Uranium metallogeny in the North Flinders Ranges region of South Australia

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SUB CRUCE LUMEN

PART TWO

Metallogeny of uranium and thorium in the Mount Painter Domain

(North Flinders Ranges, South Australia)

1 Introduction

General location

The Mount Painter Domain (MPD) is located to the north eastern extremity of the Flinders Ranges. It is composed of two Proterozoic basement inliers. These two tectonic windows provide the unique direct access to the substratum under the Adelaide Geosyncline and the Curnamona province (Fig. 1).

Historical data, explorers

The geology of this region has been investigated since the early twentieth century and was immediately recognised as a promising province for uranium exploration. The discovery of radium in 1898 was followed by a first rush for the uranium ores bearing the precious element. In 1910, shortly after the discovery of Radium Hill, the first mineralisations of the Mount Painter and Mount Gee region were recognised, and small-scale mining started in the same year. The amount of work realized by the following exploration periods leads to the publication of the first geologic maps in 1961 (Campana *et al.*, 1961a, Campana *et al.*, 1961b, Campana *et al.*, 1961c, Campana *et al.*, 1961d)and a synthesis book focused on the mineral occurrences (Coats and Blissett, 1971). Although many short reports of investigation, open files of explorations and mineral reports have described local sections of the domain, the first complete description of the region is published by the Department of Mines & Minerals of South Australia in 1995 (Teale, 1993, Teale and Flint, 1993). An airborne radiometric survey was realized by the same department in 1990 and the first radiometric maps were available for study.

Exceptionally U-Th-rich granites and mineralisations

A demarking feature of the MPD in comparison to the other Proterozoic Australian provinces is the presence of granites with extremely high thorium and uranium contents (e.g. Yerila granite, Hot Springs Gneiss with >70 ppm U and >250 ppm Th); these granites have been considered as "extremely enriched" plutons (Johnson, 1980, Neumann, 2001, Sandiford *et al.*, 1998, Sheard and Flint, 1992, Stewart and Foden, 2001). The role of metasomatism was only recently considered for the genesis of some of the granitoids (Nooldoonooldoona trondhjemite) (Elburg *et al.*, 2001). Recently, Mesoproterozoic MPD granites were divided into two suites according to their age: (1) the Mt Neill suite (1575-1570 Ma) and (2) the Moolawatana suite (1560-1555 Ma), the later including the extremely-enriched granites (Stewart and Foden, 2001). Both granites suites are K_2O-rich and their source has been interpreted to be crustal (Nd isotopes). Based on the zircon saturation temperatures, petrogenetic models are disagreeing on the possible generation of two high-T granite suites over ~20 Ma (Stewart and Foden, 2001).

The MPD is also the host of many mineralisations, especially in the southern MPI near the Mount Painter. One is particular is the hematitic breccia-hosted REE-Th-U deposit at Mt Gee. The mineralisations have been attributed to be Paleozoic based on U-Pb geochronology (Elburg *et al.* 2003) and paleomagnetism on the breccia bodies (Idnurm and Heinrich, 1993). This second generation of U concentrations has frequently been linked to Mesoproterozoic granite as being their ultimate source.

The MPD is also located in the South Australian Heat Flow Anomaly (SAHFA), a wide region of the continental Australia displaying elevated thermal regime (Neumann *et al* 2000). Furthermore, the MPD effectively host the most elevated heat flow of the so-defined anomaly with a surface Q = 126 [$mW.m^{-2}$] (Neumann *et al.* 2000). The proposed model suggest am unusually enriched crust (K, Th and U) is responsible for this anomaly.

Objectives:

One of the main objectives of this research is to understand the origin of these unusually U-Th-rich granites. The approach is based on mineralogical observation, geochronology and also geochemistry. The metasomatism evidenced by Elburg et al. (2001) could be responsible for such unusual uranium concentrations and the research was directed at finding such evidences. U and Th concentrations caused by metasomatic replacement of rocks (volcanics, sediments, shales and limestone) under the action of fluids emanating from igneous bodies have been documented worldwide (e.g., Lang *et al.*, 1962).

The presence of U-Th-REE minerals allows the possibility of U-Pb isotopic dating. Hence the second major aim of this study was to investigate these systems to define a geochronological framework to the overall mobility of these elements in the MPD. The realisation of this objectives started by the building of a comprehensive and representative dataset of REE-, U- and Th-bearing minerals from the province, involving field sampling and also inspection of the historical collections of the South Australian Museum.

Finally, we aim to describe a detailed model for the mobility of thorium, rare earth elements and uranium in the MPD. In recent years, understanding the mechanisms responsible for large-scale anomalies in heat-generating elements such as U and Th has become of practical interest not only for uranium exploration, but also for deep geothermal energy generation. The 'South Australian Heat Flow Anomaly (SAHFA) is a major target for geothermal energy exploration, and this anomaly is most probably linked with the unusual geochemistry of the Mesoproterozoic basement – of which the MPI provides a unique direct outcrop.

2 Geology & metallogeny of the Mount Painter Domain

The Mount Painter Domain (MPD) is located in the North Flinders Ranges in South Australia (Fig. 1). The MPD is composed of two inliers or tectonic windows opened on the crystalline basement. They represent portions of the Mesoproterozoic substratum under the Neoproterozoic sedimentary succession of the Adelaidean Rift Complex also known as "Adelaide Geosyncline". This later sedimentary succession extends over 700 km from the Adelaide region to the North Flinders Ranges. Before the rift complex development, the two basement inliers were attached to a former cratonic region including the Gawler craton and Curnamona province; this craton is commonly referred as the "South Australian craton" (Fig. 1). At a continental scale, the MPD represents a tiny portion of Proterozoic basement, but in comparison to other Australian provinces, numerous geological studies have been directed to its understanding, especially for its exceptional richness in uranium. Because of its complex link to the Adelaide Geosyncline and its vicinity to Tasman line separating the "Terra Australis" from the western Australian cratons (Fig. 1), the MPD records a very complex multiphase history. The review of different geological units is described in the following sections.

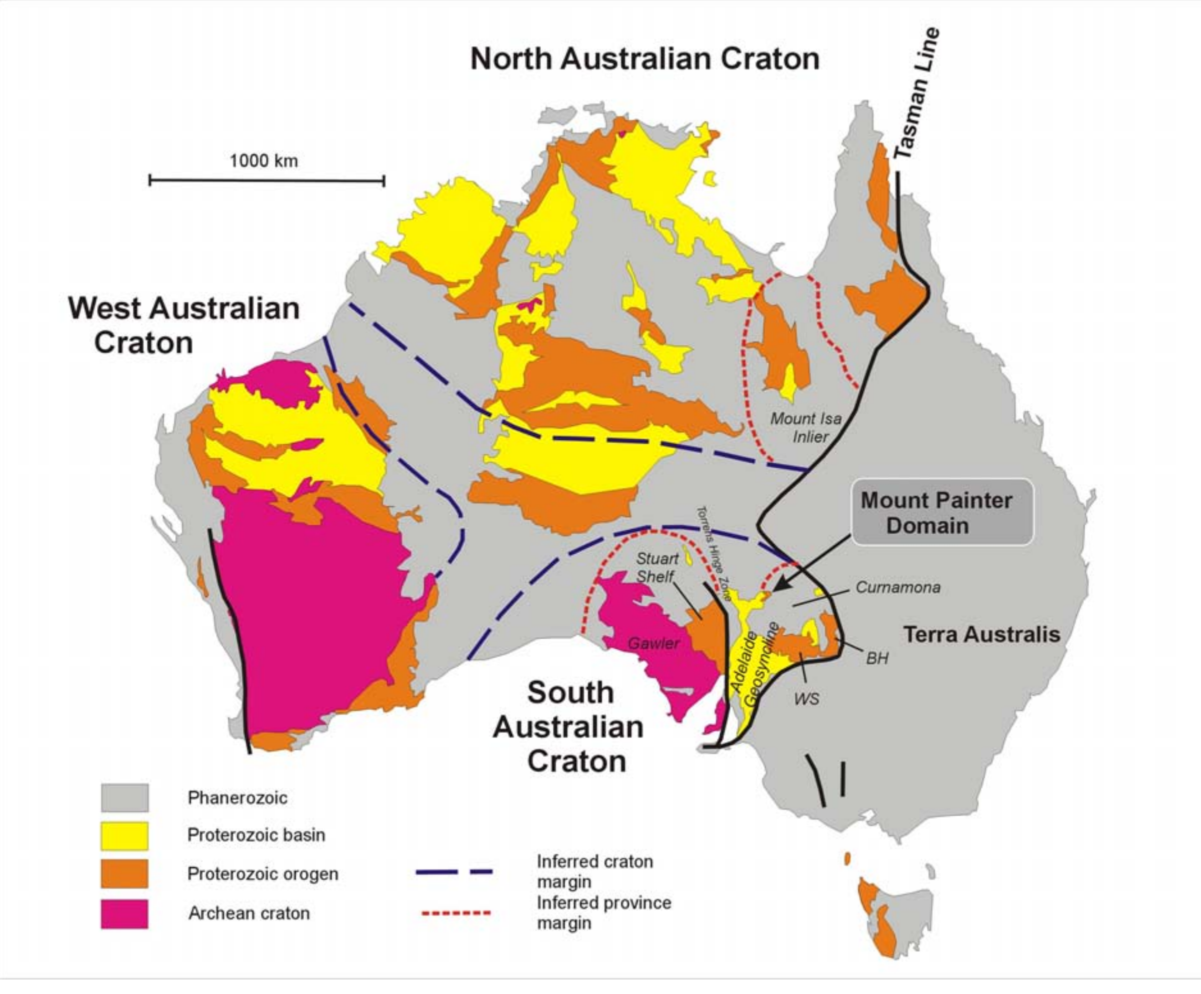

Fig. 1: Simplified tectonic map of Australia with major Proterozoic and Archaean geological provinces

The Australian continent is separated into the Phanerozoic "Terra Australis" and the western cratons: South, North and West Australian Cratons. The MPD is located in the Curnamona Province, part of the South Australian Craton; it forms as small tectonic window of Proterozoic basement in the northern extremity of the Neoproterozoic to Cambrian Adelaide Geosyncline.

2.1 The Proterozoic MPD basement and cover

The Proterozoic basement of the MPD had been divided into Paleoproterozoic and Mesoproterozoic (Teale, 1993a, Teale, 1993b) but this subdivision has been recently discarded and the entire MPD is now retained as Mesoproterozoic (Fanning *et al.*, 2003). This geochronological subdivision was based on contrasts in metamorphism and metasomatism, which are visible at the regional scale. I will retain these features by ascribing the notion of tectonic units to subdivide the MPD and introduce this terminology now for more clarity. A map showing the tectonic units is represented on the Figure 2, with most of the geographical and lithological names used later.

2.1.1 Volcano-sedimentary successions

The deeper volcano-sedimentary sequences of the MPD are located in the Eastern part of the Mt Painter Inlier, north of the Paralana Hot Springs (Fig. 2). The area of interest was described as the Paleozoic "Mudnawatana granite" on the published maps (Campana *et al.*, 1961c, Campana *et al.*, 1961d, Coats *et al.*, 1969). The same rocks are now recognised as a migmatitic suite of sediments and granitoids (suite 1 & 2) (Teale, 1993b). Reconstitutions of the prevailing conditions of migmatitisation indicate that the rocks were buried at ~18 km (~5.5 kbar), under 15 km of Adelaidean Neoproterozoic succession (Paul *et al.*, 1999, Preiss, 2000). The southern part of the Mount Painter Inlier displays metamorphic assemblages indicative of shallower burial (500°C / ~3 kbar) (Sandiford *et al.*, 1998). The southern formations also contain calcsilicate rocks. The deposition age of these metasedimentary series is still uncertain and the age populations of their detrital zircons have never been investigated.

The minimum age of the sedimentary basement of the MPD is constrained by the age of the oldest granitoids intruding it: 1580 Ma. Its maximum age has been reinterpreted in the range of 1580-1600 Ma, following the discovery of detrital zircons of this age range for several formations (Fanning *et al.*, 2003). Several formations in the Radium Ridge Metamorphics and the Paralana Plateau area are still not documented. Granites and silicic volcanics of 1580-1590 Ma are very common on the Gawler craton (Fig. 1) (e.g. Hitalba suite granitoids, Gawler Range Volcanics "GRV") and in the Curnamona Province (Benagerie Ridge Volcanics). The thickness of the detrital formations of the MPD has been estimated in (Coats and Blissett, 1971). These formations (including the Freeling Heights Quartzite, Mt Adams Quartzite, the suite 4 & 5 of Teale (1993b) have a total thickness reaching ~2 km in the region of the Mt Adams and 5-7 km in the Freeling Heights area.

Detrital series in the lower sequences (Radium Ridge Metamorphics, Brindana schists, or suites 3-4 of Teale (1993b) are composed mostly of pelitic, psammitic sediments; the metasediments are getting coarser and typical of shallower depositional environments (suite 5-6 of Teale (1993b)). Metacarbonates layers (preserved as calcsilicates, skarns) are widespread through the MPD as discontinuous layers or boudins frequently bearing allanite. The top of the sequence is followed by a "metavolcanic-granitic suite" (suite 6 of Teale (1993b)) composed of porphyritic gneisses (Yerila granite in the Babbage Inlier), with supposed volcano-sedimentary equivalents in the Mount Painter inlier (Johnson, 1980, Teale, 1993b).

The last series of sediments consists of the Yagdlin phyllite, the Freeling Heights quartzite and its equivalent Mt Adams quartzite. These two are overlain by silicic volcanics (Pepegoona rhyolite or Pepegoona Porphyry) dated at 1576 ±2 Ma (Teale (1993b). These volcanics have always been distinguished by previous authors (Coats and Blissett, 1971, McLaren *et al.*, 2006, Teale, 1993a) as they essentially occur to the east of the PFZ. Alkaline metabasalts of inferred Mesoproterozoic age are also recorded in the Northern MPI (Teale, 1993b). The Freeling Heights – Mt Adams Quartzites show well preserved sedimentary structures, which contrasts with the sheared gneisses from all other units from the volcano-sedimentary succession.

Overall the paleoenvironment of deposition of the thick Mesoproterozoic volcano-sedimentary succession of the MPD is considered to be an intracratonic rift basin, with bimodal alkaline volcanism (mainly rhyolites and minor basalts)(Teale, 1993b).

2.1.2 Granites, granitoids and volcanics

The MPD hosts numerous granitoids, granites, and orthogneisses of Mesoproterozoic age. Some bodies are true intrusive igneous rocks whereas others are reported as "granitised" or metasomatised volcanics or sediments by some authors. This situation makes a review of the literature difficult as there are major differences of interpretations between authors. The different granitoids occurrences of the MPD are represented into a synoptic table with the views of the different authors (Fig. 3). Sometimes, a "rock name" or "unit name" was first applied to a large area, and later restricted to a smaller surface; the opposite is also found. U-Pb geochronological ages on zircons are available for most of these granitoids "sensus lato". They all fit in an age range going from 1580 to 1555 Ma, defining two distinct phases of magmatism (1575 & 1560 Ma). The granitoids are especially distinctive on airborne radiometric maps and further subdivisions have been recognised using the *e*Th, *e*U and *e*K signatures (Stewart and Foden, 2001). Geochemically, these Mesoproterozoic granitoids belong to an alkaline granite suite, and are classified as A-type granites (Whalen *et al.*, 1987) and Within Plate Granites (WPG) (Pearce *et al.*, 1984). The geodynamic environment of formation for this type of granitoids is intracontinental rifting, consistently with the thick volcano-sedimentary sequence they intrude. One can expect ring structure complexes and associated alkaline rhyolites related to the formation of calderas (Barbarin, 1999). The scarcity of mafic intrusive is also noticeable in the MPD and contrasts with the abundance of granitic intrusives. Some of Mesoproterozoic granitoids display elevated concentrations in high field strength elements (HFSE), implying that metasomatism played an important role in controlling the whole-rock chemistry (Elburg *et al.* 2001). This geochemical character is widespread in the granites of the MPD and cannot be explained by magmatic differentiation solely (zircon saturation). The whole-rock chemistry of some granitoids shows extremely high Na_2O and K_2O contents (8 & 7 Wt-% respectively) (Elburg *et al.*, 2001, Stewart and Foden, 2001). Although such compositions could be primary in some cases, they result from alkaline metasomatism, at least locally. To date, the whole period of Mesoproterozoic magmatism in the MPD is restricted to an age interval of 25 Ma maximum, which temporally follows the magmatism of the Gawler craton to the west

(1590-1580 Ma). By comparison, these felsic igneous rocks (Hitalba /GRV) display geochemical patterns with lower HFSE and alkaline elements contents (Allen *et al.*, 2008, Stewart and Foden, 2001).

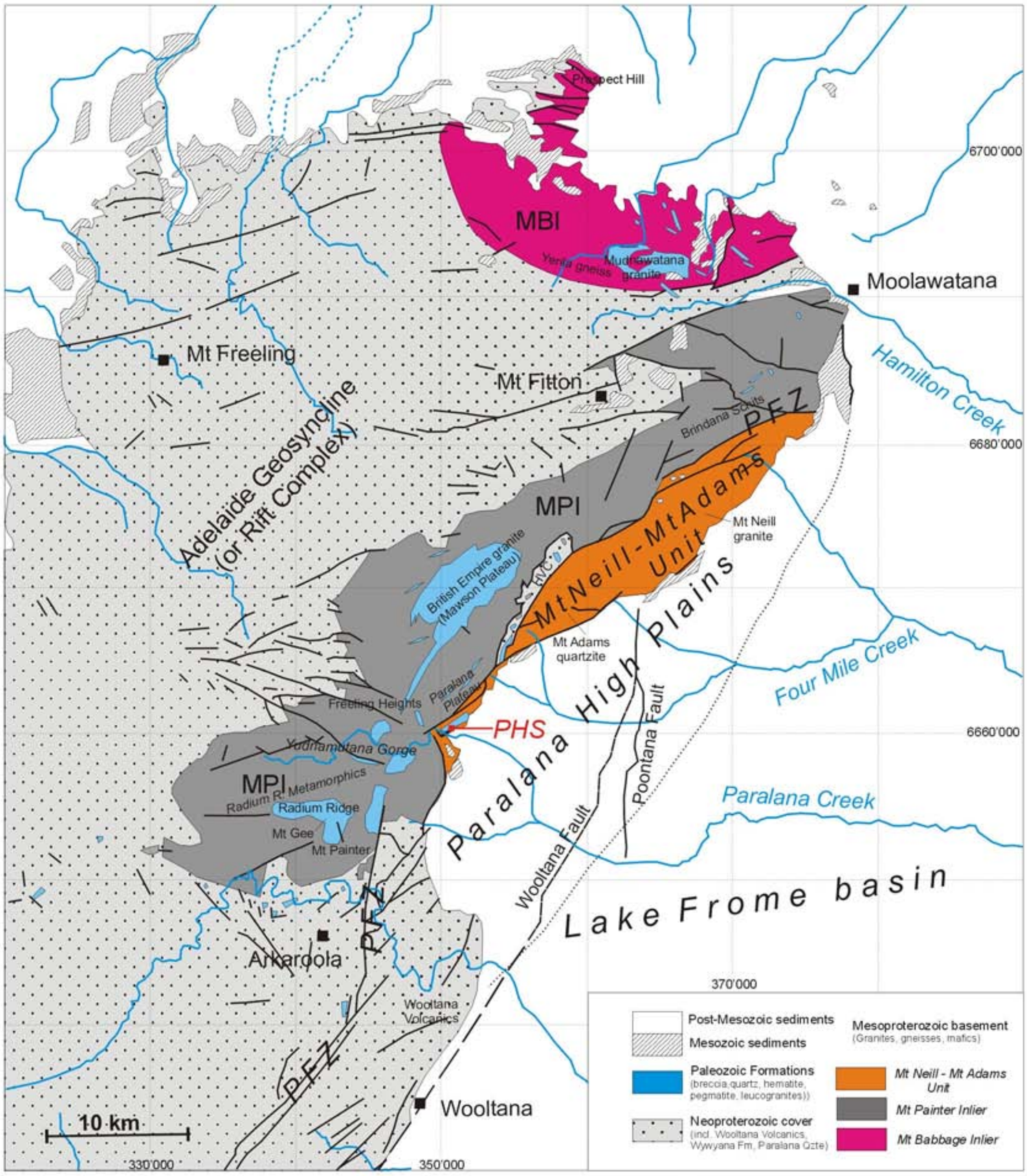

Fig. 2: Tectonic map of the Mount Painter Province and subdivisions

The tectonic map of the MPD is divided into three main elements: the MPI (Mount Painter Inlier, the MBI (Mount Babbage Inlier and Mount Neill – Mount Adams Unit. The abbreviations used on the map are: PFZ (Paralana Fault Zone), PHS (Paralana Hot Spring), and HVC (Hidden Valley Complex) .The Paralana High Plains is covered by Mesozoic-Cenozoic Units directly lying on the crystalline basement.

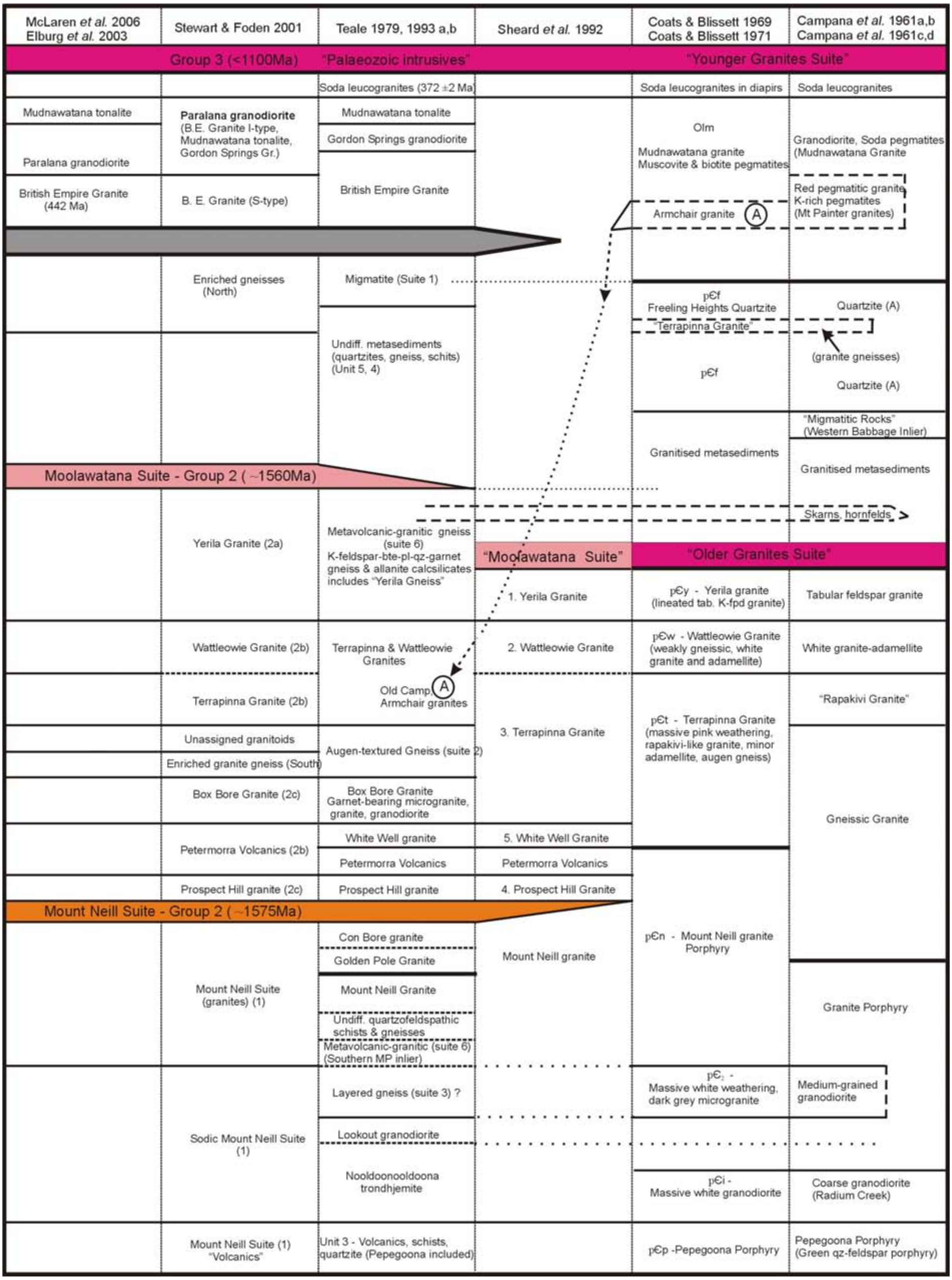

Fig. 3: Synoptic representation of the felsic igneous rocks and migmatitic rocks of the MPD

The synoptic table regroups the geological denomination of all previous authors and place the rock units in relationship to each other. This figure has to be read horizontally in order to compare the changes between authors and to understand the subdivisions and regrouping they applied to the MPD.

2.1.3 Mafic intrusions, volcanism and Neoproterozoic cover

The MPD is unconformably overlain by the Adelaide Rift Complex sequences also known as "Adelaide Geosyncline" (Preiss, 2000, Preiss *et al.*, 1993). This major rift complex extends over 700 km from the Adelaide area (Mount Lofty Ranges) to the North Flinders Ranges. The surface between the crystalline Mesoproterozoic basement and the following sedimentary unit is generally sharp and clearly shows evidence for an erosive contact. The oldest sediments at this contact are part of the Paralana Quartzite Unit (~800 Ma). This detrital series occurs to the south-east and the south-west of the MPD. Mafic dikes (diorites and amphibolites) crosscut both basement and the Paralana quartzite. Contrastingly, the median part of the MPD is directly overlain by a silicic dolomitic formation: the Wywyana formation. A thick andesitic volcanic succession is preserved on the top of the Wywyana formation: the Wooltana volcanics. The lack of precise geochronological data on mafic dikes and in the basement and the volcanics in the Neoproterozoic cover impedes solid correlation between these rocks. The abundance of andesitic volcanic material (andesitic and basaltic tuffs, lava flows) indicates the proximity of an important volcanic emission centre.

The sedimentary succession of the Adelaide Rift Complex is complicated by a major unconformity at the beginning of the Sturtian glaciation. Both crystalline basement (Babbage Inlier and North Painter Inlier) and anterior Neoproterozoic volcanics and sediments are partly eroded and redistributed during the glacial event. The rift development extends to the Cambrian. For further information on the detailed succession, we refer to the works of Preiss (1993 & 2000) and Coats & Blissett (1971).

2.2 The Paleozoic

2.2.1 Delamerian orogeny (Cambro-Ordovician)

The end of the sedimentation in the MPD region coincides with the beginning of the Delamerian orogeny at 514 ± 3 Ma (Foden *et al.*, 2006). The metamorphic peak was reached around 500 Ma all along the Adelaide Geosyncline and was accompanied by the intrusion of syntectonic granitoids. The duration of the orogeny extended until 490 ± 3 Ma, followed by a quick period of cooling and uplifting. During this final post-tectonic stage (493 to 480 Ma), magmatism was represented by mafic and granitic intrusions (Foden *et al.*, 2002, Turner, 1996). The Delamerian orogeny is well recorded in the MPD and its Neoproterozoic cover. The structural deformation during the compressive event has been modelled and the horizontal shortening calculated (Paul *et al.*, 1999). The metamorphism reached the amphibolite facies in the core of the MPD, with the highest metamorphic grade recorded in the Paralana Hot Springs – Paralana Plateau region, where a migmatitic unit developed by partial melting of Mesoproterozoic sediments and granites. This unit is described as the "Migmatite Unit 1" in (Teale, 1993b). Structural and metamorphic reconstitutions suggest maximum metamorphic conditions at ~5.4 kbar (17 km) and 600°C in the core of this unit (Paul *et al.*, 1999, Sandiford *et al.*, 1998). The metamorphism to the west of the MPD is overall in the amphibolite facies, with the biotite-in isograde recorded in both basement and adjacent cover (Preiss, 1995). The conditions of metamorphism have been estimated to be at least 500°C and ~3 kb in the near basement Neoproterozoic sediments (cordierite-biotite-muscovite) (Sandiford *et al.*, 1998). Contrastingly, the eastern part of the MPD, on the eastern side of the Paralana Fault Zone, only displays greenschist facies, with magmatic biotite transformed into chlorite in the Mt Neill granite. Only a few U-Pb dating have been conducted on minerals from the Delamerian metamorphic peak: a 474.6 ± 2 Ma monazite from a monazite-rich late-tectonic shear zone crosscutting the Mesoproterozoic gneisses (Elburg *et al.*, 2003). There are however Rb-Sr, Sm-Nd and Ar-Ar data indicating the peak of the Delamerian Orogeny took place around 495 Ma (Elburg *et al.*, 2003), affecting the entire MPD.

2.2.2 Late Ordovician thermal event

A major leucogranitic intrusion is located in the core of the MPD on the Mawson Plateau: The British Empire granite (BEG). The BEG was interpreted to be a Delamerian intrusive until recent dating revealed ages of ~440-450 Ma using U-Pb ages on monazite and titanite (Elburg *et al.*, 2003, Teale, 1979) and 440-460 Ma using zircons (McLaren *et al.*, 2006). Granitoids related to this event are also present to the north of the MPD in the Mt Babbage Inlier (Mudnawatana tonalite), in the Yudnamutana gorge, near the Paralana Hot Springs (Gordon Springs granodiorite) (Teale, 1979). Pegmatoids bodies, granite sills in the "Hot Springs Gneisses" or migmatitic unit such as the Paralana granodiorite have also been linked to the BEG magmatic event (Neumann, 1996). The BEG is separated into a S-type peraluminous pegmatitic granite forming the main body and a I-type metaluminous tail on its SE border which also relates to the Paralana granodiorite (Paul, 1998). The "soda-leucogranites" and pegmatites (Coats and Blissett, 1971, Teale and Lottermoser, 1987) present in the Neoproterozoic cover to the south of the MPD as well as in the Hidden Valley Complex (HVC) along the Paralana Fault Zone all belong to this late Ordovician thermal event and are devoid of Delamerian deformation. The S-type BEG has been generated by anatexis of the granites and metasediments under the MPD (McLaren *et al.*, 2006). The conditions of anatexis required to produce a volume of melt such as the BEG have been evaluated at 720-750°C at 4 kbar (transition amphibolite to low-P granulite facies), and these conditions have been explained because of the high thermal regime related to the highly radioactive local basement (McLaren *et al.*, 2006). The presence of a mantle source component in the Paralana granodiorite and the Mudnawatana tonalite impedes this unique possibility and the heat source can no longer be considered exclusively crust-related (Elburg *et al.*, 2003, Stewart and Foden, 2001). The mantle source is evidenced through the neodymium isotopes, and could also be represented by potentially Ordovician mafic intrusives which occur in the MPD (Schaefer, 1993). Unfortunately, there is a total lack of geochronological data on the mafic intrusives of the MPD apart from the Wooltana volcanics in the cover.

2.2.3 Post-Ordovician tectonics and hydrothermalism

Following the Delamerian orogeny and the subsequent thermal event at ~ 440 Ma, multiple stages of cooling and uplifting / erosion have progressively exposed the MPD to its current "inlier" or "tectonic window" setting. The ideas have evolved rapidly through the last 30 years and I present here a synthesis of the multiple information documenting tectonic events (faulting, uplifting), hydrothermal activity and brecciation.

Most of the studies have focused on the Mt Painter Inlier. The area of the Mt Painter and Mt Gee in the Southern part of the inlier is especially well documented because of easy access through four-wheal-drive tracks from the Arkaroola station. The Mt Gee hosts a large uriniferous hematite breccia under a thick capping of epithermal hematite-quartz sinter with presence of large vugs. The whole breccia-sinter system is hosted in the Mesoproterozoic metasediments and granites. The study of the system started early as part of the uranium exploration. The first geochronological data were obtained by U-Pb chemical method on a primary U-Nb mineral from a monazite-hematite breccia from Radium Ridge giving 400 ± 50 Ma (recalculated with new decay constants at 394 ± 38 Ma) (Kleeman, 1946). Further attempt to date the breccia using monazite failed to give precise age because of high common lead contents: 440 ± 50 Ma (Pidgeon, 1979). Other primary uranium-bearing minerals are described in the vicinity of Mt Gee as "radioactive ilmenite" but no dating is available (Broughton, 1925). The Mt Gee mineralisations contain uraninite and coffinite (Marathon Resources unpublished data); no U-Pb is available.

Some titanite-diopside pegmatite veins discovered early on by the mineral explorers in the Radium Creek, south of Mt Gee (Mawson, 1928, Mawson, 1944) were reinvestigated recently and titanite successfully dated using U-Pb method at 439 ± 1 Ma (Elburg *et al.*, 2003). The same veins were used for fluid inclusion study and evidenced that the early pegmatitic "magmatic" stage (titanite) was formed at >600 °C, followed by transitional evolution to hydrothermal conditions (510 °C / 1.3 kbar; 350 °C / 0.8 kbar and 200 °C / 0.5 kbar). A last stage of brecciation with epithermal quartz-hematite assemblage overprinted the previous mineralisation (100-140 °C / 0.01-0.05 kbar) (Bakker and Elburg, 2006).

A more generalized study of the thermochronology in the MPD using the Ar-Ar and K-Ar method on hornblende and micas gives further evidence for a succession of cooling/uplifting periods after the 440 Ma stage (McLaren *et al.*, 2002). The study reveals a first ~430 Ma cooling stage down 280-350 °C, a second 400 Ma cooling stage followed by a quiet isothermal period (>250 °C) until 330 Ma, when a last important cooling stage (330-320 Ma) brought the MPD down to <200 °C ; a denudation of the MPD of 6-7 km has been associated to these cooling and uplifting stages (McLaren *et al.*, 2002). Finally, apatite fission tracks studies document a slow cooling stage from >110 °C during the Late Carboniferous–Early Permian and a second cooling episode during the Palaeocene to the Eocene (Mitchell *et al.*, 2002). All the available thermochronological data is reported into a synoptic table, which provides a better visual overlook (Fig. 4).

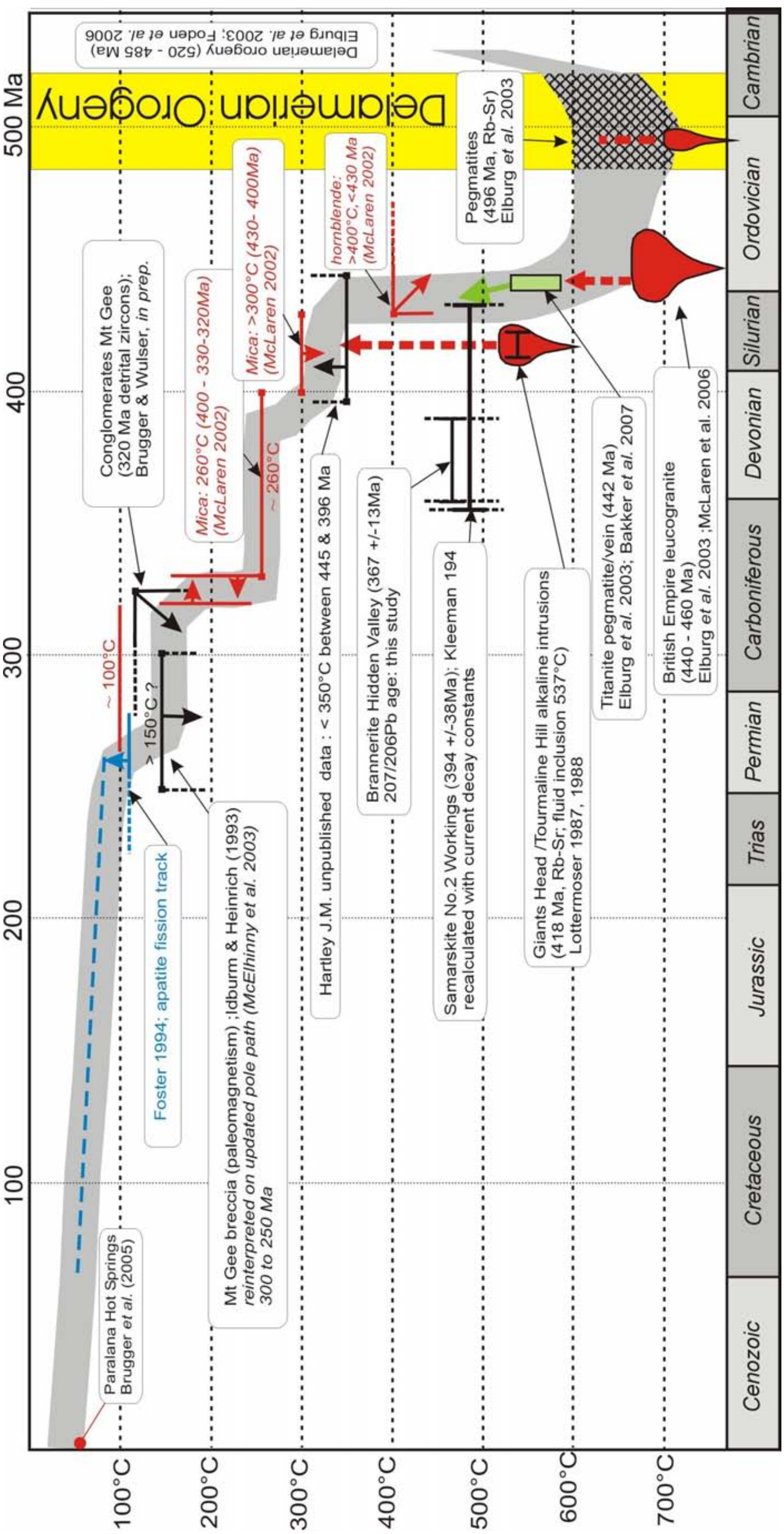

Fig. 4: Synoptic representation of thermochronological data in the MPD

2.3 Mineralisations and previous exploration overview

The MPD is the home of many small mineral indices but also of some larger deposits or prospect. This study is dedicated to the uranium, thorium and rare earth elements mineralisations only and the numerous copper, silver, gold or other metals are not discussed here unless a specific link to uranium, thorium or the rare earths is occurring.

The bulletin 43 from the Department of Mines of South Australia provides a excellent review of the mineralisation and mineral occurrences found in the province (Coats and Blissett, 1971) and almost all the references to exploration reports or unpublished data from the previous exploring companies. Further discoveries from more recent works and Adelaide University PhD research (Teale and Flint, 1993) are reported together with new locations found during the field investigations as part of this study. All the mineral occurrences are reported on a map with the following subdivision: (1) Secondary uranium minerals, (2) Dominant REE minerals, (3) U-ti-Nb minerals (brannerite, fergusonite, betafite, etc.), (4) Primary uranium (uraninite, coffinite). The sedimentary-hosted deposits are however still included in the secondary category (Fig. 5). For convenience, new mineral occurrences discovered during this research are also represented on the same map. The occurrences are listed in the Appendix I with mineralogy data and the exact location.

Uranium was first discovered in the MPD by W. B. Greenwood in 1910 around Mount Painter. Most of the subsequent discoveries were made within few kilometres of Mt Painter, Mt Gee and towards the Paralana Hot Springs area. The uranium ores, essentially hematitic and granitic breccia with torbernite, where mined between 1910 and 1915, 1926 and 1932 for radium. The extractive activities were located at Radium Ridge, No.6 Workings near Mt Gee principally, with additional minor tonnage from various locations. The exploration started again intensively in 1944 after a request from the British government to locate and produce some uranium as part of the Manhattan project. Only a small quantity of concentrated ore was ultimately shipped to the USA after the end of the Second World War. Several discoveries or "re-discoveries" of uranium occurrences were made later in the 60's and the 70's during uranium exploration rushes.

The uranium, thorium and rare earths mineralisation of the MPD can be divided into several types. The early explorers mainly focused on the secondary uranium concentrations (mostly torbernite) and hence only little information on the primary uranium mineral species has been collected. The mineralogy and the occurrences types are summarized into a scheme in the Appendix I. The mineralogy of some of the localities has been re-examined and will be discussed in detail later. The REE-Th-U mineral species reported in the MPD area at the beginning of this research (2003) are reported in the Table 1 and subdivided by type of mineralisation.

Mineral	Chemical formula	Pegmatite, intrusive	Metasomatite, skarn	Breccia-hosted	Vein type, shear zone	Metamorphic	Sediment-hosted	Surficial	Abundance
		Mineralisation type							
uraninite	UO_2	●	●	●	●	●	●		XXX
coffinite	$USiO_4.nH_2O$			●	●		●		XXX
carnotite	$K_2(UO_2)_2(VO_4)_2 .3H_2O$						●	●	XXX
brannerite	$(U,Th,Ca)Ti_2O_6$	●			●				XX
thorite	$ThSiO_4$	●	●		●				X
spriggite	$Pb_3(UO_2)_6O_8(OH)_2 . 3H_2O$							●	X
"radiocative ilmenite"	undefined	●							X
monazite-(Ce)	$CePO_4$					●			XXX
uranosphaerite	$Bi(UO_2)O_2(OH)$							●	X
samarskite	$(Y,Fe,U,Th,Ca)_2(Nb,Ta)_2O_8$	●							XX
xenotime-(Y)	YPO_4					●			XX
gummite	"undefined"							●	XXX
fergusonite-(Y)	$YNbO_4$	●							X
allanite-(Ce)	$CaCe(Al_2Fe)O(OH)SiO_4(Si_2O_7)$	●	●			●			XXX
liebigite	$Ca_2(UO_2)(CO_3)_3 . 11 H_2O$							●	X
betafite	$(Ca,U)_2(Ti,Nb)_2O_6(OH)$	●							X
(meta)-torbernite	$Cu(UO_2)_2(PO4)_2. 8\text{-}12H_2O$			●				●	XXX
dewindtite	$Pb(UO_2)_3(OH,PO_4)_4.3H_2O$								X
euxenite	$(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_6$	●							X
autunite	$Ca(UO_2)_2(PO_4)_2 .11H_2O$							●	X
uranophane	$Ca(UO_2)_2(HSiO_4)_2 .5H_2O$			●				●	XX
kasolite	$Pb(UO_2)(SiO_4).H_2O$							●	X

Table 1: U-Th-REE mineral species reported in the MPD pre-2003

The mineral species reported have been grouped by type of mineralisations and the abundance is rated with one to three crosses (rare, common and frequent).

2.3.1 Mineralisations in pegmatites & granitic rocks

U-Th-REE mineralisations have been recognised early on in the pegmatite veins crosscutting the MPD. Uranium minerals are mentioned in pegmatites by early workers but without precise localisation. A pegmatite dike mineralised in brannerite was found in the Yudnamutana gorge by R. Coats in 1959. Columbite and tantalite related to pegmatites were recorded in the Mount Babbage area but without any precise location (Simpson, 1908). Columbite and tantalite are also recorded in the Tourmaline Hill alkaline pegmatite intrusion, together with xenotime and monazite (Lottermoser and Plimer, 1987), in the Giants Head pegmatite intrusion (Coats and Blissett, 1971). At No.10 Workings, near Mount Gee, a pegmatite vein bears a mineral called "U-REE-rich ilmenite" by Broughton (1925) and Mawson (1944), and corresponding to davidite-(La) (Broughton, 1925, Mawson, 1944). Other occurrences of alkaline leucogranites-pegmatites with similar geochemistry and probably mineralogy are: the Needles, the Sitting Bull, and the Pinnacles to the South of the MPD (Coats and Blissett, 1971). Fergusonite is mentioned in a pegmatite, upstream the Paralana Hot Springs (Coats and Blissett, 1971).

Many granitoids of the MPD also host U-REE-Th minerals as primary disseminated phases and can be considered as mineralisations. Although none of these rocks have been seriously considered for mineral exploration, some local concentrations could potentially be of economical interest. However, numerous authors have considered them as fertile because they contain highly leachable uranium minerals and therefore have the potential to release or have released the uranium-rich fluids necessary for the development of potentially economic deposits; they also form a large low-intensity primary uranium mineralisation or rock-reservoir. These U-rich granitoids have a great potential for studying the geochronology of U-Th-REE mobility.

2.3.2 Metasomatic mineralisations (gneisses and skarns)

Metasomatism is widespread in the MPD, and numerous rocks display a REE-Th-U enriched mineralogy, which can not be related to their primary chemical composition. For example, calcsilicate rocks containing garnet, plagioclase, epidote, diopside, magnetite, hastingsite and allanite have been discovered in many locations of the Southern part of the MPI, around the Paralana Plateau (Teale, 1993b), and interpreted as metasomatised carbonate-rich sediments. They are described as "highly uraniferous" and "REE-enriched" (Blight, 1977). Similar formations occur to the North of the Mount Painter Inlier between the Brindana Gorge and the Parabarana Hill (Teale, 1993b). These allanite-rich calcsilicate rocks are mapped as skarns on the 1961 map (Campana *et al.*, 1961b). Further north, in the Mount Babbage Inlier, allanite-rich calcsilicate layers are present as bedding in the Yerila "granite" (Coats and Blissett, 1971). The uranium contents of the calcsilicates layers are high (Teale, 1993b) and were investigated by CRA Exploration in the 90's. The Gunsight prospect (REE, Cu, U and Au) in the Parabarana Hill area also represents a metasomatic mineralisation with abundant allanite, uraninite, monazite, scheelite and sulphides. Other localities with allanite are of minor importance.

2.3.3 Breccia-hosted mineralisations

Breccia-hosted uranium and REE mineralisations are so far the more frequent type of mineralisation in the MPD, and the only types to have been exploited for uranium. All mineralisations occur in the Southern Mount Painter Inlier, between the Paralana Hot Springs and the Mount Gee area. Uranium exploration in the MPD started again in 2004 with resource delimitation at Mount Gee (Marathon Resources Pty Ltd). In importance and tonnage, Mount Gee is currently the only uranium occurrence of economic potential in the MPD. The uranium-rich breccia of the region located between Mt Gee and Paralana Hot Springs have recently been regrouped as the "Paralana Mineral System" by the Marathon Resources workers. A long list of mineralisation could be made here. For simplification, we refer to the Appendix I in which the mineral occurrences are listed. Many breccia mineralisation only display secondary uranium minerals at the surface (mostly torbernite) but the hematitic or chloritic breccia contain fine uraninite, coffinite and monazite, as documented at Mount Gee (Coats and Blissett, 1971); Marathon reports, 2006) and at the Hodgkinson prospect (Smith, 1992).

2.3.3 Vein-hosted or shear zone mineralisations

Betafite in a quartz veinlet is mentioned near Mount Shanahan (Coats and Blissett, 1971). There is no mention of pegmatite veins in the vicinity. A monazite mineralisation occurs in a shear zone to the South of the Mount Painter (Elburg *et al.*, 2003). The U-Pb measurements on monazite indicate a late Delamerian age at 475 ± 2 Ma. Quartz veins mineralised in brannerite and uraninite are present at the Mount Olgivie (Nichols Nob) Mine, 60 km to the WSW of the Mt Painter. Although being out of the MPD, this locality is of importance and may indicate the presence of similar U-rich basement under the Neoproterozoic cover. Still on the Western flank of the Mount Painter Inlier, two mineralised faults with uraninite occur: the first one crosscuts the Freeling Heights Quartzite at the Mt Shanahan Prospect and the second one is located on a shear zone in Wooltana volcanics at the Shamrock Copper Mine (Coats and Blissett, 1971). A mineralised schist layer was recognised in the same area by Marathon Petroleum (PIRSA database No. 368671). At the Gows Diggings in the northern part of the Mount Painter Inlier (Brindana Gorge area), an ESE-oriented shear zone is mineralised with uraninite, copper sulphides and minor Au (PIRSA database, G. Teale, oral communication).

2.3.4 Metamorphism-related REE mineralisations

This type of mineralisation is restricted to concentrations of monazite and thorite in biotite-rich schists present in the Radium Creek Metamorphics unit. These concentrations occur as lenses up to 150 m in length, containing a few percents of heavy minerals. Many of these occur in the Paralana Hot Springs area, where it gave the name to a hill nearby: Monazite Hill. Xenotime is also present in the biotite schists. The origin of these schists is metamorphic. Their presence in the migmatitic gneisses also indicates they probably formed by leucosome extraction and represent restitic material. Biotite schists also occur in the Southern Mount Painter Inlier around Mount Painter.

2.3.5 Other types of U-REE mineralisations

Other types of mineralisations are (1) secondary uranium minerals resulting from the weathering of primary concentrations, and (2) Post-Paleozoic sandstone-hosted uranium mineralisations like Beverley and Four Mile. An exhaustive list of these occurrences can be found in Appendix I. These mineralisations are not considered in this part, and Beverley mineralisation is described in detail in Part I.

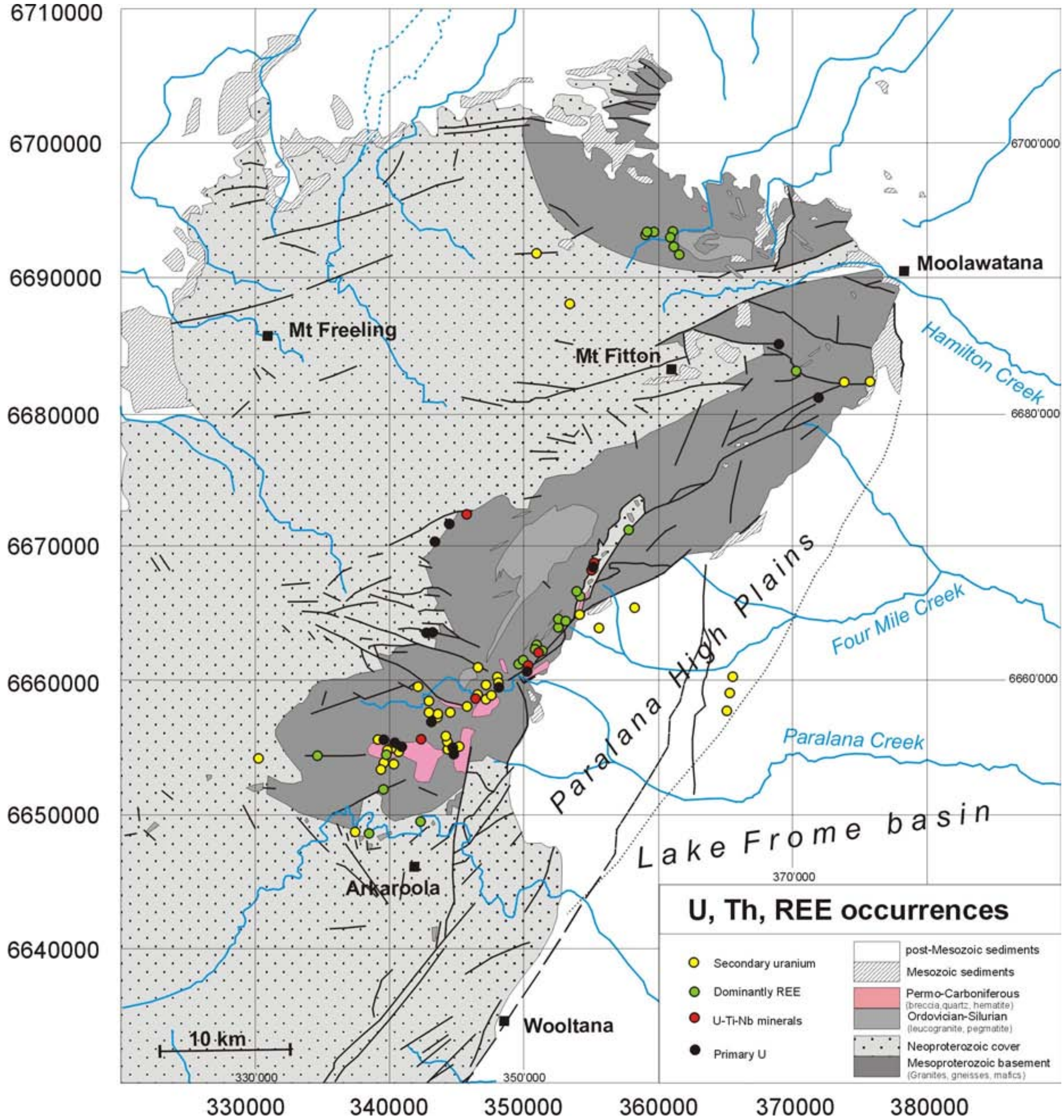

Fig. 5: U-REE-Th mineral occurrences of the MPD and region

3 Regional geochemistry of the MPD

3.1 Exploration data: radiometrics and rock analyses

The geochemical data (mineral and rock analyses) on the Mount Painter Domain has been regrouped in a database of the mine department of South Australia (PIRSA), including all available data from publications, open file reports and mining companies' folders. For the present analysis, the data was cleaned by removing incomplete analyses, and analyses for which inaccurate methods were employed. Several elements were plotted on the MPD regional map. For each map, the minimum values were adapted to coherently include all the "below detection limits" data. It appears that some areas are not well documented like the Southern Mount Painter Inlier and the Western central Mount Painter Inlier. The following elements were represented on the regional map: Na_2O, Th, U, Cu, Ce, Cd, Sn, As, Au, La and Nb. The geochemistry maps are regrouped in the Fig. 6a to Fig. 6k.

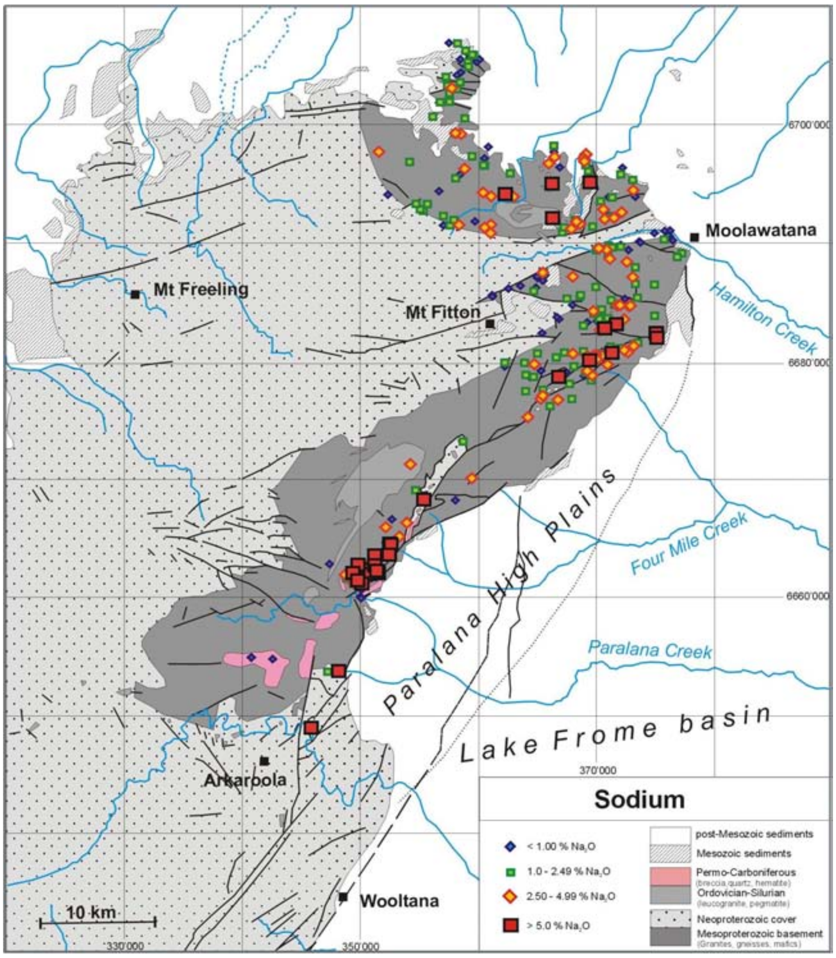

Fig. 6a: Sodium whole-rock data in the MPD

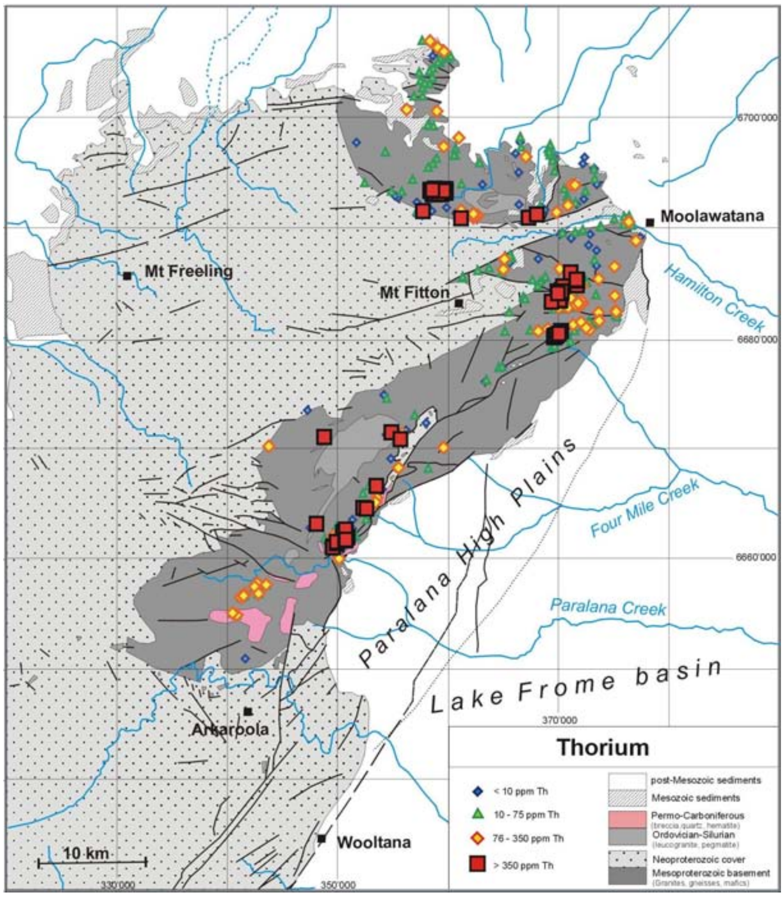

Fig. 6b: Thorium whole-rock data in the MPD

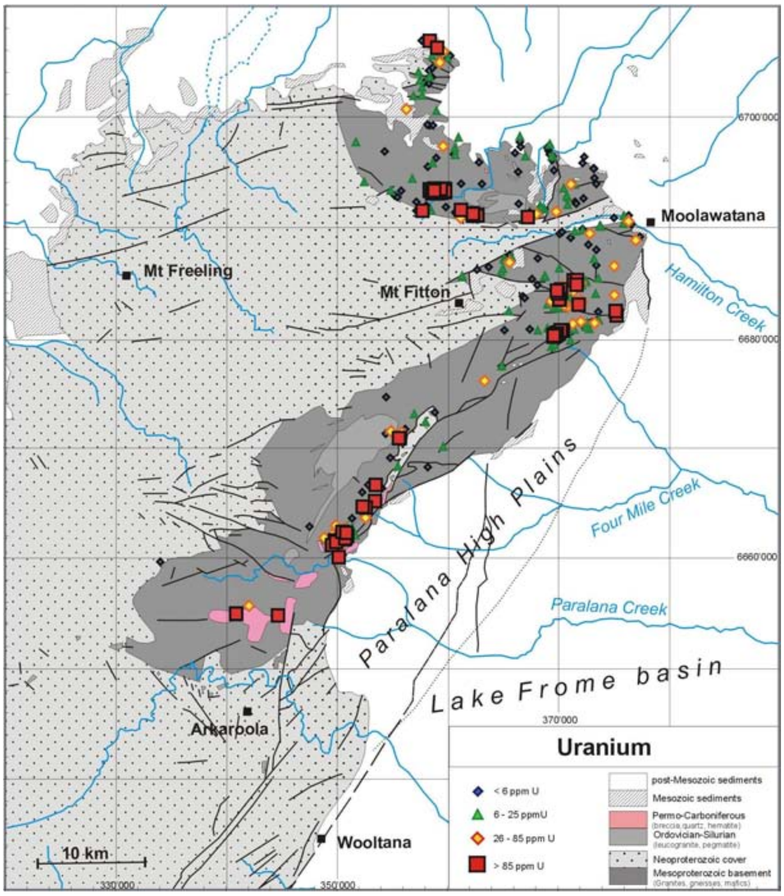

Fig. 6c: Uranium whole-rock data in the MPD

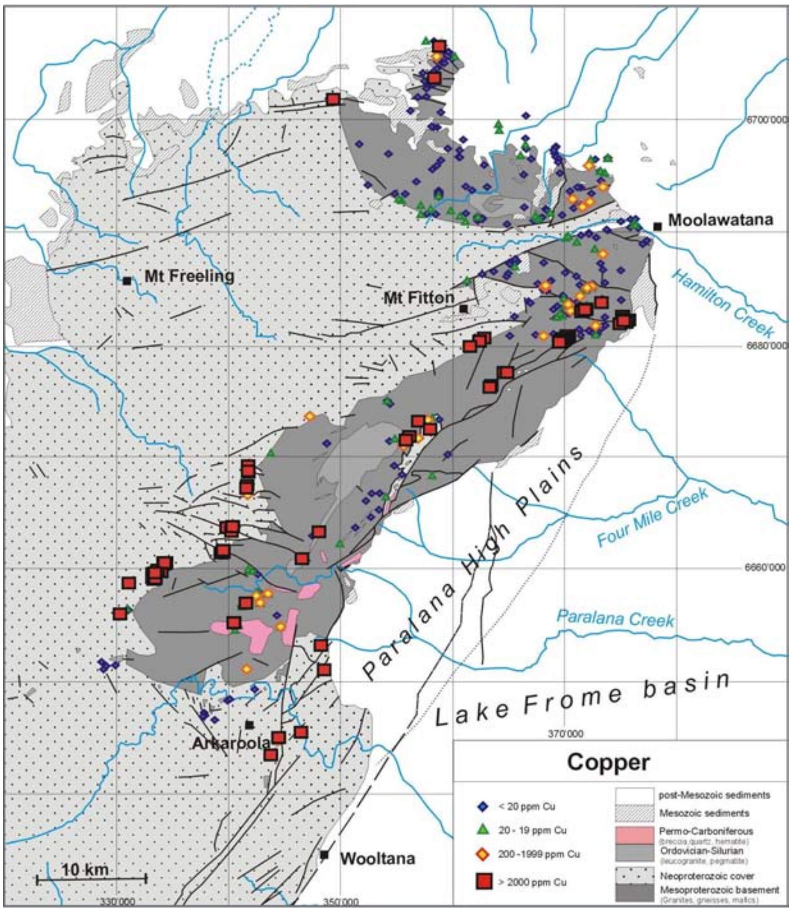

Fig. 6d: Copper whole-rock data in the MPD

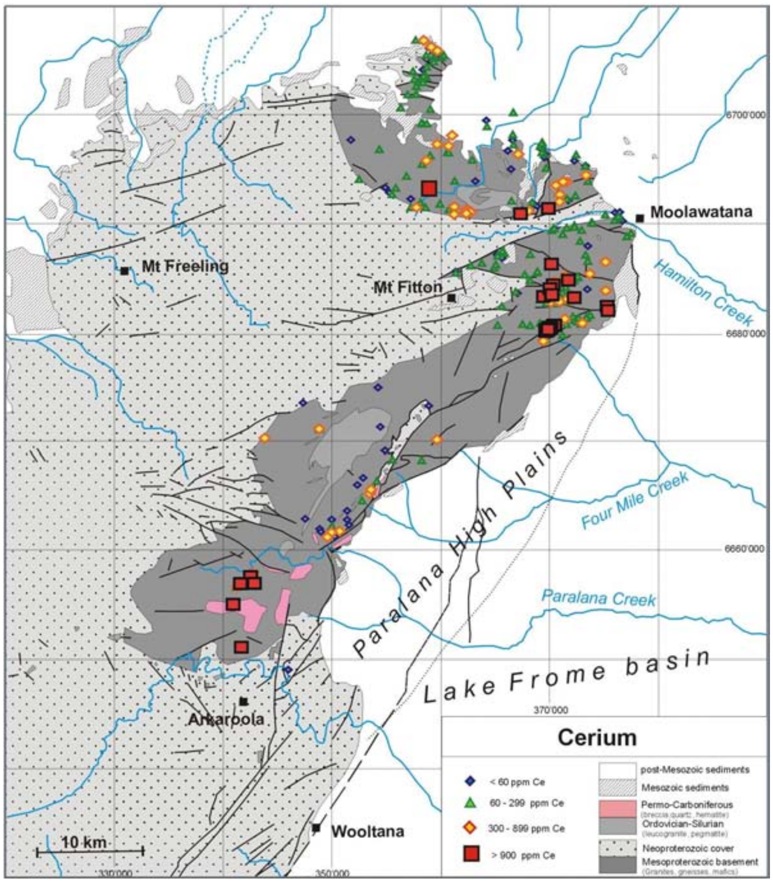

Fig. 6e: Cerium whole-rock data in the MPD

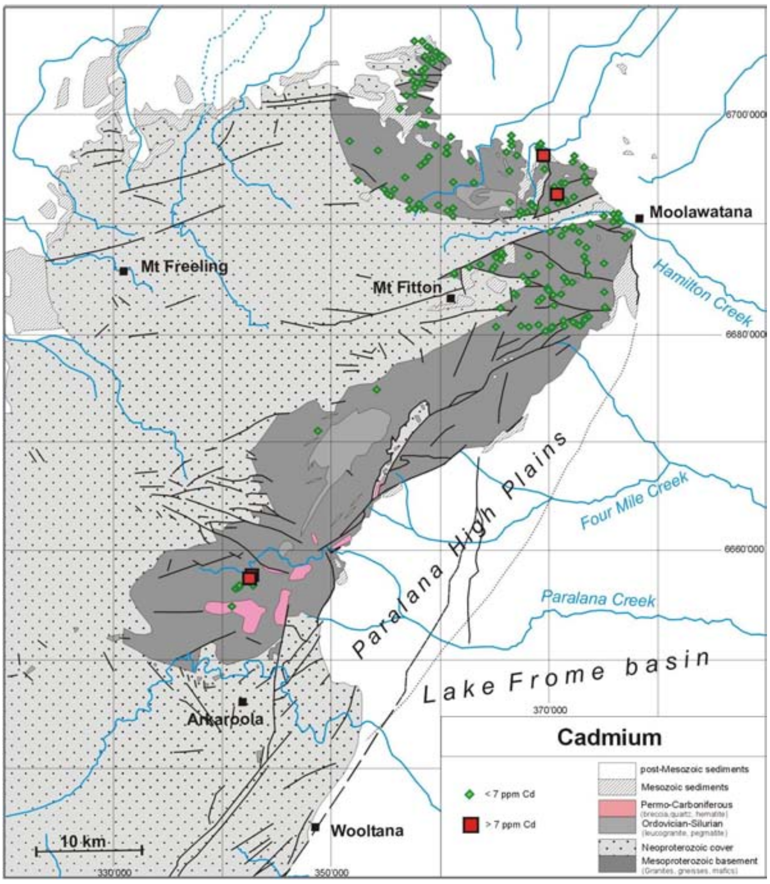

Fig. 6f: Cadmium whole-rock data in the MPD

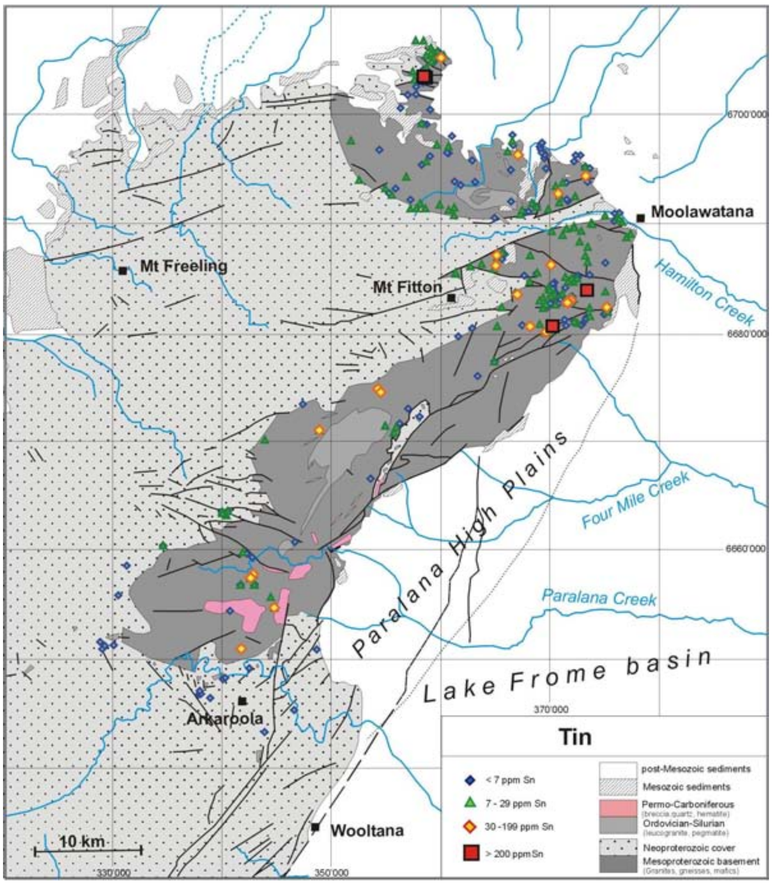

Fig. 6g: Tin whole-rock data in the MPD

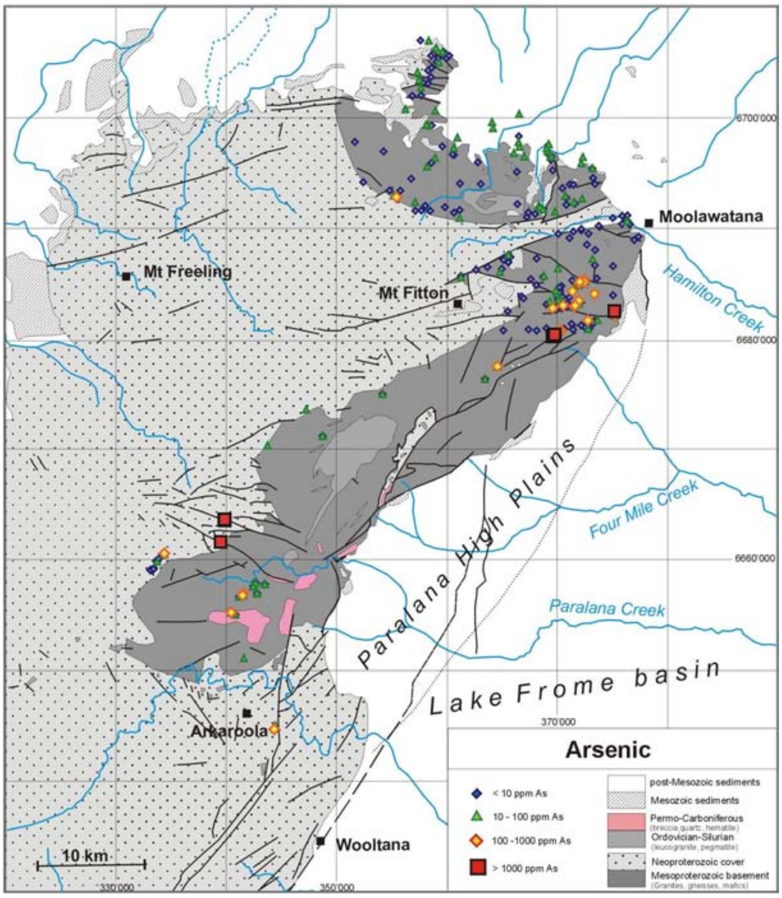

Fig. 6h: Arsenic whole-rock data in the MPD

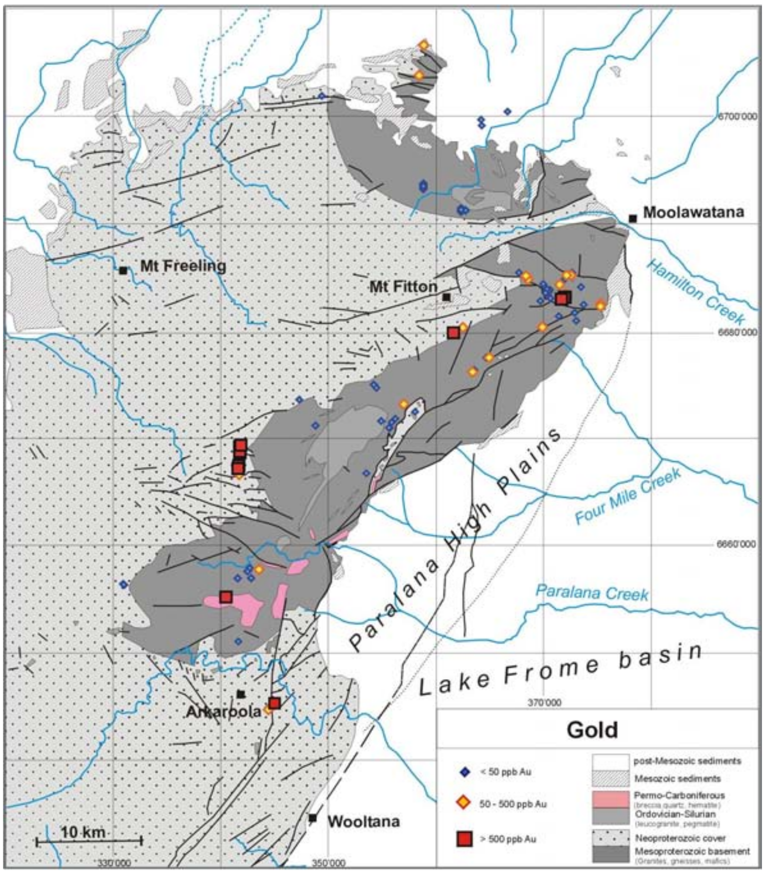

Fig. 6i: Gold whole-rock data in the MPD

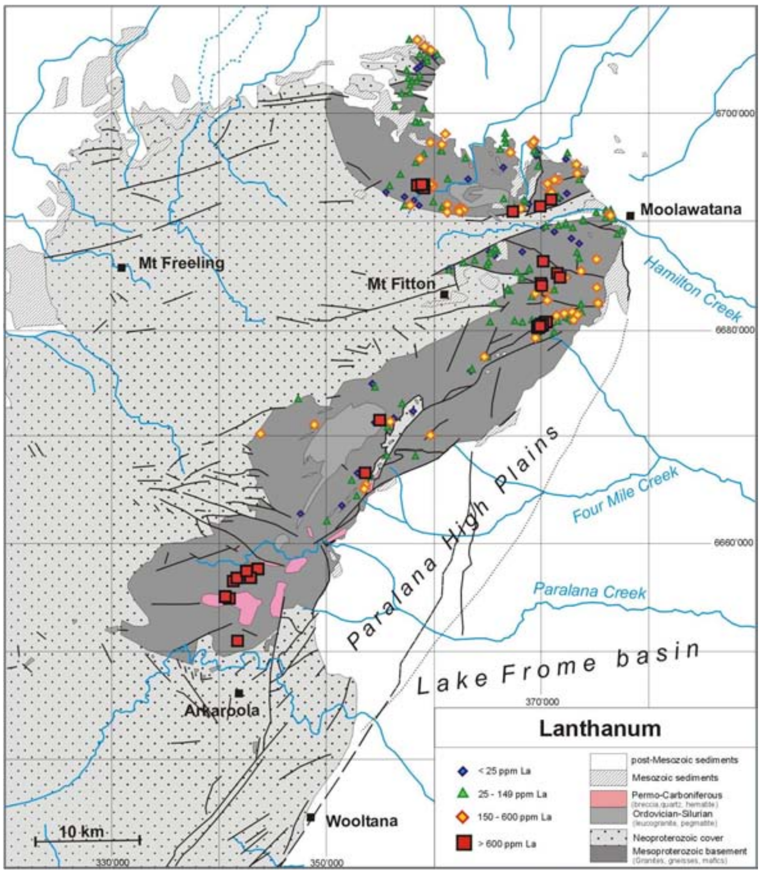

Fig. 6j: Lanthanum whole-rock data in the MPD

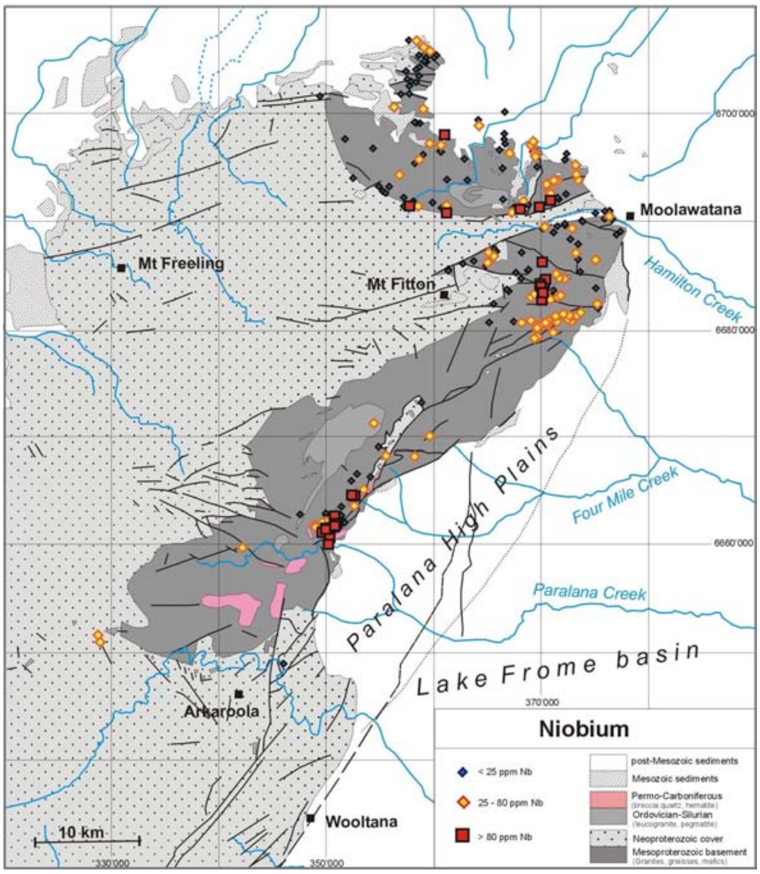

Fig. 6k: Niobium whole-rock data in the MPD

The sodium-rich analyses define a dense area near the Paralana Plateau; this corresponds to granitoids with alkaline composition, all located in the migmatite unit. Uranium, thorium and niobium also show extreme values in this location. This defines a zone of high interest for understanding the uranium and HSFE concentration mechanisms.

Higher values of copper are essentially located along fault zones, shear zones and are well represented in the Neoproterozoic cover or near the crystalline basement unconformity. Cadmium was chosen to represent an element which lies typically under the detection limit. For this reason, only a few spots at more than 7 ppm are shown. High values of tin are present in Cu-Sn mineralisations in relation to faults in the Mesoproterozoic granites or volcanics. The lower values are generally related to the metasedimentary rock samples. Zones of high REE, Th, U, Nb or other HSFE elements were selected for further investigation and additional whole-rock analyses complete the initial dataset.

The entire MPD was surveyed in 1994 by the Mine Department of South Australia and an airborne radiometric dataset was kindly provided by PIRSA. The eTh, eU and eK maps were generated to help defining the zones of high HSFE concentrations. This type of work was initiated by (Stewart and Foden, 2001) to redefine the granite nomenclature of the MPD and their distribution. The subdivisions and granite suite chemistry defined by them is discussed later in the granite section. In total intensity of gamma or in eTh only, the following granitic units are recognised as extremely high background (Fig. 7): (from the North to the South of the MPD) (1) Prospect Hill granite, (2) White Pole granite (in Terrapinna), (3) Terrapinna granite/Wattleowie granite, (4) Yerila granite, a second (4) "Yerila-type outcrop" near the Brindana gorge, (5) the Box Bore granite, (6) the Mount Neill suite (including volcanics & porphyry), (7) an "enriched granite gneiss" north of the Mawson Plateau, (8) a second "enriched granite gneiss" corresponding to the Paralana Plateau migmatite unit, (9) the Radium Ridge – Mount Gee deposits granitic-hematite breccia area, (6) further Mt Neill suite granitoids bodies in the Southern Mount Painter Inlier.

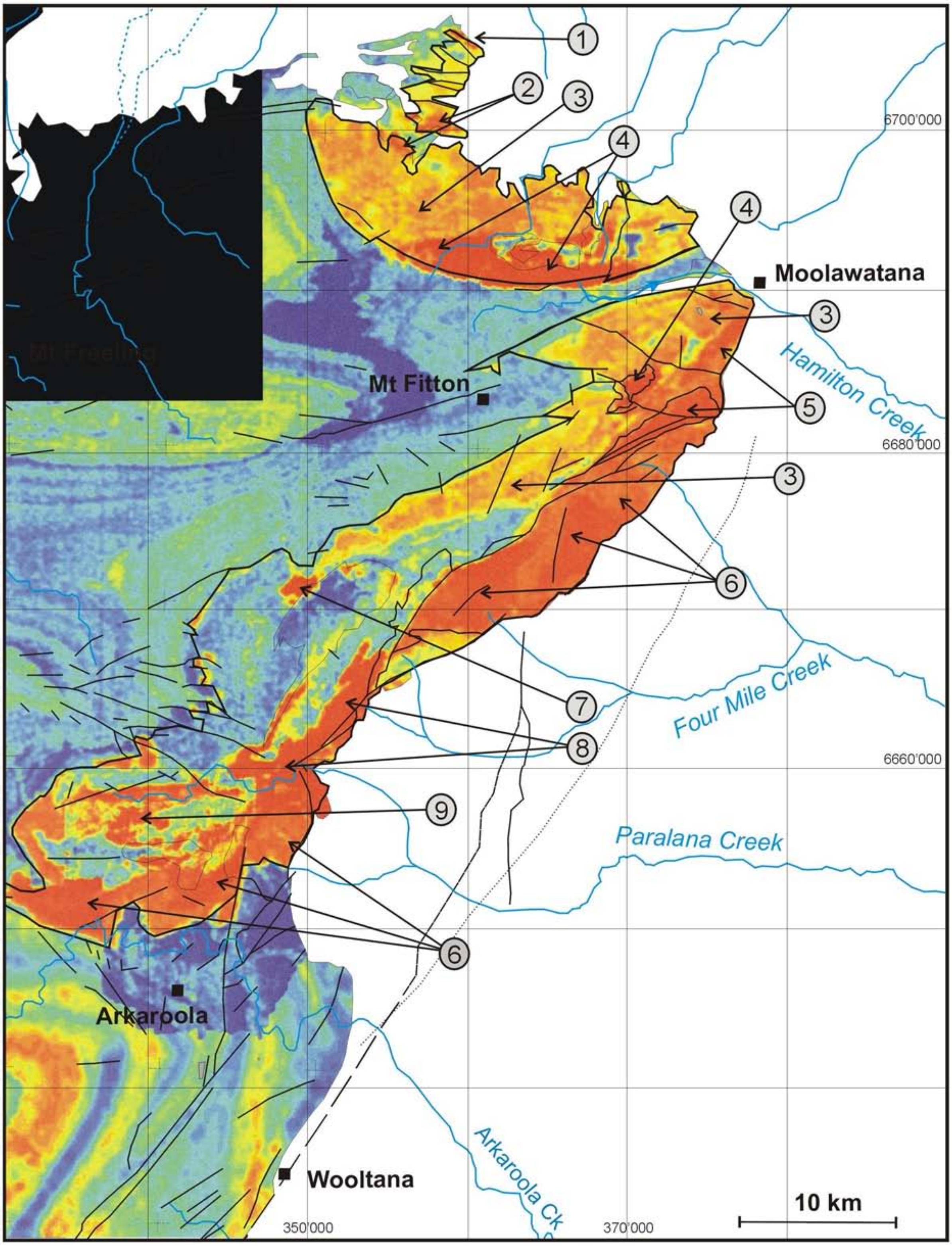

Fig. 7: Thorium radiometric map of the Pre-Mesozoic basement of the MPD region

The thorium radiometrics clearly define the rock unit with high HSFE element contents. The following unit are indicated on the map: (from the North to the South of the MPD) (1) Prospect Hill granite, (2) White Pole granite (in Terrapinna), (3) Terrapinna-Wattleowie granite, (4) Yerila granite, a second (4) "Yerila-type outcrop" near the Brindana gorge, (5) the Box Bore granite, (6) the Mount Neill suite (including volcanics & porphyry), (7) an "enriched granite gneiss" north of the Mawson Plateau, (8) a second "enriched granite gneiss" corresponding to the Paralana Plateau migmatite unit, (9) the Radium Ridge – Mount Gee deposits granitic-hematite breccia area, (6) further Mt Neill suite granitoids bodies in the Southern Mount Painter Inlier.

3.2 Samples location

Fieldwork was conducted over the whole MPD, with a special attention to the zones of high Th, U, REE concentrations and the mineralisations (Mt Gee, Mt Painter and East Painter). A special attention was given to the Hidden Valley and the Paralana Hot Springs region.

The samples acquired are reported on a map (Fig. 8) and regrouped into 9 main areas of investigations: (a) Prospect Hill granite – Petermorra volcanics area, (b) Yerila-Terrapinna granites area, (c) Brindana gorge area (Box Bore granite, allanite skarns), (d) Mt Neill granite, (e) Mawson Plateau area, (f) Hidden Valley – Paralana Hot Springs region, (g) Mt gee-Mt Painter area, (h) Radium Creek region (titanite pegmatites, Mt Neill granite), (i) Paleozoic intrusives in the Neoproterozoic sediments (Tourmaline Hill, Pinnacles, Sitting Bull etc.). The amount of work devoted to the regions (b) & (f) corresponds to 70% of the investigations.

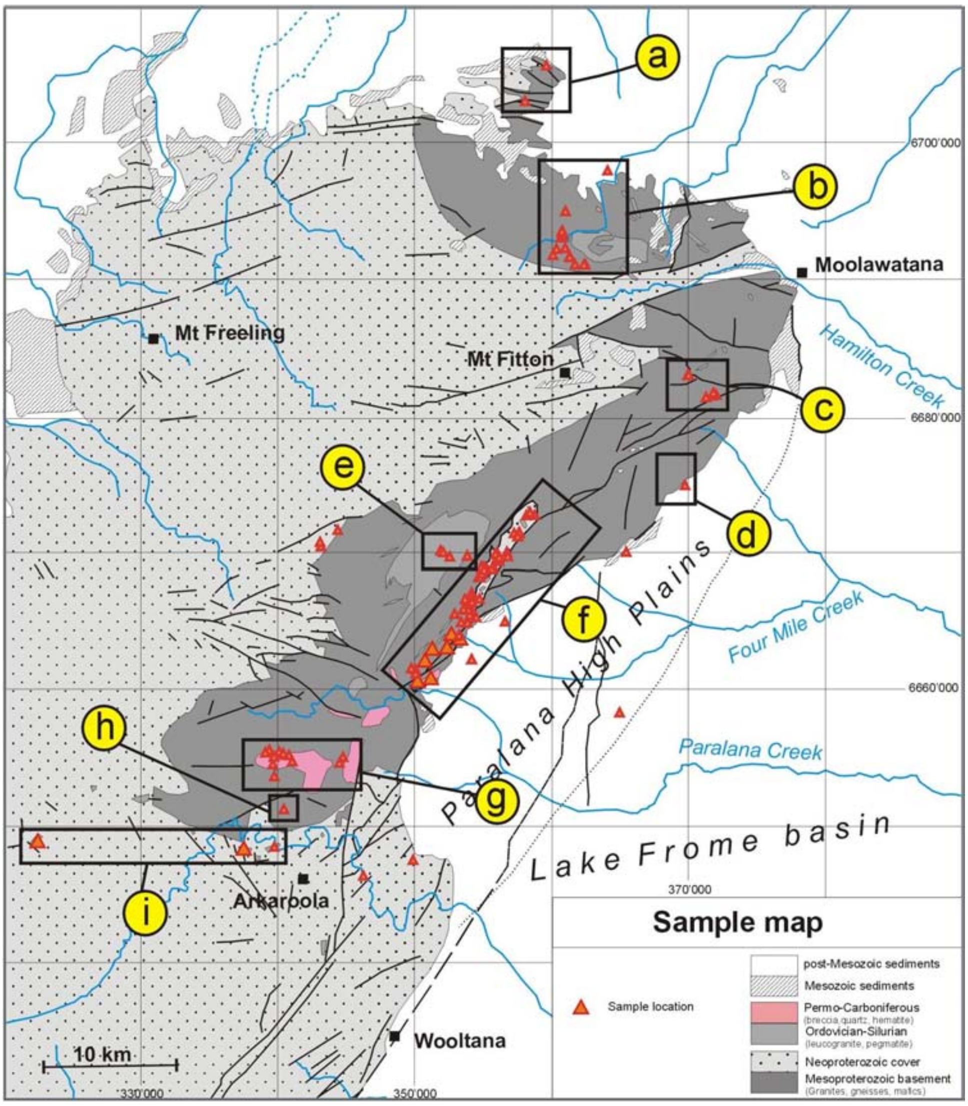

Fig. 8: Samples map

(a) Prospect Hill granite – Petermorra volcanics, (b) Yerila-Terrapinna granites, (c) Brindana gorge area (Box Bore granite, allanite skarns), (d) Mt Neill granite, (e) Mawson Plateau, (f) Hidden Valley – Paralana Hot Springs region, (g) Mt gee-Mt Painter area, (h) Radium Creek region (titanite pegmatites, Mt Neill granite), (i) Paleozoic intrusives in the Neoproterozoic sediments (Tourmaline Hill, Pinnacles, Sitting Bull).

3.3 Uranium and thorium in granites and alkaline intrusions: a review

Uranium and thorium occur mostly concentrated in the Earth crust, with average concentration of 2.8 ppm U and 10.7 ppm Th in the upper crust, especially in granites 4.75 ppm U and 17.36 ppm Th (Heier and Rogers, 1963; Rich *et al.*, 1977). These radioactive elements especially concentrate in magmatic liquids (or melts) because of their high ionic radii, which make them behave incompatible in the common silicate minerals structure; elements with these properties (Zr, Ti, Hf, Th, U, Ta, Nb, etc.) are denominated HFSE (high-field strength elements). The generation and evolution of granitic magmas from mantellic and/or crustal sources mostly operates by fractional crystallisation during the **orthomagmatic stage**, leading to an increased concentration in HFSE in the melt phase. These elements generally occur as accessory minerals in the granites such like zircon, monazite, allanite, xenotime, apatite, etc. and also have elevated fusion temperatures; for this reason they were commonly named "refractories".

By partial melting of an enriched source, and by successive differentiations, the HFSE concentration of some **late-stage intrusions** can increase dramatically. During differentiation processes, volatiles elements (F, Cl, B, P, Li, Be, H and C) generally concentrate in the melt phase; they act as depolymerising agents for the silicate melt and increase the solubility of HFSE in it (Webster *et al.*, 2004). The granitic melts are classified according to their major elements composition: (1) peralkaline, (2) metaluminous, (3) peraluminous. The solubility of the HFSE in the peraluminous and metaluminous melts is low, 10-30 ppm U (Peiffert *et al.*, 1996) but can increase considerably with the presence of elevated fluorine contents (Cuney and Friedrich, 1987). Experimentally determined uranium solubility in F-rich silicate melt systems is 900 ppm U for 3000 ppm F in slightly peraluminous melt (Peiffert *et al.*, 1996). Inversely, HFSE solubility in peralkaline melts is elevated and doesn't require the presence fluorine. Uranium solubility in peralkaline felsic melts was determined experimentally to be in the range 10^2 to $2\text{-}3 \cdot 10^4$ ppm U (Peiffert *et al.*, 1994).

Extreme differentiation by successive fractional crystallisation produces peralkaline residual melts, which are enriched in HFSE (up to 80 ppm U in the Vico peralkaline rhyolites in Italy) (Villemant and Palacin, 1987). Because of their compositions, peraluminous granites produced by anatexis of hydrated crustal rocks bear low concentrations of HFSE. F-rich strongly differentiated peraluminous granites are the exception to the rule, with the typical example of the F- and P-rich Beauvoir granite (France), which concentrated Ta, Sn and Li (Raimbault *et al.*, 1995). The most common type of highly-enriched granite is generally related to high-F concentrations in the residual melt; they form a special category of granites called "rare-metal granites". Their composition is generally peralkaline and relates to parental peralkaline magmas (Kovalenko *et al.*, 2007). They are typically strongly enriched in Zr, Nb, Th, Y, REE and U, with Nb>Th.

During the **late-magmatic/post-magmatic stages**, synchronously to the granitic magmas emplacement, the residual melt phase is getting extremely enriched in volatiles (F, H_2O, Cl, etc.). The volatile-rich melt can migrate toward the top of the intrusion and even escapes it, forming pegmatite, aplite dikes or peripheral concentrations. The dimixion of a fluid from these highly-enriched melts can migrates out of the pluton or interacts with it. Fluid circulation increases when meteoric water is added to the system. The modification of the rock chemistry through influence of these fluids is called **metasomatism**. The Suzhou granite in China provides a good example of lat-magmatic F-rich melt differentiates which migrated through the intrusion (Charoy and Raimbault, 1994); biotite (fluor-annite) concentrations extremely enriched in Zr, Th, Y, U and REE are found at the intrusion periphery. When the fluids do not escape the intrusion but only migrate in it, the phenomenon is called autometasomatism (Rogers *et al.* 1978). Other scenarios are a contact metasomatism and the formation of concentrations in country rocks adjacent to igneous intrusions (skarns), high-temperature vein concentrations **(hydrothermal)** or deposits gradational into metasomatic and pegmatite uranium deposits (Rogers *et al.*, 1978). The latter authors also mention mineralisations associated with pegmatites deposits formed by "in-situ, partial melting of uraniferous country rocks" or granites (anatexis).

The MPD contains numerous examples of uranium-rich and thorium-rich rocks with granitic composition. In order to discuss this regional feature and understand the anomalous U-Th concentrations in the MPD, it is necessary to review the occurrences of "uranium-rich" granites (purely magmatic origins).

Granitic rocks subjected to metasomatic alteration may be completely transformed and their U and Th concentrations modified. A distinction of all these rocks is necessary to understand the effect of metasomatism. As a example to illustrate the intensity of this process on uranium mobility, we mention the Ivigtut A-type granite in Greenland: the alkaline granite displays 8.5 ppm U and 28 ppm Th in the deep fresh samples recovered by drilling, whereas most of the upper part of the intrusion is metasomatised (albitization, greisenisation) with high-fluorine contents, leading to common enrichments up to 80-110 ppm U (Goodenough *et al.*, 2000).

The timing between all these successive stages of granite evolution (orthomagmatic stage, late-, post-magmatic stage metasomatism and hydrothermal stage) is highly variable, dependent of the cooling rate of the intrusions, the intervention of meteoric waters, etc.

A non-exhaustive list of granites with high U-Th contents is presented in Table 2; this table is the data source for the Figure 9; it only contains igneous granitic or alkalic silicic rocks which are devoid of hydrothermal alteration or late-magmatic fluid metasomatism. The Th & U values most probably truly represent magmatic compositions.

Granites:	References	U (ppm)	Th (ppm)
Conway granite (New Hampshire, USA)	(Fehn *et al.*, 1978)	15	57
Ballons granite (France)	(Cuney and Friedrich, 1987)	13	42
St Sylvestre granite (France)	(Cuney and Friedrich, 1987)	13	47
Streltsovskoe-Antei biotite granite (Russia)	(Chabiron *et al.* 2002)	5.9	19.5
Zinnwald microgranite	(Webster *et al.*, 2004)	11.0	20.1
Mittagfluh granite (Switzerland)	(Bajo *et al.*, 1983)	11.7	32.7
Rotondo granite (Switzerland)	(Bajo *et al.* 1983)	13.6	27.6
Bergell granite (Switzerland)	(Bajo *et al.* 1983)	7.7	25.5
Crow granite (South New Zealand)	(Muir *et al.*, 1997)	5.4	29
Aoukenek granite (HKCA), West Africa	(Liégeois *et al.*, 1998)	6.4	25
Baukwab A-type granite (Namibia)	(Jung *et al.*, 1998)	7.0	23.7
Gross Spitzkoppe biotite A-type granite, Namibia	(Haapala *et al.*, 2007)	17.0	70.0
Klein Spitzkoppe biotite A-type granite, Namibia	(Haapala *et al.*, 2007)	9.0	46.0
Ivigtut A-type fluorine –rich granite, Greenland	(Goodenough *et al.*, 2000)	8.5	28.0
Iddefjord A-type granite, Southern Norway	(Killeen and Heier, 1975)	9.9	50.2
Old Rag granite (Virginia, U.S.A.)	(Blackburn *et al.*, 1994)	8.5	53.1
Aqshatau leucogranite (Kazakhstan)	(Heinhorst *et al.*, 2000)	9.0	60.1
Batystau leucogranite (Kazakhstan)	(Heinhorst *et al.*, 2000)	3.8	28
Bektauata leucogranite (Kazakhstan)	(Heinhorst *et al.*, 2000)	6.2	15.0
Victoria Valley granite, Grampians (Australia)	(Hergt *et al.*, 2007)	5.3	23.2
Hitalba granite suite (Stuart Shelf, S- Australia)	(Neumann *et al.*, 2000):	14	55
Terrapinna A-type granite, (MPD, S- Australia)	PIRSA database	10.3	49.8
Mt Neill granite, MPD, South Australia	PIRSA database	19.2	74.5
Pepegoona porphyritic rhyolite	PIRSA database	23.3	72.1
Lusaka HKCA granite	(Katongo *et al.*, 2003)	6.6	32.8
Nchanga HKCA granite	(Katongo *et al.* 2003)	12.7	83.6
Monte Rosa fayalite granite, Colorado, USA	(Smith *et al.*, 1999)	7.9	32
Windy Point type granites, Colorado, USA	(Smith *et al.* 1999)	7.7	44.1
Kanigiri F-rich, A-type pluton, Pradesh, India	(Dharma Rao and Reddy, 2006)	18.5	62.5
Toki granite, Japan	(Sonehara and Harayama, 2007)	5.3	23
Naegi granite, Japan	(Sonehara and Harayama, 2007)	9.3	36
Nonggeori peraluminous granite, Korea	(Lee *et al.*, 2005)	5.0	10.2
Naedeokri peraluminous granite, Korea	(Lee *et al.*, 2005)	3.0	4.3
British Empire S-type granite, Australia	(Stewart and Foden, 2001)	11.4	8.9
Suzhou A-type granite pluton	(Charoy and Raimbault, 1994)	9.0	37
Podlesi peraluminous P-rich stock, Czech Republic	(Breiter *et al.*, 2005)	35.0	5.3
Irish River A-type granite	(Tollo *et al.*, 2004)	8.2	29.5
Rockfish River A-type granite	(Tollo *et al.*, 2004)	4.7	11.2
Singo Pink porphyritic granite (PO), Uganda	(Nagudi *et al.*, 2003)	14.2	47.7
Williams Batholith, Mt Isa, Australia	(McCulloch, 1988)	12.3	52.8
Sybella batholith, Mt Isa, Australia	(McCulloch, 1988)	8.4	36.0
Wonga batholith, Mt Isa, Australia	(McCulloch, 1988)	8.0	46.0
Naraku batholith, Mt Isa, Australia	(McCulloch, 1988)	10.0	57.0
Aar granite, Switzerland	(Labhart and Rybach, 1974)	13.0	32.0
Mont Blanc granite, France	(Labhart and Rybach, 1974)	19.0	31.0
Vallorcine granite, Switzerland	(Labhart and Rybach, 1974)	8.0	14.2
Giuv syenite (Switzerland)	(Bajo *et al.* 1983)	22.1	66.0

Alkaline rocks and rare-metal granites:	References	U (ppm)	Th (ppm)
Vico peralkaline rhyolite (Latium, Italy)	(Villemant and Palacin, 1987)	34	141
Streltsovskoe peralkaline rhyolite (Russia)	(Chabiron *et al.*, 2002)	21.5	68.4
Tahrmert (hybrid granite), West Africa	(Liégeois *et al.*, 1998)	6.5	33
Kidal ring complex, West Africa	(Liégeois *et al.* 1998)	5.0	22.1
Khaldzan-Buregtey peralkaline rare-metal granite	(Kovalenko *et al.*, 2007)	34	88
Khan Bogd peralkaline rare-metal granite	(Kovalenko *et al.*, 2007)	20	47
Ghurayyah peralkaline rare-metal granite	(Drysdall *et al.*, 1984)	117	399

Table 2: Granites and alkaline igneous uranium-rich rocks

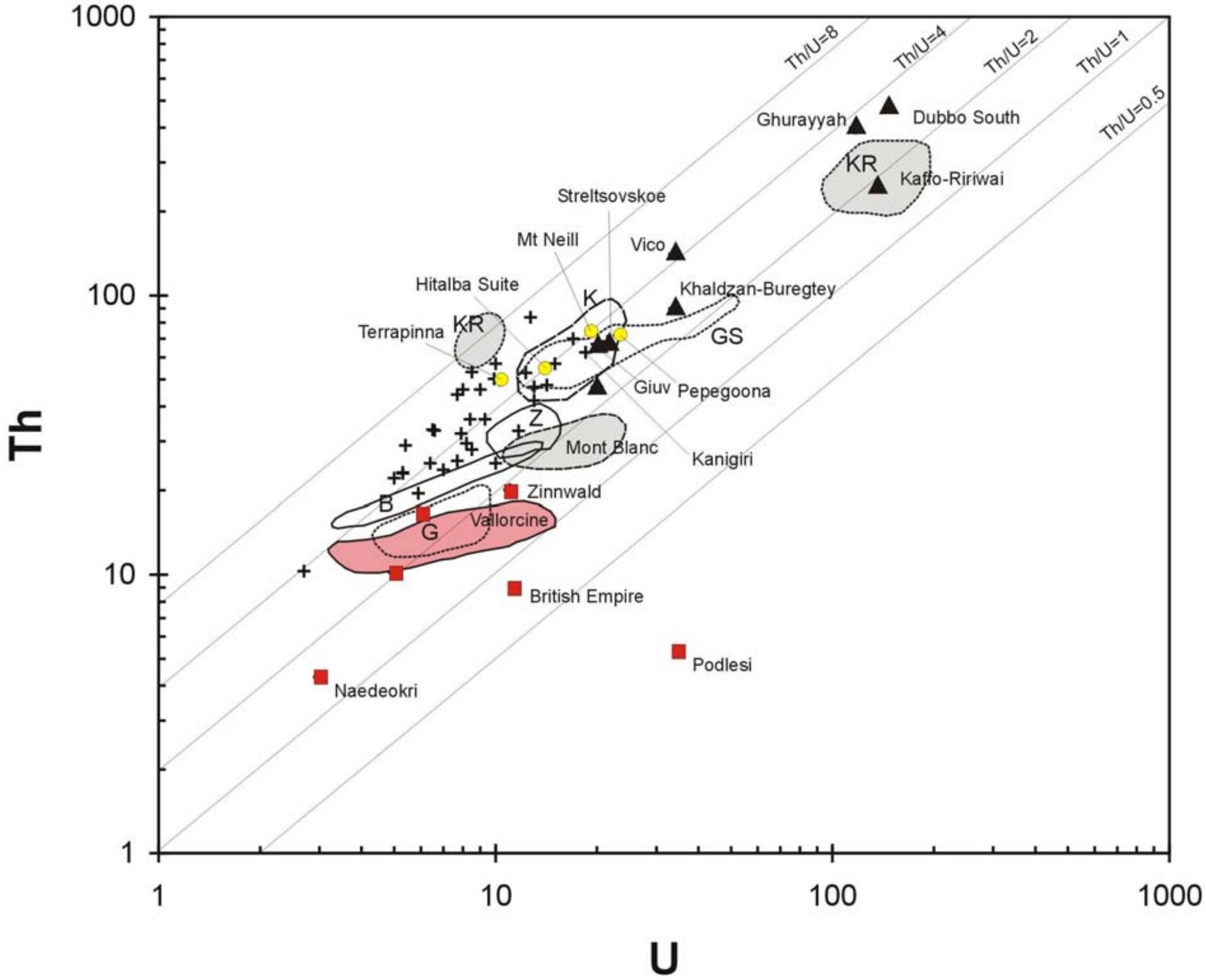

Fig. 9: Uranium versus Thorium in granites and igneous alkaline intrusions devoid of metasomatic overprint

The data used for the figure are reported in Table 2. Red squares represent the peraluminous granites, the yellow filled circles are the South Australian Mesoproterozoic granitoids, the black triangles correspond to the peralkaline granites or volcanics. The rare metal granites are also part of this category. Some plutons are better documented and zones of compositions are represented instead: G: Grimsel granite, B: Bergell granite, Vallorcine granite, Mont Blanc granite, Z: Central Aar granite, K: Kanigiri granite, KR: Kaffo-Ririwai pluton (alkali granites, albite-arfvedsonite-granites), GV: Giuv syenite (Aar massif). Granites with low-U and Th are under represented in this figure.

Form the South Australian granites a selection of uranium-rich intrusions have been considered: the Hitalba granite suite on the Gawler craton, the Mt Neill granite and the Terrapinna granites in the MPD. All these intrusives are Mesoproterozoic and have > 10 ppm U in average. Their compositions fit well in the Th-U range field of the granites as defined by Rich *et al.* (1977).

The Pepegoona rhyolite (part of the Mount Neill granite suite) (23.3 ppm U / 72.1 ppm Th in average) represents the highest average value in U for the MPD intrusives (metasomatised granites are excluded). This value is close to other silica-saturated granitoids entered in the table (Piz Giuv syenite, Switzerland: 22.1 ppm U, Kanigiri granite, India: 18.5 ppm U).

Silica-undersaturated intrusives or volcanics (peralkaline rocks) tend to reach higher U and Th concentrations.

As mentioned earlier, both differentiated peralkaline melt or F-rich peraluminous melts can lead to the formation of rare-metal granites. These later granitoids are generally of smaller size (<2 km²) and appear as late-stage stocks associated to larger A-type alkaline granite plutons with U-rich but not exceptional values (~ 10 ppm U).

3.4 Granites suites in the MPD

The characterization, spatial distribution and denomination of granites and felsic igneous rocks of the Mount Painter Domain have been modified and reformed many times. The only two published maps are the 1961 sheets at the 1:63'630 scale (Campana *et al.*, 1961a, Campana *et al.*, 1961b, Campana *et al.*, 1961c, Campana *et al.*, 1961d) and the 1969 map at the 1:125'000 scale (Coats *et al.*, 1969). A synthetic revision is given by Teale at a 1:300'000 scale with a major attempt to separate the Proterozoic Units into Paleoproterozoic and Mesoproterozoic (Teale, 1993b, Teale and Flint, 1993). Various authors also contributed to local revisions but no significant geological mapping aimed to refine the maps from the 60's. The latest revision of the granitoids is based upon the precise U-Pb dating of numerous intrusives and by comparing their geochemistry (Stewart and Foden, 2001). This later work is the first classification of the Mesoproterozoic granites into two distinctive suites: (a) the Moolawatana suite and (b) Mt Neill suite. These suites are dated to 1575 Ma and 1560-1555 Ma respectively. In the course of the research and the field investigations, I used a lot the 1961 maps, which provide the best available scale; more details are reported on them and it often appeared that the 1969 map was produced by simplification of the previous survey. Several mistakes have been introduced and it becomes evident that the geologists of the first survey (Bruno Campana, Robert. P. Coats, R. Horwitz and D. Thatcher) were more focused on the geology, whereas the second map aims essentially to provide a simplified background for mineral explorers.

The granite and different rocks of igneous felsic origin are reported in the Figure 3 in a synoptic form; the evolution of the terminology and the frequent divisions and then grouping of them are clearly illustrated in it. Across all the rock units defined, only a few have been unanimously termed and recognised in accordance with all studies:

- Pepegoona porphyry
- Granite Porphyry → Mount Neill Granite
- Rapakivi Granite → Terrapinna Granite
- White granite-adamellite → Wattleowie Granite
- Mudnawatana granite → Mudnawatana tonalite

Other granitic rocks have been subject to divergent opinion concerning their nature, extension or even their origin. A good example is the "Red pegmatitic granite" from the "Younger Granite Suite" of Campana, then denominated as Armchair granite (still in the "Younger Granites"), dated to be Mesoproterozoic (Fanning, 1995), and now regrouped into the Terrapinna granite (Stewart and Foden, 2001). A second example is the region forming the Paralana Plateau, north of the Paralana Hot Springs: the rock was initially recognised as part of the Younger Granites Suite, redefined and mapped in detail as a migmatitic unit formed of Paleoproterozoic gneisses with minor Paleozoic granitic intrusions in it (Blight, 1977, Teale, 1993b), but different from the Migmatitic granite or granitised sediments defined by Campana *et al.* (1961), The same rock unit was then renamed as "Enriched granite gneiss" unit based on its extremely Th-U-rich radiometric signature by Neumann (1996). Finally the "Gneissic granite" from Campana assigned to large variety of granitic outcrops mapped neither as "Rapakivi Granite" nor as "Granite Porphyry" were simply distributed among the "Terrapinna" or "Mt Neill" granites in the synthesis of 1969. Successive detailed studies permit to define a series of distinct granites or volcanics: Prospect Hill Granite, White Well granite, Petermorra Volcanics, Box Bore granite, Golden Pole granite and Con Bore granite (Sheard *et al.*, 1992, Teale and Flint, 1993). The integration of geochemistry and precise U-Pb dating finally bring back these units together into a granitic suite (Moolawatana Suite, Group 2, 1560-1555 Ma), which includes the Terrapinna granite (Stewart and Foden, 2001).

The complexity of the Figure 3 illustrates the difficulty of the previous workers to attribute clear names and unit limits for rocks that underwent various degrees of metamorphism and metasomatism. The MPD is also subdivided by faults and thrusts, which add a further complication when correlating units.