Reversal of Ages of the Kalkadoon/Leichhardt Complex and the Magna Lynn Metabasalt, NW Queensland

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Abstract

One of the central tenets of interpretation of the Mount Isa Inlier, North West Queensland, is that there is a median underlying belt of Paleoproterozoic acid volcanics (Leichhardt Volcanics) and granites (Kalkadoon Supersuite), 1850–1860 Ma, commonly referred to as the 'Kalkadoon-Leichhardt Basement'. A primary requirement of this interpretation is that one of the main boundaries, that between the felsic Leichhardt complex and the Magna Lynn Metabasalt, is an unconformity. This boundary is everywhere serrated and complex, and the unconformity interpretation would require it to have been deformed by a system of variably plunging, refolded folds. Mapping of this boundary in the field, and using previous mapping and remotely sensed images, shows it to be better interpreted as intrusive, with isolated bodies of Magna Lynn Metabasalt within the Leichhardt complex interpreted as relict mega xenoliths, rather than fault blocks or refolded synforms. An intrusive relationship of the Kalkadoon/Leichhardt complex calls into question the relationships of the other mafic volcanic sequences across the Inlier.

Keywords: Kalkadoon Granodiorite, Leichhardt complex, Magna Lynn Metabasalt, Mount Isa Province, metasomatism

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Introduction

Background and Aim

Most current interpretations of Mount Isa Province (Queensland, Australia, Figure 1) geology are based on 1:100,000-scale mapping from the 1970s, with many now regarded as inviolate. One of these is the notion of a Paleoproterozoic 'Kalkadoon-Leichhardt Basement' (following Carter et al., 1961), overlain unconformably and conformably by sediments and a series of mafic volcanic units with a range of ages (Derrick et al., 1977; Bierlein et al., 2011; Hutton & Withnall, 2013; Gibson et al., 2018) (Figures 1, 2). This interpretation has not changed following updating of the mapping using airborne geophysical data. A key facet of this interpretation is that the Leichhardt complex is mostly an extrusive unit, consisting mainly of rhyolite (Wilson, 1983, 1987; Hutton & Withnall, 2013).

The mafic volcanics currently interpreted to be younger than the 'basement' crop out within the MYALLY, ALSACE, PROSPECTOR, MARY KATHLEEN, DUCHESS and MARRABA 1:100,000 maps (these capitals will be used throughout for the 1970s–1980s mapping). Only the relationships of the Magna Lynn Metabasalt will be addressed in this publication. Mapping by the author (Geological Survey of Queensland 2006–2010 Mount Isa Province program) and reinterpretation of that of other workers have indicated a different history from the earlier work, with significant implications for understanding the tectonic development of the Mount Isa Province.

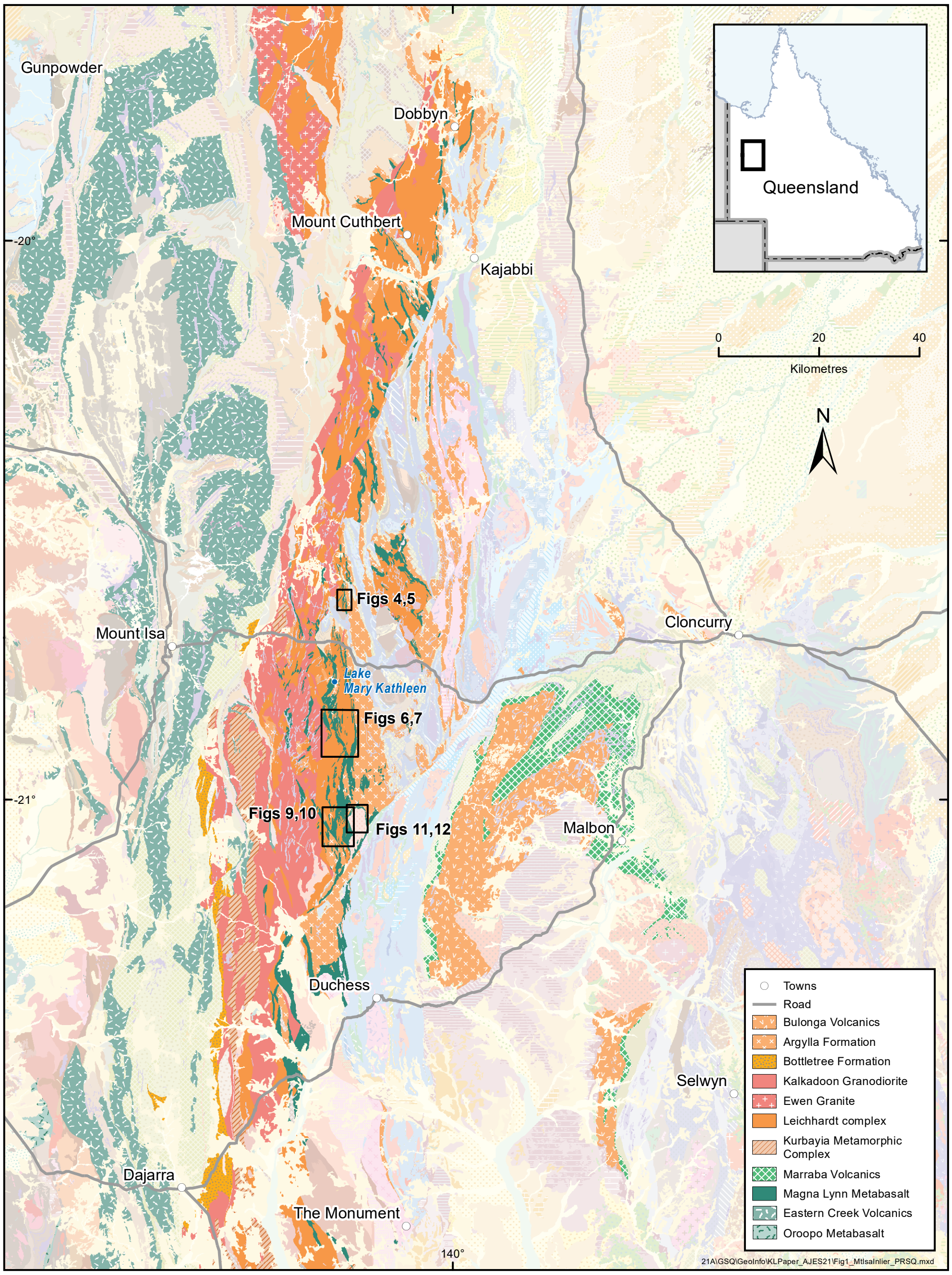

FIGURE 1. Geological unit map (modified by author) of the central portion of the Mount Isa Inlier, highlighting the Magna Lynn Metabasalt and other mafic volcanic units, together with the Kalkadoon Granodiorite, the Leichhardt complex, the Ewen Granite and the Kurbayia Metamorphic Complex. Also highlighted are the supposed felsic extrusives of the Bottletree Formation, Argylla Formation and Bulonga Volcanics. Some intrusives are interpreted within the Argylla Formation (Hutton & Withnall, 2013). The legend shows the reinterpreted age interpretation sequence of the highlighted units. Boxed areas indicate detailed maps.

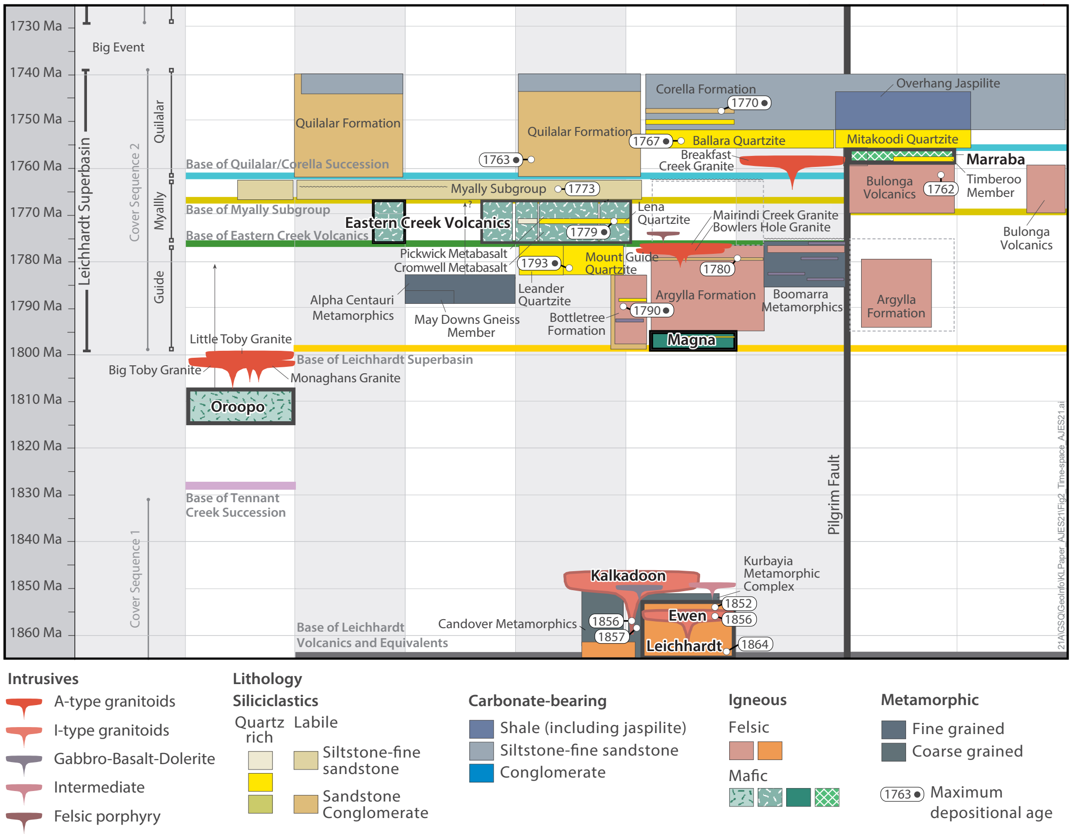

FIGURE 2. Excerpt from and simplification of a series of stratigraphic columns (Geological Survey of Queensland, 2011) across the Inlier, showing existing interpreted correlation. The mafic unit primarily addressed in this study is the Magna Lynn Metabasalt, but other mafic volcanics are also highlighted. Of significance are the four mafic units which are historically interpreted to have different ages. In addition, the Leichhardt complex, Kalkadoon Granodiorite, Ewen Granite and Kurbayia Metamorphic complex are all shown as being older than any of the mafic units. Selected isotopic dates are indicated.

Areas chosen to illustrate the revised interpretation are numbered and shown on Figure 1. The aim is to show that the Kalkadoon/Leichhardt system is intrusive into the Magna Lynn Metabasalt, rather than the universally accepted interpretation that the Leichhardt Volcanics is dominantly an extrusive unit overlain disconformably by the Magna Lynn Metabasalt. Here the intrusion is regarded as leaving residual enclaves of metabasalt with a large range of shape and size, and the term 'Leichhardt complex' is used in place of Leichhardt Volcanics.

Targeted geochemistry has been an important tool in discriminating between units in past work. As an example, the Leichhardt Volcanics and Argylla Formation could be separated using whole-rock geochemistry (Wilson, 1987), and the Argylla Formation is more strongly magnetic. Geochemistry has not been used in this study because it is felt that the discrimination of units was well established, and the features which are most contentious are unit boundaries. This view is not widely shared, and boundaries advanced here as being intrusive are generally regarded as unconformable. Geochronology, however, is most directly relevant to the relationships investigated here, and some targeted geochronology has been done as part of this mapping study. One dating site in the Leichhardt complex (Carson et al., 2011) was sampled in the area covered by this manuscript and is referred to below.

The Magna Lynn Metabasalt was not recognised as a separate extrusive unit by Carter et al. (1961), who regarded it as a dolerite. The unit is mostly metabasalt with some amphibolite, mafic schists and sedimentary intervals, dominantly quartzites (Hutton & Withnall, 2013). It also contains a complex system of dolerite dykes which can be traced from the felsic units on images but, in contrast with dolerites in the Eastern Creek Volcanics, are more difficult to discern in the field. Derrick et al. (1977, p. 16), who defined the formation, stated that "the Magna Lynn Metabasalt overlies metavolcanics of the Leichhardt Metamorphics (now the Leichhardt Volcanics), either conformably or disconformably". This was reaffirmed by Blake (1992). Derrick et al. (1977, p. 16) further indicated that "the upper part of the Leichhardt Metamorphics contains quartzite and acid agglomerate which passes rapidly upwards into massive metabasalt and metasediment of the Magna Lynn Metabasalt". Blake & Page (1988) claimed that the Kalkadoon Granodiorite/Leichhardt Volcanics were unconformably overlain by the Bottletree Formation, the Magna Lynn Metabasalt and the Argylla Formation.

The notion of a Kalkadoon-Leichhardt 'basement' is maintained in the most recent publications (Gibson et al., 2018; Hutton & Withnall, 2013, pp. 25, 33, 34, and a combination of their Figures 2.6 and 2.11). Figure 2 shows the existing interpretation of the relationships of rock units with four separate mafic extrusive units overlying the Kalkadoon/Leichhardt suite (from Geological Survey of Queensland, 2011). An estimate of 50 million years between that 'basement' and the overlying Magna Lynn Metabasalt is shown. Gibson et al. (2018) tentatively adopted equivalence of the Magna Lynn Metabasalt with the Eastern Creek Volcanics. An older unit relevant to the 'basement' question is the Kurbayia Metamorphic Complex (Figures 1, 2), which is locally intruded by the Kalkadoon Granodiorite, as supposedly is the 1850–1840 Ma Leichhardt complex.

In summary, the existing interpretation has a central belt of older migmatites, metamorphics, felsic volcanics and granitoids, flanked by quartzites and a series of mafic volcanics younging upwards into mostly sedimentary sequences (Gibson et al., 2018). In contrast, an alternative interpretation presented here is one of a shredded belt of Magna Lynn Metabasalt as the result of intrusion by the Kalkadoon/Leichhardt complex.

Relative Timing of Kalkadoon/Leichhardt Complex

Timing relationships of the Leichhardt complex relative to the Kalkadoon Granodiorite and Ewen Granite are equivocal. Historically, the Leichhardt complex has been interpreted as an extrusive quartz-feldspar porphyry with the Ewen and Kalkadoon suites intruding into it (e.g. Derrick et al., 1977). No field sites showing the timing relationships have been visited by the author. Age dating ranges suggest that the Leichhardt complex is older than the Kalkadoon Granite. Following Wyborn & Page (1983) and subsequent authors, ages for the units of the Kalkadoon/Leichhardt complex appear to be quite consistent and overlap within error at 1865–1852 Ma (Leichhardt complex), 1855–1864 Ma (Kalkadoon Granodiorite) and 1856–1859 Ma (Ewen Granite). The only dating on the Magna Lynn Metabasalt gives a minimum cooling age of 1521 ± 11 Ma (Li et al., 2020). Therefore, considering this unit alone, it could be older than the Kalkadoon/Leichhardt complex.

Lithology of the Relevant Felsic Units

The Leichhardt Volcanics (formerly the Leichhardt Metamorphics) consists of light- to medium-grey, variably foliated, massive to finely banded "non magnetic quartz feldspar phyric rhyolite, and subordinate metasedimentary rocks" (Hutton & Withnall, 2013, p. 32). Importantly, in the DUCHESS area the unit is described as "mainly massive rhyolitic volcanics containing quartz and feldspar phenocrysts enclosed in a very fine-grained groundmass showing primary igneous textures" (Blake et al., 1981). In the author's mapping experience, the unit does appear to be "mainly massive", and layered porphyrys are a rarity. Examples are shown of a typical outcrop of massive porphyry (Figure 3a) and a layered porphyry (Figure 3b). I. Withnall (pers. comm., 2008) has interpreted the latter as an original volcaniclastic feature. Alternatively, it could be the result of metasomatism of a sedimentary intercalation originally in the Magna Lynn Metabasalt.

In thin section at a dating locality 10 m east of a protrusion of typical massive Magna Lynn Metabasalt, "the (Leichhardt) sample is dominated by an equigranular very fine-grained groundmass of rounded to irregular quartz, biotite and minor plagioclase, with abundant large (2–5 mm) euhedral phenocrysts of plagioclase (variably replaced by secondary muscovite and sericite), quartz and sporadic K-feldspar. Flattened biotite aggregates and individual biotite flakes define a weak foliation" (Carson et al., 2008, p. 76); 21°2′32″S, 139°46′31″E. It is possible that this fits with being a 'porphyritic granite'. Hutton & Withnall (2013, p. 31) describe the Kalkadoon Granodiorite as consisting of "grey biotite (± rare hornblende) granodiorite and tonalite, pink biotite granite, minor leucogranite, muscovite granite, microgranite, porphyritic granophyre, porphyritic biotite-muscovite granite, monzonitic diorite and aplite".

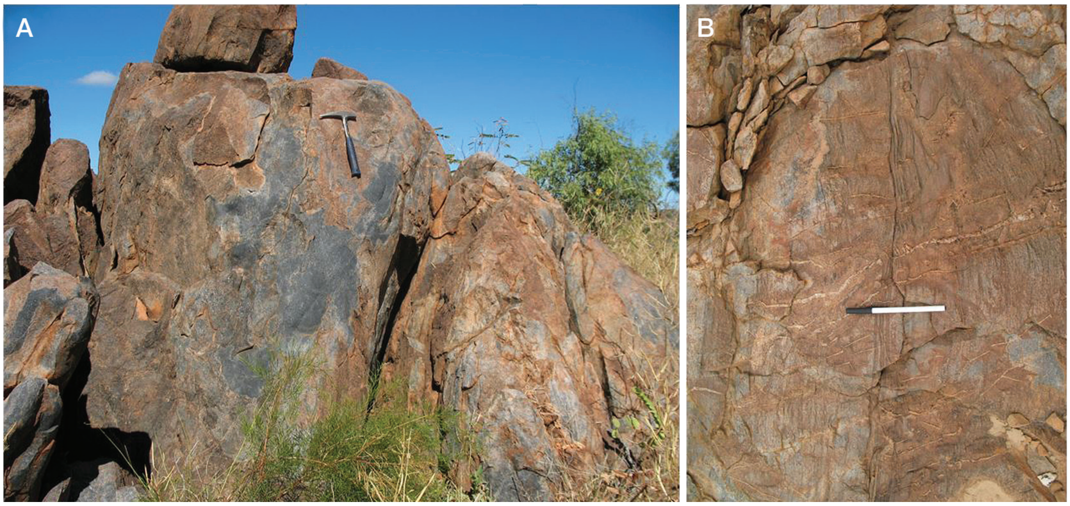

FIGURE 3. (A) Typical outcrop of Leichhardt complex. Massive porphyry with light grey-brown weathering, approx. 20°43′44″S, 139°46′8″E; (B) Uncommon layered porphyry with continuous and discontinuous layers. Identified by I. Withnall, 20°54′32″S, 139°48′10″E.

Central Belt Relationships

This section addresses the relationships in the eastern part of what is generally called the Kalkadoon-Leichhardt Belt or Domain, outcropping over a strike length of 230 km and a maximum width of 28 km. It describes three separate areas from north to south, which are considered typical of the various styles of unit relationships.

The revised maps shown in Figures 4, 5, 6, 7, 9, 10 and 11, 12 are based on the existing mapping with local critical changes. Emphasis is placed on the nature of the unit boundaries, mainly between the felsic and mafic units. The combination of 3D aerial photographs and remotely sensed images, particularly from Google Earth Pro, provide exceptional contrast in texture and colour fidelity between units, and were extremely valuable in mapping. These tools were used in combination with aeromagnetics and radiometrics. The most contentious issues derive from whether the unit boundaries, particularly those between felsic and mafic units, are intrusive/metasomatic, sedimentary/unconformable or faulted.

Outcrop Pattern of the Magna Lynn Metabasalt and Nature of the Contact with the Leichhardt Complex

South of the highway (Figure 1), the Magna Lynn Metabasalt has a complex distribution pattern, with two main belts of variable widths. The western belt has two subsidiary NNW trends and coalesces with the eastern belt 16 km south of Lake Mary Kathleen. Further south, the unit again forms multiple separate bodies of variable shapes and also includes a local NNW trend. In places, such as 7 km north of Lake Mary Kathleen, the Magna Lynn Metabasalt is missing altogether, and the Kalkadoon Granodiorite is directly in contact with

Argylla Formation. Three areas have been chosen to illustrate different aspects of the Leichhardt/Magna Lynn boundary. First is a meridional belt, second a double diagonal belt, and third a northerly trending protrusion.

Meridional Contact with the Magna Lynn Metabasalt

The boundary between the Leichhardt complex and the Magna Lynn Metabasalt is everywhere ragged or sinuous, commonly having embayments extending at least 100 m into the Leichhardt complex. These features are difficult, if not impossible, to show at 1:100,000 map scale, with the result that map boundaries have been portrayed as smooth, and thus more readily seen as either stratigraphic or faulted. Many narrow 'fingers' of metabasalt project at least 1 km into the Leichhardt complex (e.g. Figures 4, 5) in what is overall a meridional boundary.

FIGURE 4. Google Earth Pro image of an area 15 km NNE of Lake Mary Kathleen, together with inset MARY KATHLEEN. The finger-like projections of the Leichhardt complex into the Magna Lynn Metabasalt are characteristic and were mostly shown in the earlier mapping. Note that the boundary between the Argylla Formation (Pea) and the Ballara Quartzite (Pkb_2) is shown as an unconformity.

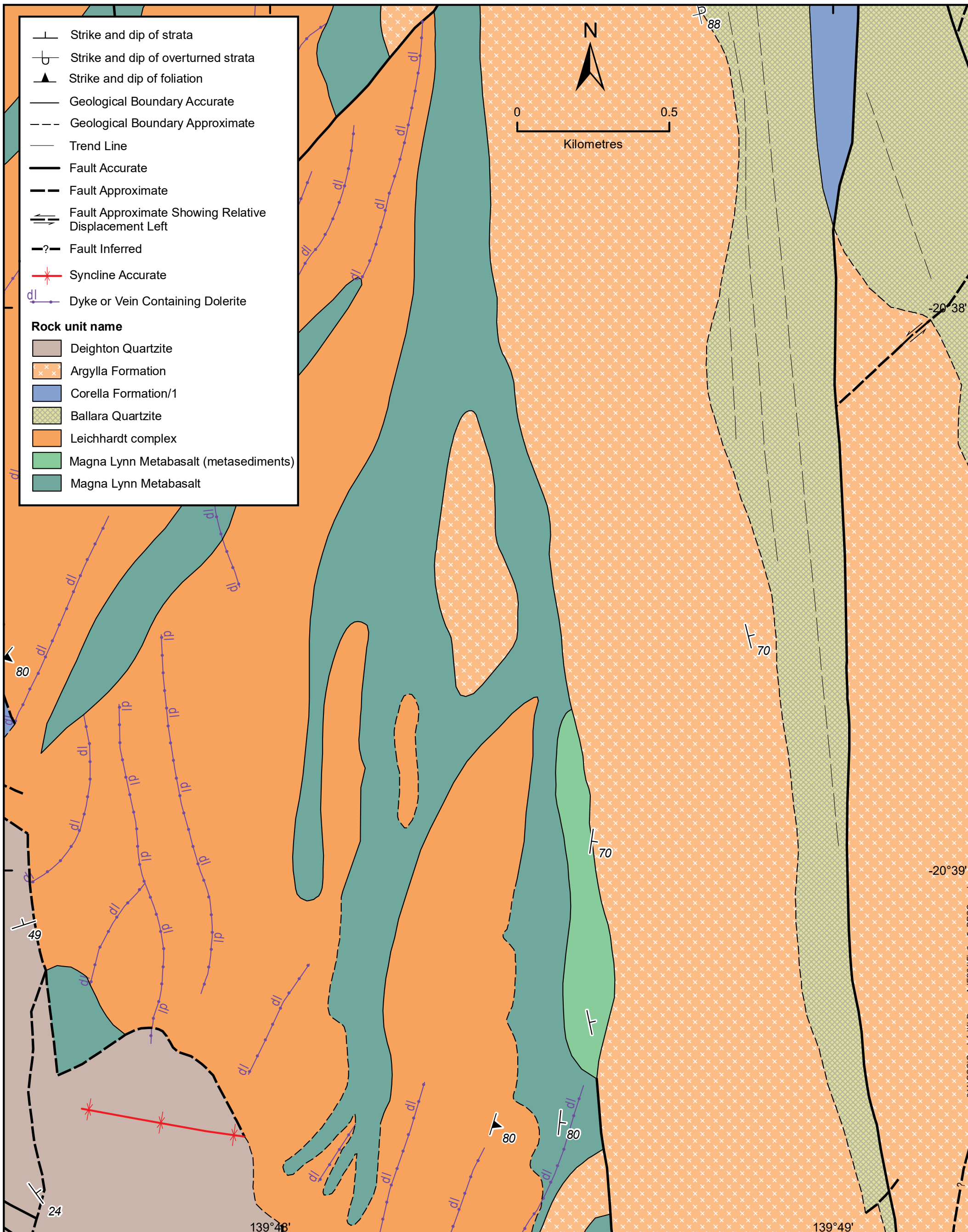

FIGURE 5. Geology of the area of Figure 4 with the Leichhardt complex interpreted as intrusive into Magna Lynn Metabasalt. It also shows Argylla Formation interpreted as intrusive into Magna Lynn Metabasalt, with the upper boundary transecting bedding in the Ballara Quartzite and also appearing to be intrusive.

Diagonal Belt of Magna Lynn Metabasalt

Located 10 km south of Mary Kathleen is a diagonal belt of Magna Lynn Metabasalt up to 1.5 km wide (Figures 6, 7). The southern boundary is deeply serrated, with embayments of the Leichhardt complex penetrating up to 500 m into the metabasalt. The northern boundary of the diagonal body is complex, with a curved inclusion of the Leichhardt complex extending 2.8 km parallel to the metabasalt boundary. The southern part of this boundary is more gently arcuate, suggesting control by a fault.

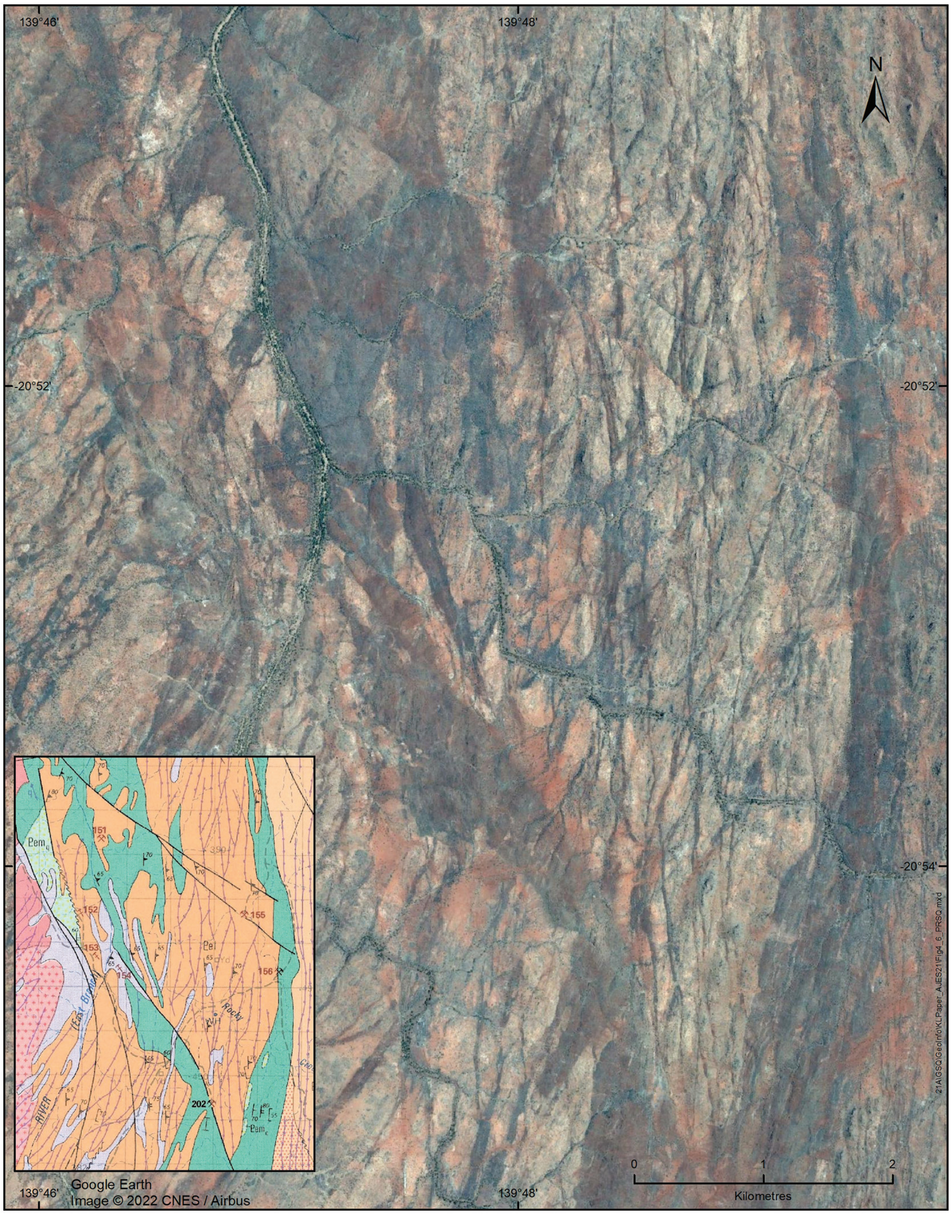

FIGURE 6. Google Earth Pro image of an area 10 km south of Lake Mary Kathleen, together with inset MARY KATHLEEN.

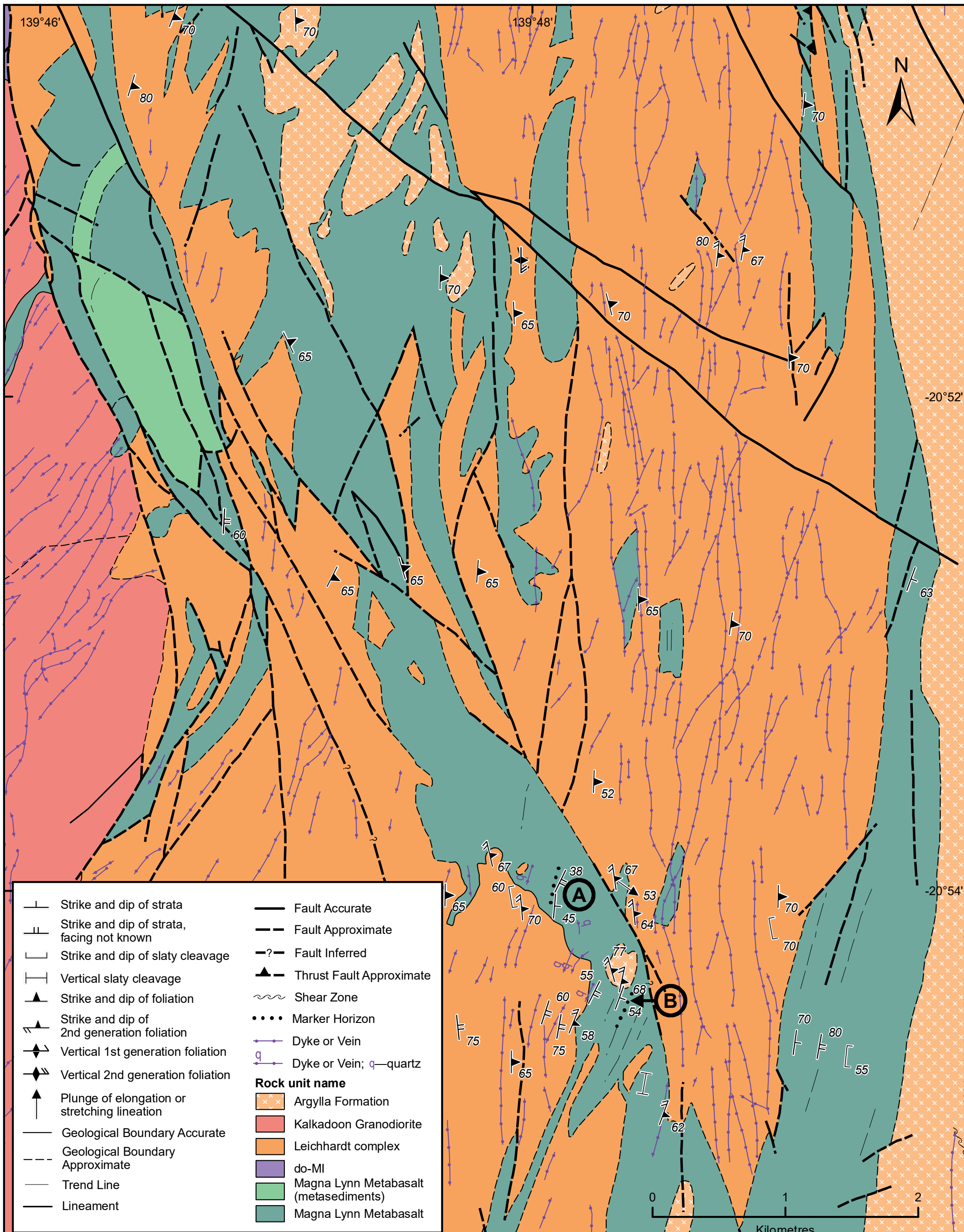

FIGURE 7. Geology of the area of Figure 6 showing a revised interpretation with the Leichhardt complex and at least part of the Argylla Formation as intrusive. The narrow quartzite unit (A) within the Magna Lynn Metabasalt is oblique to the boundary with the Leichhardt complex, indicating that the boundary is not an unconformity. The quartzite (B) is sub-parallel to (A).

Relationship of the Leichhardt Complex to Bedding in the Magna Lynn Metabasalt. At only one locality has bedding in a quartzite within Magna Lynn Metabasalt been mapped in the field adjacent to the boundary with the Leichhardt complex, although many others have been identified on images (e.g. 20°57′7″S, 139°48′4″E). In Figures 6, 7 at A, the quartzite (which is ~3 m thick) outcrops over a strike length of 160 m and terminates within 40 m of the southern Magna Lynn/Leichhardt boundary. Bedding strikes at 6° and makes an angle of 40° with the trend of that boundary. It is within 15° of the trend of a quartzite band within the metabasalt at B. Thus, the oblique boundary cannot be interpreted as a conformable or disconformable contact. Blake (1991) interpreted the boundary as a fault, which is not compatible with its highly irregular nature. In outcrop the boundary is markedly serrated with Leichhardt complex protrusions up to 170 m, and there is no evidence of a fault. Mapped and interpreted quartzite bedding trends within the Magna Lynn sequence between Lake Mary Kathleen and Figures 6, 7 are all NNE to NE, despite the complexity of the Magna Lynn/Leichhardt boundary.

Alteration within the Magna Lynn Metabasalt. On Google Earth Pro images (e.g. Figure 6), in most areas within the Magna Lynn Metabasalt there are numerous irregularly shaped, green-grey patches which appear to be transitional in character to the mappable Leichhardt complex. A possible interpretation is that these areas represent partial metasomatism of the Magna Lynn Metabasalt related to the Leichhardt complex and could agree with the "altered basic volcanics" in the unit description above. On Figure 6, within the Magna Lynn Metabasalt and up to 150 m from the southern boundary with the Leichhardt complex, is a pseudobreccia consisting of sub-rounded, dark-grey bodies in a lighter-grey matrix which has the characteristics of the Leichhardt complex. Both bodies contain feldspar laths up to 10 mm long, and the assemblage is interpreted as a partially metasomatised variant of the original metabasalt. The site is on the western margin of a slightly lighter-grey toned area on the image, which is about 100 m wide. An example of the alteration is shown in Figure 8.

FIGURE 8. Pseudobreccia consisting of irregular mafic bodies in a matrix of quartz-feldspar porphyry, Magna Lynn Metabasalt, 20°53′55″S, 139°47′59″E.

Irregular Protrusion of Leichhardt Complex Surrounded by Magna Lynn Metabasalt

Twenty-six kilometres south of Lake Mary Kathleen on DUCHESS is a 1.5 km-wide, fork-shaped protrusion of the Leichhardt complex surrounded by Magna Lynn Metabasalt (Figures 9, 10). The area is described in Bultitude et al. (1982). Dating of the Leichhardt complex in this area (21°02′32″S, 139°46′30″E) (Figure 10), gave an age of 1864 ± 3 Ma (Carson et al., 2011, p. 76). On DUCHESS inset this anomalous interpreted unconformity boundary has been rationalised with faults on the western margin. For the forked northern boundary to be an unconformity would require north-plunging triple anticlines at its extremity. Further, it requires a doubly plunging anticline at A. Smaller leucocratic bodies with the same tone as the body of the protrusion surround it (e.g. B) and were interpreted as Argylla Formation on DUCHESS inset. An alternative, given their lighter colour and lower relief, is that they are isolated intrusions of Leichhardt complex and that the entire complex is intrusive.

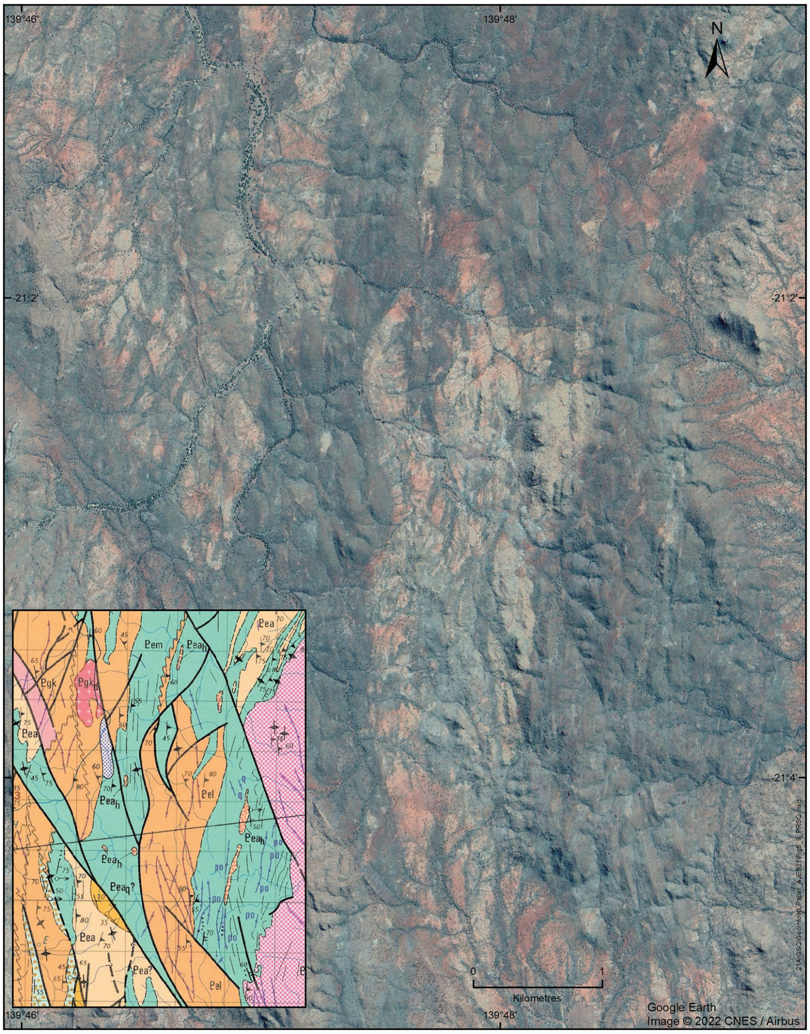

FIGURE 9. Google Earth Pro image of an irregular protrusion of the Leichhardt complex into the Magna Lynn Metabasalt. The inset from DUCHESS shows the western boundaries of the Leichhardt fingers as being mostly faulted.

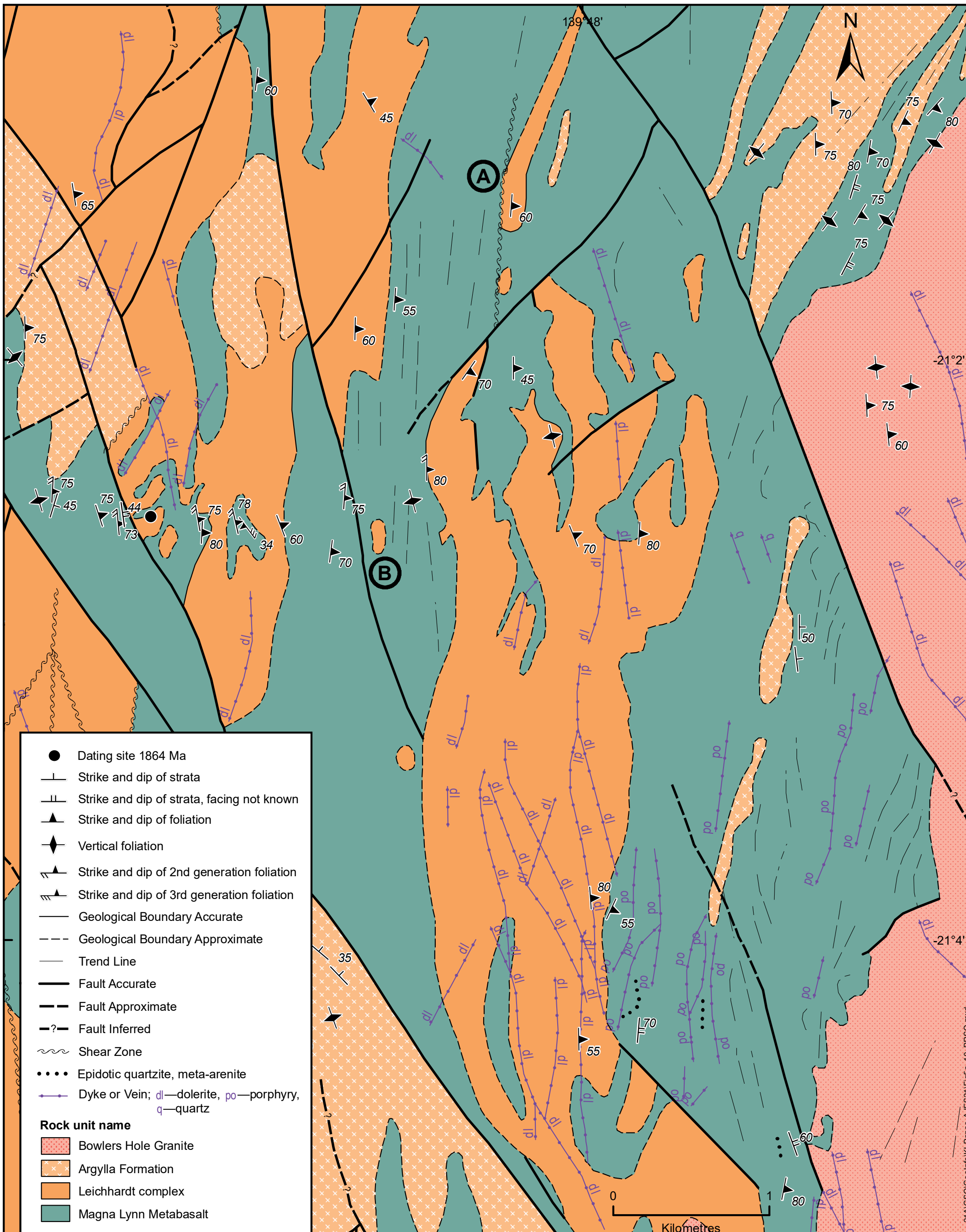

FIGURE 10. Reinterpreted area of Figure 9 showing the whole body of the Leichhardt complex as being intrusive; and smaller, lighter-coloured bodies such as B as being intrusive Leichhardt complex rather than Argylla Formation. It also shows a complex interdigitation of Leichhardt and Magna Lynn Metabasalt around the dating site.

Additional support for an intrusive interpretation for the forked Leichhardt body is the highly irregular, serrated northern boundary and 'ghosting' of metabasalt extensions within it. This margin is similar in form to the north-eastern boundary between the Bowlers Hole Granite and the Magna Lynn Metabasalt 4.5 km to the ENE (Figures 11, 12). Here, the granite is accepted as intrusive, with the same age as the Argylla Formation (1777 Ma).

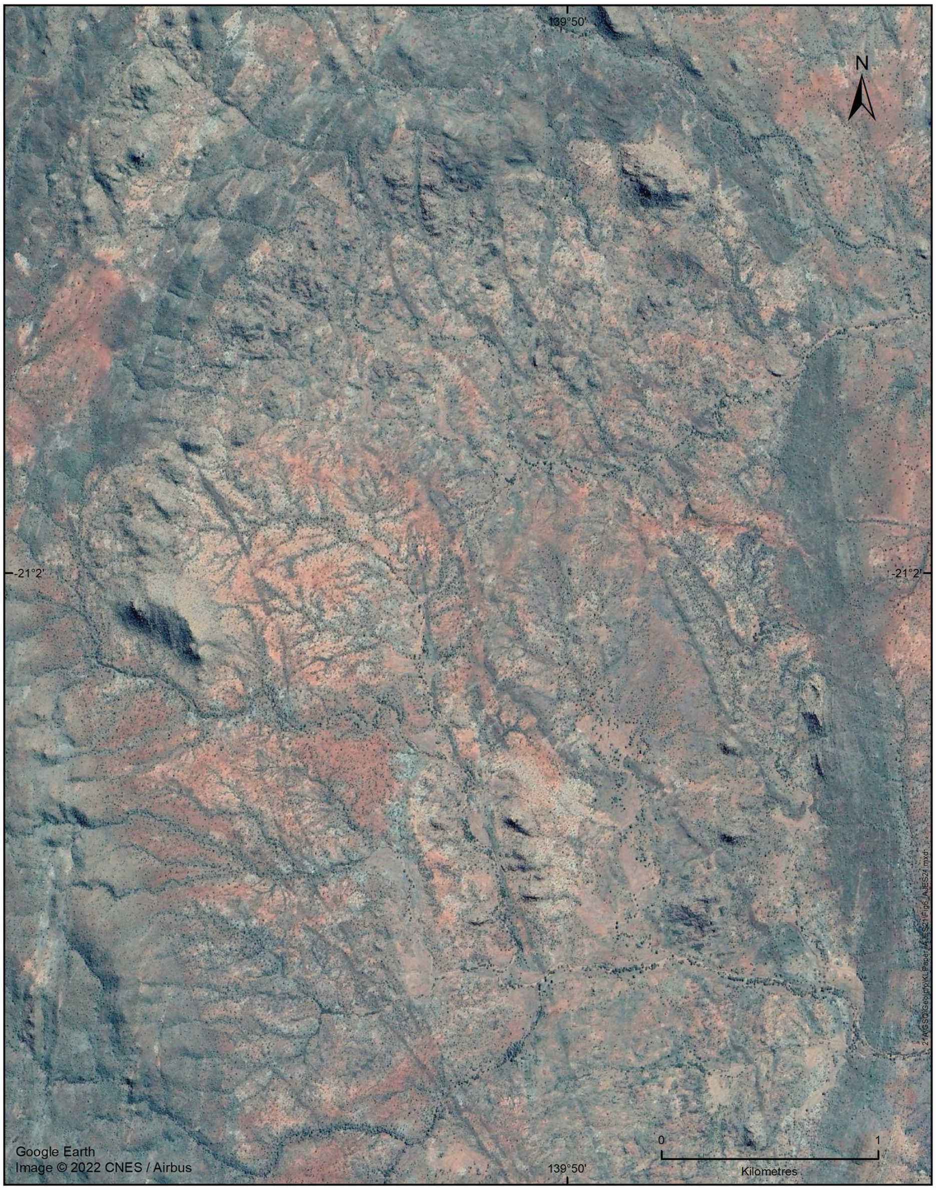

FIGURE 11. Google Earth Pro image of an area impinging on Figures 9, 10. It shows an ellipsoidal body of Bowlers Hole Granite intruding into the Magna Lynn Metabasalt. The intrusive boundary can be compared with the boundary in Figures 9, 10, which has historically always been interpreted as an unconformity.

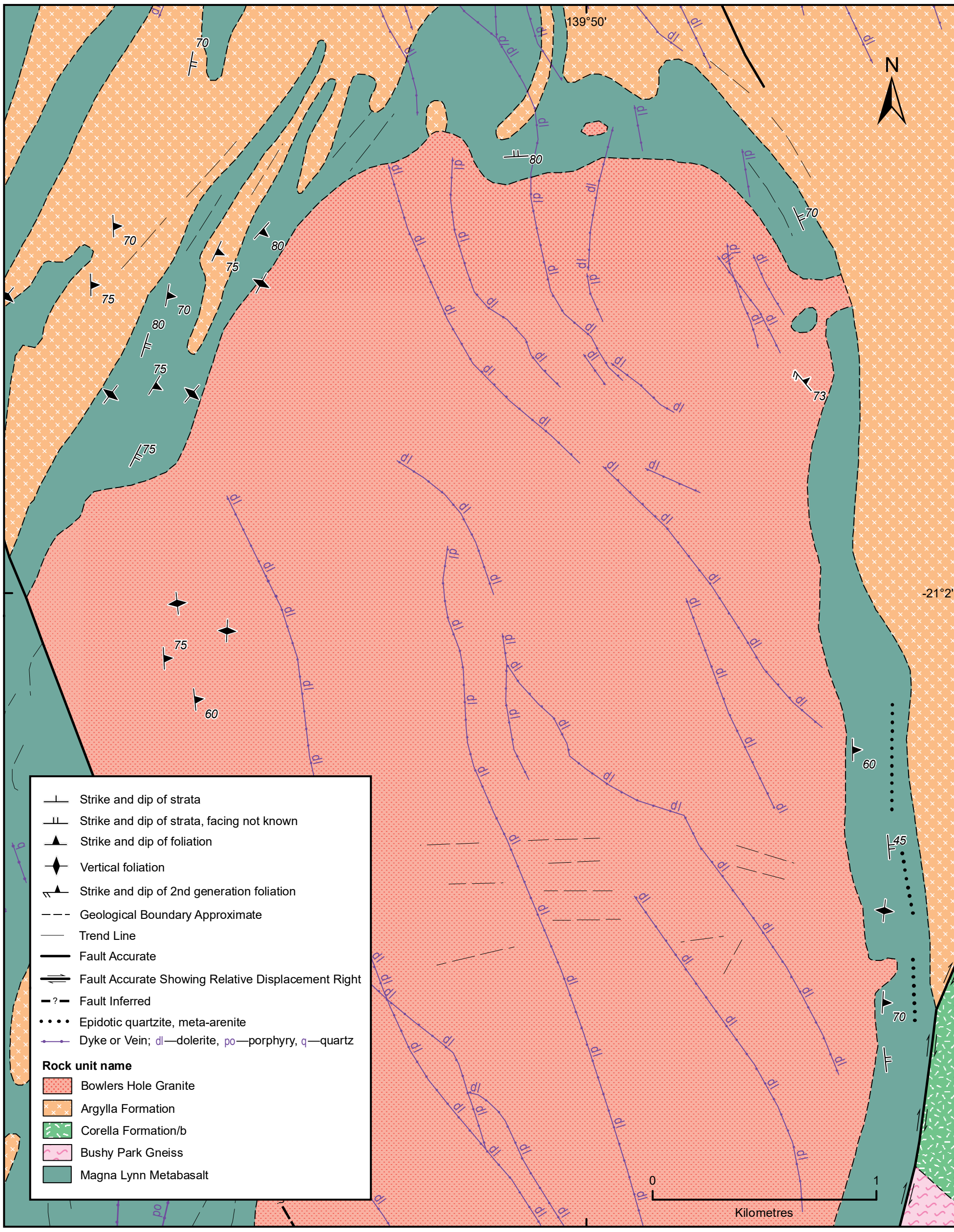

FIGURE 12. Map interpretation of Figure 11. The serrated north-eastern boundary shows similar features and metabasalt mega xenoliths to Figures 9, 10.

Characteristics of the Leichhardt/Magna Lynn Boundary

Contacts between the Magna Lynn and Leichhardt bodies may be either sharp or gradational at outcrop (Figure 13A–C) or remotely sensed scale, and where exposed, the sharp contacts have the same serrated boundaries as those bordering metabasalt xenoliths within the body of the quartz-feldspar porphyry. This suggests that the boundaries formed by the same mechanism(s) and are not compatible with an unconformity.

As well as the mega xenoliths of Magna Lynn Metabasalt within the Leichhardt complex, there are many isolated bodies of the Leichhardt complex within the Magna Lynn Metabasalt. These bodies can be approximately ovoid, circular or lenticular and are commonly 100 m to 500 m in length, with the maximum length in the Blockade block of 900 m (20°34′47″S, 139°54′35″E). Examples are shown in Figures 6, 7 and Figures 9, 10 at A and B. If the boundaries are unconformable, these relationships necessitate a very complex system of doubly plunging folds with variable axial plane orientations. Further, it requires, with local domal antiforms and synforms, that the overall form surface is most likely to be flat-lying and sheetlike. This is at odds with isolated sedimentary intercalations in the Magna Lynn Metabasalt, particularly south of Lake Mary Kathleen, which have generally intermediate to steep dips eastwards, with only locally a minimum of 30°. Trend lines within the Magna Lynn Metabasalt are shown in many areas, e.g. Figure 7, and nowhere are they seen to wrap around protrusions of the Leichhardt complex as would be expected if the boundary was an unconformity which was subsequently folded.

An observation has been made of "possible fiamme" within the Leichhardt complex (Hutton & Withnall, 2013), but an alternative interpretation is that they are small xenoliths from the Magna Lynn Metabasalt that have been variably deformed.

FIGURE 13. Field relationships between light-grey, quartz-feldspar porphyry of the Leichhardt complex, and dark blue-grey metabasalt of the Magna Lynn Metabasalt: (A) Creek barrier outcrop showing the boundary and also an isolated body (upper left) of the Leichhardt complex within the metabasalt, 20°34′12″S, 139°47′49″E; (B) Close-up of continuation of (A) showing serrated sharp boundary; (C) Creek exposure, exact location unknown, approx. 21°2′34″S, 139°46′43″E, showing a porphyry with a transitional contact into amphibolite: (D) Contact between quartz-feldspar porphyry of the Leichhardt complex and biotite schist (R. Bultitude, pers. comm., 2018) belonging to a body currently interpreted as an anomalously young dolerite dyke, 20°47′6″S, 139°47′38″E.

Mega Xenoliths or Metadolerite Dykes?

On MARY KATHLEEN east of Lake Mary Kathleen at 20°47′37″S, 139°47′50″E, a 2.1 km-long by 200 m-wide inlier of Magna Lynn Metabasalt has been shown within the Leichhardt complex. In the existing interpretation this would necessarily represent a doubly plunging syncline, but in the interpretation presented here, it is regarded as one of many mega xenoliths of metabasalt. West of this body, a dating site in a mafic rock has yielded an anomalously young U-Pb SHRIMP age of 763 ± 85 Ma (Bierlein et al., 2008; Hutton & Withnall, 2013). This body is in the spillway of Lake Mary Kathleen at 20°47′6″S, 139°47′38″E, and has been interpreted as a metabasalt dyke intruding into the Leichhardt complex (shown as 'Argylla Fm' on current maps). Alternatively, since it has similar contact features to that shown in Figure 13A–C and a similar appearance on images to the body described above, it may also be a mega xenolith. An example of the contact features of this dated body is shown in Figure 13D. It is difficult to explain the young age, unless it represents a very late phase of alteration. It contains a large proportion of biotite schist (R. Bultitude, pers. comm., 2018).

There are numerous elongate, separate NS bodies of Magna Lynn Metabasalt completely surrounded by the Leichhardt complex, with lengths of up to 2 km and widths up to 400 m (e.g. Figures 6, 7; 20°51′5″S, 139°48′5″E). The net effect is to produce a 'shredded' Magna Lynn distribution pattern.

Throughout the Kalkadoon/Leichhardt complex between Figure 6 and 8 km to the west (Figure 1) on MARY KATHLEEN is a network of generally linear mafic bodies which are shown as dolerite dykes. An exception is a 2 km-long body at 20°55′31″S, 139°43′43″E, which is interpreted therein as Magna Lynn Metabasalt. Some of the larger bodies are up to 400 m wide and 3 km long. These wider bodies are locally crisscrossed by dykes approximately 15 m wide, and are interpreted herein as residual mega xenoliths of Magna Lynn Metabasalt (Figure 1).

Kalkadoon Granodiorite Relationships with the Magna Lynn Metabasalt

Boundaries between the Kalkadoon Granodiorite and the Magna Lynn Metabasalt constitute only a small proportion of the contacts compared with the Leichhardt complex (e.g. Figures 6, 7). On MARY KATHLEEN, only a few km of this boundary are shown. With reinterpretation of many of the more massive dolerite dykes as mega xenoliths of Magna Lynn Metabasalt, these boundaries become much more extensive. An example of the contact between amphibolite, which is interpreted as Magna Lynn Metabasalt and Kalkadoon Granodiorite, is shown in Figure 14.

FIGURE 14. Leucogranite dyke of the Kalkadoon suite intruding metabasalt of the Magna Lynn Metabasalt. The leucogranite contains a xenolith of amphibolite at lower left; 20°45′50″S, 139°41′34″E.

This is interpreted as showing an intrusive relationship between a dyke of the Kalkadoon Granodiorite and the Magna Lynn Metabasalt. Alternatively, it has been suggested that the dyke could simply be part of a suite of granites known to be younger than the Magna Lynn Metabasalt. Arguments against this are that the surrounding intrusion has been mapped as Kalkadoon Granodiorite, and that the closest younger granite to this site (with an age of 1777 Ma) is the Bowlers Hole Granite which is 30 km to the SSE (Figures 11, 12).

Discussion

Interpretations of Previous Mapping

In the MARY KATHLEEN mapping by Derrick et al. (1977), the boundaries between the Leichhardt "Volcanics" and the Magna Lynn Metabasalt were mostly shown as unfaulted and interpreted as conformable or disconformable (e.g. Figures 6, 7). Faulted boundaries were relatively uncommon and mostly restricted to the NNW-SSE extensional set. In the subsequent mapping by Blake (1991), additional fault boundaries are much more common and are shown as meridional thrusts located mainly on the eastern sides of blocks of Magna Lynn Metabasalt. In this way, blocks were interpreted as variably sized thrust slices rather than mega xenoliths as advocated in this study.

An alternative suggestion for the relationships between the Leichhardt complex and the metabasalt in this area and surrounding areas is that they are coeval. This requires that the unit that has been mapped in MARY KATHLEEN (Blake, 1991; and this study) is not Magna Lynn Metabasalt at all, but an intercalation within the Leichhardt Volcanics. Furthermore, it does not explain bedding in the metabasalt at a high angle to the boundary. The irregular shapes and serrated boundaries of metabasalts described above mitigate against this viewpoint and seem more in accord with a residual mega xenolith origin. Most mafics within the Kalkadoon/Leichhardt complex on existing maps are shown as intrusive metadolerites and metagabbros.

Thickness and Extent of the Magna Lynn Metabasalt

The maximum thickness of the Eastern Creek Volcanics has been estimated at 8 km (Wilson et. al., 1984, Figure 1; Bain et al., 1992). The previously published estimated thickness of the Magna Lynn Metabasalt ranges from 200 m to 700 m (Derrick et al., 1977). The belt of metabasalt which contains sufficient sedimentary intercalations south of Lake Mary Kathleen (Figure 1) has been used here to estimate thickness. West of this belt, the unit is interpreted to extend at least a further 8 km, but the structure is unknown, so an estimate of stratigraphic thickness cannot be made. Using the interpretation herein that the mapped distribution of the Magna Lynn Metabasalt represents 'remnants' subsequent to intrusion by the Leichhardt and Kalkadoon units, and an estimate of average dip from sedimentary intercalations of 50°E, the following estimates of minimum stratigraphic thickness were obtained (relative Lake Mary Kathleen, Figure 1): 10.5 km south, 5.6 km; 20.5 km south, 5.5 km; 30.5 km south, 5.2 km. These thicknesses are nearly an order of magnitude greater than the estimates of Derrick et al. (1977) and reflect the difference in measurement between an interpreted unconformity or intrusive origin for the Leichhardt/Magna Lynn Metabasalt boundary.

Rift-controlling Structures?

In the existing interpretations, there has been considerable discussion of rift-controlling structures for the Eastern Creek Volcanics. The normal controlling faults were reckoned to be the Quilalar and Gorge Creek Faults in the east, and the Mount Isa and Mount Gordon Faults in the west (e.g. see Hutton & Withnall, 2013). These structures all appear to be better interpreted as post-Haslingden Group. No controlling structures were advocated for the Magna Lynn Metabasalt to the west. In the interpretation of this study, with the Eastern Creek Volcanics being correlated with the Magna Lynn Metabasalt (discussed elsewhere), no rift boundaries are obvious. To the east, the relationships of the Magna Lynn Metabasalt are obscured by the interpreted intrusion of the voluminous Argylla Formation.

Previous Correlations of Mafic Units

Carter et al. (1961) correlated the Eastern Creek Volcanics and Marraba Volcanics which they regarded as forming east and west of a "tectonic welt". The mafic volcanics in the Cloncurry area (now the Toole Creek Volcanics) were also regarded as being correlative. Bultitude & Wyborn (1982) correlated the Oroopo Metabasalt, Eastern Creek Volcanics and Magna Lynn Metabasalt. Bultitude (1984), in Blake et al. (1984), correlated the Oroopo Metabasalt, the Jayah Creek Metabasalt and the Eastern Creek Volcanics. Blake (1987) interpreted the Eastern Creek Volcanics and the Magna Lynn Metabasalt as being equivalents, with the Marraba Volcanics being significantly younger. In GSQ 2011, all mafic units are shown as having different ages (Figure 2). In summary, all mafic units at various stages could be regarded as correlated.

Dykes in the Granites and Leichhardt Complex

There appear to be up to four sets of dolerite dykes traversing the Kalkadoon Granite/Leichhardt complex and Magna Lynn Metabasalt. These have been interpreted to be younger than these enclosing units. Alternatively, they may represent 'residual' dykes in the Magna Lynn Metabasalt mega xenoliths following advanced overprinting by Leichhardt complex and Kalkadoon Granodiorite. The dykes appear to penetrate the interpreted mega xenoliths where interspersed with Leichhardt complex without divergence, giving the impression that they were in existence prior to the interpreted Leichhardt volume-preserving overprint. The preservation of the dykes may be related to their coarser grain size than the surrounding mafic volcanics, making them less susceptible to intrusion.

Mode of Formation of the Kalkadoon-Leichhardt Complex

It is possible that the intrusive relationships interpreted here instead represent a metasomatic overprint on original unconformities. However, it is difficult to see how such a process could 'mask' unconformities over such a broad area. Another possibility is that there is an older (~1850 Ma) suite intruded by a younger post ~1760 Ma intrusive margin for which no dating exists. A dating site in the Leichhardt complex (1864 ± 3 Ma; Carson et al., 2011, p. 76) (Figures 9, 10 herein) is 10 m from a projection of Magna Lynn Metabasalt. This example would require a very thin, younger phase of the Kalkadoon/Leichhardt complex overlying the older phases.

Conclusions

It is proposed that the origin and relative timing of the Kalkadoon-Leichhardt complex is not clear cut, and that intrusion into the Magna Lynn Metabasalt best accords with the field and image evidence. The current universally accepted interpretation has the boundary as an unconformity, with an estimate of 50 million years of separation before deposition of the Magna Lynn Metabasalt.

Where observed, the boundary is sharp and serrated, and at one locality makes a gross angle of 40 degrees with the strike of a quartzite within the Magna Lynn Metabasalt. Within the metabasalt are zones of quartzofeldspathic metasomatism which appear to be incipient formation of the Leichhardt complex. Most obviously within the Leichhardt complex is a well-developed system of dolerite dykes, and these are interpreted to be residuals following intrusion of the metabasalt. Less-continuous and thicker bodies of metabasalt are interpreted as residual *in situ* relict mega xenoliths following intrusion by the Leichhardt complex.

This interpretation brings into question the relationship of the Kalkadoon/Leichhardt system and the other sequences of metabasalt, namely the Oroopo Metabasalt, the Eastern Creek Volcanics and the Marraba Volcanics. However, unlike the Magna Lynn Metabasalt, there is a series of isotopic dates (mainly maximum depositional ages) which appear to support the 'basement' interpretation for the Kalkadoon/Leichhardt system (e.g. see Hutton & Withnall, 2013).

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Bill Perkins worked as a geologist with Mount Isa Mines Limited and its related companies from 1968 to 1996, in various roles including mining, exploration and research. In 1997 he published the seminal work from his PhD thesis on the origin of the Mount Isa lead-zinc orebodies. This paper advocated a completely different timing of formation of the deposit from the prevailing view. Bill joined the Geological Survey of Queensland, beginning with a mapping program in 2006 and concentrating on the Kalkadoon/Leichhardt Belt. This paper reports on part of this work. He still works for the Survey as a volunteer.