rawlings, D. J. (2000). Stratigraphic framework for the Leichhardt and Calvert Superbasins: Review and correlations of the pre-1700 Ma successions between Mt Isa and McArthur River. *Australian Journal of Earth Sciences*, 47(3), 381–403. <https://doi.org/10.1046/j.1440-0952.2000.00789.x>
- Jackson, M. J., Simpson, E. L., & Eriksson, K. A. (1990). Facies and sequence stratigraphic analysis in an intracratonic, thermal-relaxation basin: The Early Proterozoic, Lower Quilalar Formation and Ballara Quartzite, Mount Isa Inlier, Australia. *Sedimentology*, 37(6), 1053–1078. <https://doi.org/10.1111/j.1365-3091.1990.tb01846.x>
- Jaffey, A. H., Flynn, K. F., Glendenin, L. E., Bentley, W. C., & Essling, A. M. (1971). Precision measurement of half-lives and specific activities of ²³⁵U and ²³⁸U. *Physical Review C*, 4(5), 1889–1906. <https://doi.org/10.1103/PhysRevC.4.1889>
- Jones, S. L., Anderson, J. R., Fraser, G. L., Lewis, C. J., & McLennan, S. M. (2018). *A U–Pb geochronology compilation for northern Australia: Version 2, 2018*. Geoscience Australia Record 2018/49. <https://doi.org/10.11636/Record.2018.049>
- Kositcin, N., Purdy, D., Bultitude, R. J., Brown, D. D., & Hoy, D. (2021). Summary of results. Joint GSQ-GA Geochronology Project: Mary Kathleen Domain and rocks under younger cover east of the Mount Isa Inlier, 2019–2020. Queensland Geological Record 2021/01. Geological Survey of Queensland.
- Kositcin, N., Bultitude, R. J., Purdy, D. J. (2019). *Summary of results. Joint GSQ-GA Geochronology Project: Mary Kathleen Domain, Mount Isa Inlier, 2018–2019*. Queensland Geological Record 2019/02. Geological Survey of Queensland.
- Le, T. X., Dirks, P. H. G. M., Sanislav, I. V., Huizenga, J. M., Cocker, H. A., & Manestar, G. N. (2021a). Geochronological constraints on the geological history and gold mineralization in the Tick Hill region, Mt Isa Inlier. *Precambrian Research*, 366, 106422. <https://doi.org/10.1016/j.precambres.2021.106422>
- Le, T. X., Dirks, P. H. G. M., Sanislav, I. V., Huizenga, J. M., Cocker, H. A., & Manestar, G. N. (2021b). Geological setting and mineralization characteristics of the Tick Hill Gold Deposit, Mount Isa Inlier, Queensland, Australia. *Ore Geology Reviews*, 137, 104288. <https://doi.org/10.1016/j.oregeorev.2021.104288>
- Le, T. X., Dirks, P. H. G. M., Sanislav, I. V., Huizenga, J. M., Cocker, H. A., & Nguyen, G. T. T. (2024). P–T conditions of metamorphic and hydrothermal events at Tick Hill Gold Deposit, Mount Isa, Queensland, Australia. *Australian Journal of Earth Sciences*, 71(4), 538–552. <https://doi.org/10.1080/08120099.2024.2320195>
- Lee, J. K. W., Williams, I. S., & Ellis, D. J. (1997). Pb, U and Th diffusion in natural zircon. *Nature*, 390(6656), 159–162. <https://doi.org/10.1038/36554>
- Loosveld, R., & Schreurs, G. (1987). Discover of thrust Klippen, northwest Mary Kathleen, Mt Isa Inlier, Australia. *Australian Journal of Earth Sciences*, 34(3), 387–402. <https://doi.org/10.1080/08120098708729419>
- Magee, C. W., Withnall, I. W., Hutton, L. J., Perkins, W. G., Donchak, P. J. T., Parsons, A., Blake, P. R., Sweet, I. P., & Carson, C. J. (2012). *Joint GSQ-GA geochronology project, Mount Isa Region, 2008–2009*. Queensland Geological Record 2012/07. Geological Survey of Queensland.
- Mark, G. (1999). Petrogenesis of Mesoproterozoic K-rich granitoids, southern Mt Angelay igneous complex, Cloncurry district, northwest Queensland. *Australian Journal of Earth Sciences*, 46(6), 933–949. <https://doi.org/10.1046/j.1440-0952.1999.00756.x>
- Mark, G., Oliver, N. H. S., & Williams, P. J. (2006). Mineralogical and chemical evolution of the Ernest Henry Fe oxide–Cu–Au ore system, Cloncurry district, northwest Queensland, Australia. *Mineralium Deposita*, 40(8), 769–801. <https://doi.org/10.1007/s00126-005-0009-7>
- Middlemost, E. A. K. (1994). Naming materials in the magma/igneous rock system. *Earth-Science Reviews*, 37(3–4), 215–224. [https://doi.org/10.1016/0012-8252\(94\)90029-9](https://doi.org/10.1016/0012-8252(94)90029-9)
- Neumann, N. L., Gibson, G. M., & Southgate, P. N. (2009). New SHRIMP age constraints on the timing and duration of magmatism and sedimentation in the Mary Kathleen Fold Belt, Mt Isa Inlier, Australia. *Australian Journal of Earth Sciences*, 56(7), 965–983. <https://doi.org/10.1080/08120090903005410>
- Neumann, N. L., Southgate, P. N., Gibson, G. M., & McIntyre, A. (2006). New SHRIMP geochronology for the Western Fold Belt of the Mt Isa Inlier: Developing a 1800–1650 Ma event framework. *Australian Journal of Earth Sciences*, 53(6), 1023–1039. <https://doi.org/10.1080/08120090600923287>
- O’Dea, M. G., Lister, G. S., MacCready, T., Betts, P. G., Oliver, N. H. S., Pound, K. S., Huang, W., & Valenta, R. K. (1997). Geodynamic evolution of the Proterozoic Mount Isa terrain. In J-P. Burg & M. Ford (Eds.), *Orogeny through time* (pp. 99–122). Special Publications 121. <https://doi.org/10.1144/gsl.sp.1997.121.01.05>
- Oliver, N. H. S. (1995). Hydrothermal history of the Mary Kathleen Fold Belt, Mt Isa Block, Queensland. *Australian Journal of Earth Sciences*, 42(3), 267–279. <https://doi.org/10.1080/08120099508728201>
- Oliver, N. H. S., Cleverley, J. S., Mark, G., Pollard, P. J., Bin, F., Marshall, L. J., Rubenach, M. J., Williams, P. J., & Baker, T. (2004). Modeling the role of sodic alteration in the genesis of iron oxide–copper–gold deposits, Eastern Mount Isa block, Australia. *Economic Geology*, 99(6), 1145–1176. <https://doi.org/10.2113/gsecongeo.99.6.1145>
- Oliver, N. H. S., Holcombe, R. J., Hill, E. J., & Pearson, P. J. (1991). Tectometamorphic evolution of the Mary Kathleen fold belt, northwest Queensland: A reflection of mantle plume processes? *Australian Journal of Earth Sciences*, 38(4), 425–455. <https://doi.org/10.1080/08120099108727982>
- Page, R. W. (1983). Chronology of magmatism, skarn formation, and uranium mineralization, Mary Kathleen, Queensland, Australia. *Economic Geology*, 78(5), 838–853. <https://doi.org/10.2113/gsecongeo.78.5.838>

- Page, R. W. (1988). Geochronology of early to middle Proterozoic fold belts in Northern Australia: A review. *Precambrian Research*, 40–41, 1–19. [https://doi.org/10.1016/0301-9268\(88\)90058-7](https://doi.org/10.1016/0301-9268(88)90058-7)
- Page, R. W., & Bell, T. H. (1986). Isotopic and structural responses of granite to successive deformation and metamorphism. *The Journal of Geology*, 94(3), 365–379. <https://doi.org/10.1086/629035>
- Page, R. W., & Sun, S.-S. (1998). Aspects of geochronology and crustal evolution in the Eastern Fold Belt, Mt Isa Inlier. *Australian Journal of Earth Sciences*, 45(3), 343–361. <https://doi.org/10.1080/08120099808728396>
- Page, R. W., & Williams, I. S. (1988). Age of the Barramundi Orogeny in northern Australia by means of ion microprobe and conventional U–Pb zircon studies. *Precambrian Research*, 40–41, 21–36. [https://doi.org/10.1016/0301-9268\(88\)90059-9](https://doi.org/10.1016/0301-9268(88)90059-9)
- Paton, C., Hellstrom, J., Paul, B., Woodhead, J., & Hergt, J. (2011). Lolite: Freeware for the visualisation and processing of mass spectrometric data. *Journal of Analytical Atomic Spectrometry*, 26(12), 2508–2518. <https://doi.org/10.1039/c1ja10172b>
- Pearson, P. J., Holcombe, R. J., & Page, R. W. (1992). Synkinematic emplacement of the middle Proterozoic Wonga Batholith into a midcrustal shear zone, Mount Isa Inlier, Queensland, Australia. In A. J. Stewart & D. H. Blake (Eds.), *Detailed studies of the Mount Isa Inlier* (pp. 289–328). Australian Geological Survey Organisation, Bulletin 243.
- Perkins, C., & Wyborn, L. A. I. (1998). Age of Cu–Au mineralisation, Cloncurry district, eastern Mt Isa Inlier, Queensland, as determined by $^{40}\text{Ar}/^{39}\text{Ar}$ dating. *Australian Journal of Earth Sciences*, 45(2), 233–246. <https://doi.org/10.1080/08120099808728384>
- Pollard, P. J., Mark, G., & Mitchell, L. C. (1998). Geochemistry of post-1540 Ma granites in the Cloncurry district, northwest Queensland. *Economic Geology*, 93(8), 1330–1344. <https://doi.org/10.2113/gsecongeo.93.8.1330>
- Queensland Department of Resources. (2018). *Detailed surface geology – Queensland, 2018 version* (now replaced by August 2022 version).
- Queensland Department of Resources. (2022). *Detailed surface geology – Queensland, August 2022 version*. <https://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={9BA2F66C-1933-4439-B9C9-E631911ADD7E}>
- Reinhardt, J. (1992). Low-pressure, high-temperature metamorphism in a compressional tectonic setting: Mary Kathleen Fold Belt, northeastern Australia. *Geological Magazine*, 129(1), 41–57. <https://doi.org/10.1017/S0016756800008116>
- Rubenach, M. J., Foster, D. R. W., Evins, P. M., Blake, K. L., & Fanning, C. M. (2008). Age constraints on the tectonothermal evolution of the Selwyn Zone, Eastern Fold Belt, Mount Isa Inlier. *Precambrian Research*, 163(1–2), 81–107. <https://doi.org/10.1016/j.precamres.2007.08.014>
- Schoene, B., & Bowring, S. A. (2007). Determining accurate temperature–time paths from U–Pb thermochronology: An example from the Kaapvaal craton, southern Africa. *Geochimica et Cosmochimica Acta*, 71(1), 165–185. <https://doi.org/10.1016/j.gca.2006.08.029>
- Scott, D. J., & St-Onge, M. R. (1995). Constraints on Pb closure temperature in titanite based on rocks from the Ungava Orogen, Canada: Implications for U–Pb geochronology and P–T–t path determinations. *Geology*, 23(12), 1123–1126. [https://doi.org/10.1130/0091-7613\(1995\)023<1123:COPCTI>2.3.CO;2](https://doi.org/10.1130/0091-7613(1995)023<1123:COPCTI>2.3.CO;2)
- Sláma, J., Košler, J., Condon, D. J., Crowley, J. L., Gerdes, A., Hanchar, J. M., Horstwood, M. S. A., Morris, G. A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M. N., & Whitehouse, M. J. (2008). Plešovice zircon – A new natural reference material for U–Pb and Hf isotopic microanalysis. *Chemical Geology*, 249(1–2), 1–35. <https://doi.org/10.1016/j.chemgeo.2007.11.005>
- Spandler, C., Hammerli, J., Sha, P., Hilbert-Wolf, H., Hu, Y., Roberts, E., & Schmitz, M. (2016). MKED1: A new titanite standard for in situ analysis of Sm–Nd isotopes and U–Pb geochronology. *Chemical Geology*, 425, 110–126. <https://doi.org/10.1016/j.chemgeo.2016.01.002>
- Spence, J. S., Sanislav, I. V., & Dirks, P. H. G. M. (2021). 1750–1710 Ma deformation along the eastern margin of the North Australian Craton. *Precambrian Research*, 353, 106019. <https://doi.org/10.1016/j.precamres.2020.106019>
- Spence, J. S., Sanislav, I. V., & Dirks, P. H. G. M. (2022). Evidence for a 1750–1710 Ma orogenic event, the Wonga Orogeny, in the Mount Isa Inlier, Australia: Implications for the tectonic evolution of the North Australian Craton and Nuna Supercontinent. *Precambrian Research*, 369, 106510. <https://doi.org/10.1016/j.precamres.2021.106510>
- Stewart, A. J. (1989). Extensional faulting as the explanation for the Deighton 'Klippe' and other Mount Albert Group outliers, Mount Isa Inlier, northwestern Queensland. *Australian Journal of Earth Sciences*, 36(3), 405–421. <https://doi.org/10.1080/08120099808729497>
- Vermeesch, P. (2018). IsoplotR: A free and open toolbox for geochronology. *Geoscience Frontiers*, 9(5), 1479–1493. <https://doi.org/10.1016/j.gsf.2018.04.001>
- Whalen, J. B., Currie, K. L., & Chappell, B. W. (1987). A-type granites: Geochemical characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and Petrology*, 95(4), 407–419. <https://doi.org/10.1007/BF00402202>
- Wiedenbeck, M., Allé, P., Corfu, F., Griffin, W. L., Meier, M., Oberli, F., von Quadt, A., Roddick, J. C., & Spiegel, W. (1995). Three natural zircon standards for U–Th–Pb, Lu–Hf, trace element and REE analyses. *Geostandards Newsletter*, 19(1), 1–23. <https://doi.org/10.1111/j.1751-908X.1995.tb00147.x>
- Williams, P. J. (1998). Metalliferous economic geology of the Mt Isa Eastern Succession, Queensland. *Australian Journal of Earth Sciences*, 45(3), 329–341. <https://doi.org/10.1080/08120099808728395>
- Winton, J. D. (2014). *Principles of Igneous and metamorphic petrology* (2nd ed.). Pearson International Edition. Pearson Education Limited.
- Withnall, I. (2019). *Review of SHRIMP zircon ages for the Eastern Succession of the Mount Isa Province and magmatic events in its provenance*. Queensland Minerals and Energy Review Series, Department of Natural Resources, Mines and Energy.
- Withnall, I. W., & Hutton, L. J. (2013). North Australian Craton. In P. A. Jell (Ed.), *Geology of Queensland* (pp. 23–112). Geological Survey of Queensland.
- Wyborn, L. (1998). Younger ca 1500 Ma granites of the Williams and Naraku Batholiths, Cloncurry District, eastern Mt Isa Inlier: Geochemistry, origin, metallogenic significance and exploration indicators. *Australian Journal of Earth Sciences*, 45(3), 397–411. <https://doi.org/10.1080/08120099808728400>
- Wyborn, L. A. I., Page, R. W., & McCulloch, M. T. (1988). Petrology, geochronology and isotope geochemistry of the post-1820 Ma granites of the Mount Isa Inlier: Mechanisms for the generation of Proterozoic anorogenic granites. *Precambrian Research*, 40–41, 509–541. [https://doi.org/10.1016/0301-9268\(88\)90083-6](https://doi.org/10.1016/0301-9268(88)90083-6)
- Xu, G. (1996). Structural geology of the Dugald River Zn–Pb–Ag deposit, Mount Isa Inlier, Australia. *Ore Geology Reviews*, 11(6), 339–361. [https://doi.org/10.1016/S0169-1368\(96\)00007-8](https://doi.org/10.1016/S0169-1368(96)00007-8)