



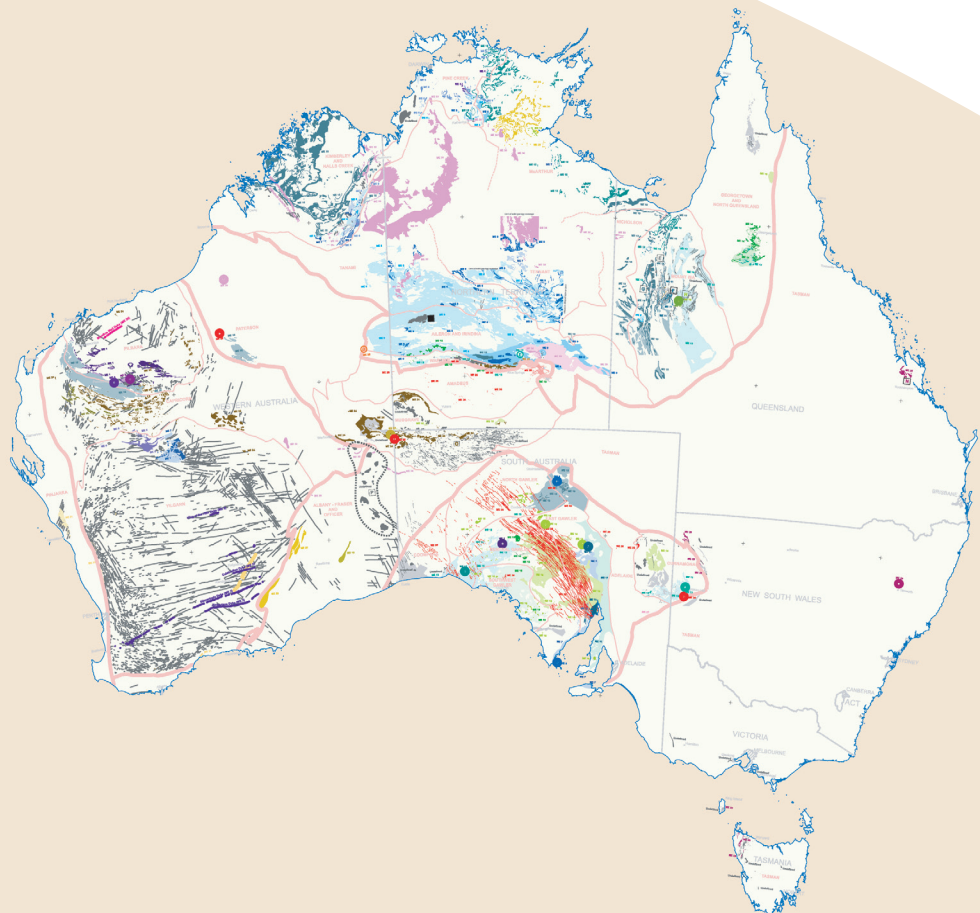
Australian Government
Geoscience Australia

Guide to Using the 1:5 000 000 Map of Australian Proterozoic Mafic-Ultramafic Magmatic Events

Dean M. Hoatson, Jonathan C. Claoué-Long, and Subhash Jaireth

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GEOSCIENCE AUSTRALIA
RECORD 2008/15

by

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Cover Illustration: Part of the new 1:5 000 000 map 'Australian Proterozoic Mafic-Ultramafic Magmatic Events'.

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- see online directory <http://www.ga.gov.au/map/index.jsp#mum>

- see CD ROM enclosed with this Record

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Executive Summary

This Record provides information to assist the use of two web-based map sheets (at 1:5 000 000 and 1:10 000 000 scales) showing the time-space distribution of Proterozoic mafic-ultramafic magmatism in Australia, and the associated mineral deposits. The 'Australian Proterozoic Mafic-Ultramafic Magmatic Events' Map (Sheets 1 and 2) was produced by Geoscience Australia (GA) in collaboration with the State and Northern Territory geological surveys and other organisations.

The event chronology of Proterozoic mafic-ultramafic igneous rocks in Australia resolves into thirty Magmatic Events (ME 1 to ME 30) which range in age from the Early Palaeoproterozoic (~2455 Ma, ME 1) to the Early Cambrian (~520 Ma, ME 30). The Early Cambrian Kalkarindji Magmatic Event (ME 30) is included even though its age lies slightly outside the Proterozoic, because it is one of the largest known Large Igneous Provinces (LIPs). The events are presented in a 1:5 000 000 National Map with rock units of different ages colour-coded; as a large-format Time–Space–Event Chart; and as derivative maps that show LIPs, and associated magmatic-hydrothermal mineral deposits.

The delineation of Magmatic Events for this study is based on several hundred published ages of mafic and ultramafic rocks from different isotopic systems and minerals. Basic requirements for inclusion of a published age in this study were: measurement by robust geochronological methods; high confidence in its interpretation; and consistency with other temporal evidence, e.g., field relationships of associated rock units. Over 90 per cent of the ages compiled were derived from U-Pb zircon and baddeleyite dating.

Regional solid-geology base maps were used for the representation of the Magmatic Events. The solid-geology maps provide insight into the total areal extent of the magmatic system, which is an important criterion when assessing mineral potential. The Australian Crustal Elements map (Shaw et al., 1995) provides a province framework for both the Map and the Time–Space–Event Chart; this is a national dataset that delineates crustal elements on the basis of composite magnetic and gravity domains.

The new Map and Time–Space–Event Chart highlight important periods of mafic-dominated tholeiitic magmatism and the concentration of mafic-ultramafic magmatism during the period ~1870 Ma to ~1590 Ma (~35% of all events). Nine of the thirty Magmatic Events are mineralised in Australia with known deposits or occurrences of nickel (Ni), copper (Cu), and/or platinum-group elements (PGEs). Six Magmatic Events (ME 1, 5, 6, 7, 19, and 26) are coeval with major Ni-Cu ± PGE deposits in other continents (e.g., ~2440 Ma Penikat in Finland; ~1918 Ma Raglan, ~1880 Ma Thompson, and ~1850 Ma Sudbury, all in Canada; ~1403 Ma Kabanga in Tanzania; and ~827 Ma Jinchuan in China). The Map and the Time–Space–Event Chart present important correlations of these mineralised magmatic systems under shallow cover and in under-explored provinces. The full geographic extent of the mafic-ultramafic magmatic systems is shown, and significant extensions to some igneous provinces are evident.

The 'Australian Proterozoic Mafic-Ultramafic Magmatic Events' Map is a fundamental national framework within which to integrate other geological and geochemical datasets, to evaluate pointers to under-explored and potentially mineralised environments, and to constrain the role of the mantle and mafic-ultramafic magmatism in the development of the Australian continent.

Scope of the Map

This Record is a user guide for the ‘Australian Proterozoic Mafic-Ultramafic Magmatic Events’ Map produced by Geoscience Australia (GA). Production of this Map was undertaken within the Mineral Exploration Promotion Project of the Onshore Energy and Minerals Division (OEMD), in close collaboration with the State and Northern Territory geological surveys, all of which made available their most recent geological and geochronological datasets ([Appendix 1](#)). The compilation (including two earlier releases of Western Australia and Northern Territory–South Australia maps) has been reviewed by more than forty geoscientists from geological surveys, universities, companies, and other organisations.

The National Map is the third and final component of the Proterozoic Mafic-Ultramafic Magmatic Event map series. It revises and supersedes the earlier Part 1 (Western Australia: GeoCat 64813) and Part 2 (Northern Territory and South Australia: GeoCat 65257) maps. It focuses attention on the continent-wide extent and volume of certain magmatic systems, and associations with mineralisation. The locations of magmatic units, correlations across the continent, and the relationship of magmatism to the evolving crustal structure of the continent, are all prominent. The new Map will be of interest to those explorers searching for nickel, platinum-group elements (PGEs: platinum, palladium, rhodium, iridium, osmium, and ruthenium), chromium, titanium, and vanadium, as well as being a fundamental resource for understanding the dynamic evolution of the Australian continent.

The National Map and accompanying information are presented as two sheets, both available in pdf and jpeg formats on the GA website (see [www links](#) on page 12). Data and references underpinning the information portrayed on the two sheets are compiled in [Appendices 2, 8, and 10](#).

Sheet 1 presents a 1:5 000 000 map showing the continental distribution of thirty mafic-ultramafic Magmatic Events which range in age from the Early Palaeoproterozoic (~2455 Ma, ME 1) to the Early Cambrian (~520 Ma, ME 30). The newly-defined Magmatic Event series (ME 1 to ME 30) is based on several hundred published age measurements, of which over 90 per cent are derived from recent U-Pb dating of zircon and baddeleyite.

Regional and local solid-geology digital maps were synthesised to produce a national presentation of mafic-ultramafic rock units, and regional rock packages that include relatively minor coeval mafic-ultramafic igneous rock components. Colour-coding of rock polygons by their age of magmatism provides a visual cue to the spatial and temporal correlations of magmatic units at province and continental scales. Their relationship to the evolution of the continent is shown with an overlay of the Australian Crustal Elements map. The new Map extends to isolated occurrences of dated magmatic units, and a commentary describing relevant rock relationships.

Sheet 2 presents a large format Time–Space–Event Chart which shows the occurrence and correlation of the thirty Magmatic Events across twenty-eight Australian crustal provinces. Those events known to be mineralised in Australia are highlighted, and six of the Magmatic Events are shown to be coeval with major Ni-Cu ± PGE deposits in other continents, e.g., Penikat in Finland; Raglan, Thompson, and Sudbury in Canada; Kabanga in Tanzania; and Jinchuan in China.

Inset maps at 1:10 000 000 scale indicate: (1) the locations of Australian Ni-Cu-Cr-V-Ti-PGE mineral deposits and occurrences, overlain on a composite of Proterozoic and Archaean mafic-ultramafic rock units; and (2) the geographic extent of five Magmatic Events which are distinguished as Large Igneous Provinces (LIPs) by exceptionally large volumes of mafic-dominated magma emplaced over short geological periods of a few million years or less.

This Record documents supporting information and provides individual time-slice maps ([Appendix 9](#)) and datasheets ([Appendix 10](#)) for each of the thirty Proterozoic Magmatic Events.

Nickel and Platinum-Group Element Exploration

Mafic and ultramafic igneous rocks are the principal source of economic concentrations of nickel, PGEs, and other metals such as chromium, titanium, vanadium, and cobalt. Such rocks constitute a major component of many of Australia's Precambrian provinces and have been a major focus for minerals exploration over the last forty years.

The economic interest became prominent in 1966 with the discovery of massive nickel sulphides hosted by Archaean komatiitic rocks at Kambalda in the Eastern Goldfields, Western Australia. More than 75 per cent of Australia's total contained nickel metal resource derived from sulphide deposits¹ (~15.3 Mt) was discovered during the relative short period of 1966 to 1973 (Figure 1), and many of the deposits commenced production within the first two years of their discovery (Figure 2). The vast majority of these deposits are hosted by Archaean komatiites emplaced in granite-greenstone belts in the Yilgarn Craton, Western Australia. Since 1966, the nickel industry has witnessed periods of buoyant metal prices and high demand, interspersed by protracted phases of relatively depressed metal prices, exploration inactivity, and variable discovery rates (Marston, 1984; Hronsky and Schodde, 2006; Hoatson et al., 2006).

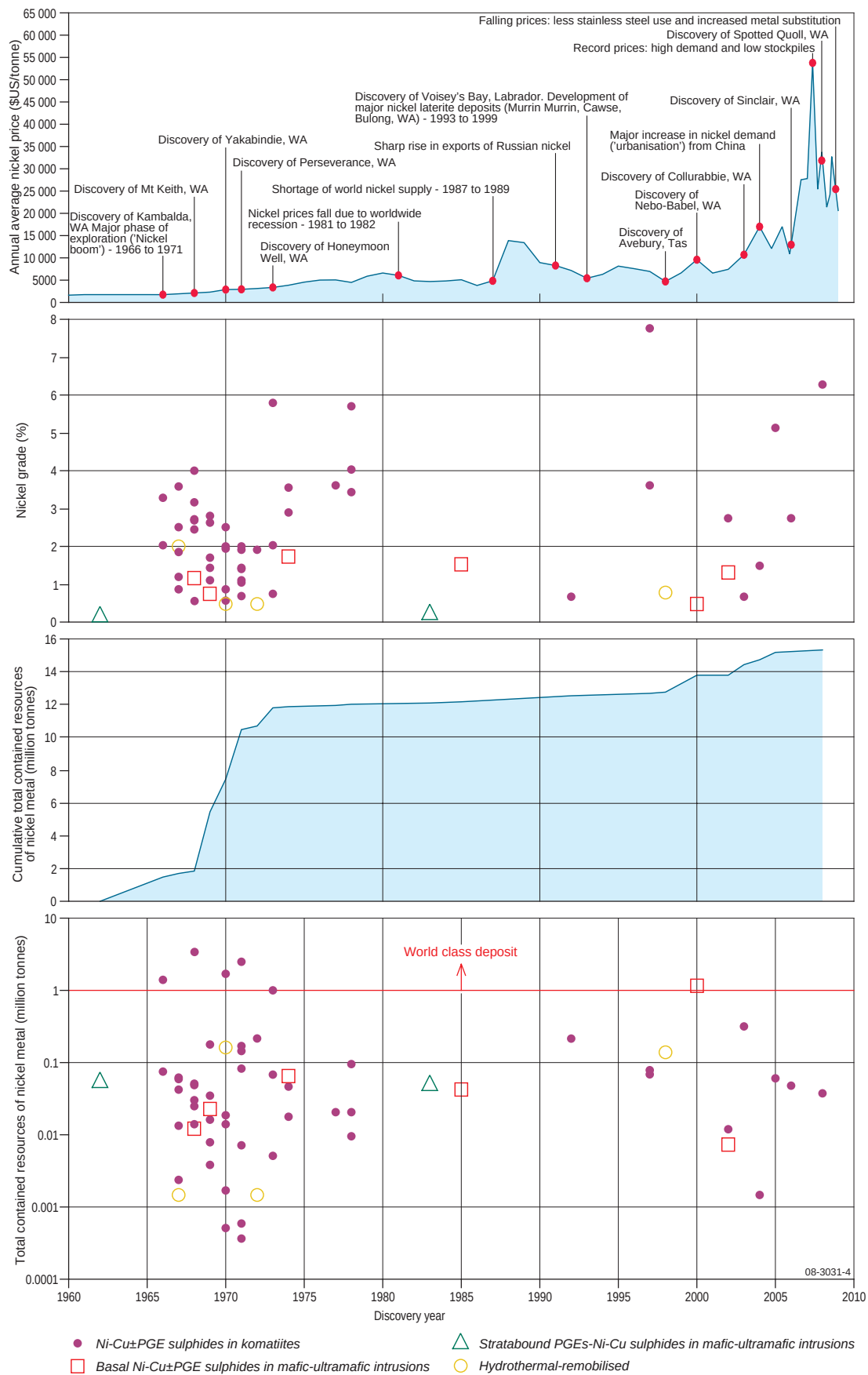
In contrast to the relatively early discovery of Archaean-age nickel mineralisation, most of the nickel deposits of Proterozoic age were discovered after 1974. So far, discovered Proterozoic nickel resources are significantly less abundant compared with the Archaean komatiitic deposits. The most important Ni-Cu ± PGE deposits hosted by Proterozoic mafic-ultramafic rocks in Australia include: Panton, Western Australia (~1856 Ma); Sally Malay, Western Australia (~1844 Ma); Copernicus, Western Australia (~1844 Ma?); and Nebo-Babel, Western Australia (~1080 Ma). The Sally Malay and Copernicus deposits in the East Kimberley are the only Proterozoic deposits with economic resources.

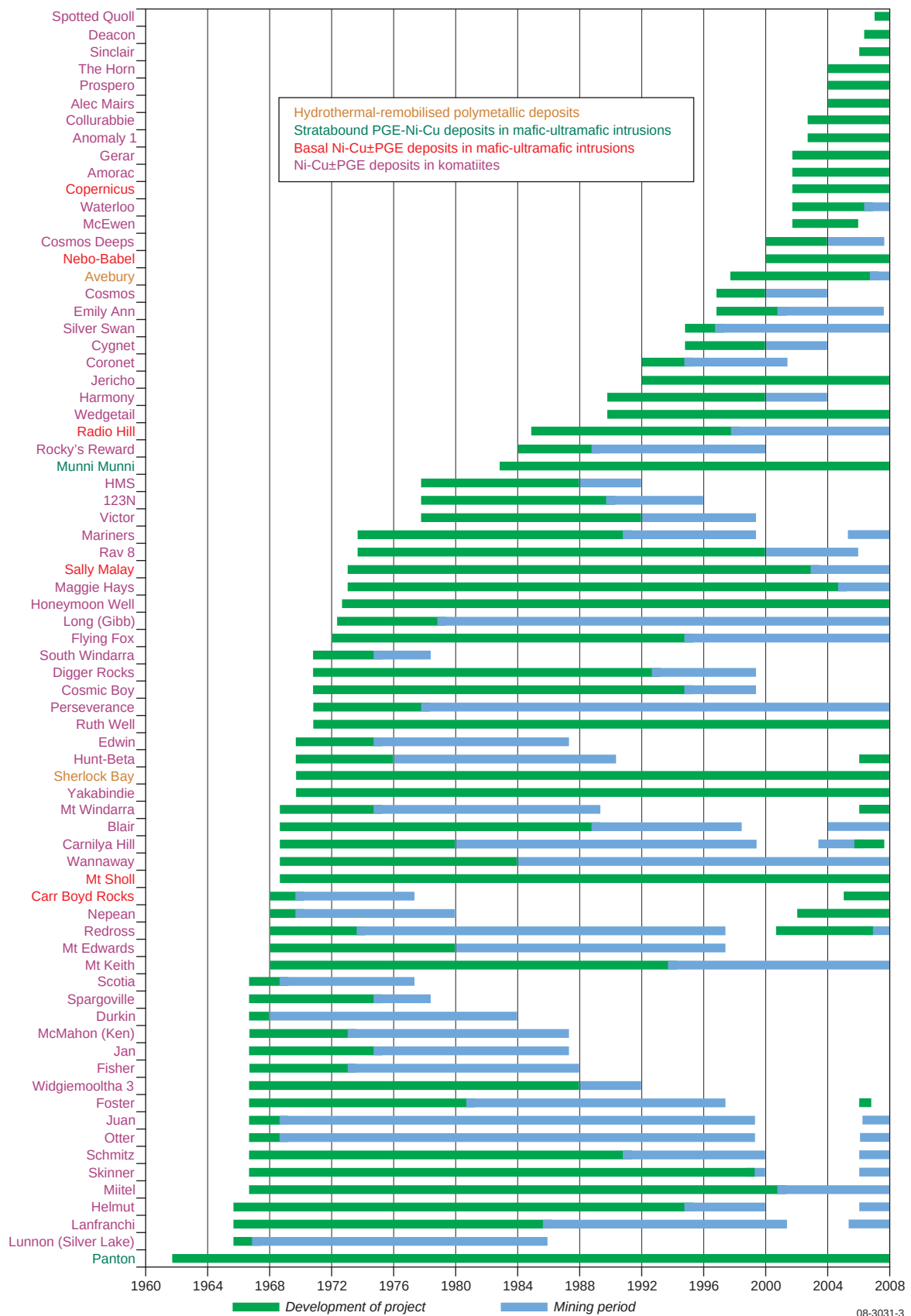
Worldwide, however, Proterozoic mafic-ultramafic rocks do host major nickel and PGE deposits (Hoatson et al., 2006). Some of the more important examples include: Monchegorsk, Russia (~2493 Ma); Penikat, Finland (~2440 Ma); Bushveld, South Africa (~2060 Ma); Pechenga, Russia (~1977 Ma); Thompson, Canada (~1880 Ma); Sudbury, Canada (~1850 Ma); Voisey's Bay, Canada (~1333 Ma); Kabanga, Tanzania (~1403 Ma); Duluth, United States of America (~1120 Ma); and Jinchuan, China (~827 Ma).

Figure 1 (on page 4): Evolution of the nickel sulphide industry in Australia from 1962 to 2008. The figure only includes those nickel (± PGE) deposits which have published total contained metal resources of nickel. The cumulative total contained metal resources trend indicates that more than 75 per cent of Australia's total resources of nickel metal from sulphide deposits were discovered during a narrow time period (1966 to 1973) early in the evolution of the industry. The annual average nickel prices (in current \$US/tonne) shown in the top graph are from the United States Geological Survey Mineral Commodity Summaries (nickel data compiled by P. Kuck, USGS) and the London Metal Exchange. Resource data for the Australian deposits in the lower three graphs are from Geoscience Australia's national database of mineral deposits and resources—OZMIN. Figure modified from Hoatson et al. (2006).

Figure 2 (on page 5): Histogram summarising the discovery and mining period(s) of Australia's nickel sulphide and platinum-group element deposits from 1962 to 2008. Data compiled from Marston (1984), Pratt (1996), Perring and Barnes (2002), Jaques et al. (2005), Hronsky and Schodde (2006), and various references cited in Hoatson et al. (2006).

¹ Total contained nickel metal resource is defined as total production plus remaining reserves and/or resources.





Intermittent efforts of intense exploration in Australia have so far failed to define a major economic resource of PGEs associated with Precambrian mafic-ultramafic rocks. The first significant discovery was in 1962 when government regional mapping programs identified PGE-bearing chromitites in the Palaeoproterozoic Panton mafic-ultramafic intrusion, East Kimberley, Western Australia (Dow and Gemuts, 1967, 1969). Intensive exploration programs have defined sub-economic quantities of PGEs in Precambrian layered mafic-ultramafic intrusions in Western Australia (e.g., Panton, Lamboo, Eastmans Bore, Munni Munni, Radio Hill, Windimurra, Weld Range, Mt Venn, Monarch), the intrusions of the Giles Complex in central Australia (Nebo-Babel, Haran, Alvey), and in the small alkaline Mordor intrusion in the Arunta Region. Domestic PGE production since the late 1960s has been restricted to minor quantities (~50 to 200 kg Pt and ~400 to 800 kg Pd annually) produced as by-products of the Archaean komatiitic-hosted nickel sulphide deposits in Western Australia.

The general buoyant nickel price in recent years (nickel metal price rose to an all-time record of US\$54 200 per tonne on 16th of May 2007) has been a response to strong demand, constrained supplies and low metal stockpiles, and robust worldwide economic growth. One driver of this growth has been China's increasing need for raw materials during its phase of urbanisation and industrialisation. Similar supply-demand pressures are affecting the prices of other metals, such as the PGEs. Platinum and rhodium prices have steadily increased since ~2002 to historical highs in recent times (Figure 3).

The recent increases in metal prices have initiated a marked increase in exploration in Australia for nickel and PGEs. The main focus has been Precambrian mafic and ultramafic rocks. More than 270 major and junior companies in Australia are currently exploring for nickel and the PGEs. Regions of interest include Archaean greenstone belts in the Yilgarn Craton (near Kambalda, Leonora, Leinster, and Forrestania), the northern margins of this craton, the western part of the Pilbara Craton, and the Proterozoic Kimberley, Musgrave, Albany-Fraser, Hamersley, and Capricorn provinces. Recent exploration successes include the discovery of: (1) increased resources at previously known deposits (many deposits around the Kambalda Dome, Flying Fox, Spotted Quoll, Lounge Lizard, Nepean, Lanfranchi, Radio Hill, Sally Malay); (2) delineation of deep and covered mineralised komatiite sequences (Cosmos Deeps, Prospero, Wedgetail, Flying Fox); (3) new discoveries of mineralisation in Precambrian mafic±ultramafic intrusions (Nebo-Babel, Haran, Mt Herculius, Alvey, Copernicus, Billy Ray, Mt Venn); and (4) new styles of mineralisation and new provinces (Avebury, Collurabbie, Sinclair, Beasley, Daltons, Hart Dolerite–Speewah Dome, Mt Cobalt–Black Snake).

Exploration targets have now broadened to include deposits at greater depths, under cover, and in remote regions previously considered to have low prospectivity, such as Neoproterozoic basins (e.g., Officer Basin, Western Australia) and younger Phanerozoic provinces (western Victoria, Tasmania). This change of direction for exploration has led to a greater diversity of nickel deposits and prospects being found (Hoatson et al., 2006). These include discoveries with the highest nickel grades in the world (5–9%: Cosmos, Cosmos Deeps, Prospero, Silver Swan, Flying Fox-T5, Spotted Quoll), multi-element ores (Ni, PGEs, Cu, Co, Au, Ag: Collurabbie, Camp Oven, Waterloo, The Horn, Bodkin, Leo Dam, Area 57, Mt Alexander, Currans Well, Camel Bore, Fly Bore, Daltons, Hart Dolerite–Speewah Dome), and other deposits with unusual remobilised mineralised settings (Avebury, Mt Cobalt–Black Snake, Sherlock Bay, Yarawindah Brook).

During the 2007 calendar year, the total expenditure for Ni-Co exploration (sulphide and laterite) in Australia was up nearly 70 per cent from the previous year to A\$252.2 million (Australian Bureau of Statistics, 2008). As with previous years, Western Australia (A\$230.6 million) dominates the exploration investment, with this state alone accounting for more than 90 per cent of the nation's Ni-Co exploration expenditure.

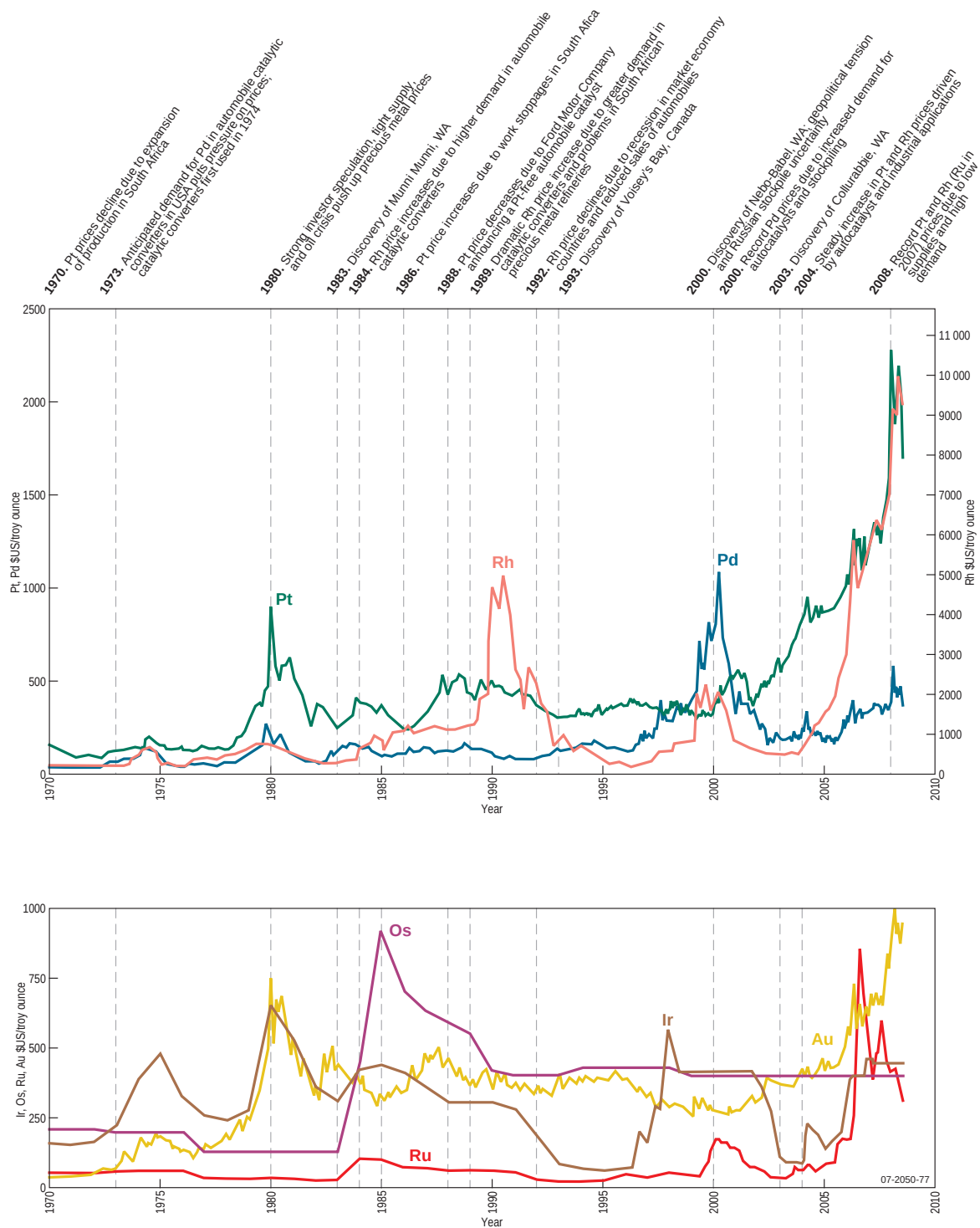


Figure 3: Variations of platinum-group element (Pt, Pd, Rh, Ru, Ir, Os) and gold (Au) prices and major global events impacting on metal prices from 1970 to 2008. Metal prices are from the London Metal Exchange.

Methods

SEQUENCE OF DEVELOPMENT

The Proterozoic era (2500 Ma to 545 Ma) was the focus of this study. The only exception is the Early Cambrian Kalkarindji Magmatic Event (~520 Ma: Glass and Phillips, 2006; Hanley and Wingate, 2000), which was included since it represents an important voluminous mafic magmatic episode that impacted on much of northern and central Australia (Bultitude, 1976). Its spatial distribution overlaps with older Proterozoic mafic-ultramafic Magmatic Events and it provides valuable insights into the geological evolution of Australia during the transitional period from the Neoproterozoic to the Early Cambrian.

The map series compilation progressed from Western Australia eastwards because:

1. Western Australia (A\$230.6 million: Australian Bureau of Statistics, 2008) dominates Ni-Co exploration expenditure in Australia—it accounts for more than 90 per cent of the nation's exploration investment;
2. Western Australia contains ~90 per cent of Australia's nickel resources in sulphide and laterite deposits; and
3. an abundance and variety of prospective mafic-ultramafic rocks of Proterozoic age occur in the western half of the continent. These rocks are particularly widespread in outcrop and under cover in Proterozoic orogenic belts, sedimentary basins, and Archaean cratons in Western Australia, South Australia, and the Northern Territory. Proterozoic mafic-ultramafic rocks represent less than a few percent of all rocks east of the Tasman Line (defined on page 9) of eastern Australia.

SOURCES OF GEOCHRONOLOGICAL DATA AND DIGITAL DATASETS

The geological and geochronological data which underpin this study were obtained from extensive searches of published and unpublished literature. Information was sourced from scientific journals and publications produced by the Bureau of Mineral Resources and its successors the Australian Geological Survey Organisation and Geoscience Australia; the Commonwealth Scientific Industrial Research Organisation; and the State and Northern Territory geological surveys. Publications from the geological surveys included first, second, and third Edition 1:100 000 and 1:250 000 geological maps and their respective explanatory notes, bulletins, reports, and records. Unpublished information was obtained from company exploration reports and university theses. Unpublished geochronological data were sourced from university theses and from OZCHRON—Geoscience Australia's national database of age determinations on Australian rock samples (<http://www.ga.gov.au/oracle/ozchron/index.jsp>). Mineral resource data are from both the Australian Mines Atlas—database of Australian minerals and energy deposits, mines, resources, and processing centres (<http://www.australianminesatlas.gov.au/>) and OZMIN—Geoscience Australia's national database of mineral deposits and resources.

The data from this compilation were integrated with the 'Proterozoic Synthesis of Australia' project of Geoscience Australia, summarised by Neumann and Fraser (2007) and Fraser et al. (2007). That study examined geological events of many kinds (sedimentary, magmatic, metamorphic, deformational, cooling, mineralising, etc) and all major rock types (igneous, metamorphic, sedimentary), together with candidate tectonic reconstructions for Proterozoic Australia.

There exists no single solid-geology map for all Australia. Consequently, the base maps used are the most current solid-geology coverages available from the State and Northern Territory geological surveys ([Appendix 1](#)). These maps vary in their mapping approaches, coverage, scale, and detail. For example, Western Australia, South Australia, New South Wales, Victoria, and Tasmania have solid-geology coverages, but variations in the mapping approaches are evident, especially where maps join at State borders. In Queensland and the Northern Territory a variety of local and regional solid-geology maps at a range of scales was used. The representation of mafic and ultramafic magmatic units across the national compilation varies significantly because of the limitations and different scales of these disparate sources.

The advantage of solid-geology maps, over outcrop-based equivalents, is that they can provide an insight into the total areal extent of rock units (e.g., extensions under the cover of younger rocks, or regolith), and hence the volume of the magmatic systems, which is an important criterion when assessing mineral potential. The actual total volumes of magmatic systems cannot be determined in most cases due to the inherent uncertainties in estimating thicknesses and amounts of erosion.

Other thematic mapping sources were integrated to achieve a more complete representation of Proterozoic mafic-ultramafic rocks. These include the province-wide coverage of undefined (age unknown) mafic dykes and sills in Western Australia (Myers and Hocking, 1998), the inferred distribution of gabbroic intrusions under cover in the Officer Basin of Western Australia (D'Ercole and Lockwood, 2004), and coverage of mafic dyke swarms on 1:250 000 geological sheets from the Northern Territory and Queensland. Where State or regional scale maps did not include important individual mafic-ultramafic units they were incorporated from other sources (e.g., Milliwindi Dolerite Dyke, Kimberley, Western Australia: Hanley and Wingate, 2000; Loongana Intrusion, Eucla Basin, Western Australia: Bunting, 2007).

CRUSTAL ELEMENTS

Over the period of the study, three different approaches to geological province boundaries were trialled. The initial map of Western Australia (Part 1) used the 1:2 500 000 Tectonic Units of Western Australia (June 2001, Geological Survey of Western Australia). The second map of the Northern Territory and South Australia (Part 2) used the Georegions ArcInfo coverage from Geoscience Australia.

The final National Map has used the Australian Crustal Elements 1:5 000 000 scale map of Shaw et al. (1995), with local modifications. The Australian Crustal Elements are based primarily on composite geophysical (magnetic and gravity) domains. The advantages of this approach to crustal elements are a consistent coverage for the entire continent, and the attempt to show the spatial distribution of provinces in the third (vertical) dimension: i.e., under younger cover. This geophysical domain map emphasises links to tectonic provinces, but is not a tectonic map as such. Shaw et al. (1996) discuss in detail the principles and applications of the Australian Crustal Elements map.

The approximate easternmost limit of the Precambrian crustal elements (and of the five LIPs mapped on Sheet 2) is defined by the Tasman Line (Shaw et al., 1996; Direen and Crawford, 2003; Glen, 2005). The Tasman Line, a controversial concept in the geology and tectonics of eastern Australia, is a zig-zag line that crosses the Australian continent from north to south. It is interpreted by some researchers to be a regional orogenic suture that demarcates the western extent of the break-up of Rodinia, followed by the growth of orogenic belts along the eastern margin of Gondwana. Other investigators have interpreted the Tasman Line to be the westernmost limit of deformation associated with the eastern Australian Palaeozoic fold belts (e.g., Tasman Foldbelt System). The region east of the Tasman Line, extending across to the eastern coast of the continent, has been referred to as the Tasmanides of eastern Australia. Detailed reviews of the Tasman Line and Tasmanides can be found in Direen and Crawford (2003) and Glen (2005), respectively.

DEFINITION OF MAGMATIC EVENTS

An important task in this study was the compilation and evaluation of all available geochronological data that can be used to constrain the timing and duration of Proterozoic Magmatic Events. 'Events' in this sense are defined as "probable geological incidents of significance that are suggested by geological, isotopic, or other evidence" (modified after Neuendorf et al., 2005).

The recognition of Magmatic Events in this study has been made possible by the vastly increased coverage of geochronology in Precambrian Australia over the last twenty years. Published ages were assessed for their geochronological methods, the interpretation confidence, and consistency with other temporal-related evidence, e.g., field relationships of associated rock units.

More than 90 per cent of the ages compiled are from U-Pb zircon and U-Pb baddeleyite systems (both by ion microprobe and thermal ionisation techniques). Sm-Nd isotopic studies (mineral and whole-rock isochrons) make up most of the balance. In a few cases (mainly for mafic volcanic units in Western Australia), some U-Pb (monazite), Pb-Pb, Rb-Sr, K-Ar, and Ar-Ar (total cooling, fusion, plateau, feldspar) ages were included. The criterion of choice in each case was the best available constraint on the magmatic age. Where there is no published age for a mafic-ultramafic unit shown on the Map, or if its age is doubtful, or inconsistent with its field relationships, the unit is assigned as Undefined Event. In some examples, ages of associated intermediate to felsic rocks were used, where the field relationships between the dated felsic rocks and the spatially associated mafic-ultramafic rocks were unequivocal, e.g., the felsic rocks were magmatically interlayered with the mafic-ultramafic rocks.

Informal Magmatic Event names are derived from the published names of reliably dated mafic±ultramafic rock units (e.g., Gairdner, Oenpelli, Hart). In cases of un-named units, a prominent associated name, e.g., for a deposit hosted by the mafic±ultramafic rock unit (Bow River nickel deposit), or the formation or group that is intruded (Lane Creek) were used. The name of the most voluminous or prominent magmatic system was used for the naming of each Magmatic Event. For example, the ~1655 Ma Lane Creek Magmatic Event 14 was named after the dolerites which intrude the Lane Creek Formation in the Georgetown province of the North Australian Crustal Element, rather than the relatively smaller coeval basalts (Tarcoola Formation) in the Central Gawler province of the South Australian Crustal Element.

Two codes in parenthesis (m) or (mu) attached to each Magmatic Event name indicate the composition of the igneous rocks constituting that event. The (m) code signifies that only mafic rocks are present, whereas (mu) indicates that both mafic and ultramafic rocks are present even if the ultramafic component may constitute only a few percent of the total mafic-ultramafic rock assemblage. An example of this is the ME 8 (mu) Edmirringee Magmatic Event. In central Australia this ~1830 Ma event comprises widespread (but volumetrically subordinate) basaltic rocks within the Tanami and Aileron provinces, and in the Halls Creek province the dominantly mafic units include very minor (<5%) ultramafic rock components in the ~1830 Ma McIntosh group of intrusions.

During the course of the study the National Magmatic Event scheme evolved from local State/Northern Territory event schemes as summarised in [Appendices 3, 4, and 5](#). The type examples of the thirty Proterozoic mafic-ultramafic Magmatic Events are listed in [Appendix 6](#).

SPATIAL REPRESENTATION OF MAGMATIC EVENTS

One of the primary functions of the Magmatic Events feature map on Sheet (1) is to highlight clearly the spatial and temporal correlations of mafic±ultramafic magmatic systems. The thirty Magmatic Events which have been defined are assigned a colour code in the colour spectrum from purple through blue, green, yellow, and red to mauve as a simple visual cue of relative age from old to young.

Available solid-geology maps do not always directly represent the presence of mafic-ultramafic rocks. Large igneous rock units are usually denoted with a discrete polygon. However, small units of mafic-ultramafic rocks are often subsumed as a minor component of a regional rock package. It is necessary to include both types of unit in this compilation to properly represent the geographic extent, correlation and likely volume of each Magmatic Event. Accordingly a two-fold system of colour legend has been deployed:

1. Bold colours are used on the map where the mafic-ultramafic rocks constitute the dominant component of a map unit.
2. Pale colours of the same hue denote the presence of a minor component of coeval mafic-ultramafic rocks within a regional package of rocks: this is applied to map units of associated sedimentary, metamorphic, and felsic igneous rocks where they include minor mafic-ultramafic units.

Examples of this dual colour legend occur in all areas of the map. The large area of Magmatic Event 8 in central Australia, for example (pale green colour, map comment I), does not denote a large mafic magmatic unit: it represents a volumetrically small but regionally widespread component of metabasalt and metadolerite in dominantly sedimentary units of the Aileron and Tanami provinces. Small colour-coded labels (e.g., ME 8) are placed within, and adjacent to, rock units on the map to facilitate the identification of Magmatic Events across the continent.

A problem encountered in construction of this Map has been the variable treatment of mafic dyke swarms in regional solid-geology maps. Individual dykes are small bodies and map compilers frequently omit them from regional-scale maps. This is unfortunate, because the collective importance of a swarm of dykes can be significant. Particular effort has therefore been made to source map representation of mafic dykes wherever they are known, sometimes by recourse to detailed 1:100 000 and 1:250 000 solid-geology and outcrop maps.

The geochronological and geological attribution data for the mapped mafic-ultramafic units were compiled for the ArcGIS geodatabase using Microsoft Excel spreadsheets, and arranged by State/Northern Territory, and geological province. The spreadsheets ([Appendix 10](#)) are contained in a CD in the pocket of this Record. The attribution data for each State and the Northern Territory are presented on two spreadsheets titled ‘Age’—those parameters largely relating to the determined age of the unit—and ‘Setting’—those parameters largely relating to the geological description and tectonic setting of the unit. The first four columns with headings CODE, STRATNO, FORMATION_GROUP, and PROVINCE are common to both spreadsheets. The CODE attribute is a map code that links each mafic-ultramafic unit entry in the spreadsheet to the polygon/line data on the relevant solid-geology base map, and STRATNO is the stratigraphic formation number for the mafic-ultramafic unit derived from the Australian Stratigraphic Units Database (ASUD: national database that records information on all Australian stratigraphic units and their usage in literature) (<http://www.ga.gov.au/oracle/stratnames/index.jsp>). FORMATION_GROUP pertains to the official Stratigraphic Formation, Group, Supergroup, and Supersuite name from ASUD, and PROVINCE is the tectonic-geological unit as defined by the base maps used for each State or the Northern Territory. All the other criteria used to characterise the mafic-ultramafic units are summarised in [Appendix 2](#), and the spreadsheets containing the attribute data are in [Appendix 10](#).

GIS TECHNIQUES

The National Map was produced using ArcGIS version 9.2. The feature files showing the distribution of mafic and ultramafic rocks and the attributes of Magmatic Events are stored in an ArcGIS geodatabase. The feature files are grouped by event to obtain event-maps showing the distribution of mafic and ultramafic rocks of that event. Since the geological datasets from the State and Northern Territory geological surveys do not follow standardised attributes for rocks, it was not possible to create a seamless nation-wide dataset of mafic and ultramafic rocks. The inclusion of ASUD, however, will allow the integration of the mafic and ultramafic rocks dataset with other national-scale datasets in GA, such as OZCHEM (national database of whole-rock and stream-sediment geochemistry: <http://www.ga.gov.au/gda/index.jsp>). The same lack of standardisation across regional and State/Northern Territory map sources and datasets prevents publication as a unified GIS or geodatabase, so the resulting multi-source map is made available as pdf and jpeg images.

Maps and Reports

Bibliographic and metadata details of the maps derived from the 'Australian Proterozoic Mafic-Ultramafic Magmatic Events' map series can be found using GeoCat (GA's catalogue database of products: <http://www.ga.gov.au/oracle/agsocat/textonly.jsp>). Outcomes from the study are available in these main forms:

1. Map Sheet 1: 1:5 000 000 map of Australian Proterozoic Mafic-Ultramafic Magmatic Events, published July 2008, GeoCat 66114;
2. Map Sheet 2: Time-Space-Event Chart; 1:10 000 000 map of Large Igneous Provinces; 1:10 000 000 map of mineral deposits and occurrences, published July 2008, GeoCat 66114;
3. Geoscience Australia Record 2008/15 (this document) documents the information base of the maps and Time-Space-Event Chart, GeoCat 66624;
4. Appendix 9 of this Record provides individual time-slice maps of Australia for each of the thirty Proterozoic Magmatic Events, GeoCat 66624; and
5. scientific findings are to be published in two compendium journal manuscripts that will summarise regional event correlations and metallogeny implications.

The study was a staged process over three years and earlier interim maps were published as follows:

6. 1:3 500 000-scale map 'A Synthesis of Australian Proterozoic Mafic-Ultramafic Magmatic Events. Part 1: Western Australia' published October 2006, GeoCat 64813; and
7. 1:4 000 000-scale map 'A Synthesis of Australian Proterozoic Mafic-Ultramafic Magmatic Events. Part 2: Northern Territory and South Australia' published July 2007, GeoCat 65257.

The stages in the production of the maps are summarised in Figure 4. It should be noted that ideas and information evolved during the course of the study. Hence the Magmatic Event time series used in the interim maps is only a subset of the comprehensive thirty-event series compiled for the final National Map. The Shaw et al. (1995) Australian Crustal Elements dataset was used as the framework for the final National Map in preference to the Tectonic and Georegions frameworks that were used for the interim Western Australia, and the Northern Territory-South Australia maps.

Both the interim maps and the final National Map have similar formats in that they comprise a main feature map showing the spatial distribution of the major Proterozoic magmatic mafic-ultramafic events identified, enlarged inset maps of certain regions which provide the polygon and line data in more detail, and minor associated maps showing the distributions of LIPs, and mineral deposits and occurrences. Time-Space-Event charts summarise the geological ages that underpin the rock correlations on the main map, and relate mineralised events in Australia to major Ni-Cu $\pm$ PGE deposits overseas. Magmatic Events depicted on these charts are linked by colour to those event elements shown on the main maps.

The two large-format National Map sheets can be downloaded free on-line in pdf and jpeg formats from Geoscience Australia's map website: <http://www.ga.gov.au/map/index.jsp#mum> under the heading Mineral Maps of Australia-Mafic-Ultramafic Magmatic Events. The earlier maps of Western Australia, and of Northern Territory-South Australia, are also available at the same web location.

The dimensions of the National Map Sheets 1 and 2 are approximately 86 cm by 120 cm, excluding margins. The earlier State/Northern Territory maps are: Western Australia, 82 by 125 cm; Northern Territory-South Australia, 82 by 114 cm. The pdf files can be viewed and explored using the zoom function of pdf reader programs. Both the pdf and jpg files can be printed using large-format colour printers. To avoid truncation, or the compression of scales, it is important to select paper sizes and printing protocols appropriate to your plotter when printing large-format images.

In addition to this Record, short promotional articles announcing the release of the first two maps appeared in:

AUSGEO News issue 84: December 2006

(<http://www.ga.gov.au/ausgeonews/ausgeonews200612/productnews.jsp#product2>), and

AUSGEO News issue 87: September 2007

(<http://www.ga.gov.au/ausgeonews/ausgeonews200709/productnews.jsp#product1>)

The new National map and this Record were described in AUSGEO News issue 91: September 2008

(<http://www.ga.gov.au/ausgeonews/ausgeonews200809/productnews.jsp#product2>).

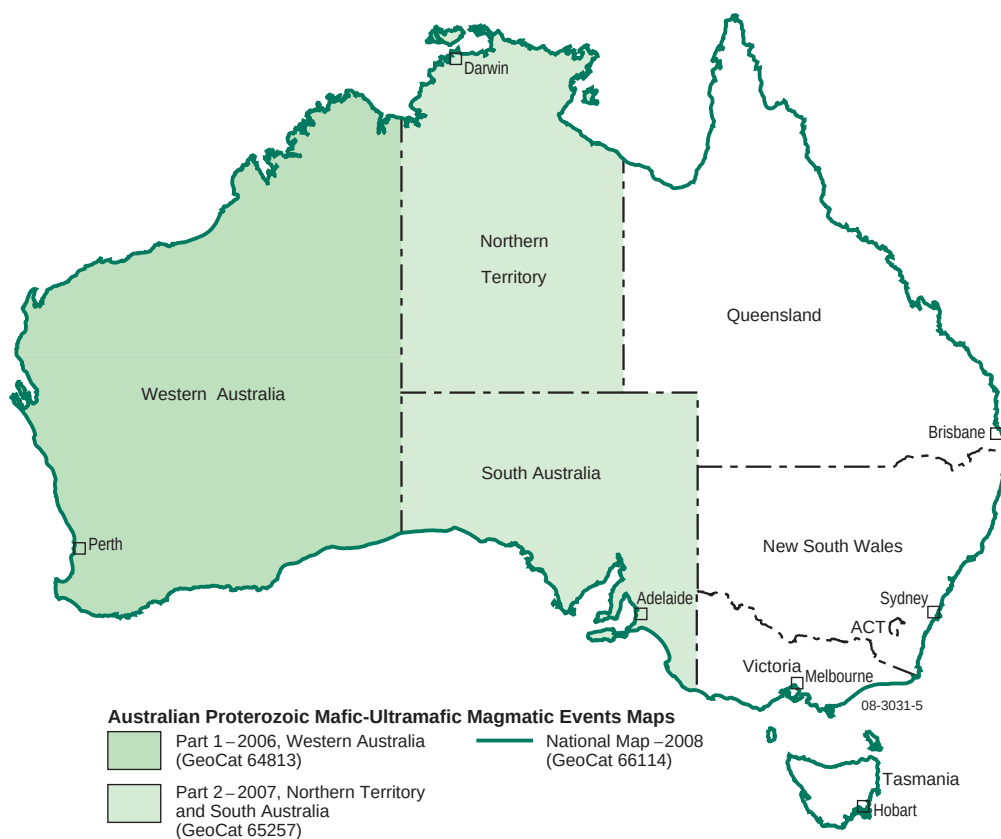


Figure 4: Production stages for the Australian Proterozoic Mafic-Ultramafic Magmatic Event map series.

Components of the Map

PROTEROZOIC MAFIC-ULTRAMAFIC MAGMATIC EVENTS MAP

Sheet 1 is devoted to a 1:5 000 000-scale coloured map showing the distribution of Proterozoic mafic-ultramafic igneous rocks in Australia, colour coded by their age. Magmatic units have been assigned to thirty Magmatic Events (ME) ranging in age from the Early Palaeoproterozoic ~2455 Ma (ME 1) to the Early Cambrian ~520 Ma (ME 30). This latter event was included, although its age lies slightly outside the Proterozoic, because it represents one of the largest known LIPs and impacted on much of northern and central Australia.

The Magmatic Events are shown superimposed on the framework of the Major Crustal Elements of the Australian continent, and their constituent provinces (modified after Shaw et al., 1995). The five Major Crustal Elements comprise West Australian, South Australian, North Australian, Central Australia, and Tasman. The framework delineates upper-crustal elements based primarily on composite geophysical domains, each of which shows a distinctive pattern of magnetic and gravity anomalies. The elements are related to basement features, rather than the covering sedimentary basins which tend to mask or distort the geophysical characteristics. Boundaries between these regional elements are interpreted to define crustal-scale changes in composition or structural pattern, or both (Shaw et al., 1996).

Some of the Shaw et al. (1995) province boundaries have been modified locally for the purpose of the current map, to take account of new geophysical and other datasets obtained since 1995. Modifications are:

- the locus of the Tasman Line in North Queensland is modified to reflect the recommendations of Nishiya et al. (2003);
- the Warumpi province boundary in central Australia is drawn to accommodate the description of Scrimgeour et al. (2005);
- the boundary of the South Australian Element is drawn to exclude the Albany-Fraser province and include the Peake and Denison Inliers; and
- subdivision of the South Australian Element into Southwest Gawler, Central Gawler, East Gawler, North Gawler and Coompana provinces follows recommendations of Skirrow (pers. comm., 2008, GA; & in press) based on a detailed recent study of the Gawler Craton by Geoscience Australia and the Department of Primary Industries and Resources, South Australia.

Three inset maps in the surrounds to the main Magmatic Events map show enlarged versions of parts of the Halls Creek–Kimberley (Inset 1), Aileron–Irindina–Warumpi–Amadeus (Inset 2), and the Musgrave (Inset 3) provinces. These insets assist with the clarity of event attribution of small polygons and dykes in complex, multi-event areas.

Along the left margin, below the legend of the main map, is a list of ‘Isolated occurrences of dated Magmatic Events’, which are examples of dated mafic-ultramafic rocks that have no defined spatial extent (e.g., from drillhole or outcrop) in contrast to the polygon information portrayed elsewhere on the map. These are linked to letters A to S in circles on the map, which are colour coded to the Magmatic Event. These occurrences are important since they may represent the named example of the dated Magmatic Event, or they may be the only known example of a particular Magmatic Event in a given province; in some cases, such as the Saxby and Elizabeth Hills Magmatic Events, there is only one occurrence known in the entire continent.

Along the right margin of the map is a list of ‘General map comments’ containing items of information or clarification for regional areas on the main map which are indicated by the letters A to Z in squares. Both these and the ‘Isolated occurrences of dated Magmatic Events’ comments in circles A to S are arranged alphabetically on the map from north to south and west to east across the continent.

TIME–SPACE–EVENT CHART

The presence and correlation of the thirty identified Proterozoic mafic-ultramafic Magmatic Events in twenty-eight provinces are represented in the Time–Space–Event Chart on Sheet 2 (see also [Appendix 7](#) in this Record). Event names and ages, symbol colours, and provinces (with informal names) are those of the main 1:5 000 000 Map on Sheet 1. The geological provinces are grouped into Major Crustal Elements adapted from Shaw et al. (1995).

The Time–Space–Event Chart is a particularly useful way of depicting the geological timing, duration, and spatial extent of geological events. It highlights the lateral extent of Magmatic Events, and important correlations across provinces. For example, it can be seen that some events are isolated to one province, whereas others have widespread presence across many provinces. In addition, the chart shows that some provinces have experienced multiple Magmatic Events (e.g., seven Magmatic Events affected the Central Gawler province from 1850 Ma to 1590 Ma). It also highlights the frequency and groupings of Magmatic Events, such as the prominent grouping of Magmatic Events in the Late Palaeoproterozoic (~1870 Ma to ~1590 Ma) which represents one of the most important geological periods of mafic±ultramafic magmatism in the Proterozoic evolution of Australia.

It is emphasised that time-equivalent magmatism in different Crustal Elements and provinces shown on the chart does not necessarily imply cogenetic magmatism.

Horizontal coloured bands in the chart indicate the presence of known Ni-PGE-Cr-V-Ti-(± Au-Cu-Ag) mineralisation within certain Magmatic Events, either in Australia or overseas. Six of the Australian Magmatic Events (ME 1, 5, 6, 7, 19, and 26) are time-equivalent with important world Ni-Cu ± PGE deposits elsewhere (e.g., ~2440 Ma Penikat in Finland; ~1918 Ma Raglan, ~1880 Ma Thompson, and ~1850 Ma Sudbury, all in Canada; ~1403 Ma Kabanga in Tanzania; and ~827 Ma Jinchuan in China).

DISTRIBUTION OF MINERAL DEPOSITS AND OCCURRENCES

The distributions of nickel, chromium, platinum-group elements, vanadium, and titanium deposits and occurrences are shown on a 1:10 000 000-scale map on Sheet 2. Deposits are those occurrences containing a defined resource. The deposits and occurrences are superimposed on a base map of Precambrian mafic-ultramafic rock units that have been divided into Archaean (brown) and Proterozoic (green) rock components. The commodities listed above are typically associated with mafic and ultramafic igneous rocks and in some cases they attain economic quantities in these rocks. The economically most important commodity, nickel, has been divided on the map into sulphide and laterite deposits. Note that the deposits and occurrences shown on this map include examples from the Archaean, Proterozoic, and Phanerozoic. Data are from Geoscience Australia's OZMIN and MINLOC resource databases.

PROTEROZOIC LARGE IGNEOUS PROVINCES

Large Igneous Provinces (LIPs) are formed by the rapid and voluminous emplacement of mafic, ultramafic, and/or felsic magmas in intraplate settings (Ernst and Buchan, 2001). These transient Magmatic Events that punctuate Earth's history are believed to be related to large-scale processes in the Earth's upper and/or lower mantle region through processes that are not linked with normal plate tectonic magmatism (Coffin and Eldholm, 2001). Most LIPs are thought to be associated with mantle upwellings, e.g., mantle plumes, and they are preserved as coeval continental flood basalts, layered mafic-ultramafic intrusions, mafic sills, and large mafic dyke swarms. LIPs evolve over extremely short geological time periods of a few million years or less.

Five major LIPs cover extensive regions of the continent and these are shown on a 1:10 000 000-scale map on Sheet 2. These LIPs are expressed only by time-equivalence of intrusion and extrusion; cogenetic magmatism across crustal elements and provinces is not necessarily implied. Colours and unit polygons are linked to the 1:5 000 000 Map on Sheet 1, and to the Time–Space–Event Chart. The

spatial distributions of the LIPs incorporate the findings of this study and are modified from the published sources indicated in parentheses below.

In age order, the five LIPs shown are:

Kalkarindji LIP: ME 30 ~520 Ma (modified after Glass and Phillips, 2006): extensive preservation of basaltic lavas across the North Australian and Central Australia Crustal Elements; intrusions in the Kimberley and Irindina provinces.

Gairdner LIP: ME 26 ~825 Ma (modified after Zhao et al., 1994): northwest-trending Gairdner Dyke Swarm traversing the South Australian Crustal Element and the Musgrave and Paterson provinces of the Central Australia Crustal Element; basaltic lavas low in the sedimentary sequences of the Amadeus and Adelaide provinces; and possible correlatives in the Paterson province.

Warakurna LIP: ME 24 ~1070 Ma (modified after Wingate et al., 2004): time-equivalent magmatism in an east-trending belt that includes the Musgrave province and crosses the West Australian Crustal Element; dolerite dykes in the southern margin of the North Australian Crustal Element.

Marnda Moorn LIP: ME 21 ~1210 Ma (modified after Wingate and Pidgeon, 2005): extensive coeval dolerite dyke swarms and sills, with variable emplacement orientations, in the Yilgarn and Pinjarra provinces.

Hart LIP: ME 10 ~1780 Ma (modified after Tyler et al., 2006): dolerite and basalt within the Kimberley province; possible extension to the south and southeast encompasses time-equivalent magmatism in eight other provinces across the West, North, and South Australian Crustal Elements, and in Central Australia.

A very large southeasterly extension of the Hart LIP, from its type occurrence in the Kimberley province in north Western Australia, to encompass all the Major Crustal Elements west of the Tasman Line, is suggested by the dating compilation in this study. Basaltic rocks coeval with the ~1790 Ma Hart Dolerite and Carson Volcanics are identified in parts of the Mount Isa, Nicholson, McArthur, Aileron, East and North Gawler, Paterson, Capricorn, and Pilbara provinces.

Other Proterozoic Magmatic Events may potentially meet the definition of LIPs, but their attribution will require further work. An example is the ~1720 Ma doleritic dykes and sills of the Oenpelli Event. Mafic magmatism of this age extends from its type occurrences in the Pine Creek province southeastwards into the McArthur province; there is also an isolated drill-hole occurrence of a 1727 ± 8 Ma gabbro (Isolated occurrence Point P on Sheet 1) in the Central Gawler province of the South Australian Element. Further detailed petrological and petrochemical studies are necessary to test if these isolated mafic rock occurrences truly represent a LIP as strictly defined by Ernst and Buchan (2001).

Map users are cautioned that polygons of Subordinate colour for a given Magmatic Event may represent very small components of mafic rocks: for example, the geographically widespread presence of Edmirringee Magmatic Event ME 8 in central Australia represents a very subordinate quantity of metabasalt and metadolerite in the dominantly sedimentary rock packages of that region.

The eastern limit of the known LIPs is shown abutting the Tasman Line (Shaw et al., 1995, 1996; Direen and Crawford, 2003; Glen, 2005). The locus, meaning, and even the existence of this zig-zag line that crosses the Australian continent from north to south is controversial (c.f., Direen and Crawford, 2003). The tectonic significance of the Tasman Line is discussed on page 9. The Tasman Line in this study is modified after Shaw et al. (1995). It is used as a simplified notional reference for the easternmost limit of the Precambrian components of the continent. However, the youngest Proterozoic mafic Magmatic Event (ME 29, ~575 Ma) occurs east of the Tasman Line; and the Early Cambrian

Kalkarindji LIP (ME 30, ~520 Ma) occurs wholly on and within the earlier Proterozoic basement west of the line.

References that underpin all the data used for the definition of the LIPS are listed on pages 21 to 26 and in [Appendix 8](#). A visual summary of the spatial extent of the LIPS and the other Proterozoic Magmatic Events defined in this study is shown in the individual time-slice event maps of [Appendix 9](#).

Applications and Conclusions

The two sheets delineating ‘Australian Proterozoic Mafic-Ultramafic Magmatic Events’ classify and map the Proterozoic mafic-ultramafic igneous rock units preserved in components of what is now the Australian continent. Rather than focus only on the large magmatic systems, this study attempts to record and present every known mafic-ultramafic igneous rock unit in the geological period from ~2455 Ma to ~520 Ma, so that the well-known large systems can be seen in the context of the many smaller and local occurrences.

The National Map has been made possible by the relative abundance of robust geochronological data produced in recent years, and by advances in the coverage of solid-geology mapping over much of Australia. Both of these fundamental datasets are capable of much improvement, and current limitations, in both the map and the time–space–event understanding, must await resolution with new data and research.

Mafic-ultramafic magmatism in Australia has been resolved into thirty Magmatic Events from the Palaeoproterozoic to the Early Cambrian. Each Magmatic Event is defined as a short period of less than 20 million years, in keeping with the resolution of current geochronology. The reader is directed to the time-slice maps of [Appendix 9](#), and to the Time–Space–Event Chart on Sheet 2, for detailed information about the Magmatic Event series, correlations of events across provinces, and their geographic extent.

A number of important observations emerge from the portrayal of Magmatic Events in [Appendix 9](#) and the Time–Space–Event Chart. The Proterozoic record includes protracted periods of mafic-dominated tholeiitic magmatism in the form of flood basalts, mafic dyke swarms and sills, and mafic±ultramafic intrusions. It also includes long periods with no apparent record of mafic-ultramafic magmatism. Approximately one-third of all the Magmatic Events took place during one Palaeoproterozoic period of time from ~1870 Ma (ME 6) to ~1590 Ma (ME 16). Many Magmatic Events, which were thought to be local to certain provinces, can now be correlated across the continent, thereby creating the potential for locating undiscovered large-volume magmatic systems. The compilation presents the correlation across provinces of magmatic systems which are known to be mineralised in Australia, or in other continents. Five major LIPs, formed by the rapid and voluminous emplacement of mafic-dominated magmas in intraplate settings, have left a record of intrusions and lavas across extensive regions of the continent; and some of the LIPs may be even more extensive than previously thought (e.g., ~1790 Ma Hart LIP: ME 10). The event record of Proterozoic mafic-ultramafic magmatism is comprehensive, including both minor and major occurrences, so it serves as a reference for the correlation of other geodynamic systems and for the evolution observed in other continents.

The map of Magmatic Events on Sheet 1, and the Time–Space–Event Chart on Sheet 2, are both shown on a base of Australian Crustal Elements modified after Shaw et al. (1995). These provinces and their groupings into Major Elements are primarily geophysical entities (gravity and magnetic), and the reader is cautioned that their delineation and tectonic meaning are not always clear. It is probable that some provinces were not in their current configuration, relative to each other, at the time of emplacement of

many of the mapped Magmatic Events. Some of the provinces, and their assembly into Major Elements, may not yet have formed when some of the earlier Magmatic Events occurred. The newly-defined evolution of Proterozoic mafic-ultramafic Magmatic Events is, itself, a new constraint on the development of the Australian continent into its current form.

The solid-geology presentation suggests significant exploration opportunities, especially in greenfields-type environments, by extending magmatic systems that may be mineralised into regions masked by shallow cover or younger basinal sequences. Solid-geology datasets also provide an estimate of the total areal extent of each mafic-ultramafic magmatic system, which is an important consideration in assessing magmatic-associated mineralising systems. Importantly, matching to past exploration can help to define if a particular magmatic system has been adequately tested during exploration. The integration with geophysically-defined Major Crustal Elements and provinces permits the mafic-ultramafic igneous rock units of each event to be evaluated in the context of the major continental-scale structures and crustal processes that may be important in controlling the distribution of mineral deposits.

The National Map and its derivative charts provide a fundamental framework for the exploration of orthomagmatic and hydrothermal mineral deposits, and for assessing their generation in geodynamic processes that range in scale from the local to the continent-wide. It is notable that the 1:10 000 000 map of Australian Mineral Deposits and Occurrences (on Sheet 2) shows an apparent deficit of discovered mineral deposits in Proterozoic rocks, relative to Archaean and Phanerozoic examples; an intention of this Map is the provision of information that may lead to redressing this discovery imbalance. Users are encouraged to overlay and integrate their own datasets, and to evaluate:

- the spatial distribution of Proterozoic mafic and ultramafic rocks, their geological settings, the frequency of emplacement and potential coeval relationships;
- the secular variation of mafic and ultramafic magmatism, such as mafic-dominated systems *versus* ultramafic-dominated systems;
- the magnitude of each magmatic system (including LIPs) which has implications for structural frameworks, tectonic settings, and metallogenesis;
- correlatives of magmatic units that are mineralised elsewhere in the Australian continent, and in other continents;
- relationships with favourable reactive (e.g., carbonaceous, sulphur-bearing) country rocks that may potentially induce contamination and sulphur saturation of mafic-ultramafic magmatic systems during emplacement; and
- the spatial distribution of extrusive *versus* intrusive magmatic components within each Magmatic Event, as an indication of erosional levels and potential vectors to favourable mineralised environments, such as feeder conduits and basal contacts of intrusive bodies.

Datasets that should be considered for integration include geochemical and isotopic data for specific Magmatic Events of interest: these can now be placed within a systematic context of correlation in time and space, and so used to discriminate coeval systems and their potential for mineralisation. The context of other metamorphic and igneous rocks, including alkaline igneous rocks (kimberlite, lamprophyre, etc) can be used to evaluate mantle processes and the wider geodynamic systems of which the mafic-ultramafic magmatism is a part. Integration with the increasing coverage and sophistication of geophysical surveys, including continental seismic traverses, can improve knowledge of the fundamental crustal architecture within which the magmatic systems are emplaced, and enhance the capacity to detect and evaluate igneous rock units under cover.

Finally, we note that three of the important framework components (Australian Crustal Elements map, solid-geology map, geochronology of mafic-ultramafic rocks) of the new National Map and its derivative Charts, are at an early stage of development:

1. the Australian Crustal Elements map of Shaw et al. (1995) was an initial attempt to integrate the then-new national coverages of geophysical data: an updated assessment to incorporate new

geophysical and geological knowledge would improve basic understandings on which this, and many other, studies depend;

2. the available solid-geology mapping of Australia varies from region to region and is still developing towards a seamless national coverage that accurately portrays the spatial distribution of mafic-ultramafic rocks both at the surface and under cover. It is particularly important for such maps to progress towards depicting apparently minor, but in fact important, units such as mafic dykes and sills; and
3. perhaps the most important advance for the future will be the application, in quantity, of modern geochronology techniques to mafic-ultramafic rocks, a neglected target for geochronology in comparison with felsic igneous rocks, metamorphic terranes, and sedimentary basins. The way forward has been shown in selected Australian provinces by Page and Hoatson (2000), Wingate et al. (2000, 2002, 2004), Hoatson and Sun (2002), Claoué-Long and Hoatson (2005), Fanning (1997), and Fanning et al. (2007). These studies successfully dated mafic±ultramafic magmatic systems (in particular dykes, sills, and intrusions) of Proterozoic and Archaean age. The process of successfully obtaining U-bearing zircon and baddeleyite from fractionated mafic (and even ultramafic) igneous rocks, using an integrated approach of field and geochemical criteria to guide sampling, opens the possibility of routinely dating mafic-ultramafic magmatic systems. Such sampling strategies are described in detail by Claoué-Long and Hoatson (2005). The National Map highlights abundant mafic and ultramafic rock units whose age and event affiliations are undefined. The dating of these rocks can reveal new Magmatic Events or increase the spatial extent of Magmatic Events previously defined.

Future attempts to add detail to the current Map and event chronology for Australian Proterozoic mafic-ultramafic Magmatic Events will require advances in all three of these fields. The benefit will be better-understood pointers towards important magmatic mineral deposits, and better understanding of the role of the mantle and mafic-ultramafic magmatism in the development of the Australian continent.

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Appendix 1. Digital Geological and Geophysical Datasets and Publications Used in this Study

Solid-geology coverage of Western Australia, South Australia, Victoria, New South Wales, and Tasmania is available as State Maps from the relevant State geological surveys. Coverage of Queensland and the Northern Territory was assembled from a variety of regional solid- and surface-geology sources at scales ranging from 1:100 000 to 1:1 000 000.

Geological base maps and relevant publications:

Western Australia:

- Distribution of Precambrian mafic and ultramafic rocks in Western Australia: Geological Survey of Western Australia, 2001. 1:500 000 Interpreted Bedrock Geology Map of Western Australia, Geological Survey of Western Australia (June 2001).
- Distribution of dolerite dykes and sills: Myers, J.S. and Hocking, R.M., 1998. Geological Map of Western Australia, 1:2 500 000 (13th Edition). Geological Survey of Western Australia, Perth.
- Distribution of gabbroic intrusions under cover in the Officer Basin: D’Ercole, C. and Lockwood, A.M., 2004. The tectonic history of the Waigen area, western Officer Basin, interpreted from geophysical data. Western Australia Geological Survey, Annual Review 2003–04, Technical Paper, 71–80.

Northern Territory:

- Ahmad, M. and Scrimgeour, I.R., 2006. Geological map of the Northern Territory (1:2 500 000 scale map, 2006 Edition), Northern Territory Geological Survey, Darwin.
- Donnellan, N. and Johnstone, A., 2004. Mapped and interpreted geology of the Tennant Region (1:500 000 scale map, First Edition), Northern Territory Geological Survey, Darwin and Alice Springs.
- Edgoose, C.J., Close, D.F. and Scrimgeour, I.M., 2004. Musgrave Block Special, Northern Territory (First Edition) 1:500 000 scale geological map. Northern Territory Geological Survey, Alice Springs.
- Lally, J. and Doyle, N., 2005. Pine Creek Orogen 1:500 000 Solid Geology Interpretation, preliminary release, Northern Territory Geological Survey, Darwin.
- Liu, S.F., Raymond, O.L., Stewart, A.J., Sweet, I.P., Duggan, M.B., Charlick, C., Phillips, D. and Retter, A.J., 2007. Surface Geology of Australia, Northern Territory, 1:1 000 000 GIS dataset. Geoscience Australia, Canberra.
- Meixner, A. and Hoatson, D.M., 2004. Geophysical interpretation of Proterozoic mafic-ultramafic intrusions in the Arunta Region, central Australia, Geoscience Australia, Record, 2003/29, 125 pp.
- Meixner, T., Scrimgeour, I.M., Close, D.G. and Edgoose, C.J., 2004. Mount Liebig, Northern Territory (Second Edition) 1:250 000 interpreted geological map series (Sheet SF 52–16). Northern Territory Geological Survey, Alice Springs.
- Rawlings, D.J., 2001. Tectonostratigraphy of the McArthur Basin (1:1 000 000 scale map, First Edition), Northern Territory Geological Survey, Darwin.
- Shaw, R.D. and Warren, R.G., 1995. Hermannsburg, Northern Territory (Second Edition), 1:250 000 Geological Series map (Sheet SF 53–13). Australian Geological Survey Organisation, Canberra.
- Shaw, A.D., Langworthy, A.P., Stewart, A.J., Offe, L.A. and Jones, B.G., 1983. Alice Springs, Northern Territory (Second Edition), 1:250 000 geological map (Sheet SF 53–14). Bureau of Mineral Resources, Australia.
- Slater, K.R., 2000a. Tanami 1:250 000 integrated interpretation of geophysics and geology (First Edition), Northern Territory Geological Survey, Darwin.
- Slater, K.R., 2000b. The Granites (SF 52–3) 1:250 000 integrated interpretation of geophysics and geology (First Edition), Northern Territory Geological Survey, Darwin.
- Slater, K.R., 2004. Musgrave Block Special, Northern Territory, integrated interpretation of geophysics and geology (1:500 000 scale map, First Edition), Northern Territory Geological Survey, Darwin and Alice Springs.
- Vandenberg, L.C., Johnstone, A., Donnellan, N., Green, M.G. and Crispe, A., 2004. Northern Arunta Region integrated interpretation of geophysics and geology, Northern Territory (1:500 000 scale map, First Edition), Northern Territory Geological Survey, Alice Springs.

South Australia:

- Cowley, W.M. (Compiler), 2006. Solid geology of South Australia. Department of Primary Industries and Resources, South Australia. Mineral Exploration Data Package, 15 (version 1.1.).

Queensland:

- Bain, J.H.C. and Draper, J.J., 1997. North Queensland Geology. Australian Geological Survey Organisation, Bulletin, 240, and Queensland Department of Mines and Energy, Queensland Geology, 9, 600 pp.
- Geological Survey of Queensland, 2002a. North Queensland gold and base metal study, Stage 1 (Georgetown) geoscience (GIS) dataset. Department of Mines and Energy, Queensland, Brisbane.
- Geological Survey of Queensland, 2002b. South-east Queensland region geoscience (GIS) dataset. Department of Mines and Energy, Queensland, Brisbane.
- Geological Survey of Queensland, 2003. North Queensland gold and base metal study, Stage 2 (Charters Towers) geoscience (GIS) dataset. Department of Mines and Energy, Queensland, Brisbane.
- Geological Survey of Queensland, 2005. Central Queensland region (Yarrol–Connors–Auburn) geoscience (GIS) dataset (version 2). Department of Mines and Energy, Queensland, Brisbane.
- Geological Survey of Queensland, SRK Consulting, ESRI Australia, and Taylor, Wall and Associates, 2006. North-west Queensland mineral province geoscience (GIS) dataset (version 2006). Department of Mines and Energy, Queensland, Brisbane.

New South Wales:

- Scheibner, E. and Hayward, D., 1999. New South Wales State Geoscience Package. Geological Survey of New South Wales, Sydney.

Victoria:

- Simons, B.A. and Moore, D.H., 1999. Victoria 1:1 000 000 Pre-Permian Geology. Geological Survey of Victoria, Melbourne.

Tasmania:

- Brown, A.V., Calver, C.R., Clarke, M.J., Corbett, K.D., Everard, J.L., Forsyth, S.M., Goscombe, B.A., Green, D.C., Green, G.R., McClenaghan, M.P., Pemberton, J. and Vicary, M.J., 2007. 1:250 000 Digital Geology of Tasmania. Mineral Resources Tasmania, Hobart.

Geophysical datasets used for Parts 1 and 2 Interim Maps

- Total Magnetic Intensity, Fourth Edition, 2004: Milligan, P.R. and Franklin, R., 2004. Magnetic Anomaly Map of Australia (1:5 000 000 scale map, Fourth Edition), Geoscience Australia, Canberra.
- Bouguer Gravity, Second Edition, 1997: Murray, A.S., Morse, M.P., Milligan, P.R. and Mackey, T.E., 1997. Gravity Anomaly Map of the Australian Region (1:5 000 000 scale map, Second Edition), Australian Geological Survey Organisation, Canberra.
- Digital Elevation and Bathymetry, 2006: Image compiled from Land Digital Elevation Model (SRTM), National Geospatial–Intelligence Agency and the National Aeronautics and Space Administration; Australian bathymetry and topography grid (June 2005), Geoscience Australia; and ETOPO2 Global 2-Minute Gridded Elevation data-ocean bathymetry, U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Crustal Elements and Provinces used for National Map

- Shaw, R.D., Wellman, P., Gunn, P., Whitaker, A.J., Tarlowski, C. and Morse, M., 1995. Australian Crustal Elements 1:5 000 000 map based on the distribution of geophysical domains (First Edition), GIS dataset. Australian Geological Survey Organisation, Canberra.

Appendix 2. Attributes, Definitions, and Values Used for Characterising Proterozoic Mafic-Ultramafic Units in Appendix 10 (Spreadsheets: Age and Setting)

CODE, SYMBOL, RCODE, MAPUNIT, LABEL, MAP_SYMB, MAP_SYMB, OLDMAP_SYMB

Codes of mafic±ultramafic rock units listed in the solid-geology digital datasets that were used for each State and the Northern Territory (see Appendix 1 for relevant State and Northern Territory datasets)

STRATNO

Stratigraphic formation number from the Australian Stratigraphic Units Database (ASUD)

FORMATION_GROUP

Stratigraphic Formation, Group, Supergroup, Supersuite, etc, names from the Australian Stratigraphic Units Database (ASUD)

CRUSTAL_ELEMENT

From Australian Crustal Elements, 1:5 000 000 scale map by Shaw et al. (1995)

PROVINCE

National Map (in Excel data spreadsheets provided on CD)—from Australian Crustal Elements, 1:5 000 000 scale map by Shaw et al. (1995); (Part 1 map)—Western Australia: 1:2 500 000 Tectonic Units of Western Australia, June 2001, Geological Survey of Western Australia; (Part 2 map)—Northern Territory and South Australia: Georegions ArcInfo coverage, Geoscience Australia

STRATAGE

General stratigraphic age from published maps/reports

Archaean (>2500 Ma)

Proterozoic (2500–545 Ma)

Palaeoproterozoic (2500–1600 Ma)

Mesoproterozoic (1600–1000 Ma)

Neoproterozoic (1000–545 Ma)

Cambrian (545–490 Ma)

AGE_CHRON

Absolute measured age (in million years: Ma) from published reports, maps, etc

ERROR

Calculated error in ± million years

AGE_COMMENT

Additional information regarding measured age

METHOD

U-Pb (zircon), Pb-Pb (zircon evaporation), TIMS, Sm-Nd, Rb-Sr, K-Ar, mineral isochron, whole-rock, Ar-Ar (total cooling, fusion, plateau), etc

REFERENCE

Reference for absolute age

GAREF

GAREF number of reference for determined age from Geoscience Australia's Bibliographic Reference Database GAREF

NATIONAL_MAG_EVENT

Magmatic Event (ME 1 to ME 30 and Undefined) defined in the National study. The type example of the dated Magmatic Event is indicated by a horizontal blue bar

EVENT_NAME

Informal Magmatic Event name defined in the National study

APPROX_AGE

Approximate age (in million years: Ma) defined in the National study

MIN_AGE

Relative minimum age (in million years: Ma) from published reports, maps, etc

ERROR

Calculated error in $\pm$ million years

METHOD

Geochronological method used: U-Pb (zircon), Pb-Pb (zircon evaporation), TIMS, Sm-Nd, Rb-Sr, K-Ar, mineral isochron, whole-rock, Ar-Ar (total cooling, fusion, plateau), etc

REFERENCE

Reference for minimum age data

GAREF

GAREF number of reference for minimum age from Geoscience Australia's Bibliographic Reference Database GAREF

MAX_AGE

Relative maximum age (in million years: Ma) from published reports, maps, etc

ERROR

Calculated error in $\pm$ million years

METHOD

Geochronological method used: U-Pb (zircon), Pb-Pb (zircon evaporation), TIMS, Sm-Nd, Rb-Sr, K-Ar, mineral isochron, whole-rock, Ar-Ar (total cooling, fusion, plateau), etc

REFERENCE

Reference for maximum age data

GAREF

GAREF number of reference for maximum age from Geoscience Australia's Bibliographic Reference Database GAREF

INDEX250

Relevant 1:250 000 geological sheet

REFINDEX250

Reference of relevant 1:250 000 geological sheet

GAREF

GAREF number of reference for 1:250 000 geological sheet from Geoscience Australia's Bibliographic Reference Database GAREF

INDEX100

Relevant 1:100 000 geological sheet

REFINDEX100

Reference of relevant 1:100 000 geological sheet

GAREF

GAREF number of reference for 1:100 000 geological sheet from Geoscience Australia's Bibliographic Reference Database GAREF

COMP_BULK

Bulk composition of mafic±ultramafic body:

- Mafic
- Ultramafic
- Alkaline
- Intermediate

SETTING

Broad emplacement setting of mafic±ultramafic body:

- Intrusive
- Extrusive
- Hypabyssal

ROCKTYPE

Most common mafic-ultramafic-(felsic) rock types (igneous-metamorphic-pyroclastic) cited:

- Granophyre
- Anorthosite
- Gabbro, Olivine gabbro, Magnetite gabbro, Leucogabbro, Melanogabbro
- Gabbronorite, Norite
- Troctolite
- Pyroxenite, Orthopyroxenite, Clinopyroxenite
- Dunite, Peridotite, Harzburgite
- Komatiite
- Basalt (olivine, tholeiitic, magnesian, high-magnesian, siliceous high-magnesian, high-Al, breccia)
- Granulite, Mafic granulite, Felsic granulite
- Amphibolite
- Dolerite, Quartz dolerite, Hornblende dolerite
- Tonalite
- Monzogranite
- Syenite, Trachyte
- Diorite
- Tuff, Agglomerate, Pumice
- Peperite
- Hyaloclastite

ABUNDANCE

Relative abundance of mafic±ultramafic rock component to other rocks in Formation, Group, etc

Major: mafic±ultramafic rocks comprise a major component of total rock package

Minor: mafic±ultramafic rocks comprise a minor component of total rock package

MODE_OCCURRENCE

Style/form of occurrence of mafic±ultramafic body:

- Dyke, layered dyke, massive dyke

Sill
 Plug
 Lava
 Xenolith
 Raft
 Feeder conduit
 Flood basalt
 Lava channel
 Komatiitic flow, komatiitic intrusion
 Intrusion, layered intrusion, massive intrusion
 Fault-bounded intrusion
 Tectonised intrusion
 Alpine intrusion
 Alaskan intrusion
 Ophiolite intrusion

THICKNESS

Stratigraphic thickness (in metres) of mafic±ultramafic rocks

COUNTRYROCK

Major country rocks for intrusive mafic±ultramafic body, or associated rock types if extrusive

MIN_STYLE 1

Mineralisation/deposit style, using modified version of Cox and Singer (1986) classification (e.g., 1. Basal mafic-ultramafic Ni-Cu; 2. Stratabound mafic-ultramafic Cr-PGE)

MIN_STYLE 2

Mineralisation/deposit style, using modified version of Cox and Singer (1986) classification (e.g., 1. Basal mafic-ultramafic Ni-Cu; 2. Stratabound mafic-ultramafic Cr-PGE)

MIN_STYLE 3

Mineralisation/deposit style, using modified version of Cox and Singer (1986) classification (e.g., 1. Basal mafic-ultramafic Ni-Cu; 2. Stratabound mafic-ultramafic Cr-PGE)

GEOTECTONICS

Published comment about geotectonic setting of mafic±ultramafic rocks

REFERENCE

Reference for geotectonics comment

GAREF

GAREF number of reference for geotectonics from Geoscience Australia's Bibliographic Reference Database GAREF

REFERENCE

General reference for mafic±ultramafic rocks, formation, mineralisation, and/or deposit

GAREF

GAREF number of general reference for mafic±ultramafic rocks, formation, mineralisation, and/or deposit from Geoscience Australia's Bibliographic Reference Database GAREF

Appendix 3: Proterozoic Mafic-Ultramafic Magmatic Events Defined in Western Australia (Part 1 Map)

U-Pb (zircon, zirconolite, baddeleyite), Pb-Pb, Sm-Nd, and Ar-Ar geochronological data of mafic, ultramafic, and spatially associated comagmatic rocks have highlighted 15 Proterozoic mafic±ultramafic Magmatic Events in Western Australia.

NOTE—this partial chronology is specific to Western Australia and is now superseded by the aggregated National-event chronology of thirty Magmatic Events.

ME 15 (m): Kalkarindji Event ~510 Ma. A spatially significant event that defines the early-middle Cambrian boundary at ~510 Ma (Kalkarindji LIP–Antrim Plateau Volcanics, Table Hill Volcanics: Ord–Bonaparte–Officer Basins)

ME 14 (m): Mundine Well Event ~755 Ma (Mundine Well Dyke Swarm: Pilbara Craton, Gascoyne Complex, Hamersley–Ashburton Basins)

ME 13 (m): Gairdner Event ~825 Ma (Gairdner Dyke Swarm: Musgrave Orogen)

ME 12 (mu): Warakurna Event ~1070 Ma (Various dolerite dykes (Warakurna LIP–Edmund Basin, Collier Basin, Hamersley Basin, Earahedy Basin; Giles Complex: Musgrave Orogen)

ME 11 (m): Marnda Moorn Event ~1210 Ma (Undefined dolerite dykes (Marnda Moorn LIP: Yilgarn Craton)

ME 10 (mu): Fraser Event ~1300 Ma (Fraser Complex: Albany–Fraser Orogen)

ME 9 (m): Bangemall Event ~1465 Ma (Undefined dolerite dykes: Edmund Basin)

ME 8 (m): Hart Event ~1790 Ma (Hart Dolerite, Carson Volcanics: Halls Creek Orogen–King Leopold Orogen–Kimberley Basin; June Hill Volcanics: Ashburton Basin)

ME 7 (mu): Sally Malay Event ~1860–1830 Ma (Sally Malay, Panton, Toby, Springvale, and McIntosh layered intrusions, Paperbark Granite Supersuite, Wombarella Gabbro, Woodward Dolerite, Koongie Park Formation: Halls Creek Orogen–King Leopold Orogen)

ME 6 (m): Bow River Event ~1880–1860 Ma (Biscay Formation, Tickalara Metamorphics: Halls Creek Orogen)

ME 5 (m): Narracoota Event ~1910 Ma (Narracoota Formation: Bryah Basin–Padbury Basin; Ding Dong Downs Volcanics: Halls Creek Orogen)

ME 4 (m): Paraburdoo Event ~2010 Ma (Undefined dolerite dykes: Hamersley Basin)

ME 3 (m): Turee Creek Event ~2210 Ma (Undefined dolerite dykes: Hamersley Basin)

ME 2 (mu): Widgiemooltha Event ~2420 Ma (Widgiemooltha Dyke Swarm: Yilgarn Craton)

ME 1 (m): Weeli Wolli Event ~2450 Ma (Weeli Wolli Formation: Hamersley Basin)

Legend:

ME 1 (m): Weeli Wolli Event ~2450 Ma = Magmatic Event (ME) number 1; mafic exclusive or mafic-dominated (m) rock types present; informal event name; magmatic crystallisation age at ~2450 Ma

ME 2 (mu): Widgiemooltha Event ~2420 Ma = Magmatic Event (ME) number 2; mafic and ultramafic (mu) rock types present; informal event name; magmatic crystallisation age at ~2420 Ma

Appendix 4: Proterozoic Mafic-Ultramafic Magmatic Events Defined in the Northern Territory and South Australia (Part 2 Map)

U-Pb (zircon, baddeleyite), Sm-Nd, K-Ar, Ar-Ar, and Rb-Sr geochronological data of mafic, ultramafic, and spatially associated comagmatic rocks have highlighted 19 major ‘Proterozoic’ mafic±ultramafic Magmatic Events in the Northern Territory and South Australia.

NOTE—this partial chronology is specific to the Northern Territory and South Australia and is now superseded by the aggregated National-event chronology of thirty Magmatic Events.

ME 19 (m): Kalkarindji Event ~530–510 Ma (Kalkarindji LIP: NT; Kulyong Volcanics, Table Hill Volcanics: Officer Basin; Antrim Plateau Volcanics: NT–WA–SA–Qld)

ME 18 (m): Boucaut Event ~775 Ma (Boucaut Volcanics: Adelaide Geosyncline)

ME 17 (m): Gairdner Event ~825 Ma (Gairdner Dyke Swarm, Amata Dolerite: Musgrave Orogen, Gawler Craton; Woollana Volcanics, Adelaide Geosyncline)

ME 16 (mu): Warakurna Event ~1070 Ma (Giles Complex, Alcurra Dyke Swarm: Musgrave Orogen)

ME 15 (mu): Mordor Event ~1130 Ma (Mordor Complex: Aileron Province)

ME 14 (m): Derim Derim Event ~1320 Ma (Derim Derim dolerite: McArthur Basin)

ME 13 (mu): Curramulka Event ~1590 Ma (Curramulka Gabbro, mafic volcanics in Gawler Range Volcanics, gabbroic intrusions in Hiltaba Suite: Gawler Craton; Yalwarra Volcanics, McArthur Basin)

ME 12 (mu): Andrew Young Event ~1640–1630 Ma (mafic-ultramafic intrusions: Warumpi and Aileron provinces; anorthosite intrusions in Muckanippie Suite, dolerite in St Peters Suite and St Francis Suite: Gawler Craton)

ME 11 (m): Tarcoola Event ~1655 Ma (Tarcoola Formation basalt: Gawler Craton)

ME 10 (m): Woman-in-White Event ~1685 Ma (Woman-in-White Amphibolite: Curnamona Craton; gabbro intrusions in Engenina Adamellite: Gawler Craton; dolerite in Ongeva package: Aileron Province)

ME 9 (m): Oenpelli Event ~1725 Ma (Oenpelli Dolerite: Pine Creek Region; Colona Metagabbro: Gawler Craton)

ME 8 (m): McGregor Event ~1740 Ma (McGregor Volcanics: Gawler Craton)

ME 7 (m): Attutra Event ~1790–1770 Ma (Attutra intrusion: Aileron Province; Tidnamurkuna Volcanics, Myola Volcanics, Bill’s Lookout gabbro: Gawler Craton)

ME 6 (m): Mount Hay Event ~1820–1800 Ma (metagabbro intrusions and Ongeva package bimodal volcanics: Aileron Province; Hatches Creek Group volcanics: Tennant Region; Tournefort Metadolerite: Gawler Craton)

ME 5 (m): Edmirringee Event ~1840–1820 Ma (Ooradidgee Group basalts: Tennant Region; Tanami dolerites: Tanami Region; Lander package dolerite: Arunta Region)

ME 4 (m): Mumbilla Event ~1850 Ma (gabbros/dolerites: Pine Creek Region; gabbro component in Tennant Granites: Tennant Region; Donington Suite-quartz gabbro: Gawler Craton)

ME 3 (m): Wangi Event ~1860 Ma (Wangi Basalts, Zamu Dolerite: Pine Creek Region)

ME 2 (m): Stag Creek Event ~2020 Ma (Stag Creek Volcanics: Pine Creek Region)

ME 1 (mu): Blackfellow Hill Event ~2460 Ma (Blackfellow Hill Pyroxenite: Gawler Craton)

Appendix 5. Reconciliation of State–Northern Territory Event Schemes into National Magmatic Event Series

National Event	National Event Name	Age ± 10 Ma ¹	Abundance	Western Australia Event	Local Name	Abundance	Northern Territory–South Australia Event	Local Name	Abundance	Queensland Event	Local Name	Abundance	Tasmania–Victoria–New South Wales Event	Local Name	Abundance
ME 30 (m)	Kalkarindji	~520	Major, Minor	ME 15	Kalkarindji	Major	ME 19	Kalkarindji	Major, Minor	ME 11	Kalkarindji	Major			
ME 29 (mu)	Skipworth	~575	Major							ME 10	Princhester	Major	ME 3	Skipworth	Major
ME 28 (m)	Mundine Well	~755	Major	ME 14	Mundine Well	Major									
ME 27 (m)	Boucaut	~775	Minor				ME 18	Boucaut	Minor						
ME 26 (m)	Gairdner	~825	Major, Minor	ME 13	Gairdner	Major	ME 17	Gairdner	Major, Minor				ME 2	Gairdner	Major
ME 25 (m)	Elizabeth Hills	~975	Major	New ²	Elizabeth Hills	Major									
ME 24 (mu)	Warakurna	~1070	Major	ME 12	Warakurna	Major	ME 16	Warakurna	Major						
ME 23 (mu)	Mordor	~1135	Major				ME 15	Mordor	Major	ME 9	Lakeview	Major			
ME 22 (m)	Pitjantjatjara	~1180	Major	New ²	Pitjantjatjara	Major									
ME 21 (m)	Marnda Moorn	~1210	Major, Minor	ME 11	Marnda Moorn	Major, Minor									
ME 20 (mu)	Fraser	~1310	Major	ME 10	Fraser	Major	ME 14	Derim Derim	Major						
ME 19 (mu)	Loongana	~1415	Major	New ²	Loongana	Major									
ME 18 (m)	Bangemall	~1465	Major	ME 9	Bangemall	Major									
ME 17 (m)	Saxby	~1530	Minor							ME 8	Saxby	Minor			
ME 16 (mu)	Curramulka	~1590	Major, Minor				ME 13	Curramulka	Major, Minor	ME 7	Snake/Chelmsford	Major			
ME 15 (mu)	Andrew Young	~1635	Major, Minor				ME 12	Andrew Young	Major, Minor						
ME 14 (m)	Lane Creek	~1655	Major, Minor				ME 11	Tarcoola	Minor	ME 6	Lane Creek	Major, Minor			
ME 13 (m)	Woman-in-White	~1680	Major, Minor				ME 10	Woman-in-White	Major, Minor	ME 5	Toole Creek	Major	ME 1	Woman-in-White	Major, Minor
ME 12 (m)	Oenpelli	~1720	Major, Minor				ME 9	Oenpelli	Major, Minor	ME 4	Fiery Creek	Major			
ME 11 (m)	Lunch Creek	~1750	Major, Minor				ME 8	McGregor	Minor	ME 3	Lunch Creek	Major			
ME 10 (m)	Hart	~1780	Major, Minor	ME 8	Hart	Major, Minor	ME 7	Attutra	Major, Minor	ME 2	Eastern Creek	Major			
ME 9 (m)	Mount Hay	~1810	Major, Minor				ME 6	Mount Hay	Major, Minor						
ME 8 (mu)	Edmirringee	~1830	Major, Minor	New ²	McIntosh	Major	ME 5	Edmirringee	Major, Minor	ME 1	Saint Ronan	Major, Minor			
ME 7 (mu)	Sally Malay	~1850	Major, Minor	ME 7	Sally Malay	Major, Minor	ME 4	Mumbilla	Minor						
ME 6 (m)	Bow River	~1870	Major, Minor	ME 6	Bow River	Major, Minor	ME 3	Wangi	Major, Minor						
ME 5 (m)	Ding Dong Downs	~1910	Major, Minor	ME 5	Ding Dong Downs	Major, Minor									
ME 4 (m)	Stag Creek	~2015	Major, Minor	ME 4	Paraburdoo	Major	ME 2	Stag Creek	Major, Minor						
ME 3 (m)	Turee Creek	~2210	Major	ME 3	Turee Creek	Major									
ME 2 (mu)	Widgiemooltha	~2420	Major	ME 2	Widgiemooltha	Major									
ME 1 (mu)	Weeli Wolli	~2455	Major, Minor	ME 1	Weeli Wolli	Major, Minor	ME 1	Blackfellow Hill	Major						
Undefined	Undefined		Major, Minor	Undefined	Undefined	Major, Minor	Undefined	Undefined	Major, Minor	Undefined	Undefined	Major, Minor	Undefined	Undefined	Major, Minor

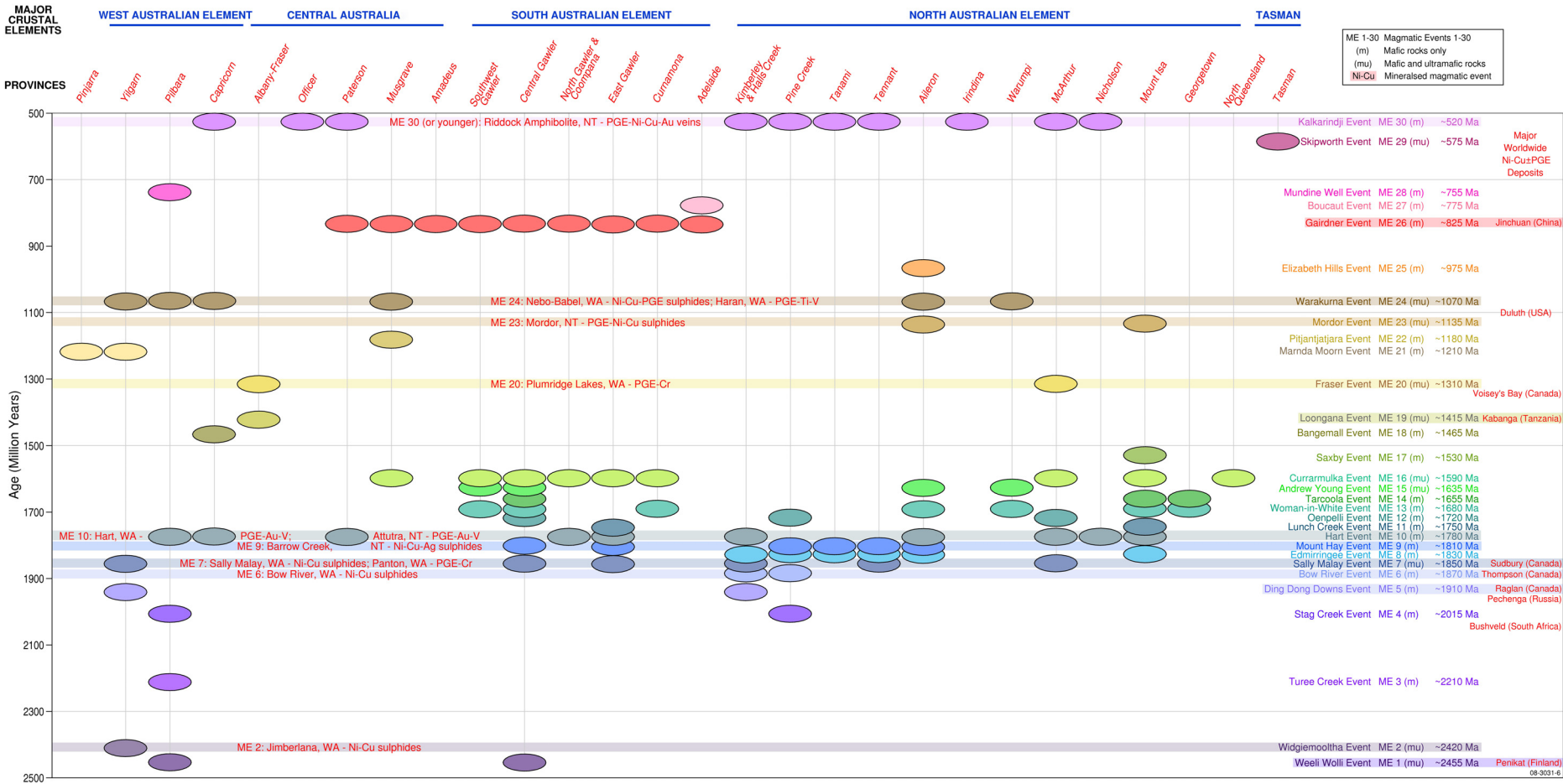
¹ All ages shown are in million years

² New Magmatic Events recognised subsequent to publication of the Western Australia (Part 1) interim map

Appendix 6. Type Examples of Proterozoic Mafic-Ultramafic Magmatic Events

Magmatic Event	Informal Event Name	Event Age ± 10 Ma	Dated Representative Unit	Major Crustal Element	Province	Age (Ma ± 2σ)	Method	Geochronology Reference	General Reference
ME 30 (m)	Kalkarindji	~520 Ma	Milliwindi Dolerite Dyke (part of Kalkarindji LIP)	North Australian Craton	Kimberley	513 ± 12	U-Pb (zircon)	Hanley & Wingate (2000)	Thorne et al. (1999)
ME 29 (mu)	Skipworth	~575 Ma	Skipworth Subgroup Volcanics	Tasman	Tasman	579 ± 16	Sm-Nd isochron	Meffre et al. (2004)	Calver (2007)
ME 28 (m)	Mundine Well	~755 Ma	B6 & B7 dolerite dykes, Mundine Well Dyke Swarm	West Australian Craton	Pilbara	755 ± 3	U-Pb (zircon)	Wingate & Giddings (2000)	Wingate & Giddings (2000)
ME 27 (m)	Boucaut	~775 Ma	Boucaut Volcanics	South Australian Craton	Adelaide	777 ± 7	U-Pb (zircon)	Preiss (2000)	Forbes (1991)
ME 26 (m)	Gairdner	~825 Ma	RL1 dolerite dyke (part of Gairdner LIP)	South Australian Craton	East Gawler	827 ± 6	U-Pb (baddeleyite)	Wingate et al. (1998)	Wingate et al. (1998)
ME 25 (m)	Elizabeth Hills	~975 Ma	Un-named dolerite dykes near Elizabeth Hills	North Australian Craton	Aileron	976 ± 3	U-Pb (zircon & baddeleyite)	Wyborn et al. (1998)	Wyborn et al. (1998)
ME 24 (mu)	Warakurna	~1070 Ma	Un-named dolerite sills intruding Collier Group (part of Warakurna LIP)	West Australian Craton	Capricorn	1070 ± 6	U-Pb (zircon)	Wingate et al. (2002)	Morris & Pirajno (2005)
ME 23 (mu)	Mordor	~1135 Ma	Mordor mafic-ultramafic intrusion	North Australian Craton	Aileron	1133 ± 5	U-Pb (zircon)	Claoué-Long & Hoatson (2005)	Hoatson et al. (2005)
ME 22 (m)	Pitjantjatjara	~1180 Ma	Un-named Pitjantjatjara Suite gabbro intrusion	Central Australia	Musgrave	1176 ± 5	U-Pb (zircon)	Glikson et al. (1996)	Glikson et al. (1996)
ME 21 (m)	Marnda Moorn	~1210 Ma	Un-named dolerite dyke, Fraser Dyke Swarm (part of Marnda Moorn LIP)	West Australian Craton	Yilgarn	1212 ± 10	U-Pb (baddeleyite)	Wingate et al. (2000)	Wingate & Pidgeon (2005)
ME 20 (mu)	Fraser	~1310 Ma	Un-named mafic rocks, Unit 5, Albany-Fraser Complex	Central Australia	Albany-Fraser	1301 ± 6	U-Pb (zircon)	Clark et al. (1999)	Fitzsimons & Buchan (2005)
ME 19 (mu)	Loongana	~1415 Ma	Loongana mafic-ultramafic intrusion	Central Australia	Officer	1415 ± 7	U-Pb (zircon)	Bunting (2007)	Bunting (2007)
ME 18 (m)	Bangemall	~1465 Ma	Un-named dolerite sills intruding Edmund Group, Bangemall Supergroup	West Australian Craton	Capricorn	1465 ± 3	U-Pb (zircon)	Wingate et al. (2002)	Morris & Pirajno (2005)
ME 17 (m)	Saxby	~1530 Ma	Un-named gabbros and dolerites associated with Saxby Granite	North Australian Craton	Mount Isa	1527 ± 4	U-Pb (zircon)	Rubenach et al. (2008)	Mark et al. (2005)
ME 16 (mu)	Curramulka	~1590 Ma	Curramulka Gabbronorite, Hiltaba Suite	South Australian Craton	East Gawler	1589 ± 5	U-Pb (zircon)	Zang et al. (2007)	Zang et al. (2007)
ME 15 (mu)	Andrew Young	~1635 Ma	Andrew Young Hills gabbro	North Australian Craton	Aileron	1633 ± 3	U-Pb (zircon)	Claoué-Long & Hoatson (2005)	Hoatson et al. (2005)
ME 14 (m)	Lane Creek	~1655 Ma	Un-named leucogabbro sill, Lane Creek Formation	North Australian Craton	Georgetown	1656 ± 3	U-Pb (zircon)	Black et al. (1998)	Withnall (1985)
ME 13 (m)	Woman-in-White	~1680 Ma	Woman-In-White Amphibolite, Lady Louise Suite	South Australian Craton	Curnamona	1685 ± 4	U-Pb (zircon)	Conor & Fanning (2001)	Conor & Fanning (2001)
ME 12 (m)	Oenpelli	~1720 Ma	Oenpelli Dolerite	North Australian Craton	Pine Creek	1723 ± 6	U-Pb (zircon)	Page (1996)	Ferenczi & Sweet (2005)
ME 11 (m)	Lunch Creek	~1750 Ma	Lunch Creek Gabbro	North Australian Craton	Mount Isa	1737 ± 15	U-Pb (zircon)	Page (1983)	Derrick (1980)
ME 10 (m)	Hart	~1780 Ma	Hart Dolerite (part of Hart LIP)	North Australian Craton	Kimberley	1790 ± 4	U-Pb (zircon)	Hoatson & Blake (2000)	Tyler et al. (2006)
ME 9 (m)	Mount Hay	~1810 Ma	Mount Hay Granulite	North Australian Craton	Aileron	1803 ± 5	U-Pb (zircon)	Claoué-Long & Hoatson (2005)	Hoatson et al. (2005)
ME 8 (mu)	Edmirringee	~1830 Ma	Edmirringee Volcanics	North Australian Craton	Tennant	1840 ± 4	U-Pb (zircon)	Claoué-Long et al. (2008)	Blake et al. (1987)
ME 7 (mu)	Sally Malay	~1850 Ma	Sally Malay mafic-ultramafic intrusion	North Australian Craton	Kimberley	1845 ± 3	U-Pb (zircon & baddeleyite)	Page & Hoatson (2000)	Hoatson & Blake (2000)
ME 6 (m)	Bow River	~1870 Ma	Un-named mafic granulite host to Bow River Ni prospect, Tickalara Metamorphics	North Australian Craton	Kimberley	1880 ± 3	U-Pb (zircon)	Blake et al. (1999)	Hoatson & Blake (2000)
ME 5 (m)	Ding Dong Downs	~1910 Ma	Ding Dong Downs Volcanics	North Australian Craton	Kimberley	1907 ± 6	U-Pb (zircon)	Blake et al. (2000a)	Hoatson & Blake (2000)
ME 4 (m)	Stag Creek	~2015 Ma	Stag Creek Volcanics	North Australian Craton	Pine Creek	2021 ± 10	U-Pb (zircon)	Worden et al. (2008)	Needham et al. (1988)
ME 3 (m)	Turee Creek	~2210 Ma	Un-named dolerite sills and dykes, Turee Creek Group	West Australian Craton	Pilbara	2208 ± 10	U-Pb (baddeleyite)	Müller et al. (2005)	Thorne & Tyler (1997)
ME 2 (mu)	Widgiemooltha	~2420 Ma	Binneringie Dyke, part of Widgiemooltha Dyke Suite	West Australian Craton	Yilgarn	2418 ± 3	U-Pb (baddeleyite)	Nemchin & Pidgeon (1998)	Griffin (1989)
ME 1 (mu)	Weeli Wolli	~2455 Ma	Un-named basalt, Weeli Wolli Formation	West Australian Craton	Pilbara	2449 ± 3	U-Pb (zircon)	Barley et al. (1997)	Tyler et al. (1991)

Appendix 7: Time-Space-Event Chart of Australian Proterozoic Mafic-Ultramafic Magmatic Events



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Appendix 9: Time-Slice Maps of Proterozoic Mafic-Ultramafic Magmatic Events

Major Crustal Elements and Provinces (modified after Shaw et al., 1995).

National Series of Thirty Magmatic Events (ME 1 to ME 30), in age order:

ME 30 (m) ~520 Ma Kalkarindji Event (Kalkarindji LIP: modified after Glass and Phillips, 2006). Extensive preservation of basaltic lavas and associated sills across the North Australian and Central Australia Crustal Elements; intrusions in the Kimberley and Irindina provinces.

ME 29 (mu) ~575 Ma Skipworth Event

Named after mafic-ultramafic volcanics (Skipworth Subgroup) on King Island; other isolated dated occurrences of basalt and dolerite east of the Tasman Line in Tasmania and New South Wales; also dolerite and gabbro pods within the Princhester Serpentinite in Queensland. Other fault-bounded occurrences of mafic-ultramafic rocks in the Tasmanides are undated and could belong to this, or later Phanerozoic, events.

ME 28 (m) ~755 Ma Mundine Well Event

Only dated occurrence is the Mundine Well Dolerite dyke in the Pilbara province; other dykes in the Pilbara and Capricorn provinces could belong to this event.

ME 27 (m) ~775 Ma Boucaut Event

Only known occurrence is the Boucaut Volcanics near the southeastern margin of the Adelaide province.

ME 26 (m) ~825 Ma Gairdner Event (Gairdner LIP: modified after Zhao et al., 1994).

Northwest-trending Gairdner Dyke Swarm traversing the South Australian Crustal Element and the Musgrave and Paterson provinces of the Central Australia Crustal Element; basalt lavas in the basal stratigraphy of the Adelaide and Amadeus provinces; and possible correlatives in the Paterson province.

ME 25 (m) ~975 Ma Elizabeth Hills Event

Only known occurrence is un-named dolerite dykes near Elizabeth Hills in the western Aileron province.

ME 24 (mu) ~1070 Ma Warakurna Event (Warakurna LIP: modified after Wingate et al., 2004).

Time-equivalent magmatism in an east-trending belt that includes the Musgrave province and crosses the West Australian Crustal Element; dolerite dykes in the southern margin of the North Australian Crustal Element.

ME 23 (mu) ~1135 Ma Mordor Event

Named after the sub-circular Mordor ultramafic-mafic intrusion in the Aileron province; only other known occurrence is the northeast-trending Lakeview dolerite dykes in the Mount Isa province.

ME 22 (m) ~1180 Ma Pitjantjatjara Event

Only known occurrence is a dated gabbro intrusion and associated mafic granulite associated with granitic rocks of the Pitjantjatjara Supersuite, Musgrave province.

ME 21 (m) ~1210 Ma Marnda Moorn Event (Marnda Moorn LIP: modified after Wingate and Pidgeon, 2005).

Extensive coeval dolerite dyke swarms and sills, with variable emplacement orientations in the Yilgarn and Pinjarra provinces.

ME 20 (mu) ~1310 Ma Fraser Event

Named for dated mafic intrusions in the Albany-Fraser province; correlative is the Derim Derim dolerite sills in the McArthur province.

ME 19 (mu) ~1415 Ma Loongana Event

Only known occurrence is the Loongana mafic-ultramafic intrusion in the basement to the Officer Basin.

ME 18 (m) ~1465 Ma Bangemall Event

Only known occurrence is dated dolerite sills in the Bangemall Supergroup of the Capricorn province.

ME 17 (m) ~1530 Ma Saxby Event

Only known occurrence is small gabbro and dolerite bodies associated with the ~1530 Ma Saxby Granite, Mount Isa province.

ME 16 (mu) ~1590 Ma Curramulka Event

Named after the Curramulka gabbro-norite in East Gawler province; correlated mafic magmatism throughout the South Australian Crustal Element; minor correlatives in North Queensland, Mount Isa and McArthur provinces.

ME 15 (mu) ~1635 Ma Andrew Young Event

Named for the Andrew Young Hills gabbro intrusion and numerous associated mafic and ultramafic intrusions in the Warumpi and southern Aileron provinces; correlatives in the South and Central Gawler provinces.

ME 14 (m) ~1655 Ma Lane Creek Event

Named for un-named sills and basalt associated with the Lane Creek Formation in the Georgetown province; minor basalt correlatives known in the Central Gawler province.

ME 13 (m) ~1680 Ma Woman-in-White Event

Named after Woman-in-White Amphibolite in Curnamona province; widespread correlatives in Curnamona and Central Gawler provinces, and the Warumpi, Aileron, Mount Isa, and Georgetown provinces in northern Australia.

ME 12 (m) ~1720 Ma Oenpelli Event

Named after the Oenpelli Dolerite in the Pine Creek province; correlated basalt and mafic sills in parts of the stratigraphy of McArthur and Mount Isa provinces.

ME 11 (m) ~1750 Ma Lunch Creek Event

Named for the Lunch Creek Gabbro in Mount Isa province and associated mafic intrusions; correlatives in the Eastern Gawler province.

ME 10 (m) ~1780 Ma Hart Event (Hart LIP: modified after Tyler et al., 2006).

Dolerite and basalt within the Kimberley province; possible extension of this LIP to the south and southeast encompasses time-equivalent magmatism in eight other provinces across the West, North, and South Australian Crustal Elements, and in Central Australia.

ME 9 (m) ~1810 Ma Mount Hay Event

Named for the Mount Hay Granulite and associated gabbro intrusions in the Aileron province; geographically extensive basalt elsewhere in the stratigraphy of the Aileron, Tennant, and Tanami provinces; minor correlatives in the Eastern Gawler province.

ME 8 (mu) ~1830 Ma Edmirringee Event

Named for the Edmirringee Basalt in the Tennant province; geographically extensive but volumetrically minor metabasalt and metadolerite in the regional sedimentary rock packages of the Aileron, Tennant, and Tanami provinces, minor correlatives in the Kimberley and Pine Creek provinces.

ME 7 (mu) ~1850 Ma Sally Malay Event

Named for the Sally Malay mafic-ultramafic intrusion and correlatives in Kimberley province; minor gabbros in Tennant province, correlatives in East and Central Gawler provinces; basalt and dolerite sills in Yerrida Basin overlying Yilgarn province.

ME 6 (m) ~1870 Ma Bow River Event

Named for the Bow River nickel deposit hosted by un-named gabbro in the Tickalara Metamorphics in Kimberley province, and associated basalt and mafic intrusions; correlated Wangi Basics in Pine Creek province.

ME 5 (m) ~1910 Ma Ding Dong Downs Event

Named for the Ding Dong Downs Volcanics in Kimberley province; correlated basalt in Bryah Basin overlying Yilgarn province.

ME 4 (m) ~2015 Ma Stag Creek Event

Named for the basaltic component of the Stag Creek Volcanics in Pine Creek province; isolated correlative in the Pilbara province.

ME 3 (m) ~2210 Ma Turee Creek Event

Only known occurrence is un-named dolerite dykes and sills near Turee Creek in Pilbara province.

ME 2 (mu) ~2420 Ma Widgiemooltha Event

The Widgiemooltha mafic-ultramafic dyke swarm crossing the Yilgarn province; many un-named and undated mafic dykes assigned as Undefined Event may belong to this event.

ME 1 (mu) ~2455 Ma Weeli Wolli Event

Named for dolerite dykes and sills and basalt in the Weeli Wolli Formation, Pilbara province; correlative is Blackfellow Hill Pyroxenite in Central Gawler province.

Undefined Event (age unknown)

Units assigned as Undefined Event include all mafic-ultramafic rocks that are known to be Proterozoic in age, but are without reliable isotopic age control. Prominent examples are mafic dyke swarms of many orientations and possible ages throughout most provinces.

Composite Map

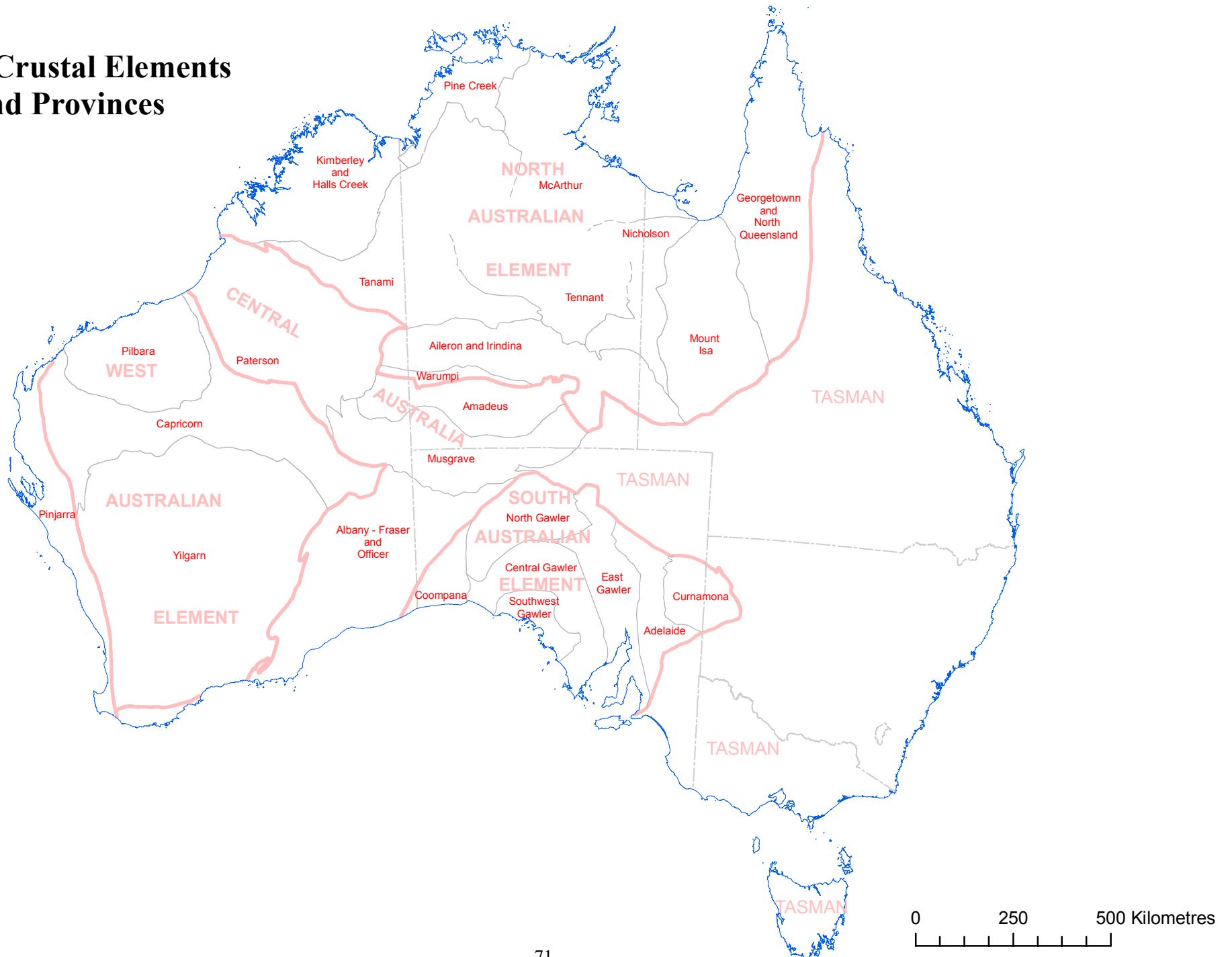
Proterozoic Mafic-Ultramafic Magmatic Events: ME 1 to ME 30, and Undefined Event.

Province Templates used for the Parts 1 and 2 Interim Maps:

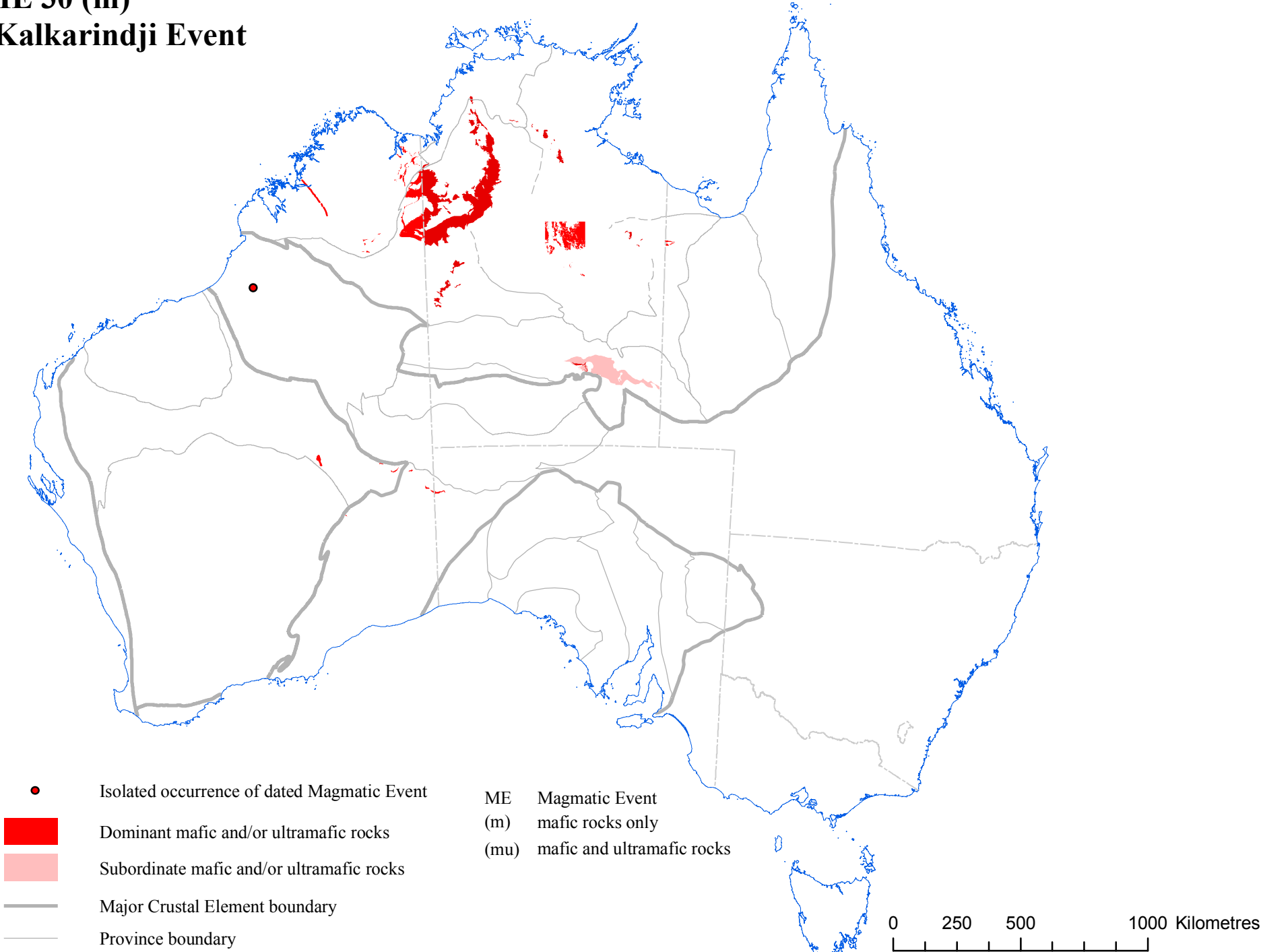
Tectonic units (Provinces) used for 'A Synthesis of Australian Proterozoic Mafic-Ultramafic Magmatic Events. Part 1: Western Australia'.

Georegions used for 'A Synthesis of Australian Proterozoic Mafic-Ultramafic Magmatic Events. Part 2: Northern Territory and South Australia'.

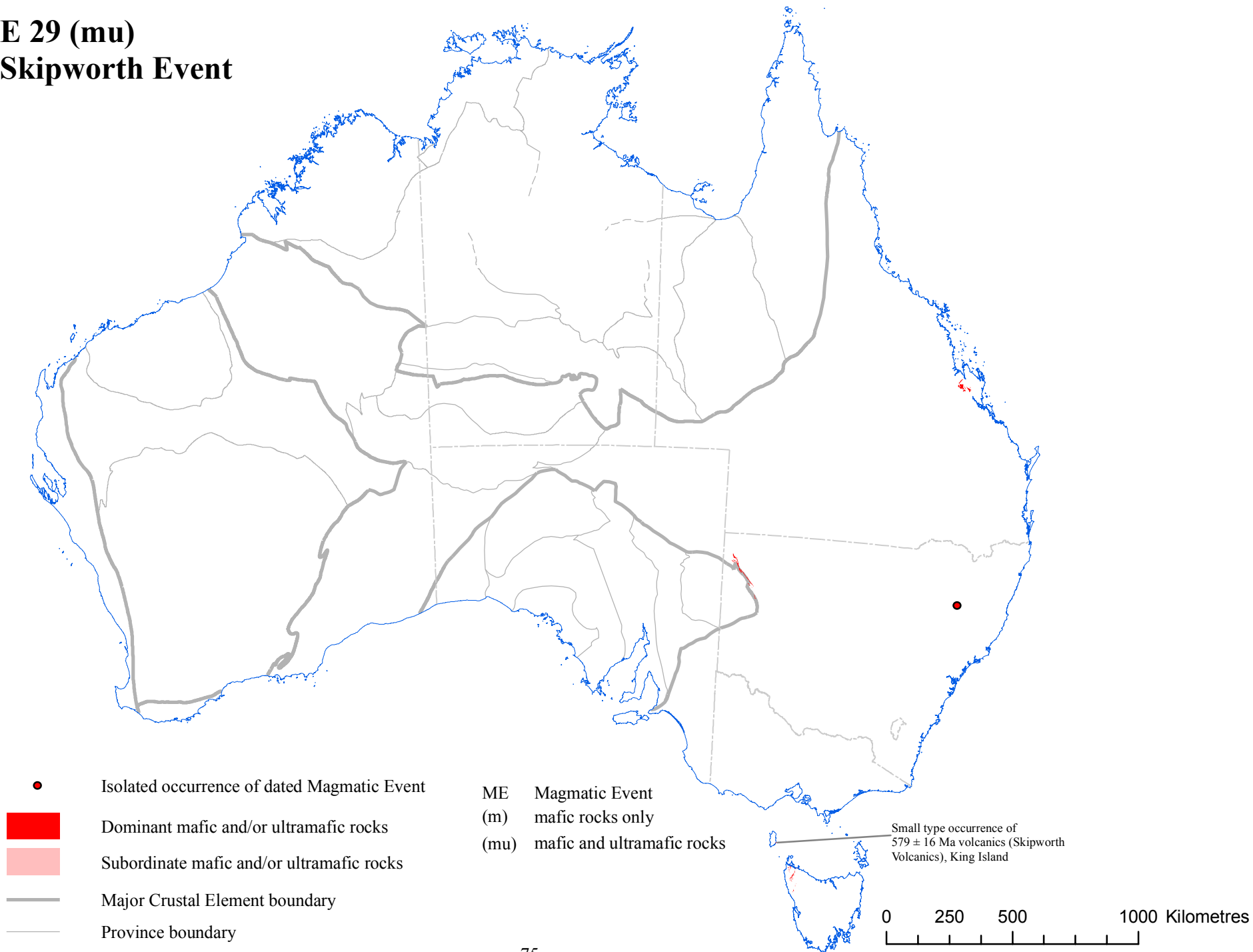
Major Crustal Elements and Provinces



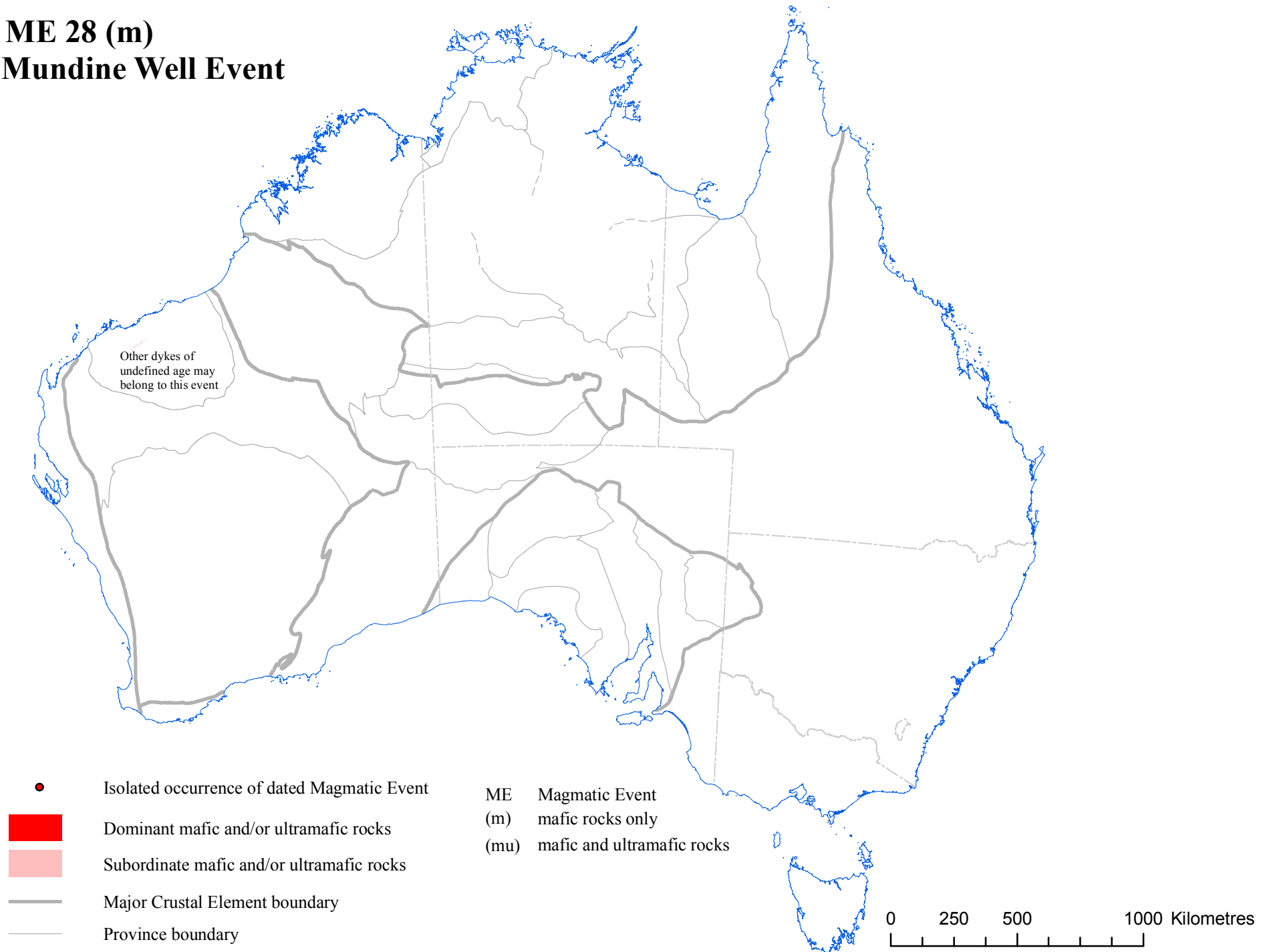
ME 30 (m) ~520 Ma Kalkarindji Event



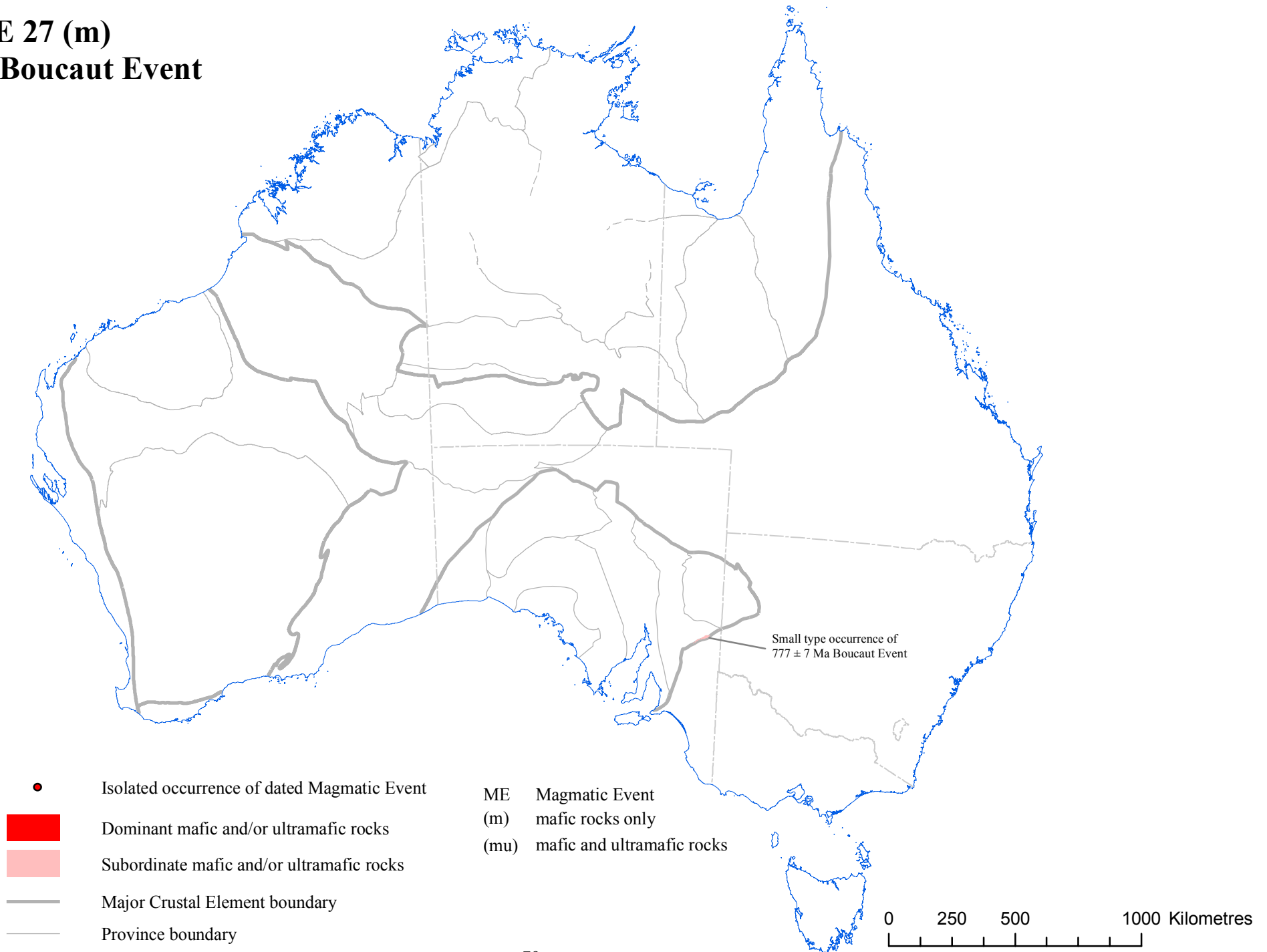
ME 29 (mu) ~575 Ma Skipworth Event



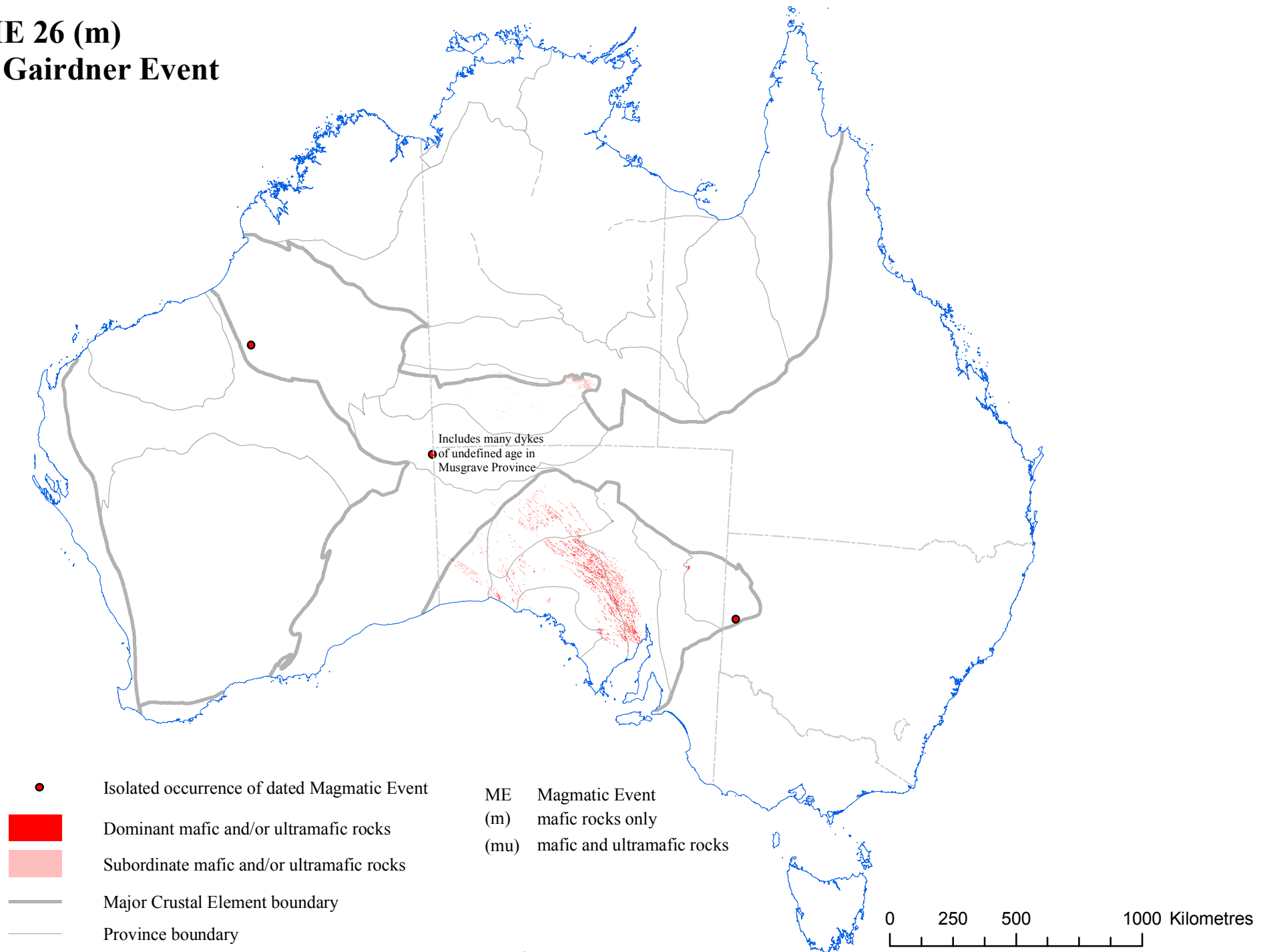
ME 28 (m) ~755 Ma Mundine Well Event



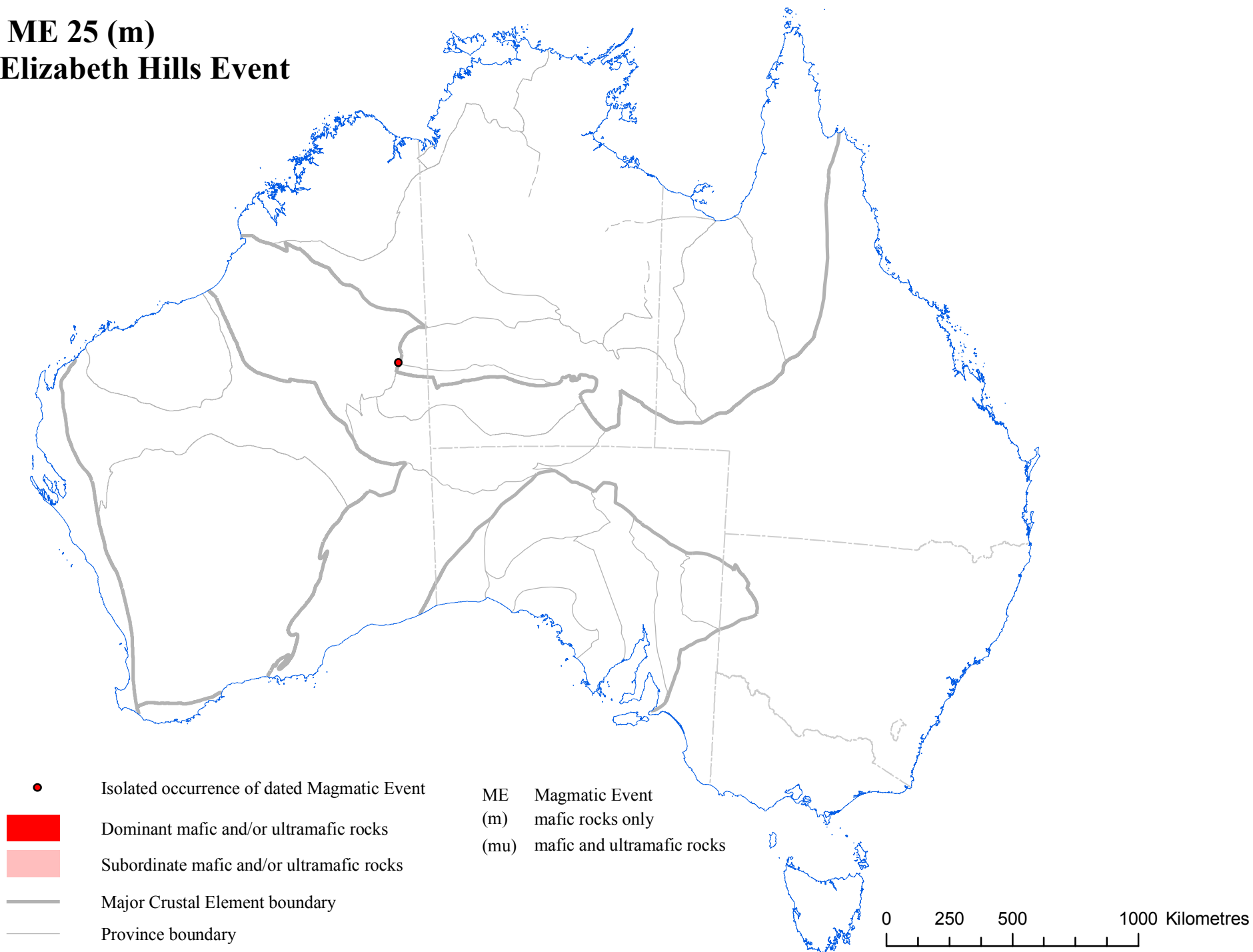
ME 27 (m) ~775 Ma Boucaut Event



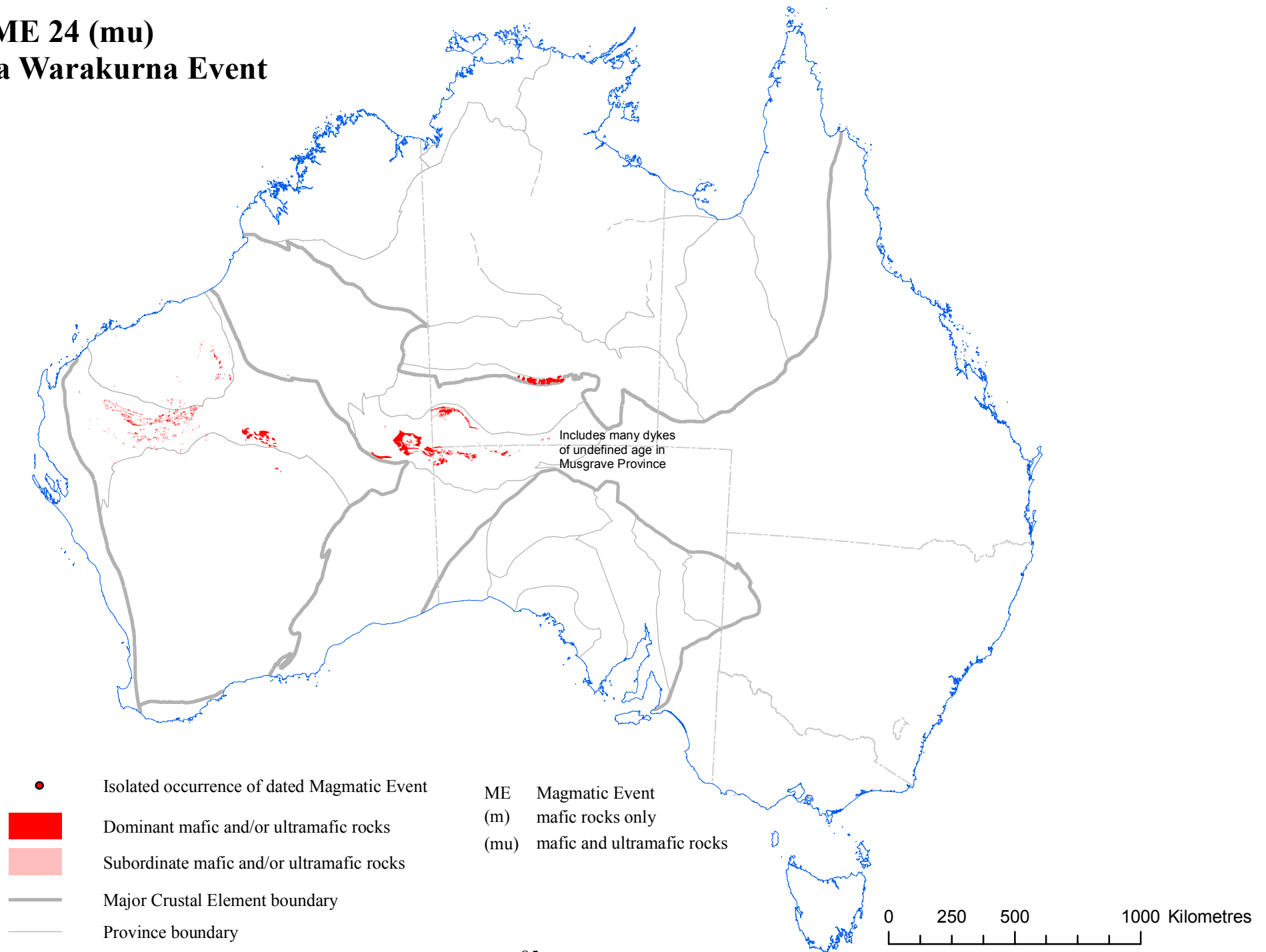
ME 26 (m) ~825 Ma Gairdner Event



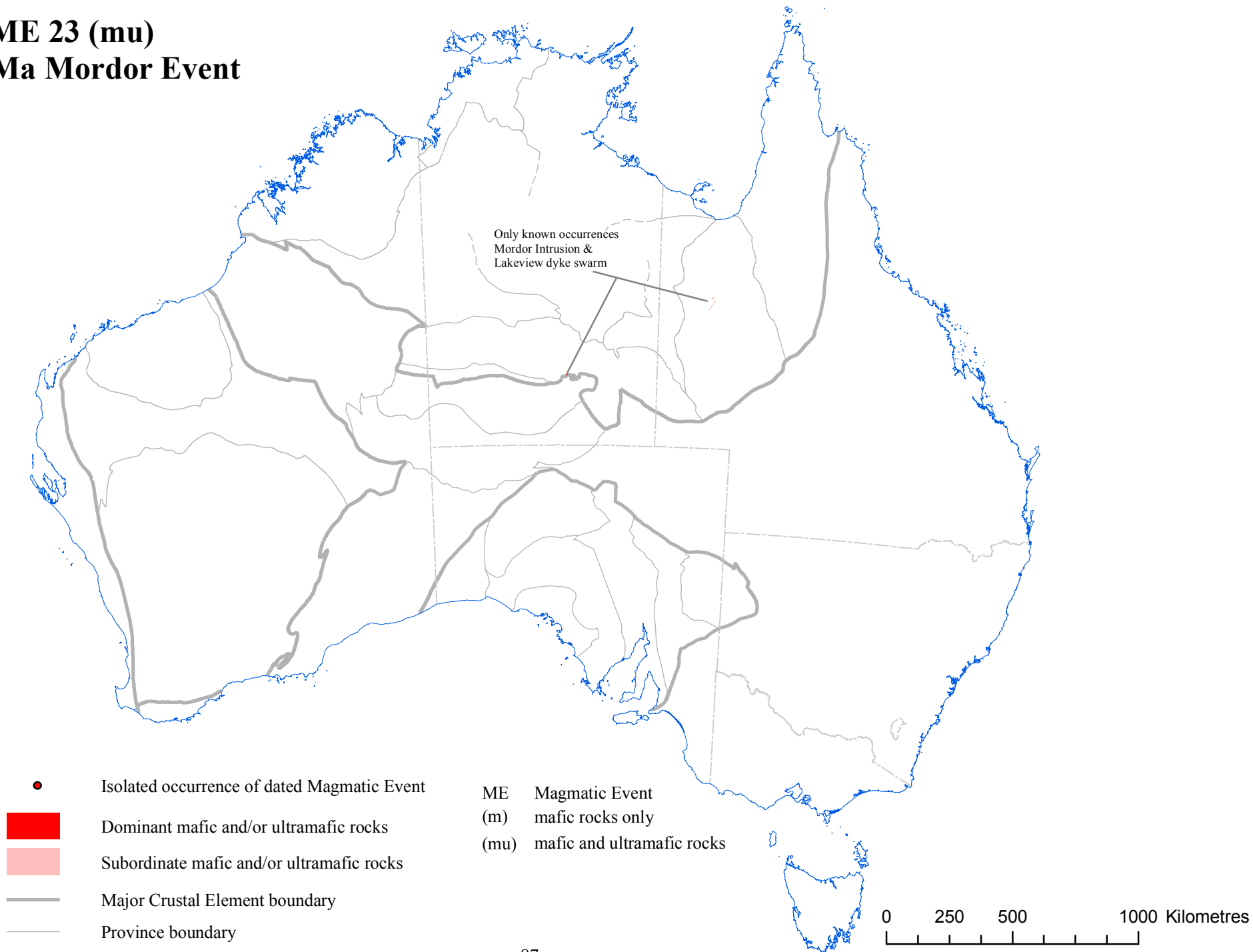
ME 25 (m) ~975 Ma Elizabeth Hills Event



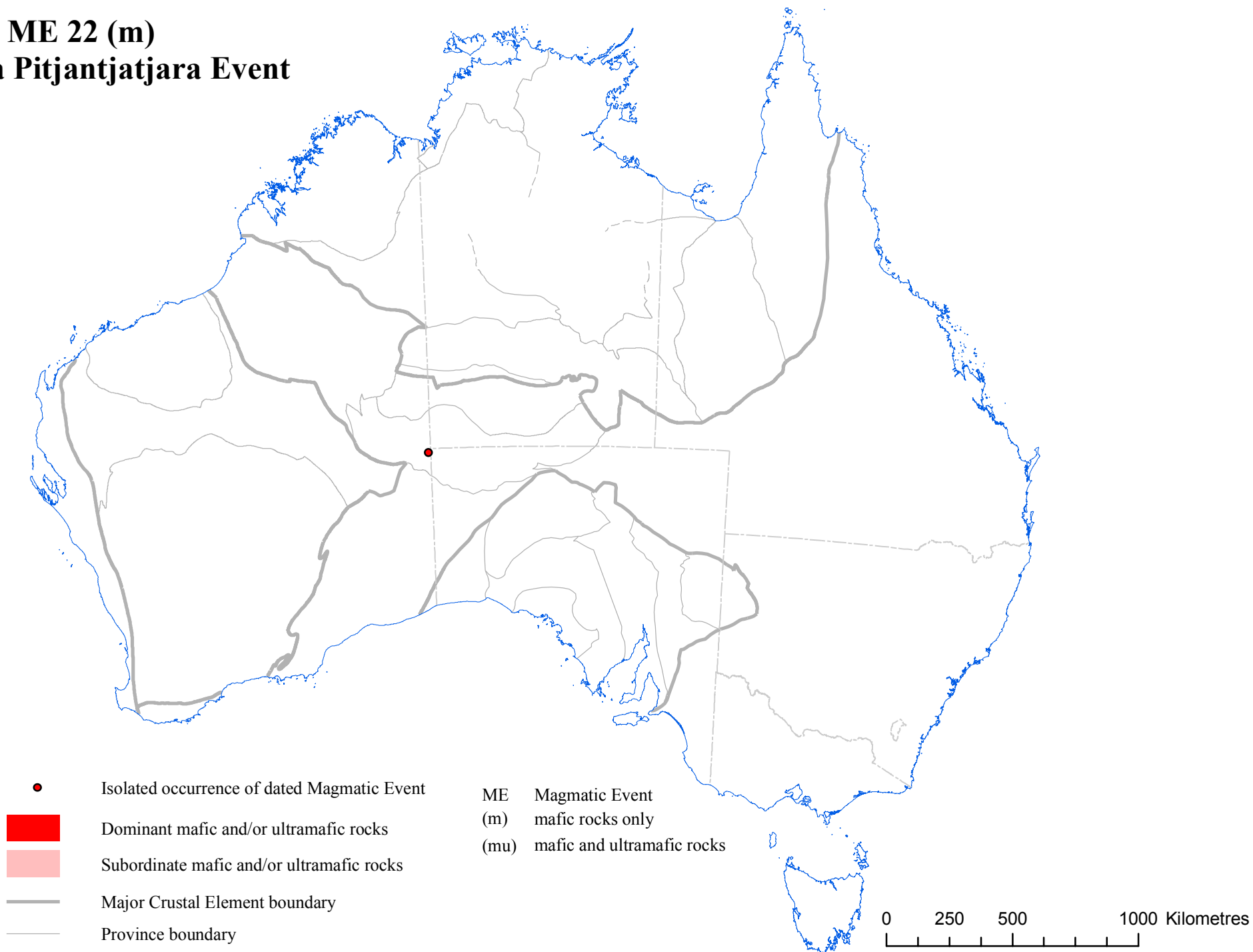
ME 24 (mu) ~1070 Ma Warakurna Event



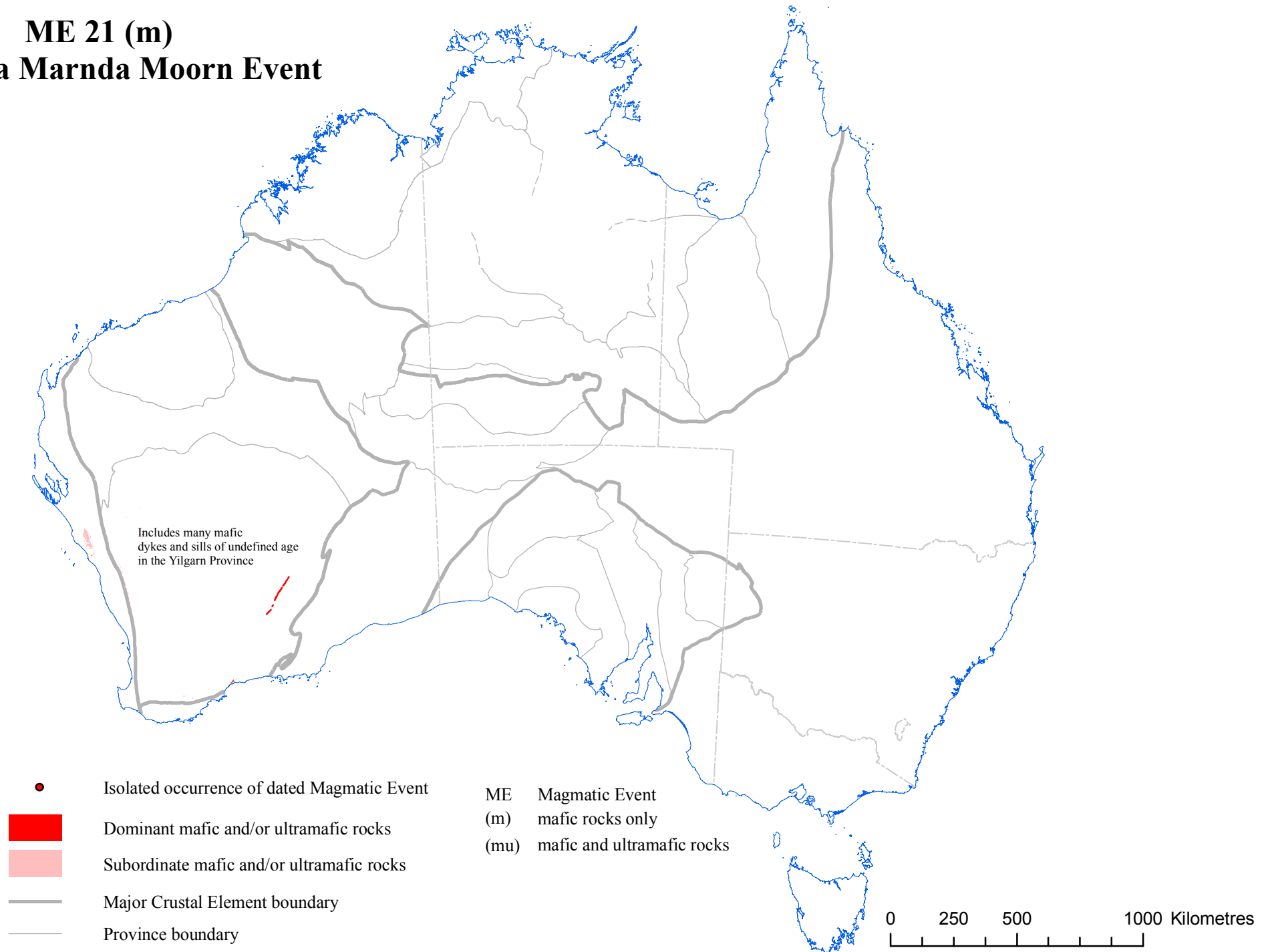
ME 23 (mu) ~1135 Ma Mordor Event



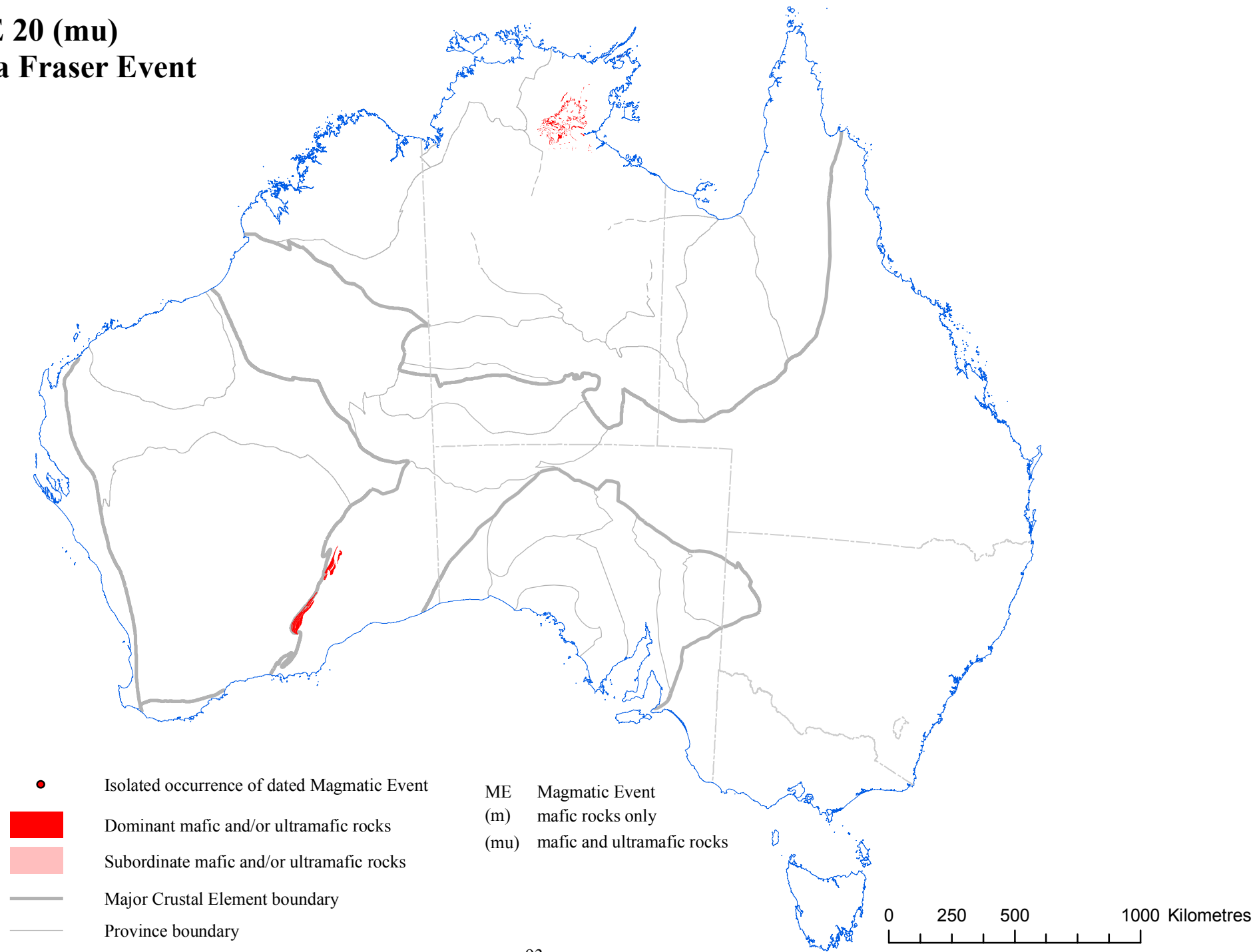
ME 22 (m) ~1180 Ma Pitjantjatjara Event



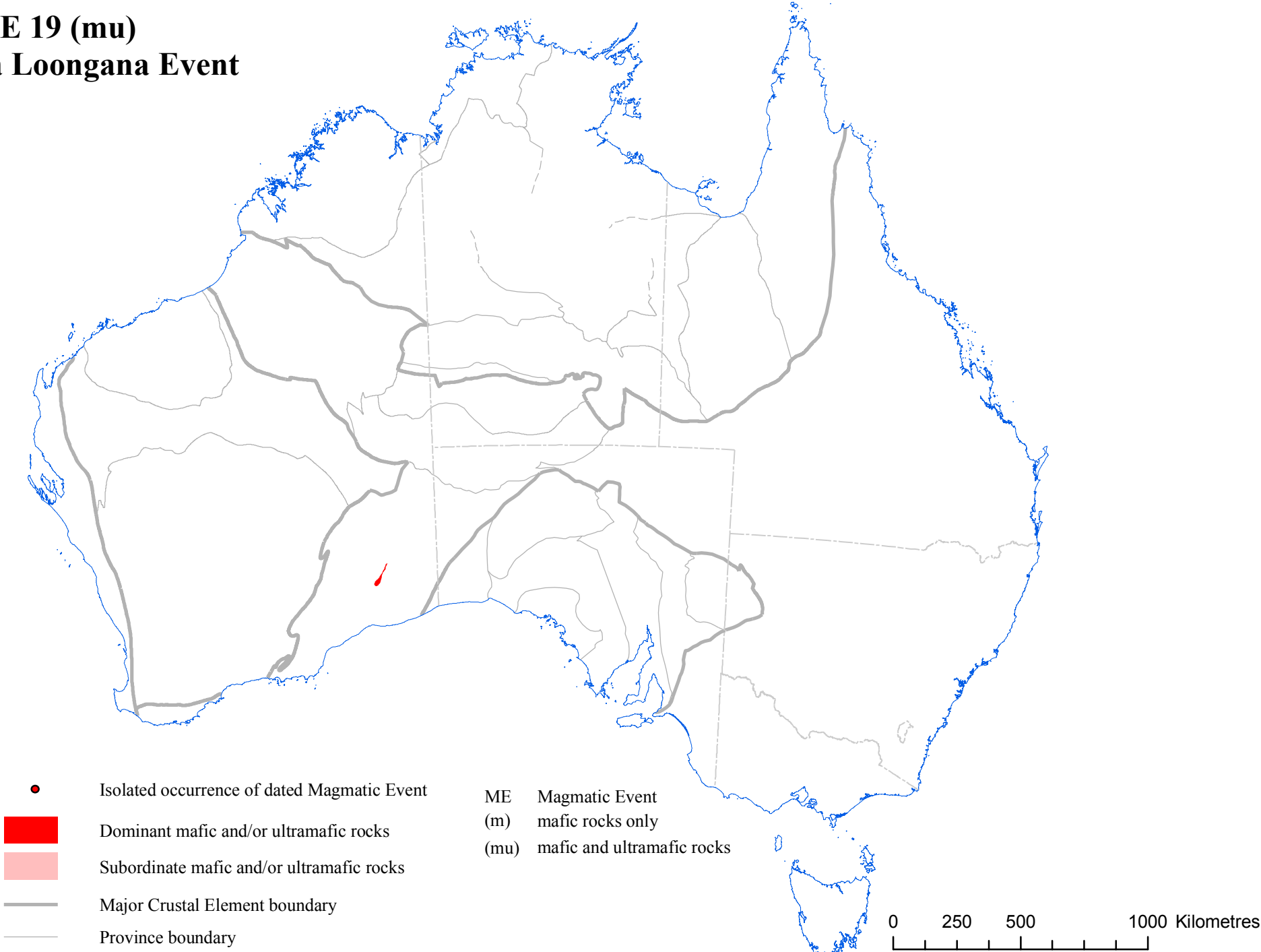
ME 21 (m) ~1210 Ma Marnda Moorn Event



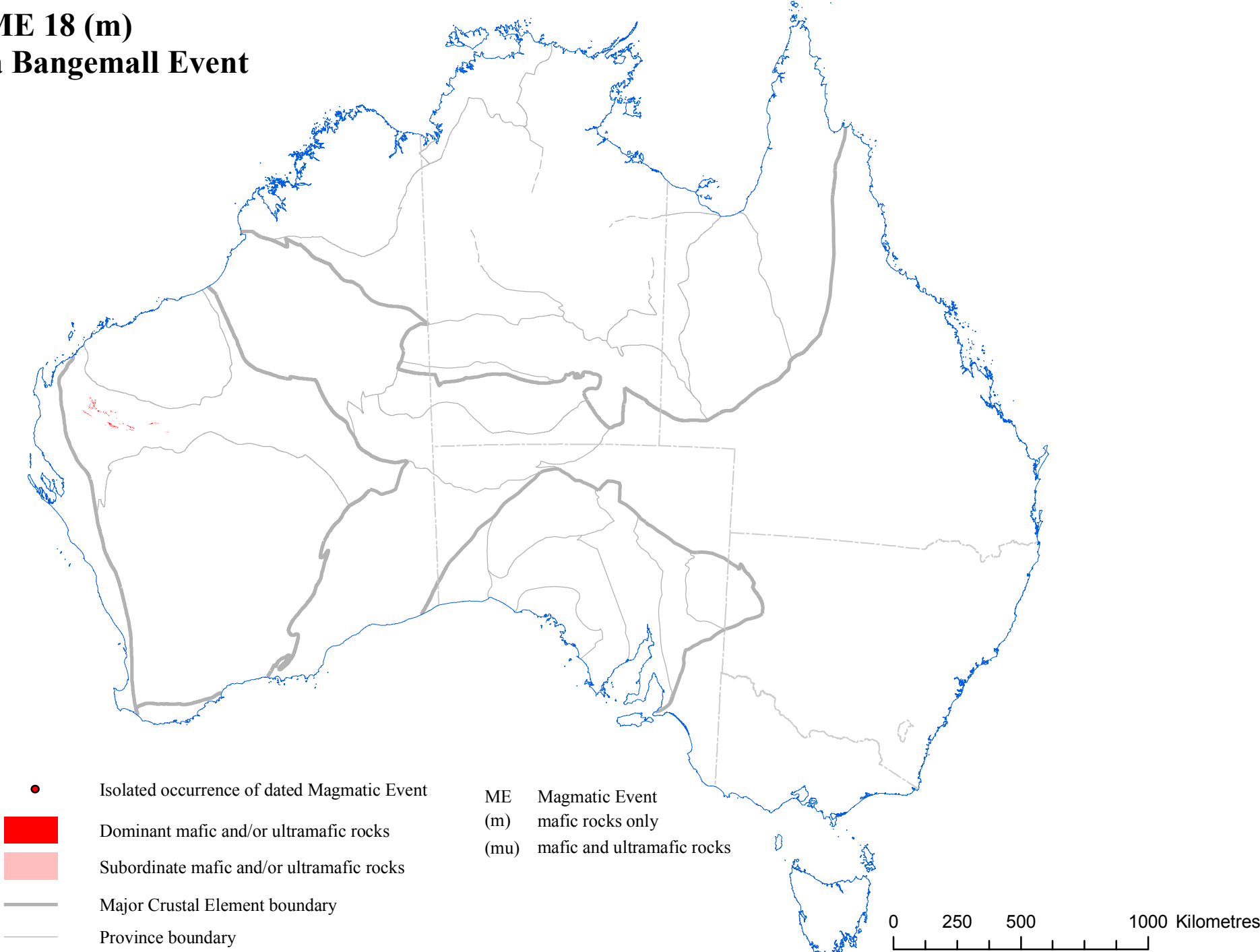
ME 20 (mu)
~1310 Ma Fraser Event



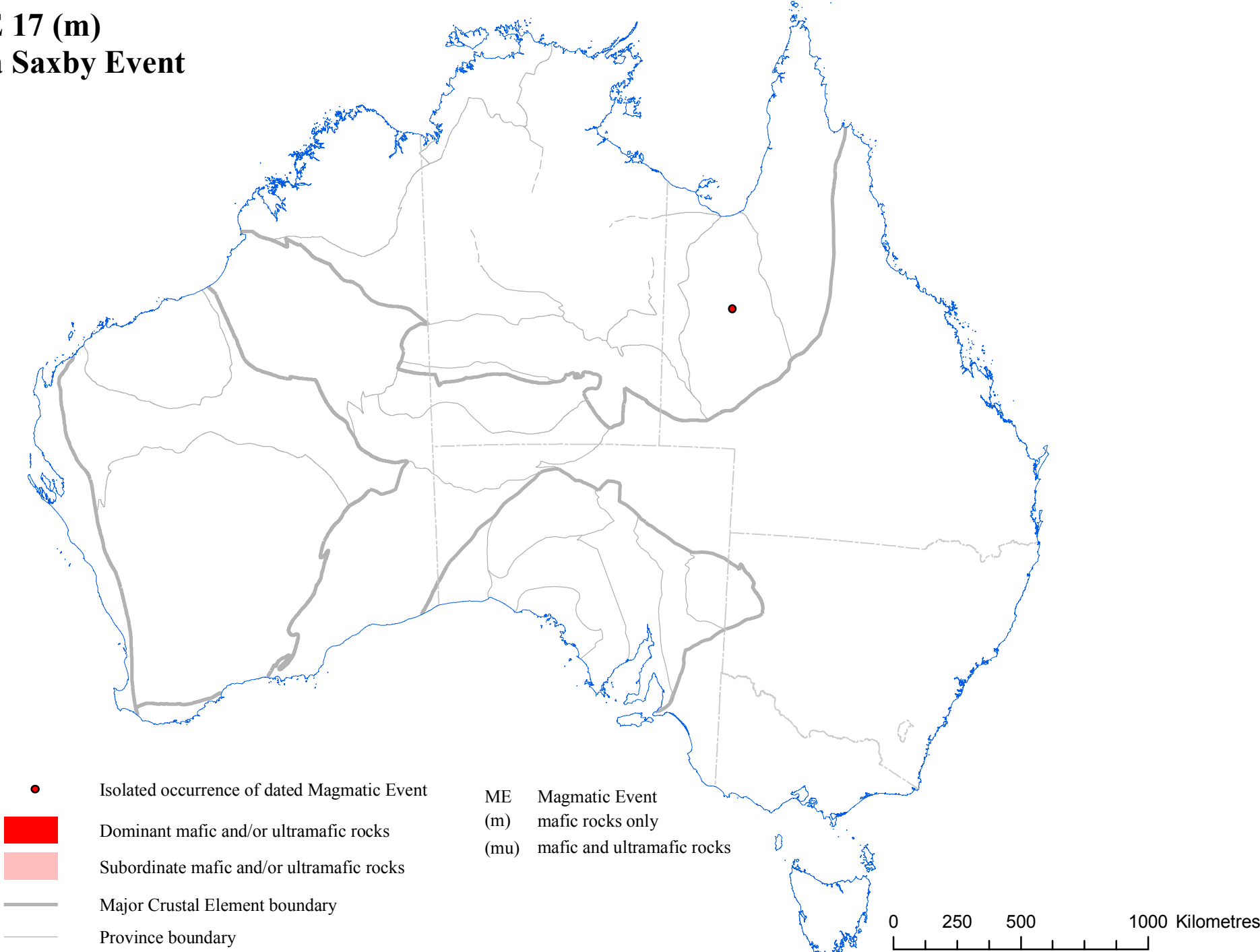
ME 19 (mu)
~1415 Ma Loongana Event



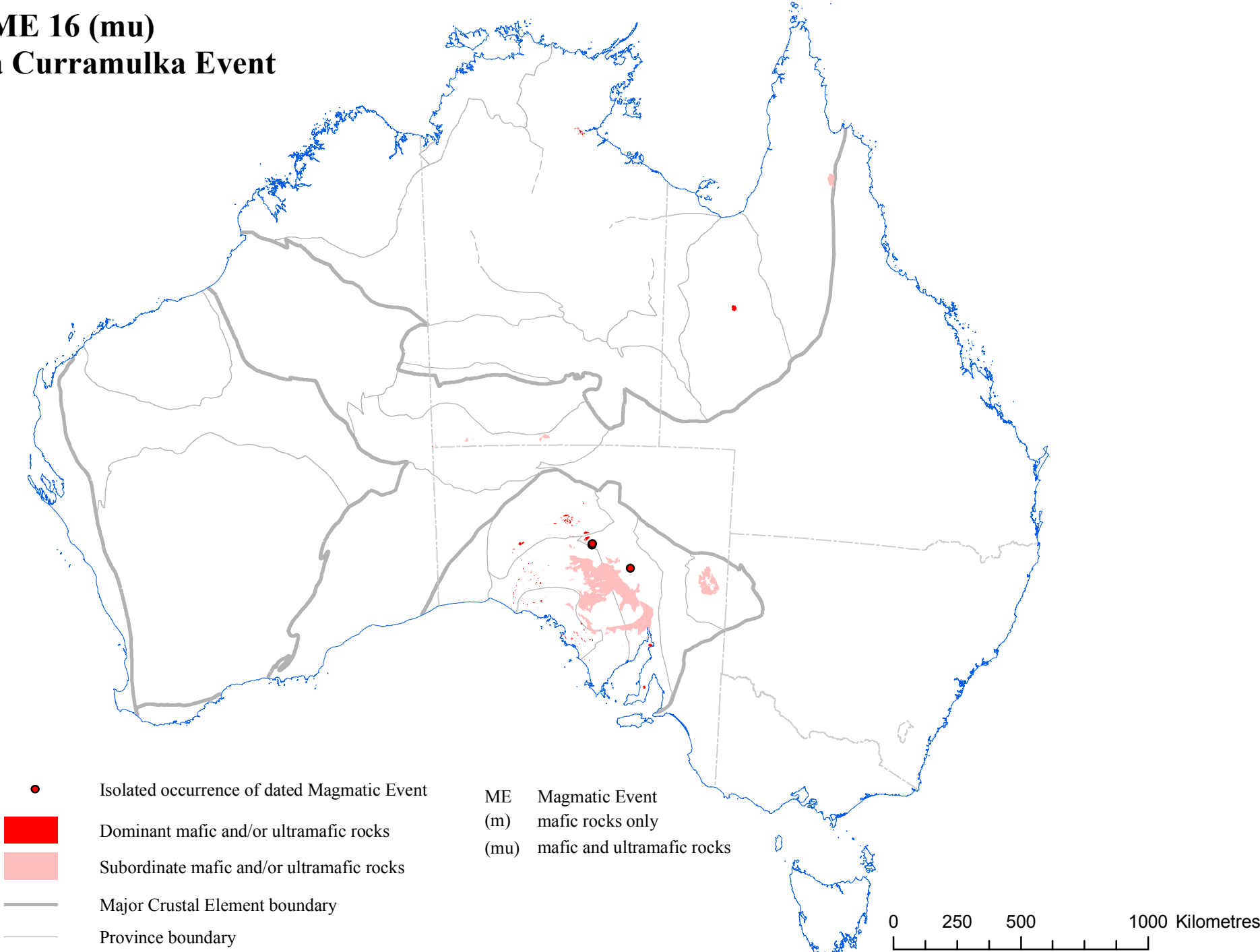
ME 18 (m)
~1465 Ma Bangemall Event



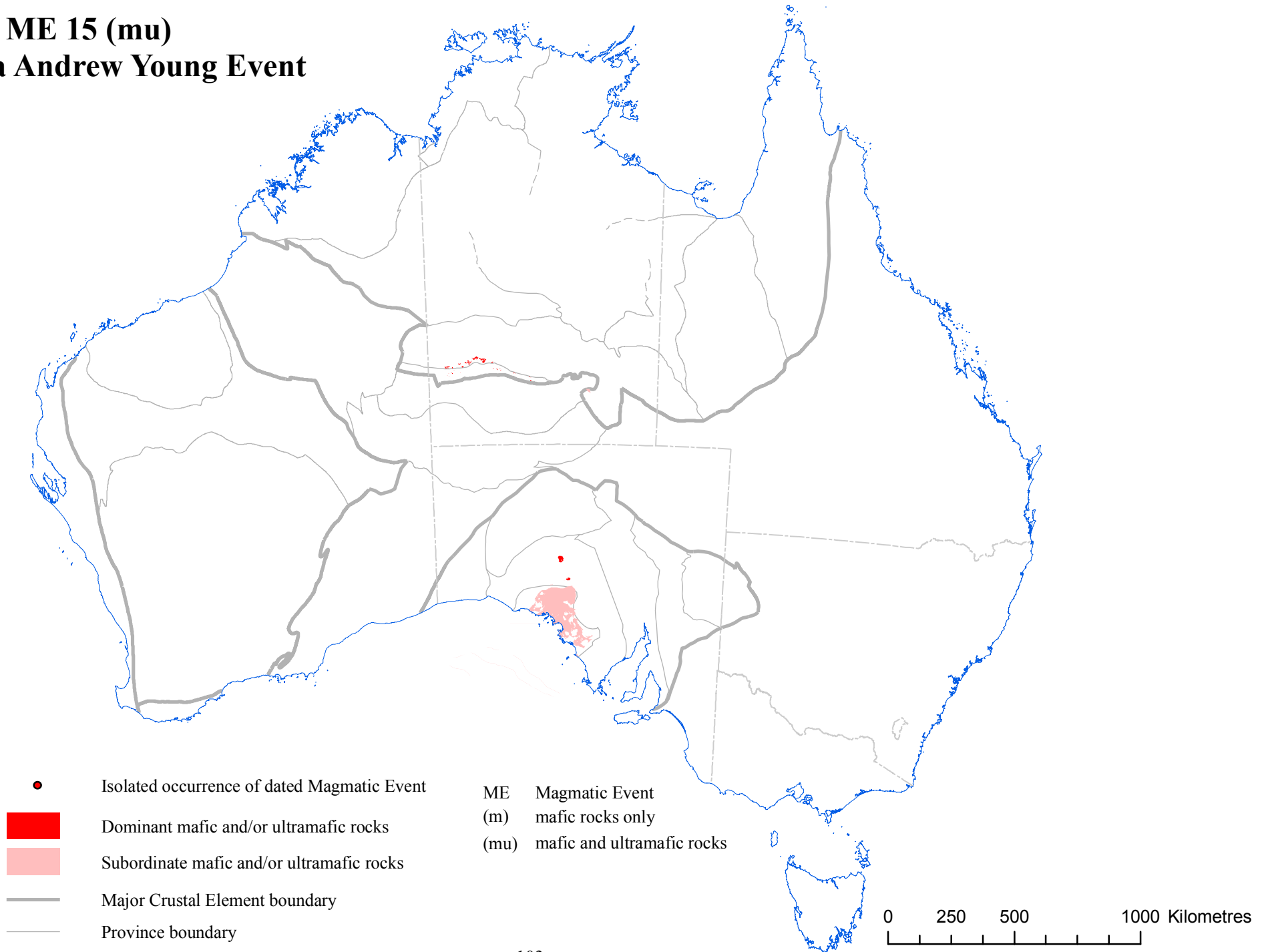
ME 17 (m)
~1530 Ma Saxby Event



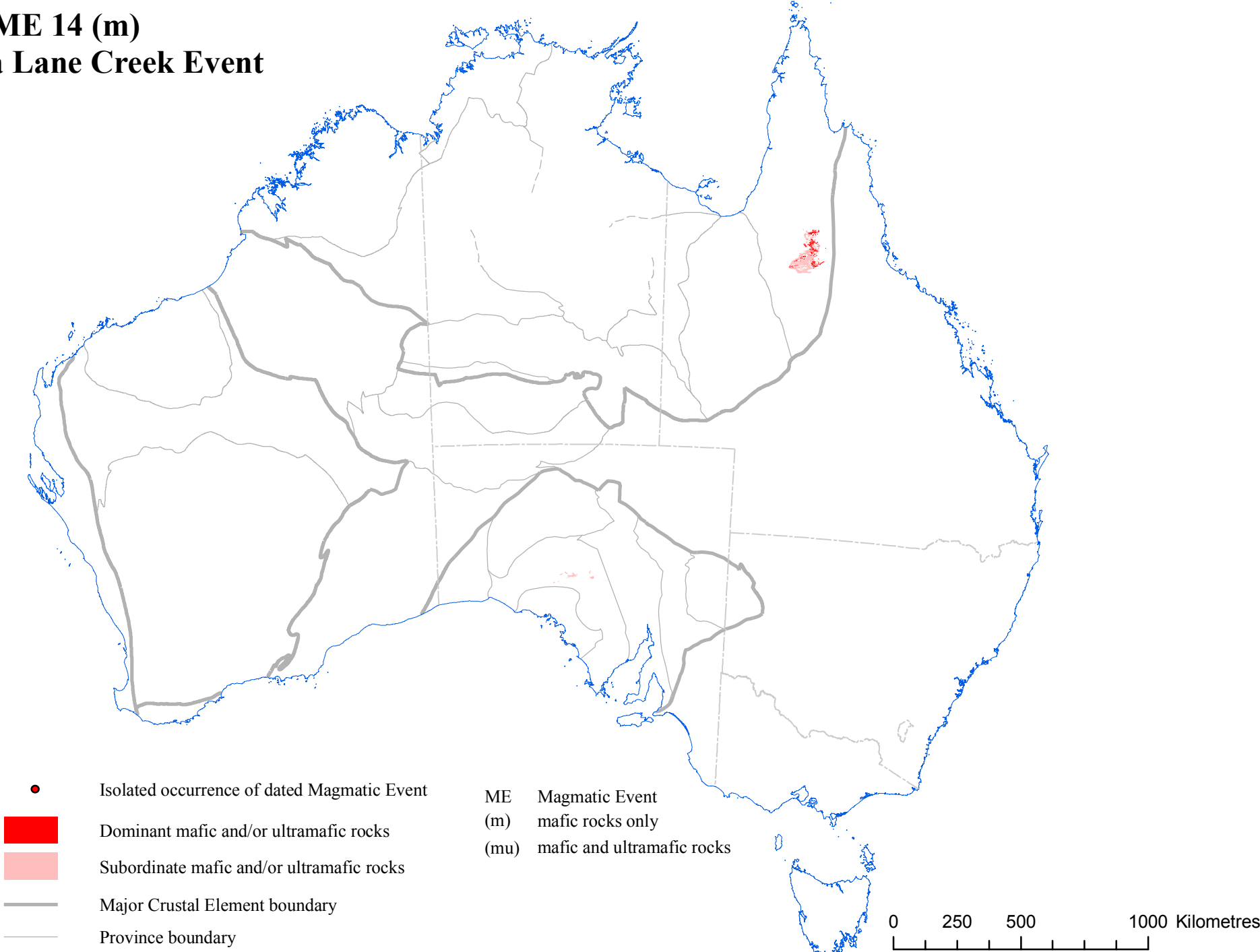
ME 16 (mu)
~1590 Ma Curramulka Event



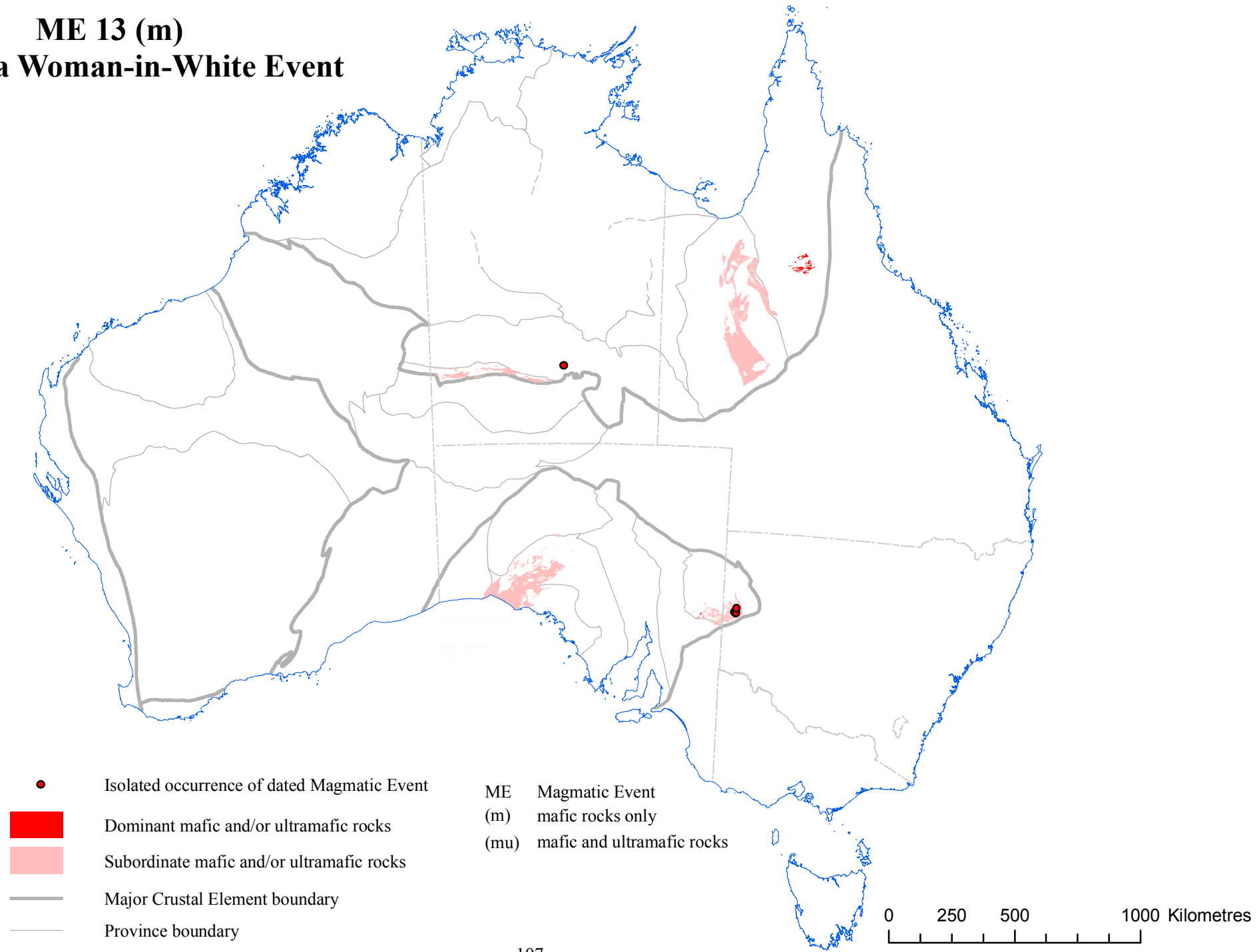
ME 15 (mu) ~1635 Ma Andrew Young Event



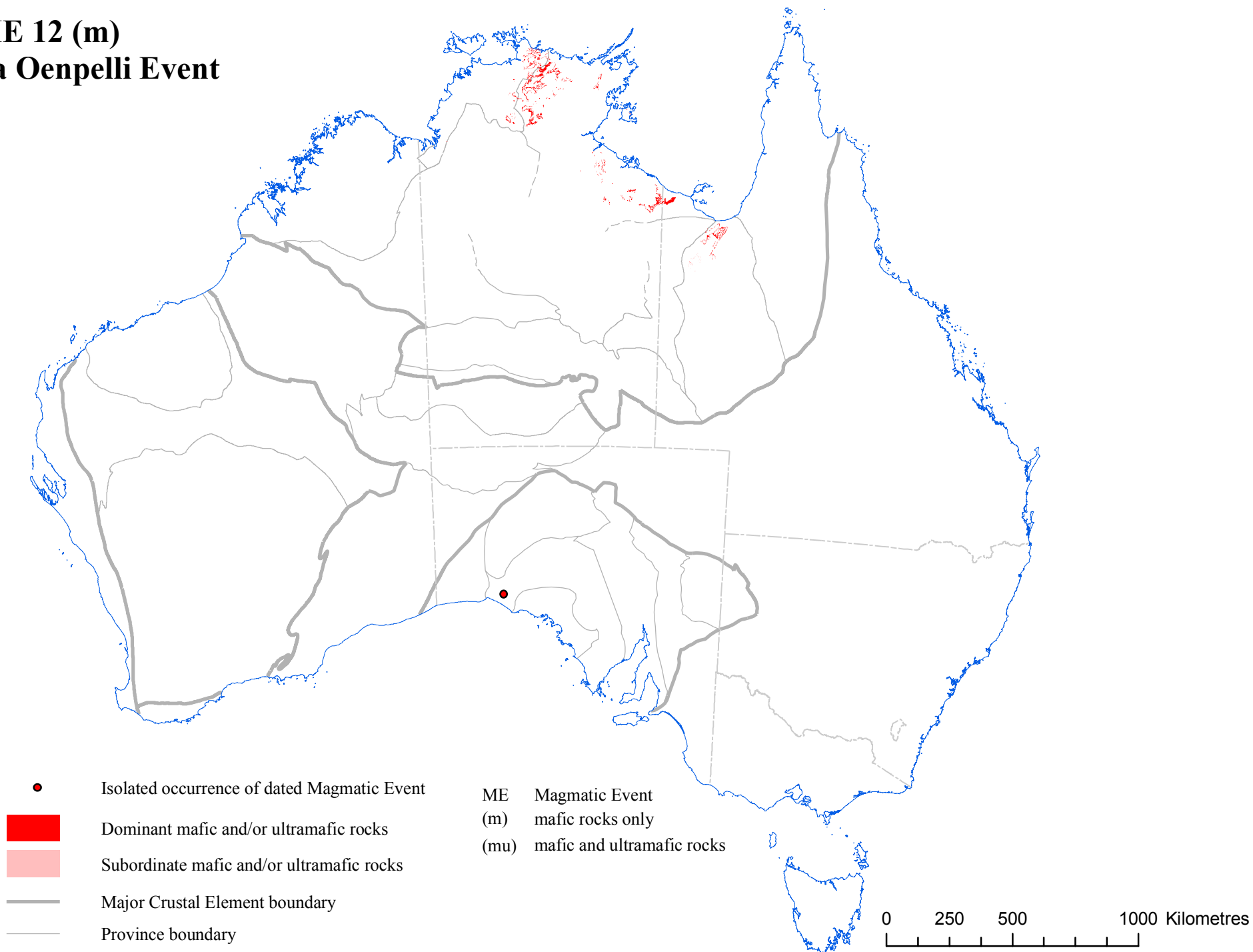
ME 14 (m)
~1655 Ma Lane Creek Event



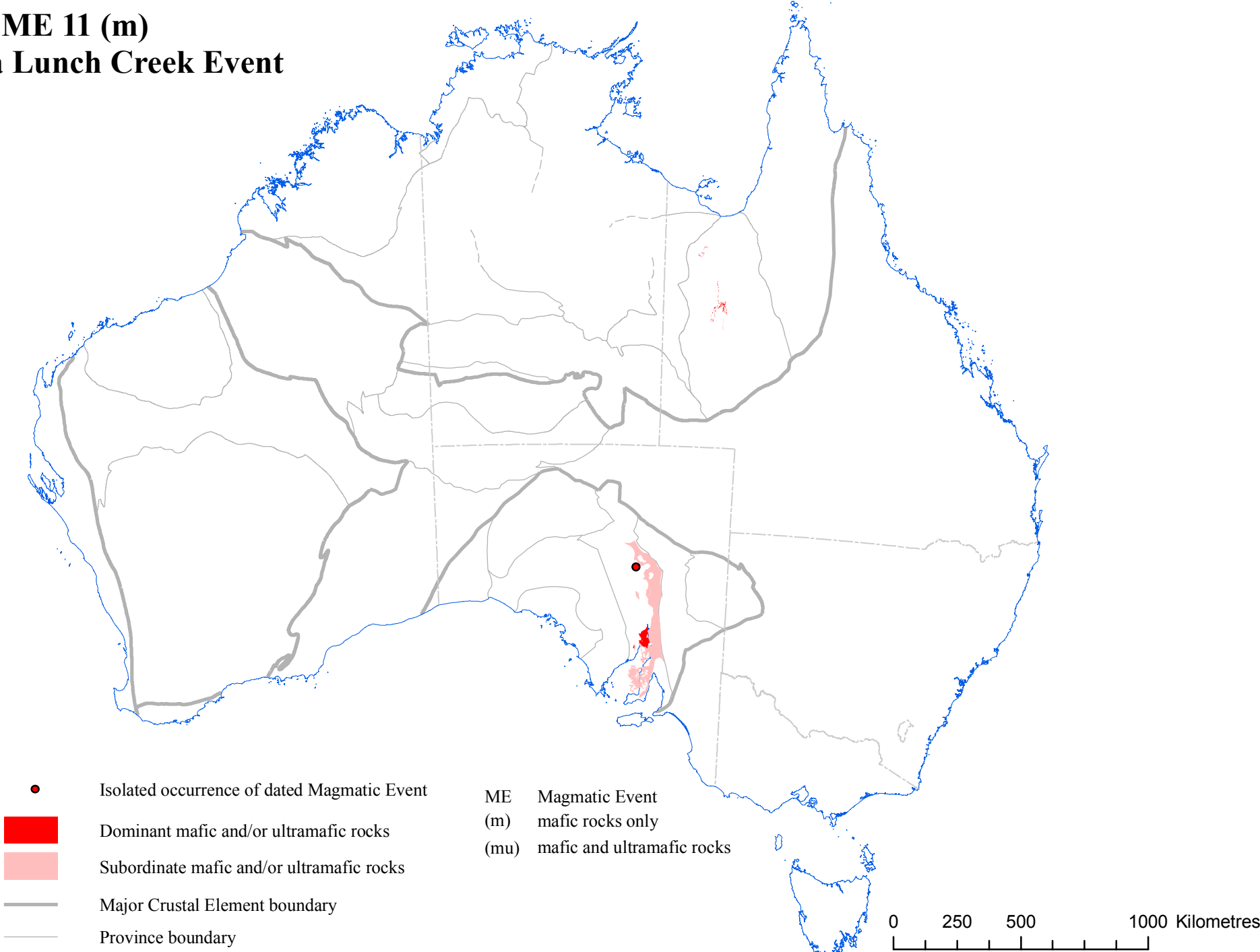
ME 13 (m)
~1680 Ma Woman-in-White Event



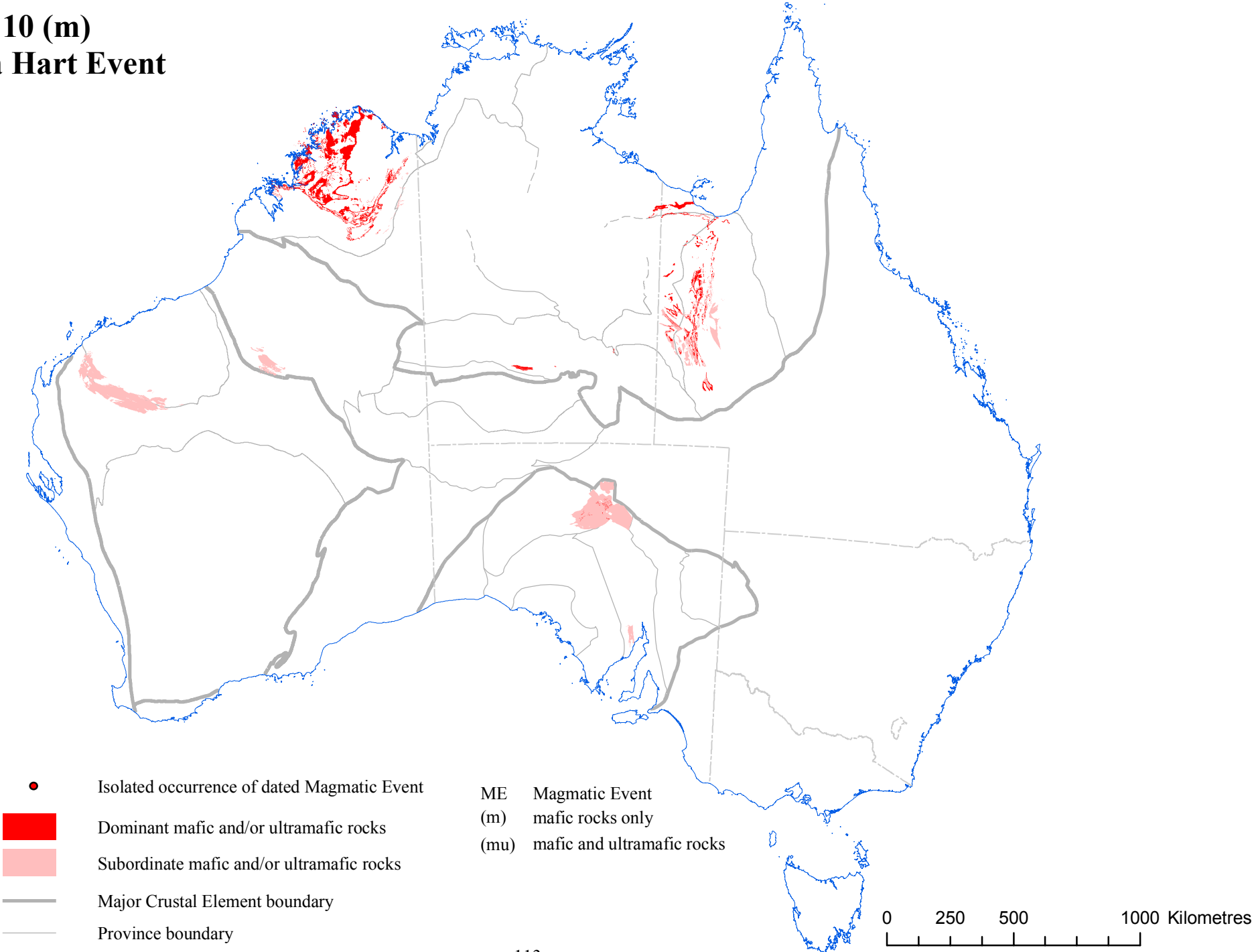
ME 12 (m) ~1720 Ma Oenpelli Event



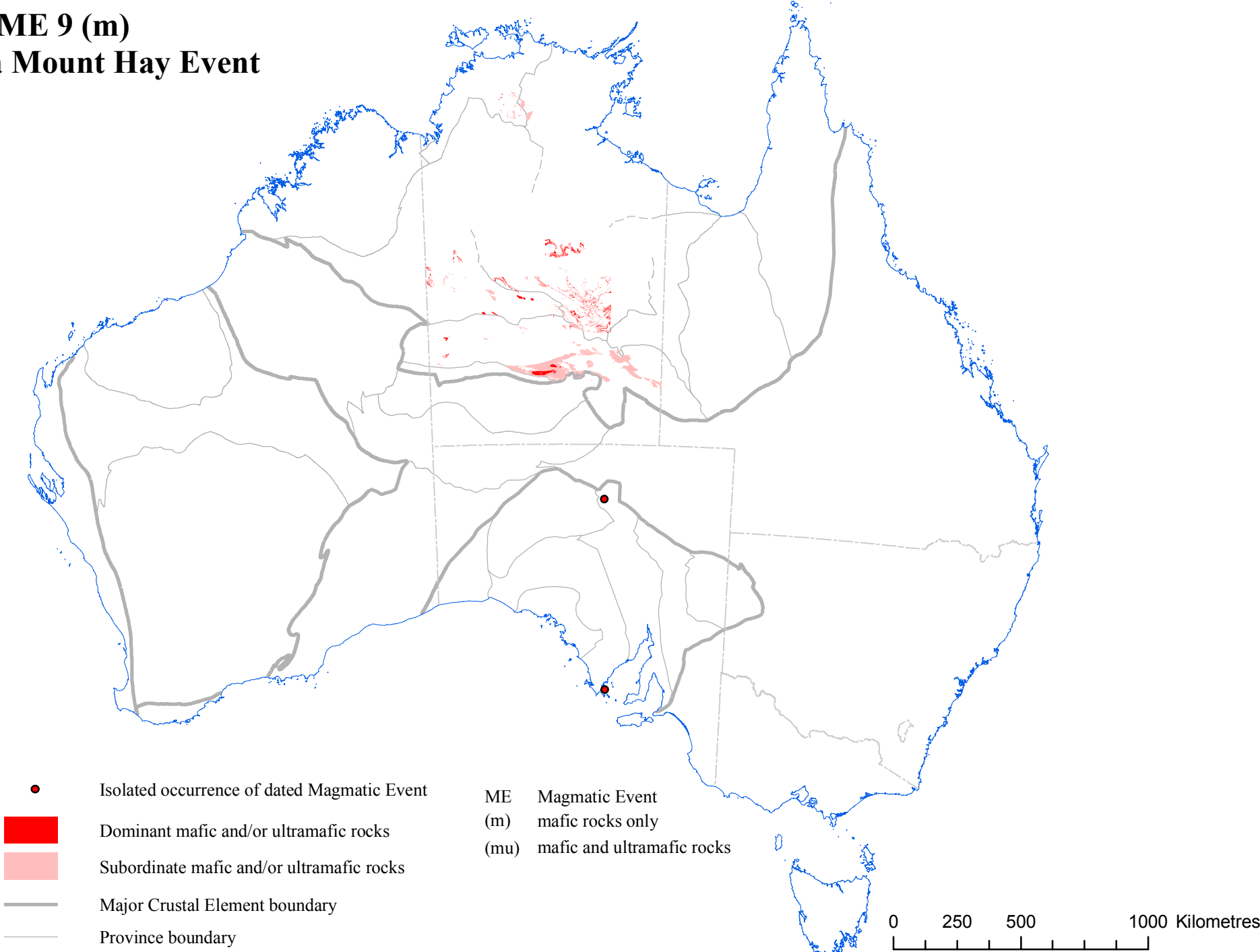
ME 11 (m)
~1750 Ma Lunch Creek Event



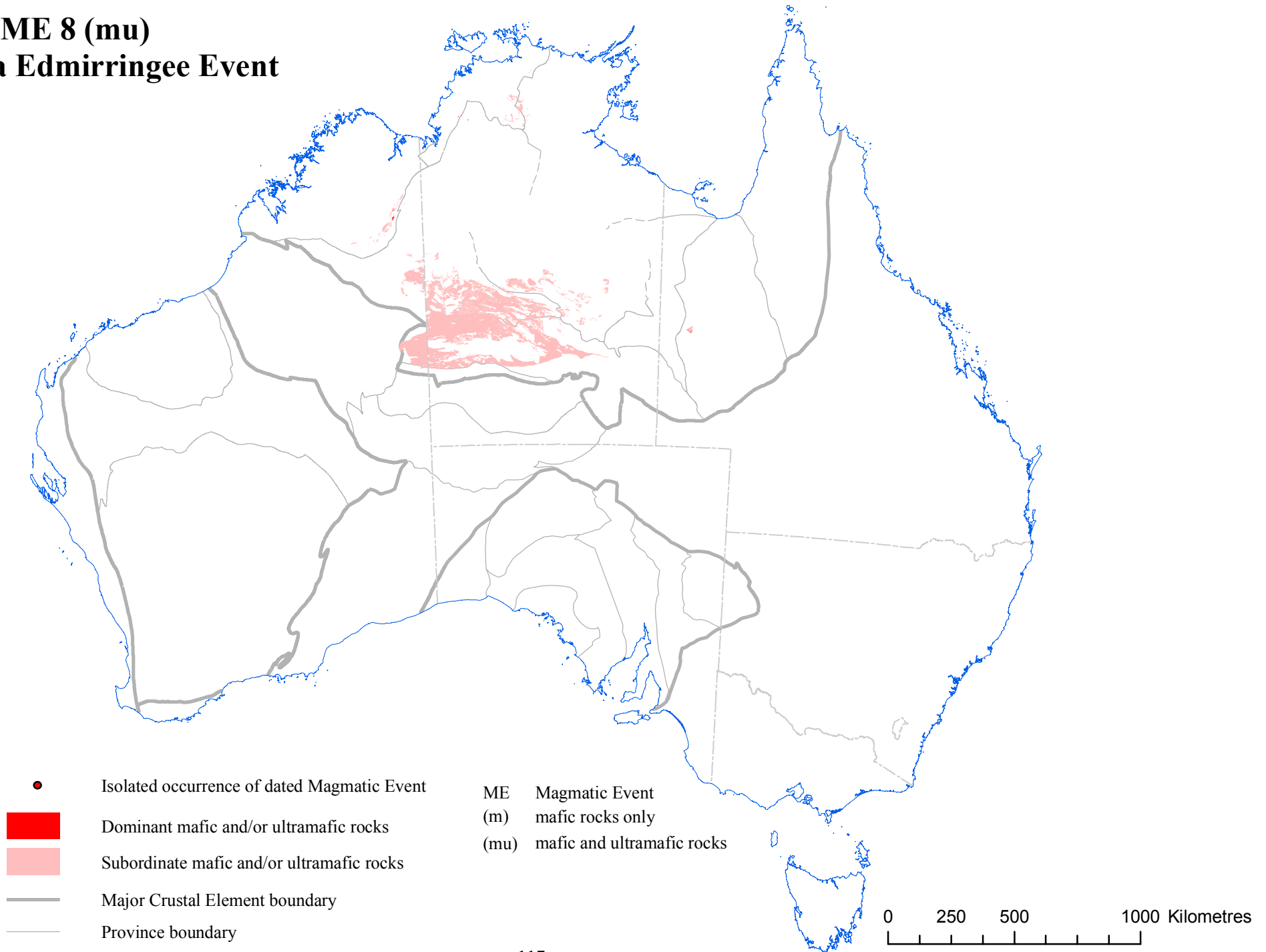
ME 10 (m) **~1780 Ma Hart Event**



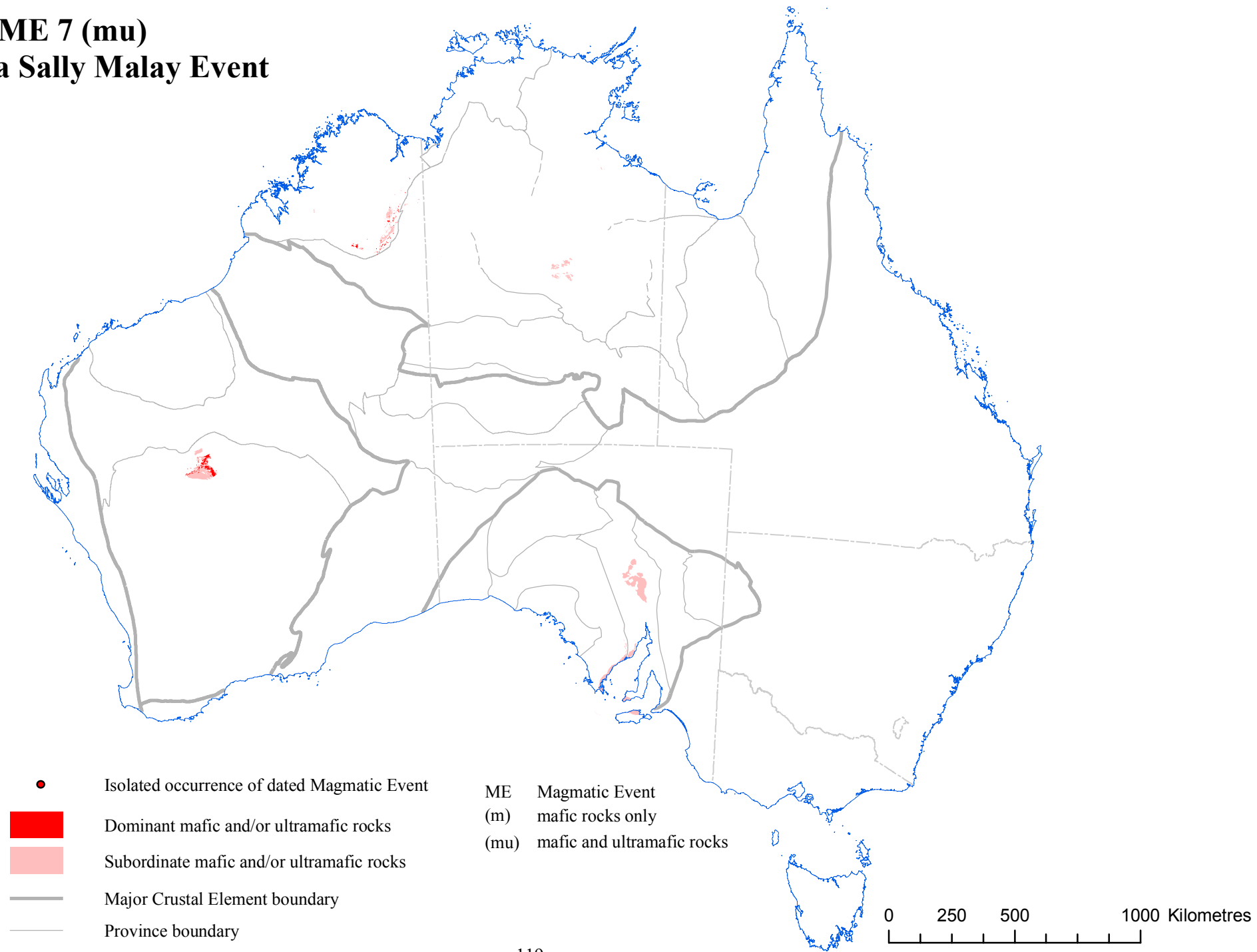
ME 9 (m)
~1810 Ma Mount Hay Event



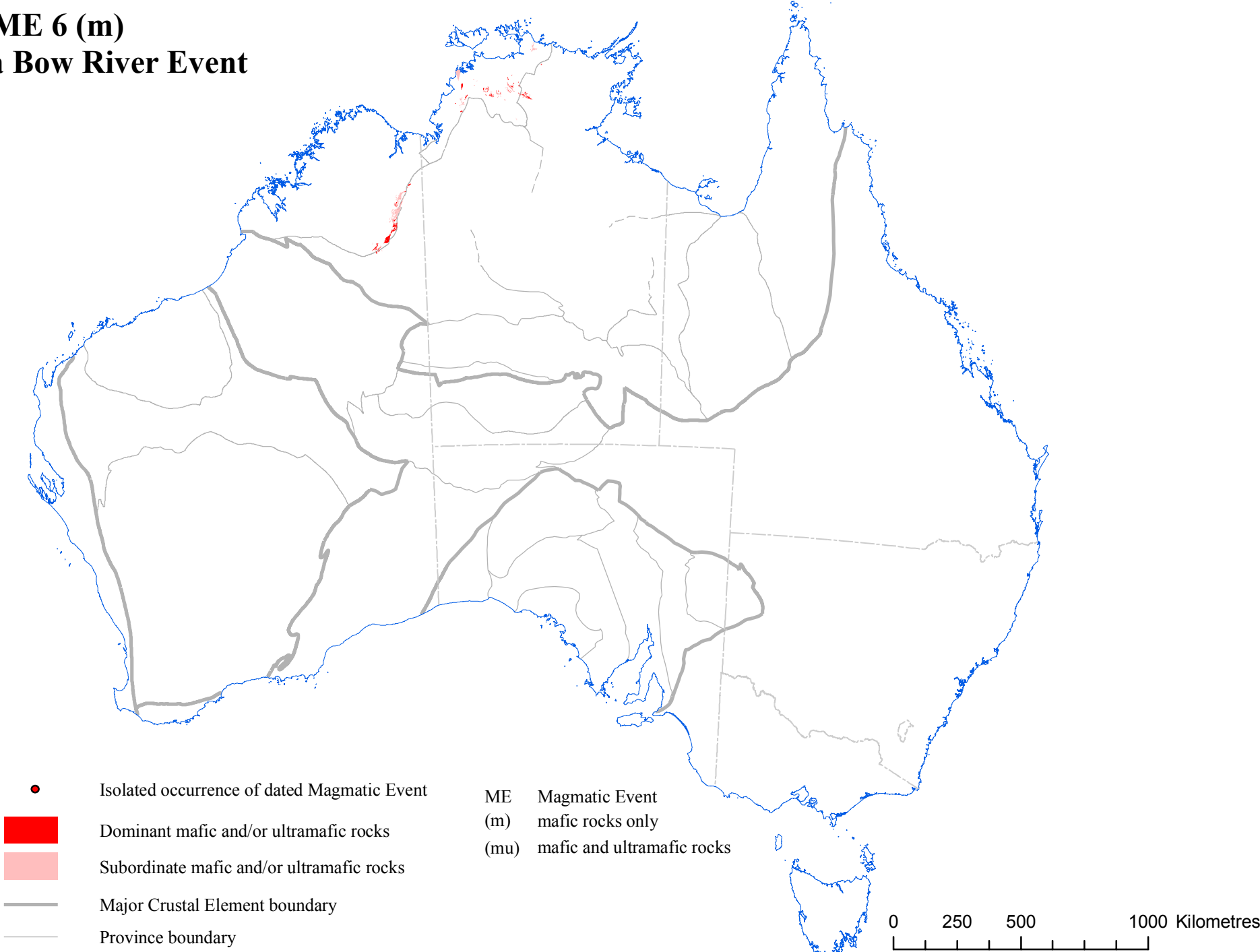
ME 8 (mu) ~1830 Ma Edmirringee Event



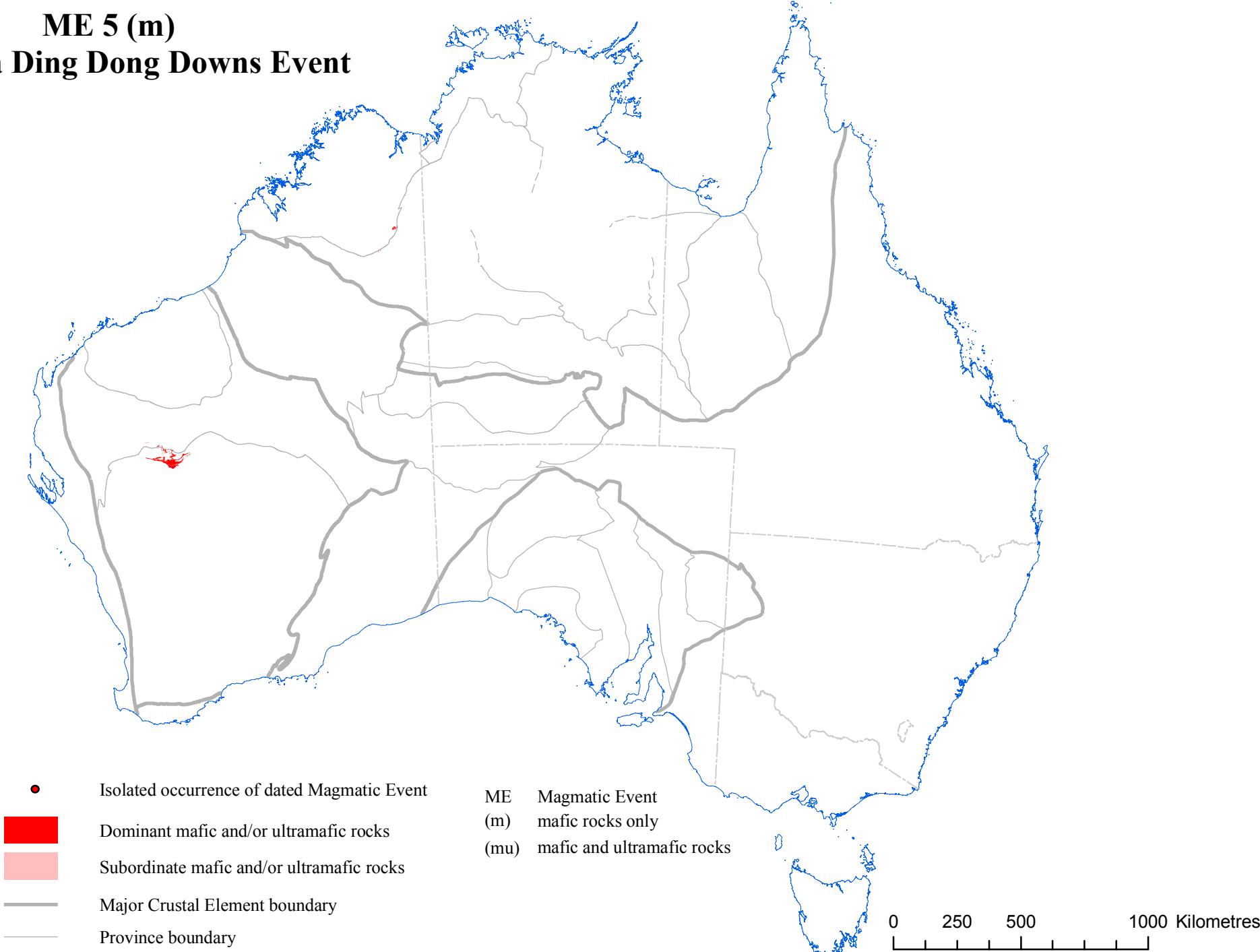
ME 7 (mu)
~1850 Ma Sally Malay Event



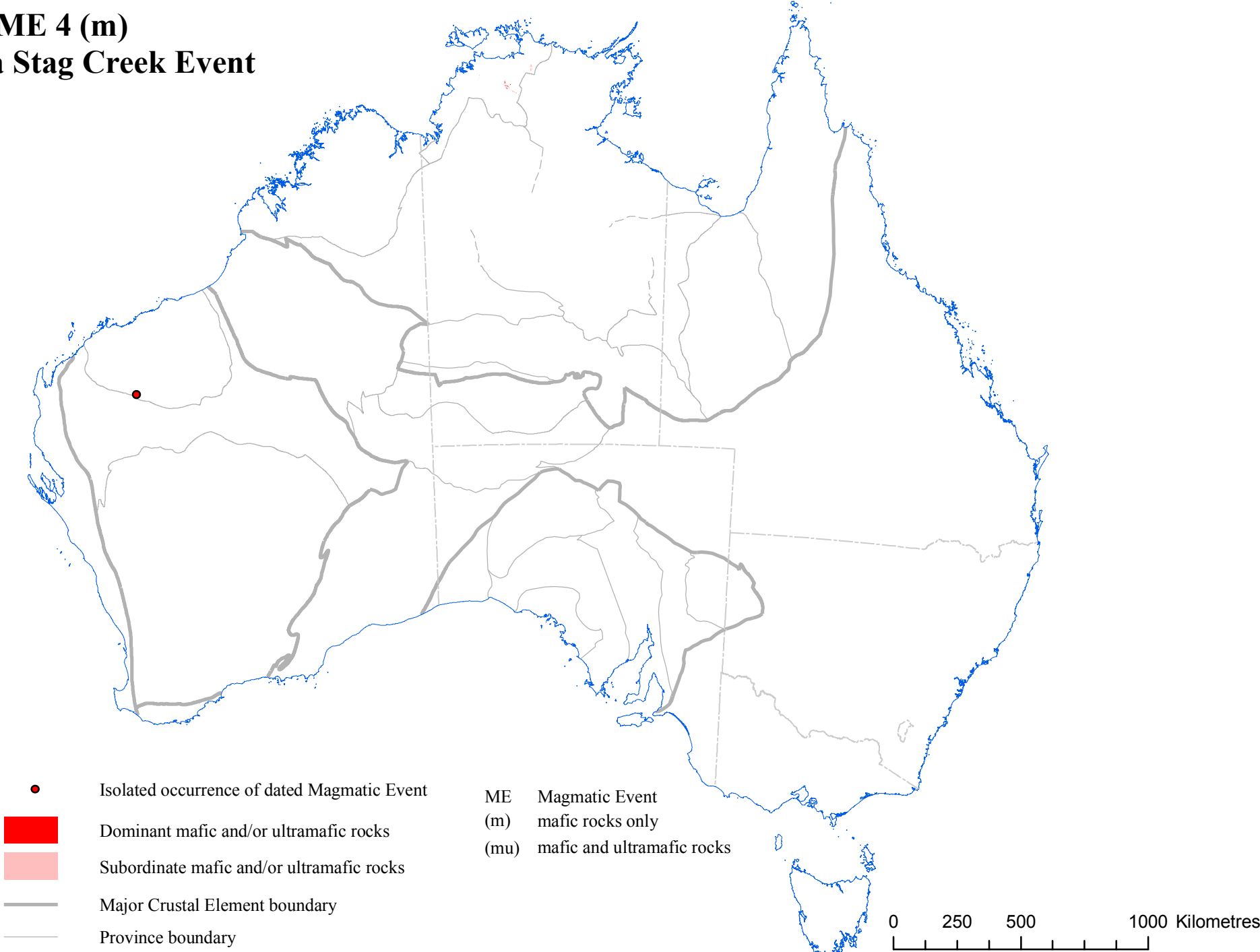
ME 6 (m)
~1870 Ma Bow River Event



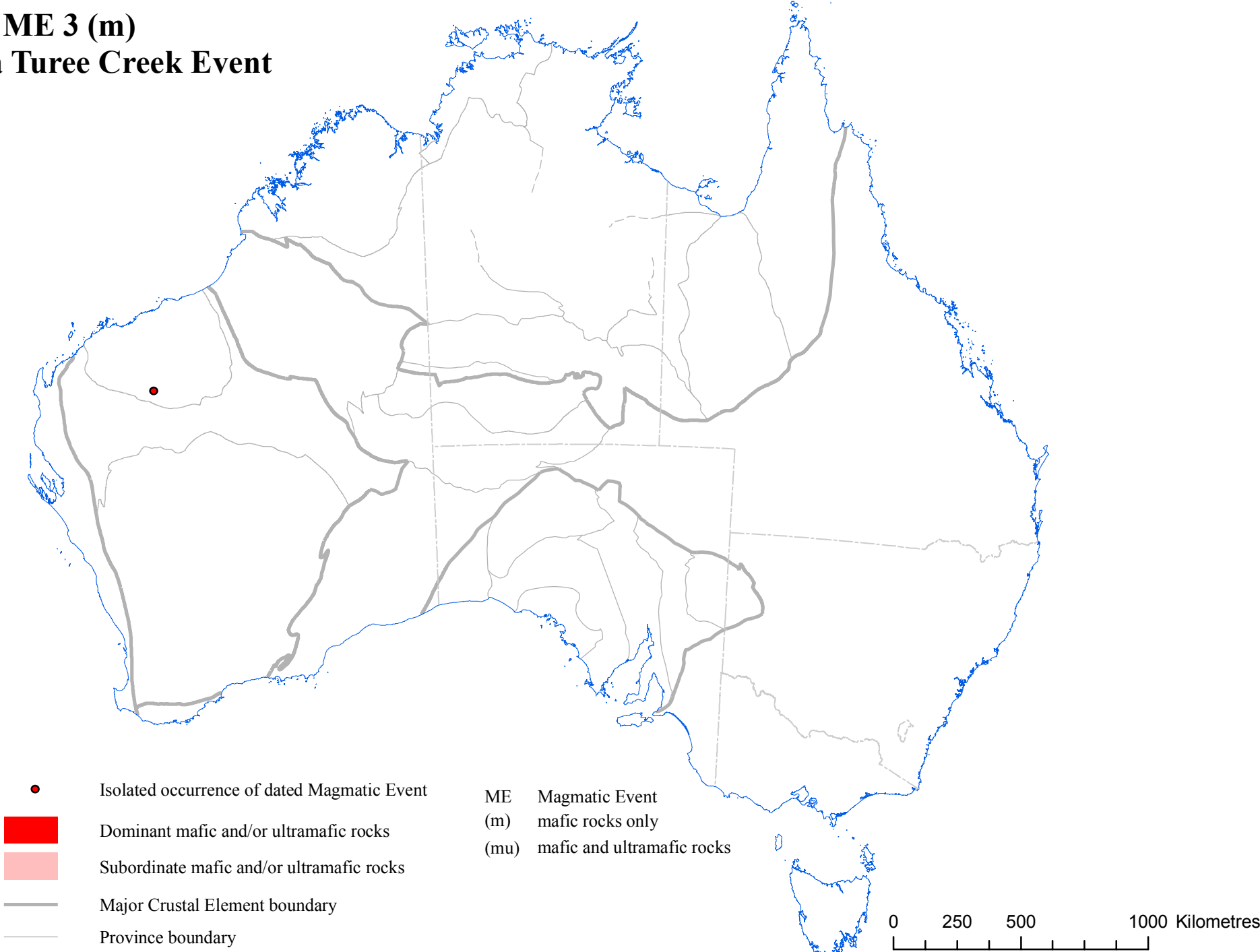
ME 5 (m)
~1910 Ma Ding Dong Downs Event



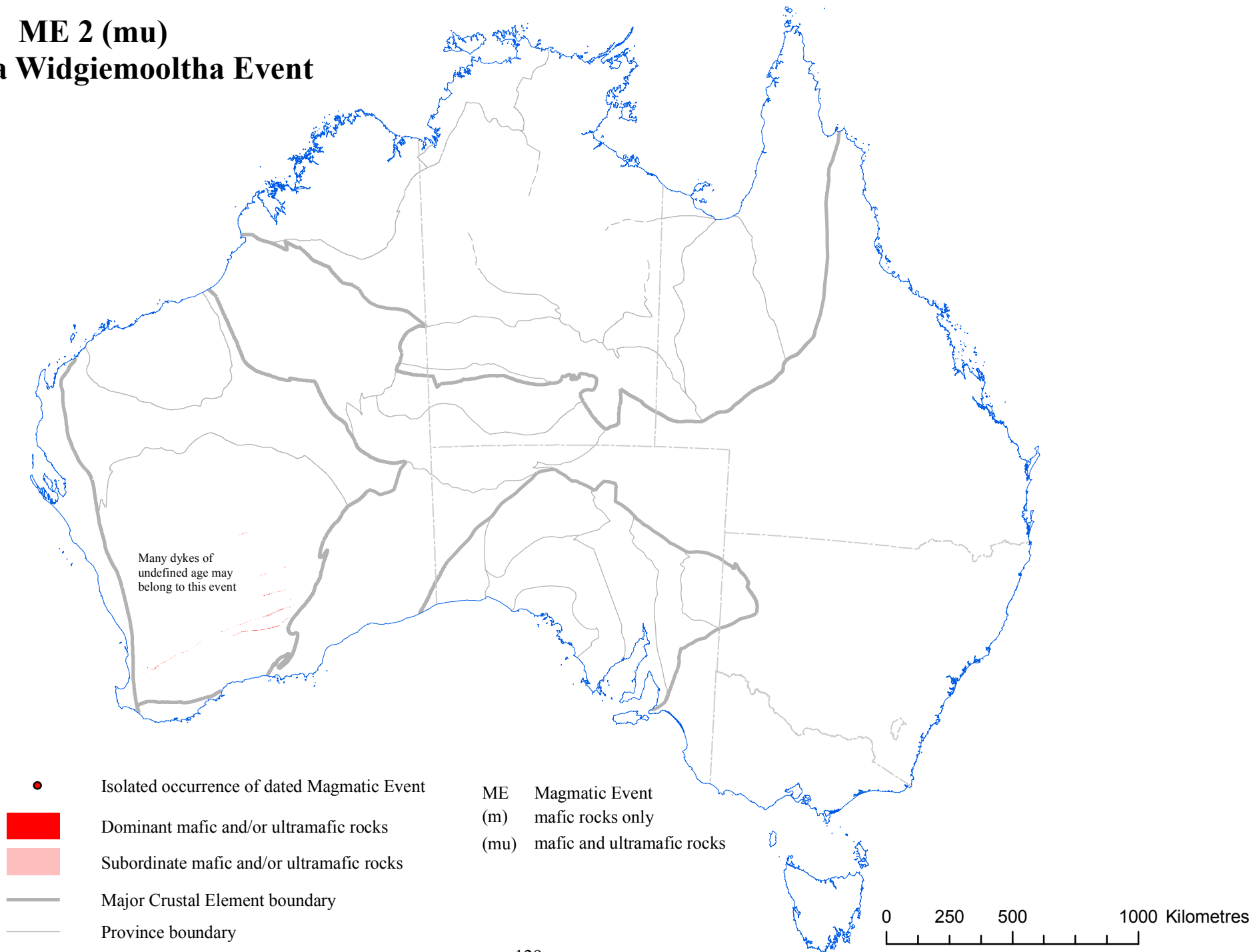
ME 4 (m)
~2015 Ma Stag Creek Event



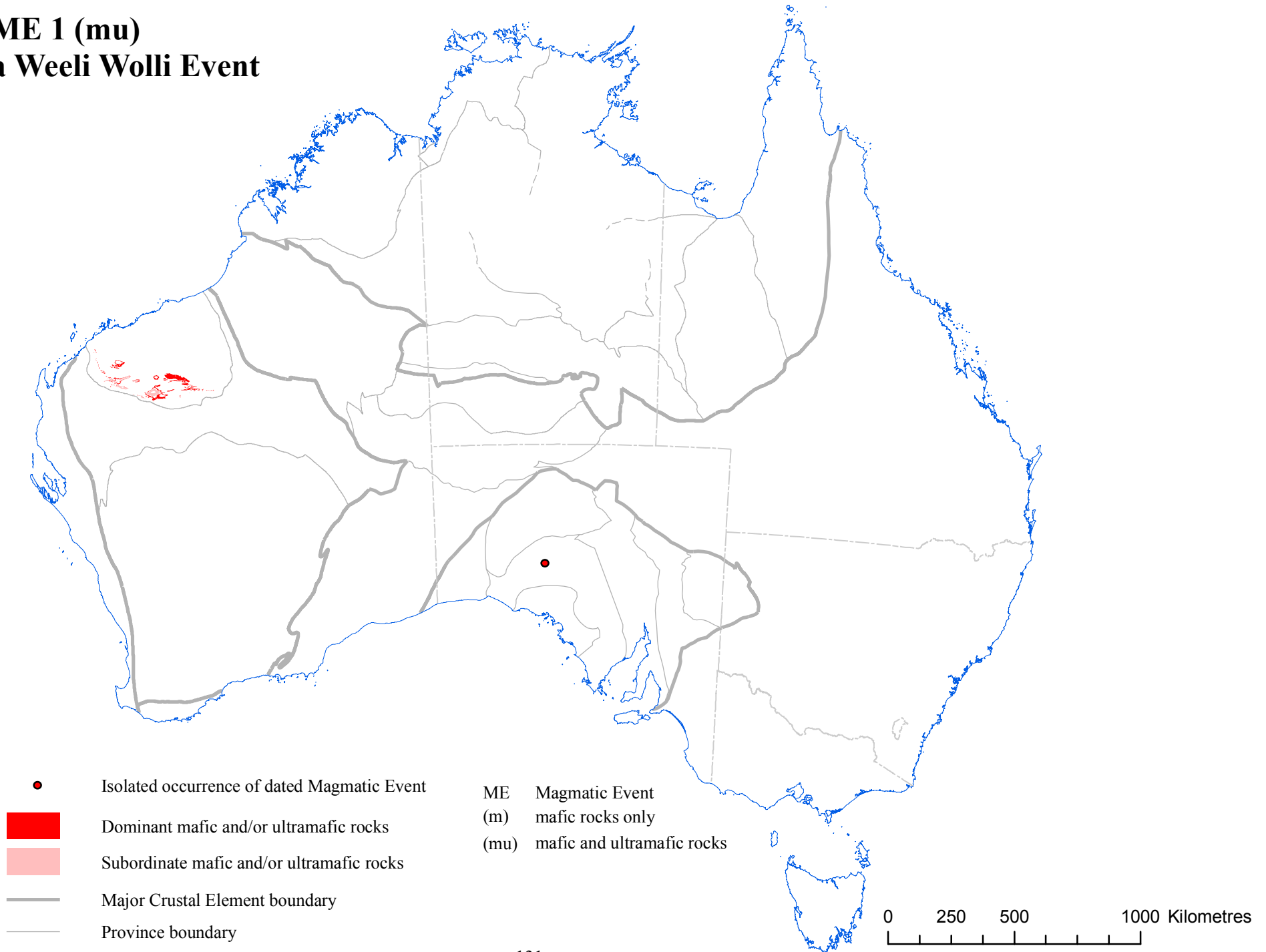
ME 3 (m)
~2210 Ma Turee Creek Event



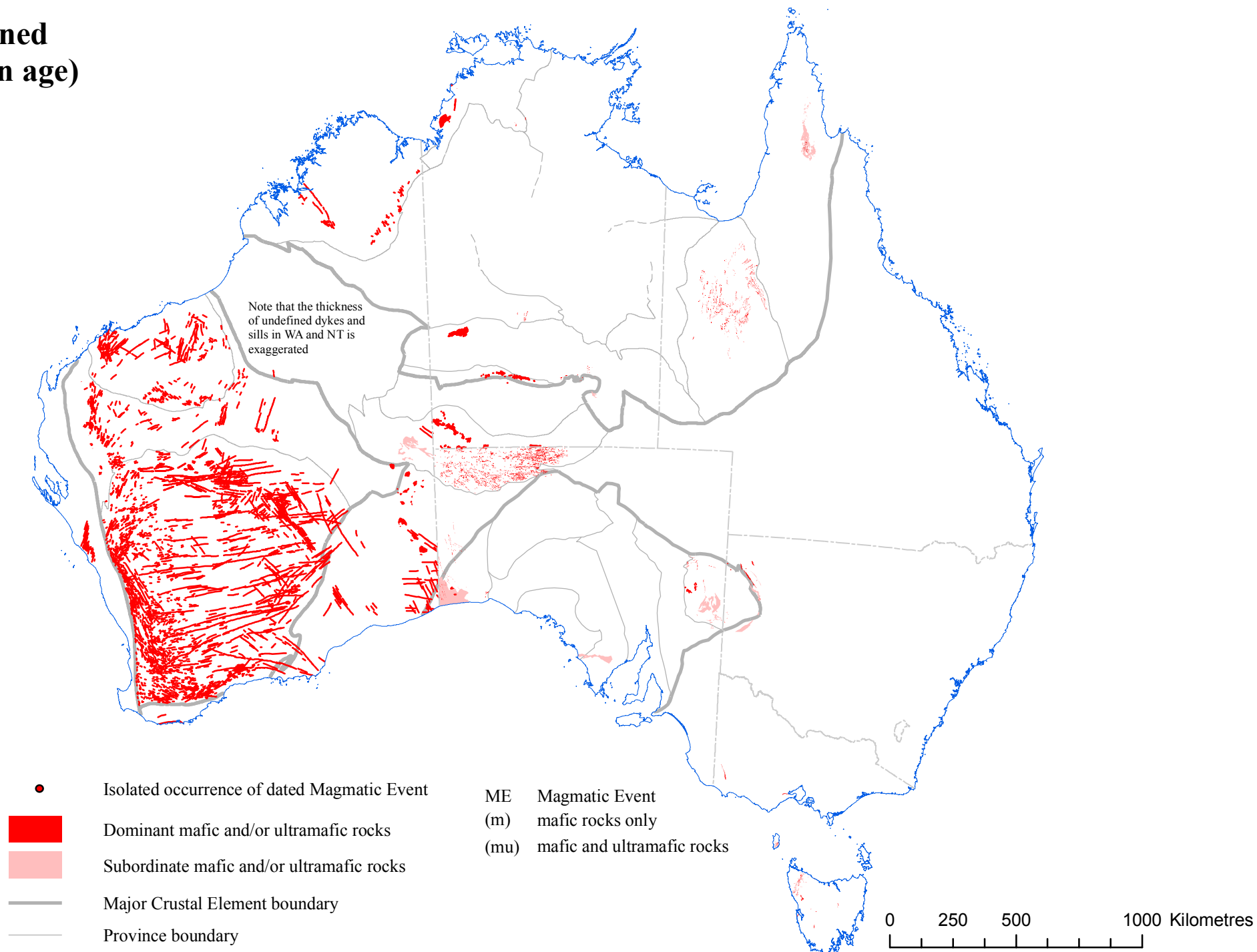
ME 2 (mu) ~2420 Ma Widgiemooltha Event



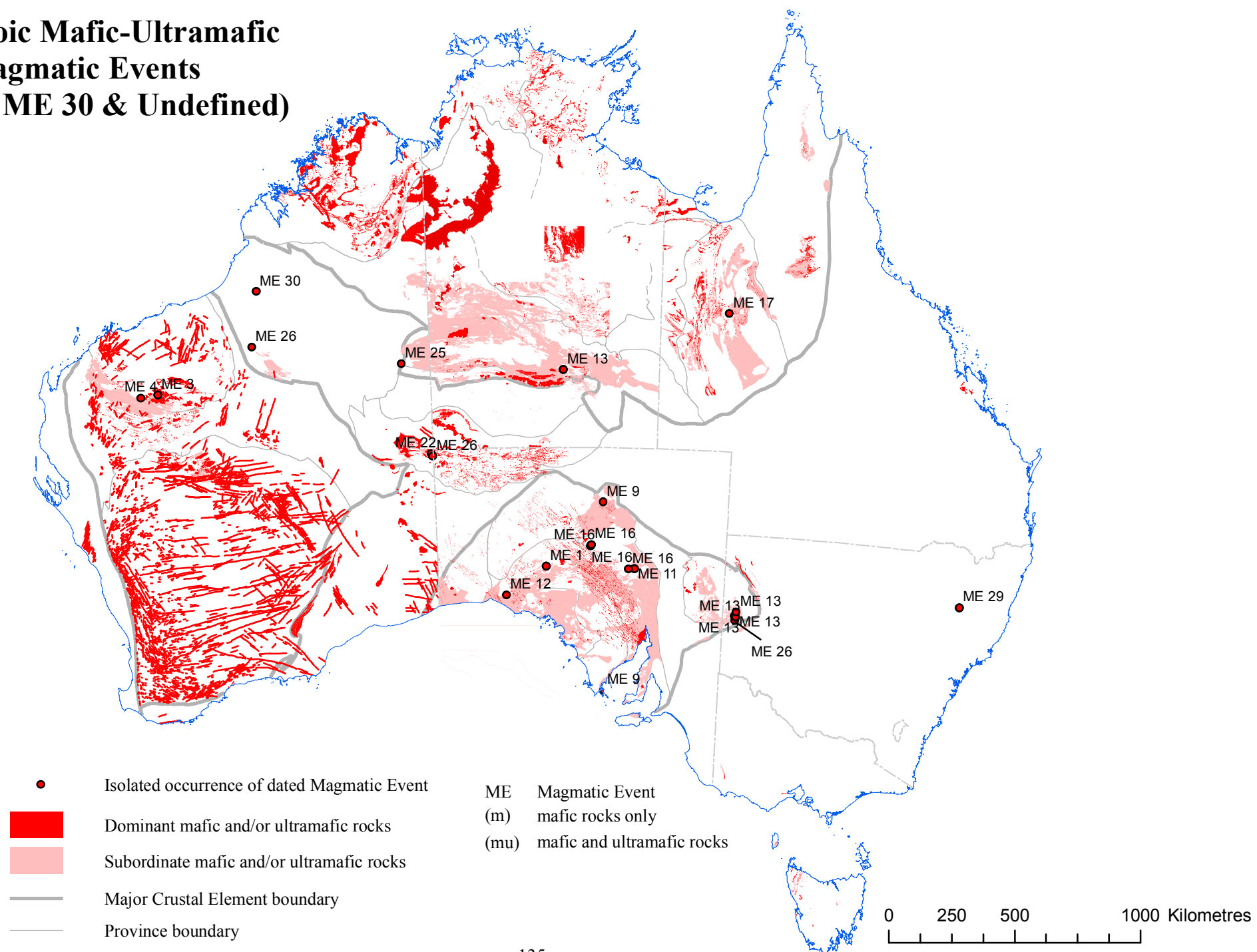
ME 1 (mu) ~2455 Ma Weeli Wolli Event



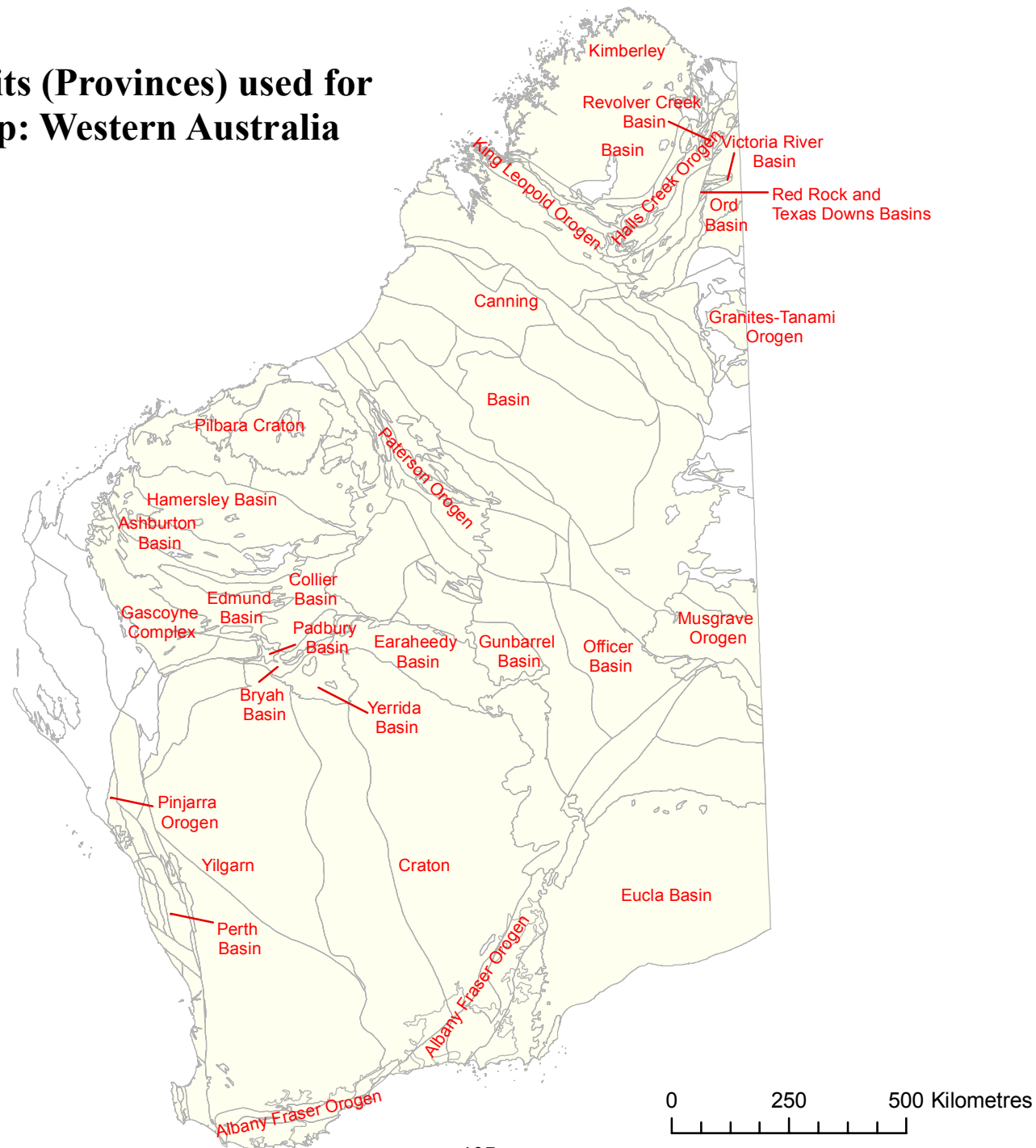
Undefined (unknown age)



Proterozoic Mafic-Ultramafic Magmatic Events (ME 1 to ME 30 & Undefined)



Tectonic Units (Provinces) used for Part 1 Map: Western Australia



Georegions used for Part 2 Map: Northern Territory and South Australia



Appendix 10: Geological and Geochronological Data of Proterozoic Mafic-Ultramafic Rock Units in Australia.

- Separate pdf spreadsheet files (viewable only)
- see online directory at <http://www.ga.gov.au/map/index.jsp#mum>
- see CD-ROM enclosed with printed Record