Uranium metallogeny in the North Flinders Ranges region of South Australia

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PART TWO

Metallogeny of uranium and thorium in the Mount Painter Domain

(North Flinders Ranges, South Australia)

5 Geochronology

The aim of this geochronological survey was to provide a temporal framework for U-REE mobility in the MPD, and to identify minerals that would be best suited for high-quality geochronological studies in future works. The geochronology data were obtained by La-ICPMS with the exception of a regional survey of monazites in the sediments, which were dated using the electron microprobe. The LA-ICPMS became available in 2005, in the nearby facility at the Adelaide Microscopy Centre, allowing a quick and flexible access. The technique was considered the most appropriate as an exploratory relatively cheap technique, also because of the elevated number of required analyses (>800). Form a scientific point of view, the generally obtained accuracy was judged sufficient for the geological problems. The results are reported either by localities or by type of origin for the dated minerals (e.g., Paleozoic intrusives or mafic rocks).

5.1 Regional data

The monazites recovered from different watersheds in the MPD were dated using the electron microprobe. The technique was selected because of its cheap and quick procedure in order to access a general distribution of ages through the region. Monazite generally occurs in the gneisses, in antinomic relationship with allanite, which appears in the more calcic rocks. The studied location are (a) SED-BAD, in the southern MBI on the Yerila granite complex, (b) FMC, in the Bottleneck Creek draining the Freeling Heights Unit and the migmatitic gneisses from the eastern flank of the central MBI, and finally (c) SED1, on the Mawson Plateau, draining both the metasediments and the British Empire granite.

All results are reported in detail in Appendix VII and plotted on Fig. 30, as diagrams of cumulated ages. Owing to the technique, the error on individual ages varies between 40 and 100 Ma. The method also implies that the common lead cannot be corrected. For this reason an additional error can be present. This means that a statistical approach is most relevant for the interpretation of these ages, whereas individual ages may not be significant (Montel *et al.*, 1994; Parrish, 1990). The same polished blocks could however be used again for more accurate dating techniques.

Unexpectedly and surprisingly, the results of the regional survey showed a clear predominance of Paleozoic ages in all three samples. The results of the different samples are described by locality:

- Monazites from the FMC sample are essentially coming from the migmatitic gneisses and schists (50% of the watershed) and only minor outcrop of BEG (<5%) could contribute to the overall sample: ages are clustered around 450-500 Ma, with minor spreading in older ages. A minor peak may indicate a population of 650 Ma, but this may not be statistically significant due to the errors. The 450-500 Ma population is clearly Delamerian, perhaps slightly younger, and certainly corresponds to the metamorphic peak recorded in the migmatitic gneiss unit. Note that BGE-related monazites would also plot in the tail. However, the monazite chemistry from the BEG is slightly different.

- The monazites from the Mawson Plateau are Ca-rich and no doubt come from the British Empire granite (BEG) dominantly (60% of the watershed) The remaining portion of drainage is represented by sandstones and quartzites with low REE content. Monazite issued from these quartzitic sediments would be well rounded and probably did not react to Delamerian metamorphism (Parrish, 1990). Many of them did not contain enough Th-U-Pb to be dated by EMPA, reducing considerably the number of points reported on Figure 30. This chemical character is opposite to the Th-rich monazites from the FMC and this observation is in good agreement with the Th-poor monazite chemistry from the BEG (Elburg *et al.* 2003). Here again, a peak centred at 500 Ma reflects the Paleozoic age of this granitic intrusion. The shift between the 442 Ma age obtained by U-Pb isotopic data on the BEG (Elburg *et al.* 2003) and our EMPA results is well within the error.

- The last sample (SED-BAD) is showing a more complicated age distribution from the Mesoproterozoic to the Paleozoic. Most ages are clustered in the 500-640 Ma range with a peak at 560-580 Ma. Minor clusters also appear at ~900 Ma and ~1200 Ma. It can be interpreted as a mixing of primary magmatic monazite (~1600 Ma) and a Delamerian partial or complete recrystallisation. The apparent shift from 560-580 Ma relative to the metamorphic peak elsewhere in the Delamerian fold belt (500 Ma) is again in the error range of the technique employed and a this will be documented later with La-ICPMS data.

Monazite ages nicely evidence the general imprint of the Delamerian orogeny in the Proterozoic basement and the Ordovician magmatism locally (BEG).At a regional scale, these results have major implications for the geological history of the MPD and: they clearly indicate the Delamerian orogeny had a strong metamorphic impact on the MPD (amphibolite facies) and also a global effect on REE-Th-U mobility.

5.2 The Four Mile Creek zircons- British Empire granite/migmatites

The zircons from the FMC sample (Bottleneck Creek) are derived from potentially 3 rock units: the "granite escarpment" bordering the SW edge of the Mawson Plateau (BEG), the migmatitic gneisses from the Paralana Plateau and the Freeling Heights Quartzite. Assessing the ages from all these units would require 3-4 different samples in gullies or creek draining one specific unit only. A typical random approach with 100 zircons dated would give 90 zircons from the zircons-rich unit, 10 crystals from the Freeling Height Quartzite and maybe one inherited zircon from the BEG. After dating maybe 70 zircons only would give a concordant age. To avoid dating hundreds of Proterozoic zircons, we applied a selective typology-morphology technique on the total recovered zircon fraction (6.4 g). Out of around 30'000 zircons, a selection of grains showing crystal faces was made and grouped by typology before dating. The detailed isotopic data ICPMS data is reported in Appendix V and plotted in Figure 31. Apart from two near-concordant Paleoproterozoic zircons around 2400 Ma, all zircons are younger than 1750 Ma. They can be divided in several groups: 1650-1740 Ma, 1530-1600 Ma, 1240 Ma and 460 Ma. The distribution of discordant zircons is quite regular and indicates a first Pb loss around 400-500 Ma as well as recent (Fig. 31a to Fig. 31c). Three concordant zircons at 456 ± 11, 459 ± 9 and 456 ± 9 Ma were found. One of them (P1-02) possesses a near-concordant core at 1560 ± 13 Ma. All three zircons have high-U and low-Th with U/Th ratio from 5.7 to 19.5. I interpret these zircons as sourced from the British Empire granite tail for the following reasons: (1) the zircons have the same chemistry than previously investigated BEG zircons (McLaren *et al.* 2006), (2) morphology indicates a short distance transportation in accordance with the small watershed and excluding an origin from the quartzite, (3) the zircon typology is coherent with calk-alkaline granites (Pupin, 1980) and (4) the only rock of this age in the watershed is the I-type BEG granite tail at the headwaters of the creek. One could argue some minor granitic intrusions are undiscovered, but this would not change the geological meaning of these ages. A selection of three zircons from the BEG tail reported in McLaren et al. (2006) is given in the Figure 31e. The chemistry of these zircons is also reported for comparison. U/Th patterns are similar and give an upper intercept age which coincides with the 456-459 Ma age. The three zircons reported in McLaren et al. (2006) have between 5000 and 7500 ppm U, whereas the FMC zircons set between 750 and 4500 ppm U, which means less radiation-induced damages.

Our zircons provides a first concordant zircons for the BEG, a granite reputed to only host discordant bad quality crystals because of their high U contents and frequent inherited cores.

5.3 The Mawson Plateau watershed

The zircons collected from the Mawson Plateau creek (SED1) were sorted by typology-morphology. A small selection of S-types and P-types was analysed, after rejection of the well-rounded zircons (90%) interpreted to be sourced from the Freeling Heights Quartzite. The search for Ordovician zircons failed. The zircons are plotted in Fig. 32 and are all Mesoproterozoic. The U-Th contents of the analysed zircons were generally much lower than those from the local granites investigated by McLaren *et al.* (2006) (hundreds of ppm instead of thousands). The same 1700-1750 Ma zircons population observed in FMC is present; this age group probably comes from the Freeling Heights Quartzite Unit upstream. The presence of this Paleoproterozoic zircons component confirms the results obtained by (Fanning *et al.*, 2003) on a sample of Freeling Heights Quartzite

5.4 The Yerila granite region

The age of the Yerila granite was previously investigated by several authors: U-Pb isotopic data on purified zircon populations gave an upper intercept age of 1556 ± 10 Ma (Cooper *et al.*, 1982), based on the original data of (Johnson, 1980): 1551 ± 38 Ma. The 1556 ± 10 Ma age has been retained as a magmatic crystallisation age. K-Ar analyses on biotite indicated cooling ages of 400 Ma (Webb, 1976), with current biotite Tc = 320 °C (von Blanckenburg *et al.*, 1989).

Our U-Th-Pb isotopic data was acquired on both allanite and zircon from YER03.

Several coarse allanite grains (3 mm in diameter) were analysed, selecting the less weathered zones. It appears that most of the points are reveres discordant in the U-Pb system and fail to provide an accurate crystallisation age (Fig. 33a). This result indicates that the mineral lost part of its uranium or that U migrated through the different damaged zones of the mineral. The mineral is x-rays amorphous and hence interpreted as metamict. The ^{232}Th-^{208}Pb-^{204}Pb system provides an Isochrone age of 1542 ± 44 Ma (Fig. 33b). This age itself is not satisfactory because of the large (2σ) error, but proves that the REE-Th-U disseminated mineralisation from the gneiss is Mesoproterozoic, either primary magmatic or metasomatic post-magmatic.

The zircon U-Pb isotopes were measured on single crystals obtained from a large purified population. The zircons were annihilated for 2 h at 850°C in a small sealed platinum capsule; this was conducted to harden the least damaged part of the metamict zircons (Mattinson, 2005). The zircons changed colour from black to light orange upon treatment. The annealed zircons were rinsed with pure 10% HCl and leached in concentrated HF overnight (12 h).

The remaining zircons were abraded mechanically and rinsed several times with pure water before being mounted on the epoxy section for LA-ICPMS dating. Only 10-15% of the total mass of zircons was recovered.

Results are plotted along Concordia curve on the Figures 33c to 33d. The first striking observation was the nearly total absence of discordant points, which confirms the selective disappearance of damage zircons. The analysed zircons generally contain very little ^{204}Pb and common lead correction applied was therefore minimal. A perfectly concordant zircon gives 1521 ± 12 Ma. The results indicate a slightly younger age than the previous determinations. Because of the restricted analysed population and due to the treatment, it doesn't provide any more constraining age interval. Allanite and zircons are considered synchronous with this isotopic dataset.

Zircons from SED-BAD were also analysed using the same procedure with or without HF final leaching. A two point Discordia on a single zircon gives an age of 1564.5 ± 7.4 Ma (Fig. 34a). Three zircons were used to define a concordant age at 1565 ± 6 Ma (Fig. 34c).

Zircons from the albite-rich metasomatic Yerila granite (YER5) define a Discordia line with an upper intercept age of 1539 ± 10 Ma (Fig. 34b).

Zircons and apatites from a Terrapinna granite outcrop (TERAP2) north of YER5 were also dated. Concordant zircons give an age of 1572 ± 15 Ma (Fig. 34d). All U-Pb ages on apatite were concordant, ranging from 400 to 430 Ma. This can be interpreted as a cooling age with $T>^{U-Pb} T_C$ (450°C) prior to 400-430 Ma (Fig. 34e) (Chamberlain and Bowring, 2000). The Th-Pb system in apatite is of lesser quality due to the low levels of Th. The low initial calculated $^{208}Pb/^{204}Pb$ ratio evidences this problem and the isochrone age is meaningless (Fig. 34f).

In addition to the regional survey conducted using EMPA monazite dating, several xenotime from AMPH9 were dated by LA-ICPMS; xenotimes were observed as free crystals or in association with the biotite-monazite schist from the local gneiss. Because of the restricted watershed, the xenotime is certainly coming form the Yerila granite. The ages obtained on xenotime are concordant and of excellent quality; this in part due to the absence of common lead, and also to the high and homogenous content of U and Th in the mineral which is not metamict. Mean ages from single crystals give 495.5 ± 3.3 Ma and 490.3 ± 4.2 Ma (Fig. 35a & 35b). The most likely explanation is to interpret these ages as the Delamerian orogeny peak in the area. Together with the K-Ar ages on biotite form the Yerila granite reported by (Webb, 1976) and the monazite regional data.

Close to the headwaters of the SED-BAD and AMPH9 watershed, the local Yerila biotite gneiss is crosscutted by a major amphibolite dike (20-50 m wide), itself crosscut by a muscovite-bearing pegmatite. A zircon displaying overgrowths was recovered from this pegmatite and dated on its core and rim; the core gives a near concordant Mesoproterozoic age. A two points discordia using the rim and the core gives an upper intercept at 1544 ± 17 Ma and a lower intercept at 488 ± 32 Ma (Fig. 35c). This confirms the Delamerian age for the pegmatite.

Zircons were also extracted from the amphibolite dike in an attempt to find some baddeleyite. Several small zircons aggregates and cauliflower shaped twinned zircons were separated. As for the previous pegmatite, inherited zircons from the surrounding Yerila granite are present. One cauliflower zircon gives a concordant age of 790 ± 14 Ma (Fig. 35d). The ^{232}Th-^{208}Pb-^{204}Pb system using all cauliflower-shaped zircons defines a 774 ± 61 Ma (Fig. 35e). This ~790 Ma age constrains the dike intrusion to the timing of the initiation of the Adelaide Geosyncline rifting. This is the first U-Pb geochronological data on amphibolite dikes for the Adelaide Geosyncline.

5.5 The allanite skarns from the Brindana Gorge area

Several U-Th-bearing mineral species were extracted from the allanite-bearing magnetite diopside skarn from the Brindana Gorge region (JB05-37): allanite, hydrated thorite, euhedral zircons and rutile. U-Th-Pb isotopes were measured by LA-ICPMS on all of them. These minerals are interpreted to have crystallized during the metasomatic stage responsible for skarn formation. The replaced rock could have been a dolomitic limestone or an impure limestone.

Zircons are uranium-rich and display a similar concentration in U or Th than the Yerila zircons. A concordant euhedral zircon gives an age of 1501 ± 6 Ma (Fig. 36a). Zircons define a Discordia with intercepts at 1501 ± 45 Ma and 283 ± 99 Ma. Thorite is present as hydrated yellow grains on the rims of allanite patches. This texture between thorite and allanite suggests that thorite could have been exsolved from allanite. In order to document this, a large thorite grain was attempted to be dated: thorite gives discordant U-Pb isotopic compositions and a $^{207}Pb/^{206}Pb$ age at 284 ± 25 Ma (Fig. 36b). Both thorite and zircons indicate a Permian uranium remobilisation.

Allanite crystals have the advantage to provide higher Th concentrations (~1% ThO_2), which produce accurate ^{208}Pb-^{232}Th ages. A Th-Pb isochrone was calculated for allanite using all fresh allanite cores (Fig. 36c); the method has the advantage to be independent from any common Pb corrections. The 1381 ± 280 Ma age is not distinguishable from the zircons with such a large error. The allanite U-Pb isotopic data are very scattered and indicate a more complex Pb and U remobilisation, as observed with the thorite exsolution (Fig. 36d); it indicates at least one Mesozoic-Paleozoic thermal disturbance.

The last mineral investigated is rutile. The mineral was found in small amount in the zircon concentrate, as anhedral black to reddish grains up to 200 μm in size. Rutile was corrected for common lead using ^{208}Pb instead of ^{204}Pb because of the absence of thorium (^{232}Th). This correction has the advantage to provide a very accurate correction on the lead. Some rutile had even no ^{208}Pb detected. Both corrected and uncorrected data are represented in the Fig. 37a and Fig. 37b for comparison; two rutile grains fully devoid of ^{208}Pb give concordant ages at 460 ± 11 Ma (Fig. 37c) and 464 ± 10 Ma (Fig. 37d). The U-Pb closure temperature (T_C) of rutile was for a long time estimated at 400°C (Mezger *et al.* 1989), although field studies indicated higher T_C. Recent studies on rutile both experimentally (Cherniak, 2000) and using U-Pb geochronology on slowly cooled granulites systems (Vry and Baker, 2006) have demonstrated the rutile T_C to be 600-640°C. Therefore, the 460-464 Ma age is interpreted to date the onset of the cooling of the rock assemblage below 600°C. Some of the larger rutile grains bear older concordant U-Pb ages (~500 Ma). This certainly records the peak of the Delamerian orogeny (>600°C) but Pb diffusion stopped earlier due to the size of the crystals. The U-Pb system in rutile is not sensitive to the Mesozoic-Paleozoic Pb loss recorded in allanite, zircon and thorite.

5.6 The Hidden Valley Complex

The geochronological study of the Hidden Valley Complex (HVC) was initiated by the separation of zircons from several units or tectonic blocks to document the unit they one day belonged to. The heteroclite and altered nature of the HVC sediments was difficult to interpret and the use of detrital zircon was considered to be a good approach. The dataset obtained on the main green metasomatic sediments were inconclusive because of the lack of concordant zircons and the small numbers of zircons dated (Fig. 38a); additionally, zircons from a quartzite block were found to bear a population of Mesoproterozoic ages ranging from 1580 to 1700 Ma, similar to the Freeling Heights Quartzite Unit (Fanning *et al.,* 2003) (Fig. 38b). These results had of poor impact on the general understanding of the HVC. Several units were then investigated to better constraint the nature of the HVC (including mafic intrusives, veins, and pegmatites).

Xenotime-(Y) crystals were extracted from a major muscovite pegmatite intruding a basement block to the north of the valley (JB06-01). The basement block is essentially composed of migmatitic gneisses with a strong radiometric signature due to thorium and uranium. They give perfectly concordant age of 453.3 ± 4.6 Ma on a transparent prismatic crystal (Fig. 38c). The entire xenotime dataset obtained on several crystals is represented on (Fig. 38d); the isotopic analyses suggest a slightly discordant trend and a calculated lower intercept age is reported (297 ± 230 Ma).

Zircons were extracted from a large microgabbro body to the north of the valley. The zircons crystals have a sub-rounded shape with resorption structures on the surface. For this reason and also due to the abundance of zircons in the gabbro (169 ppm Zr), it seems more censed to interpret them as inherited. A large group of zircons were analysed and the results are reported in (Fig. 38e) and (Fig. 38f); the first model takes into account only the most discordant zircons, which define a Discordia with an upper intercept 1592 ± 17 Ma and a lower intercept at 759 ± 45 Ma. The entire population gives a more accurate estimate with an upper intercept at 1602 ± 10 Ma and a lower intercept at 782 ± 31 Ma. This new age is undistinguishable from the amphibolite dike age (790 ± 14 Ma) crosscutting the Yerila granite in the MBI.

Titanite appears in a metasomatic marble rock in the vicinity of a muscovite-free pegmatitic intrusion in central Hidden Valley (JB05-21). The crystals where extracted from a calcite matrix, next to diopside and scapolite crystals. Titanite crystals are euhedral and vary in size from 100 μm to 2 mm. The isotopic U-Th-Pb data are reported in (Fig. 39). Concordant U-Pb ages are dispersed between 700 Ma and 490 Ma. There is a cluster of points around 580 Ma. Several Th-Pb isochrones models are presented in Figures 39c and 39e; the isochrones are drawn using different points analysed on separate crystals. Both isochrones are imprecise and suggest that the titanite underwent some Pb diffusion. The U-Pb closure temperature of titanite is 680-700°C (Verts et al., 1996; Scott and St-Onge, 1995) with the exception of some very slow cooling temperatures for which the U-Pb closure temperature T_C can be lowered down to 500-550°C. Our concordant U-Pb analyses are interpreted to record contact metamorphism with Neoproterozoic nearby intrusions.

Unusual medium-grained alkali granite from the central HVC was found in a near contact to a large gabbro intrusion (GX01). The rock display extremely low zirconium content (<10 ppm), and a potential link with the gabbro intrusion is possible. Zircons from the rock were extracted for geochronology study. Isotopic data is reported in (Fig. 39f). Despite the absence of fully concordant zircons, it is noticeable that the rock lacks any 1560-1650 Ma local granitic zircons, which suggests the granitic melt originated from a distinct metasedimentary source.

5.7 Mt Gee - Radium Ridge to Hidden Valley

Davidite-(La) from the Nr.10 Workings, Mt Gee West

Davidite, $(REE)(Y,U)(Ti,Fe)_{20}(O,OH)_{38}$ is complex oxide minerals belonging to the crichtonite group of minerals. Its mineral structure hosts two larger crystallographic sites A & B which may hosts (La, Ce, Pb, Sr, Ba, K, Na) and (Y, Zr, hREE, U, Mn, Fe) respectively. The mineral has the ability to accommodates both uranium and lead like in the end-member cleusonite $(Pb,Sr)(U)(Ti,Fe)_{20}(O,OH)_{38}$ (Gong *et al.* 1995; Wülser *et al.* 2005). The mineral can be formed under different pressure and temperature environments but davidite is mostly occurring in granite pegmatites ($T > 650°C$) whereas the Pb, Sr, Ba or Na dominant end-member form in metasomatic environments and hydrothermal veins ($T < 350°C$) (Wülser *et al.* 2005).

The U-Pb isotopic data obtained on the davidite is plotted on Figure 40a, showing a reverse discordant composition, with both $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ Paleozoic ratio. The $^{207}Pb/^{206}Pb$ age indicates 286 ± 6 Ma using a uranium loss or lead gain at t = 0. The $^{204}Pb/^{206}Pb$ ratio is low, and implies that the lead composition does not contain more than 1.2% common lead (using the global second-stage Pb reservoir of Stacey & Kramer (1975)). Even with this correction, the $^{207}Pb/^{206}Pb$ apparent age remains close to ~290 Ma. Davidite also contains Th and the ^{232}Th-^{208}Pb-^{204}Pb system gives a Delamerian 492 ± 20 Ma isochrone age (Fig. 40b). This interpretation suits well the Permo-Carboniferous age (300-250 Ma) obtained by paleomagnetism on the Radium Ridge and Mt Gee breccia in the neighbourhood (Idnurm and Heinrich, 1993) and is also in accordance with the ~320 Ma maximum age obtained using detrital zircons populations on conglomerates crosscut by the epithermal Mt Gee system at Mt Gee East (Brugger & Wulser, *in prep.*).

Polycrase-(Y) from the Paralana Plateau area

The U-Pb isotopic composition of zircon and polycrase-(Y) from a cobble of migmatitic gneiss recovered from the Bottleneck Creek (FMC) was investigated as a complement. A two points Discordia using core and rims on a zircon from this cobble gives intercepts at 99 ± 26 & 1544.1 ± 6.7 Ma. The polycrase-(Y) contains very minor common lead and is reversely discordant, giving $^{207}Pb/^{206}Pb$ apparent ages between 317 and 424 Ma. After common lead correction, and using a recent uranium loss model, the $^{207}Pb/^{206}Pb$ composition intersects the Concordia curve at 418 ± 15 Ma (Fig. 40c). Because of the metamict nature of the mineral, I interpret the mineral experienced a recent uranium loss, leading to the reverse discordance like for davidite-(La) from Mt Gee. The ^{232}Th-^{208}Pb-^{204}Pb system gives a Delamerian 487 ± 16 Ma isochrone age (Fig. 40d).

Brannerite from "Jacob", Brannerite Hill, Hidden Valley

The large brannerite crystals from "Jacob" were analysed for dating using LA-ICPMS. Polished sections of brannerite observed in reflected light show two types of reflectance intensity: (a) black zones with higher hardness to polishing and (b) black-brownish zones of lesser hardness. The "black" areas were found to be of less discordant than the others and this may be due to different intensities of weathering. The isotopic compositions are reported in Figure 40e (near-concordant analysis) and in Figure 40f. The Discordia line gives an upper intersect at 367 ± 13 Ma and a lower intercept at 21 ± 39 Ma. Unlike the polycrase or the davidite, brannerite experienced a lead loss instead of uranium loss.

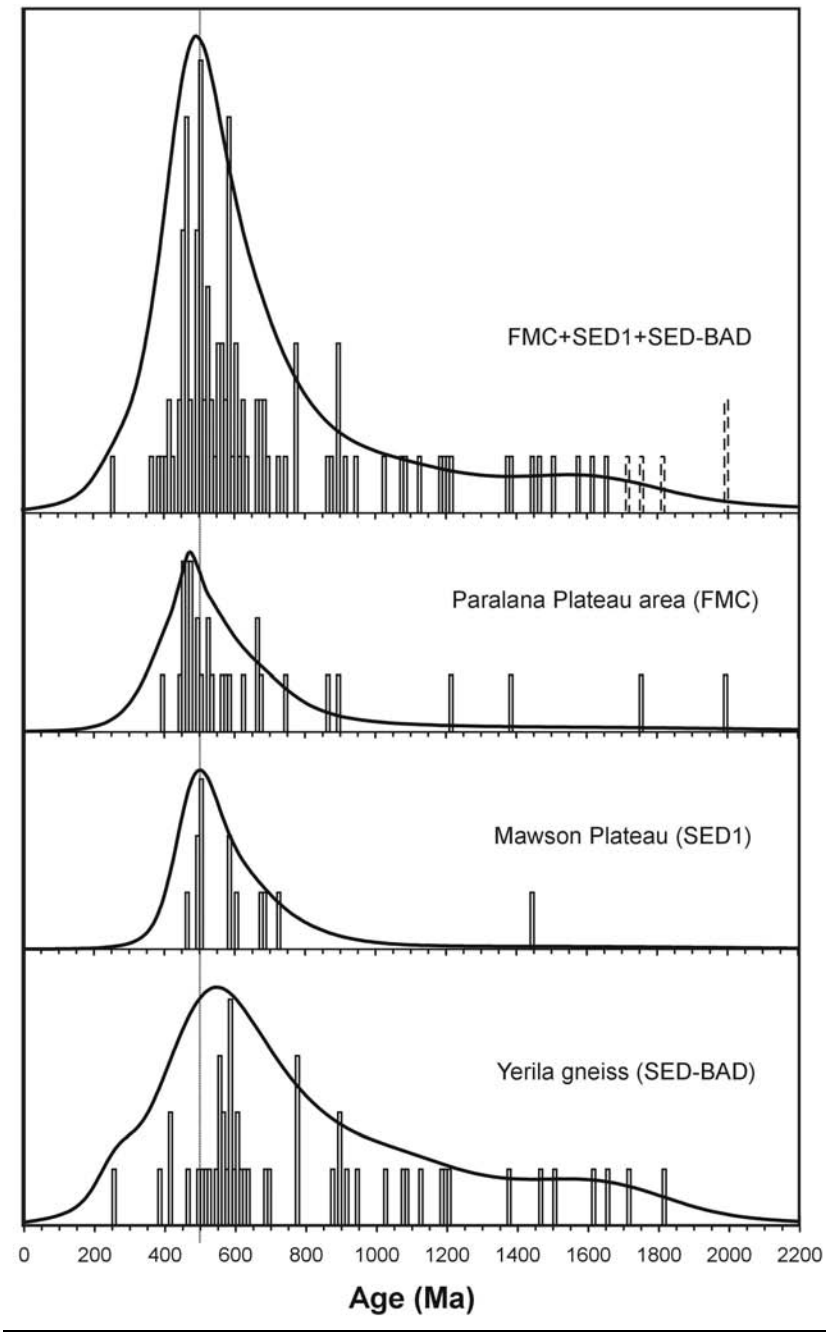
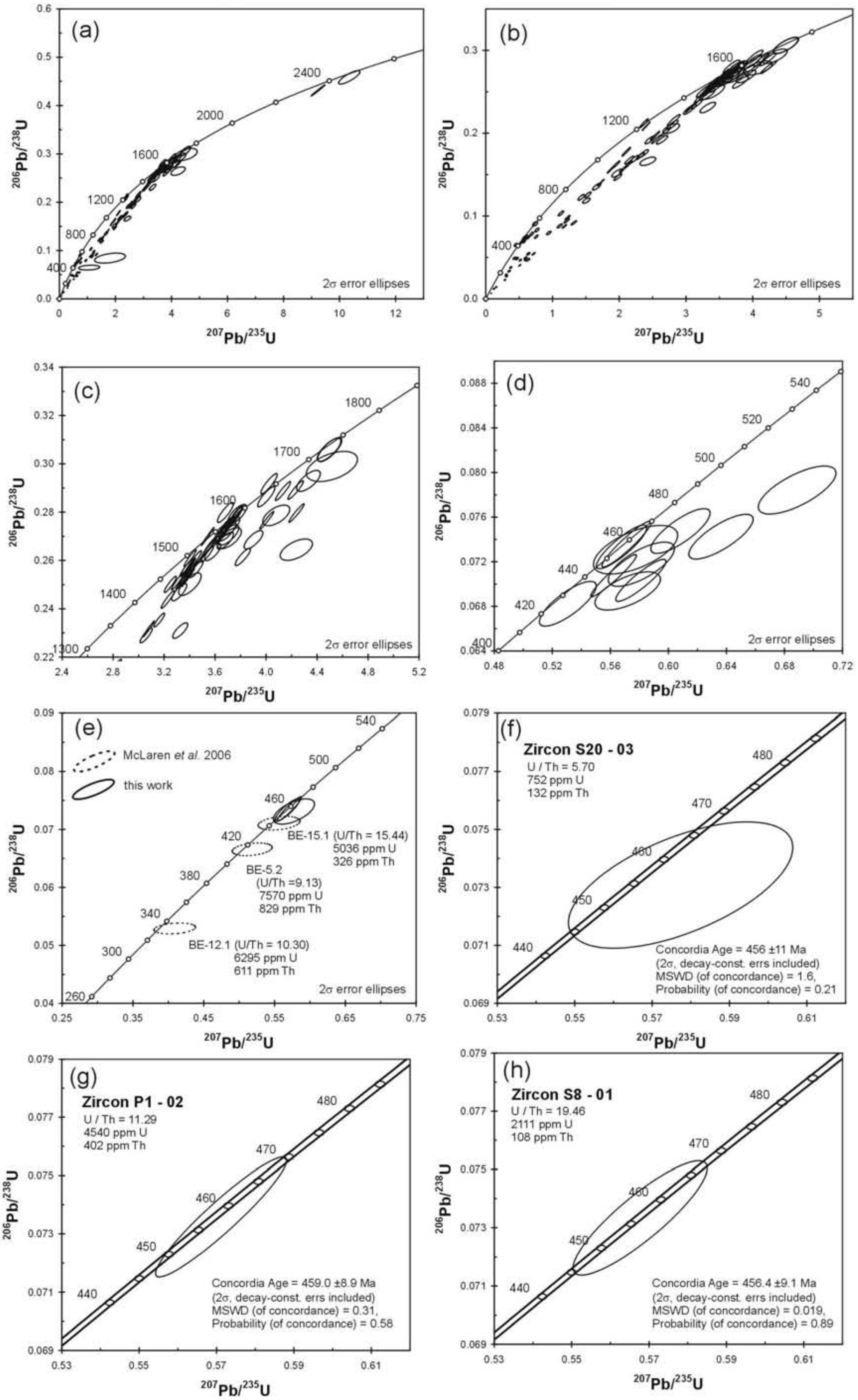


Fig. 30: Electron microprobe cumulative ages for monazites from the MPD

The three samples used for this regional dataset are SED1, SED-BAD and FMC, representing respectively the Central Babbage Inlier, the Mawson Plateau of the Central Mount Painter Inlier (MPI) and the Western part of the central MPI. The precision on individual ages is large (between 40 Ma and 200 Ma; see data in Appendix VII), depending upon the Th, U and Pb contents. The age distribution shows a dominance of Paleozoic ages, indicating either a Delamerian origin around 500 Ma or a possible contribution from the Ordovician magmatic-hydrothermal event.

Fig. 31: Zircons from FMC samples with BEG Ordovician concordant zircons *(next page)*

The FMC zircons come from a watershed draining the Mesoproterozoic gneisses and quartzites and the British Empire granite and its SW tail. (a) all zircons, (b) zoom on the main population (c) Mesoproterozoic zircons with preserved morphology are mostly coming from the migmatitic gneisses; a 1700-1750 Ma sub-population of age is present; (d to h) Ordovician zircons; data from McLaren et al. (2006) were obtained from crushed granite samples from the BEG tail; the high proportion of inherited zircons from the Mesoproterozoic crustal sources combined with the extremely high U content of them have impaired the application of U-Pb zircon dating for BEG. The three concordant Ordovician zircons do not contain common lead.


(a)
(b)
(c)
(d)
(e)
McLaren et al. 2006
this work
BE-15.1 (U/Th = 15.44)
5036 ppm U
326 ppm Th
BE-5.2
(U/Th =9.13)
7570 ppm U
829 ppm Th
BE-12.1 (U/Th = 10.30)
6295 ppm U
611 ppm Th
2σ error ellipses
(f)
Zircon S20 - 03
U / Th = 5.70
752 ppm U
132 ppm Th
Concordia Age = 456 ±11 Ma
(2σ, decay-const. errs included)
MSWD (of concordance) = 1.6,
Probability (of concordance) = 0.21
(g)
Zircon P1 - 02
U / Th = 11.29
4540 ppm U
402 ppm Th
Concordia Age = 459.0 ±8.9 Ma
(2σ, decay-const. errs included)
MSWD (of concordance) = 0.31,
Probability (of concordance) = 0.58
(h)
Zircon S8 - 01
U / Th = 19.46
2111 ppm U
108 ppm Th
Concordia Age = 456.4 ±9.1 Ma
(2σ, decay-const. errs included)
MSWD (of concordance) = 0.019,
Probability (of concordance) = 0.89
206Pb/238U
207Pb/235U

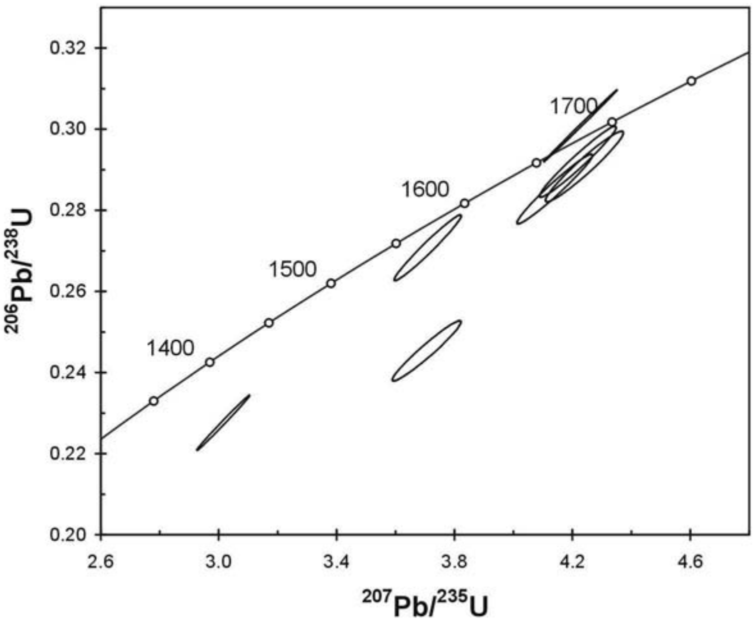


Fig. 32: Zircons from the Mawson Plateau creek (SED1)

The zircons were selected from the HM's concentrates when euhedral or subhedral. The only S-types zircons from the Pupin (1980) typology were sub-rounded, excluding the possibility they could have been sources in the local BEG. All zircons are Mesoproterozoic; the only zircon showing a high U/Th ratio belongs to the "1550-1590 Ma" local granitic basement. Others are probably derived from the Freeling Heights Quartzite.

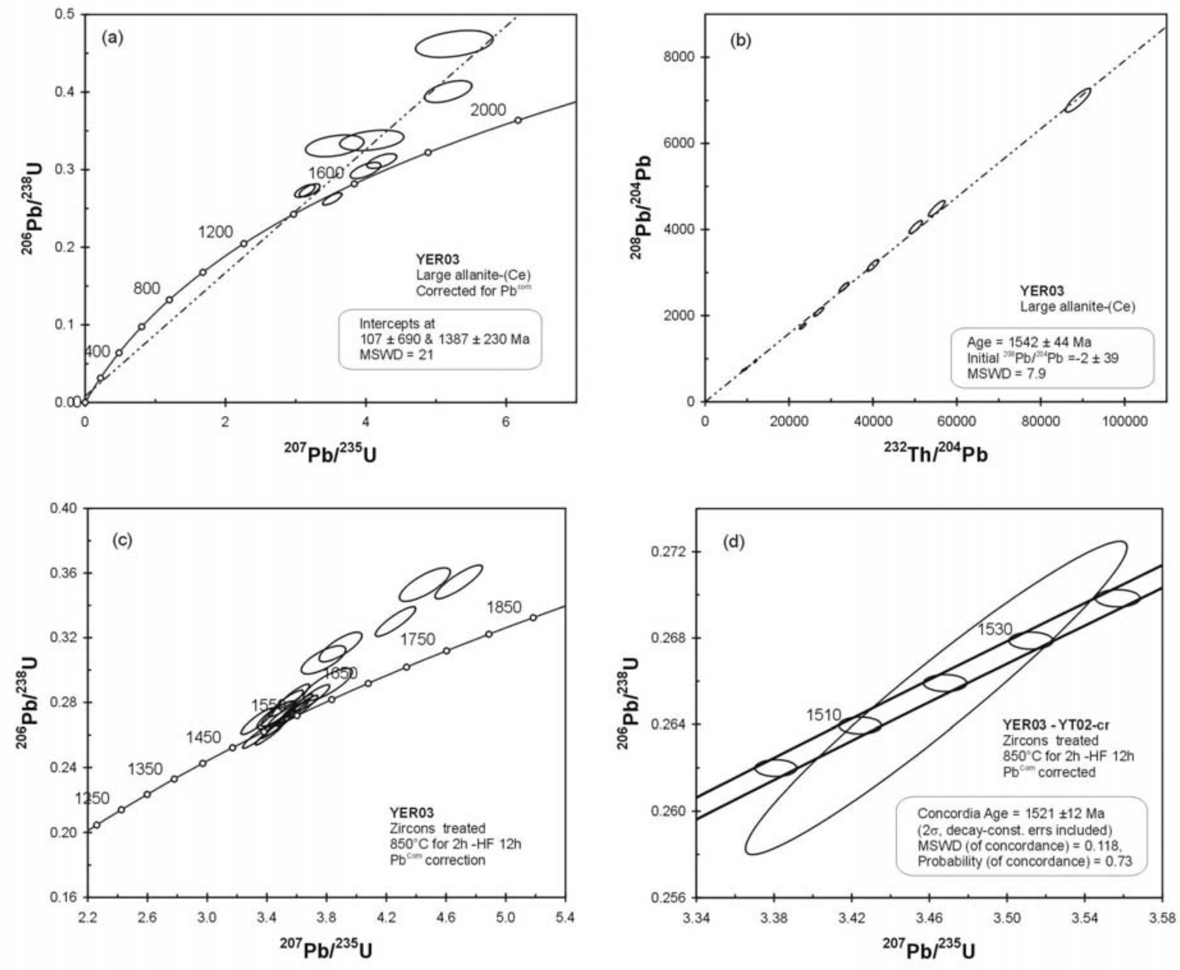


Fig. 33: U-Pb isotopic data for minerals in the Yerila granite (YER03)

(a) U-Pb isotopic data for allanite crystals; because of the zoning in low-U and high-U, allanite ages are very inaccurate; (b) Th-Pb isochrone age provides the best estimate for allanite crystallization age; (c) and (d) metamict zircons heated at 850°C for 2 h (annealing radiation damages) and then leached at room temperature with HF for 12 h: values have been corrected for common lead using ^{204}Pb. The heat treatment followed by HF leaching also selectively removed potentially damaged zircons from the dated population. The reverse discordant zircons have lower Th and U contents and represent inherited zircons.

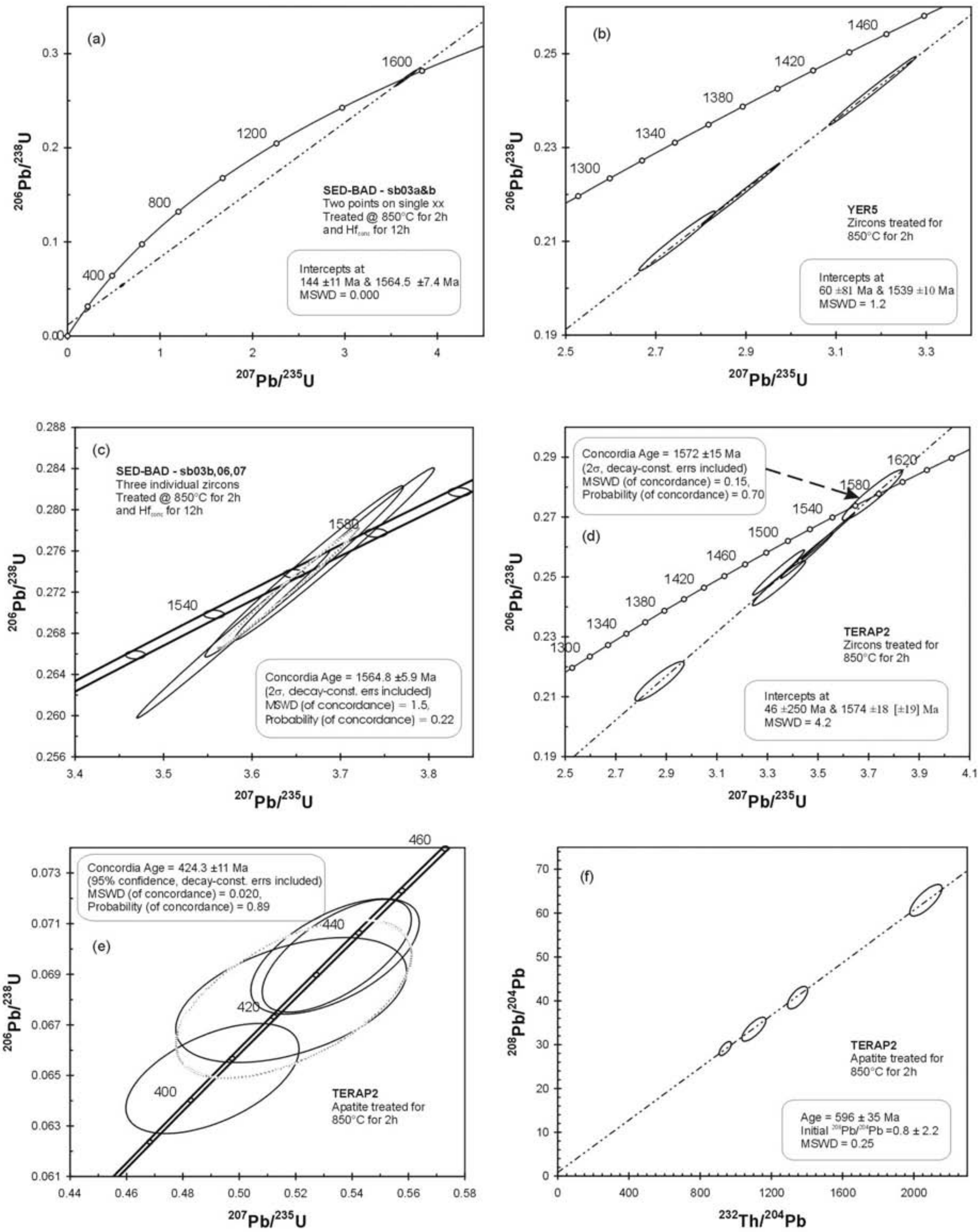


Fig. 34: U-Pb isotopic data for diverse samples from Yerila granite and Terrapinna granite

(a) Alluvial concordant zircon with discordant rim from SED-BAD on Yerila; the lower intercept age suggests a Mesozoic Pb loss; (b) a three-points discordia on treated zircons from the sodic metasomatic YER5 define an upper intercept age of 1539 ±10 Ma.
(c) Concordant zircons from SED-BAD. (d) Zircons from the Terrapinna granite (TERAP2). Both concordia and intercept ages indicates a slightly older age than the Yerila granite. (e) U-Pb concordant fluorapatite from TERAP2: the apatite ages represent cooling ages recording T > 400°C at 400-430 Ma.(f) Th-Pb isochrone for fluorapatite from TERAP2; the very low Th content and the presence of common Pb impede the meaning of this age.

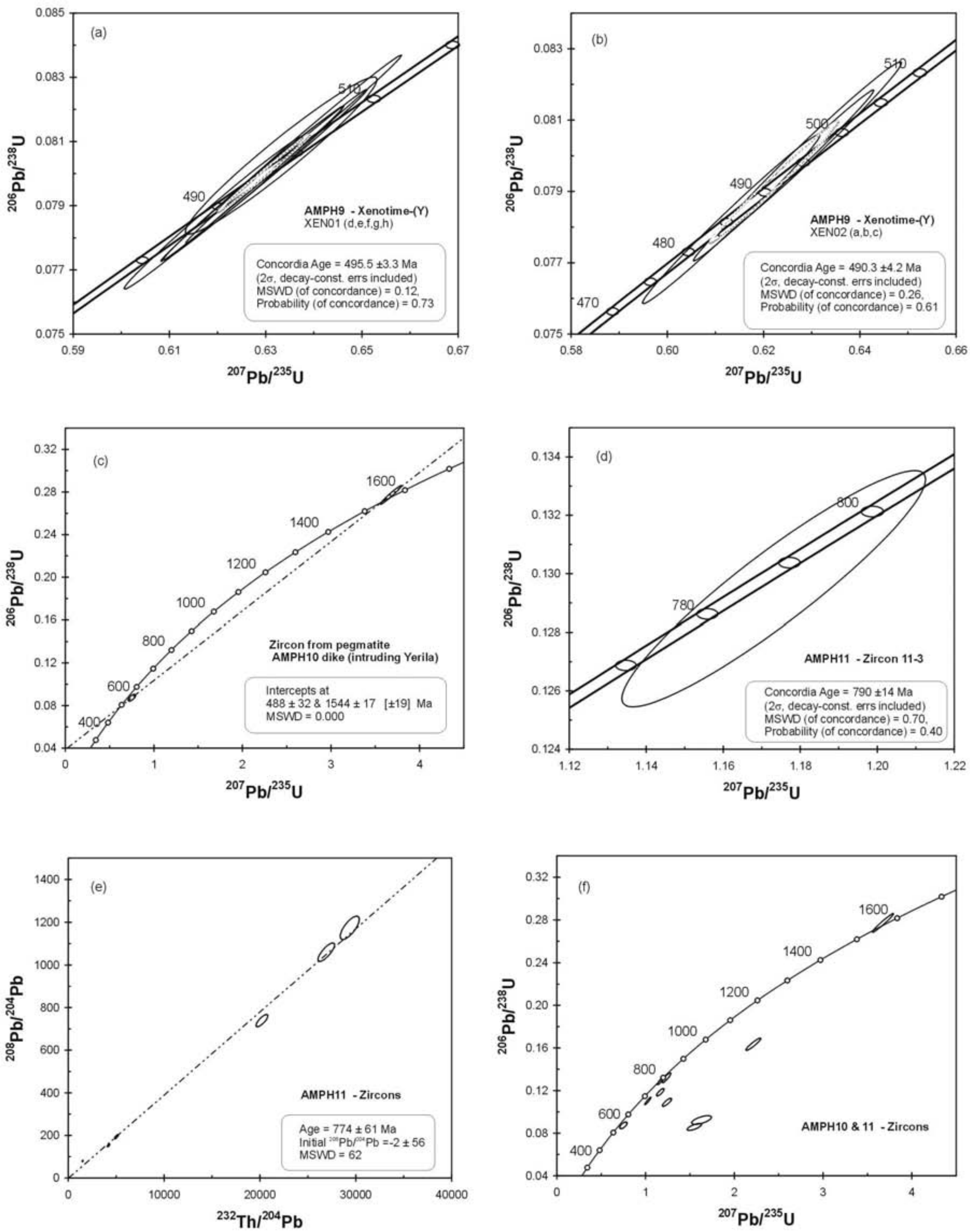


Fig. 35: U-Pb isotopic data for minerals in the Yerila granite and intruding amphibolite

(a, b) Concordant large xenotime-(Y) gem-quality crystals from AMPH9; the high-U-Th content and the total absence of common Pb provides an excellent age for the recrystallisation of the Yerila granite during the metamorphic peak of the Delamerian orogeny; (c) inherited zircon from the footwall of a muscovite pegmatite intrusion crosscutting an amphibolite dike. (d) Cauliflower-shaped zircon from the same amphibolite dike, several hundreds of meters away; the concordant age is the primary intrusion age. (e) Th-Pb isochrone from cauliflower-shaped zircons from the same AMPH11 sample. (f) All dated zircons from the samples AMPH10-11.

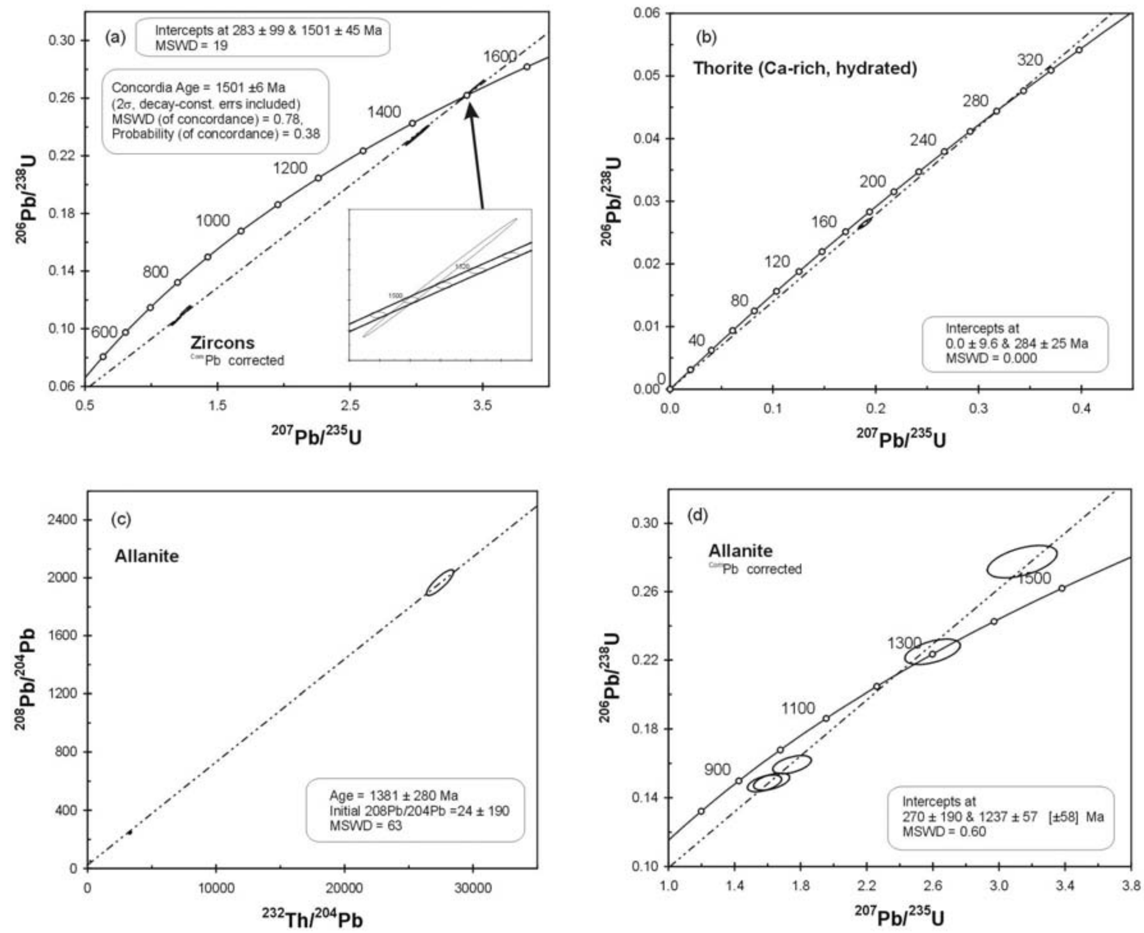


Fig. 36: U-Pb isotopic data for zircons, thoride and allanite-(Ce) from the Allanite Skarn (JB05-37)

(a) Concordant zircon with high U (2209 ppm) giving a primary age of 1501 ± 6 Ma; this age is significantly younger than all Mesoproterozoic ages on zircons recorded elsewhere in the MPD, dating a post-magmatic metasomatic skarn formation. The same zircons together with other define a Discordia with intercepts at 283 ± 99 Ma and 1501 ± 45 Ma. (b) Hydrated thorite with calcium was plotted against a fictive 0±10 Ma Pb loss; the $^{207}Pb/^{206}Pb$ age is Paleozoic. (c) Th-Pb isochrone for allanite; the high Th/U ratio in the fresh allanite cores was used to calculate an isochrone age; the errors do not permit any distinction between the allanite and the zircon crystallisation time. (d) The allanite U-Pb isotopic data are very scattered and a more complex Pb and U remobilisation; it indicates at least one Mesozoic-Paleozoic disturbance.

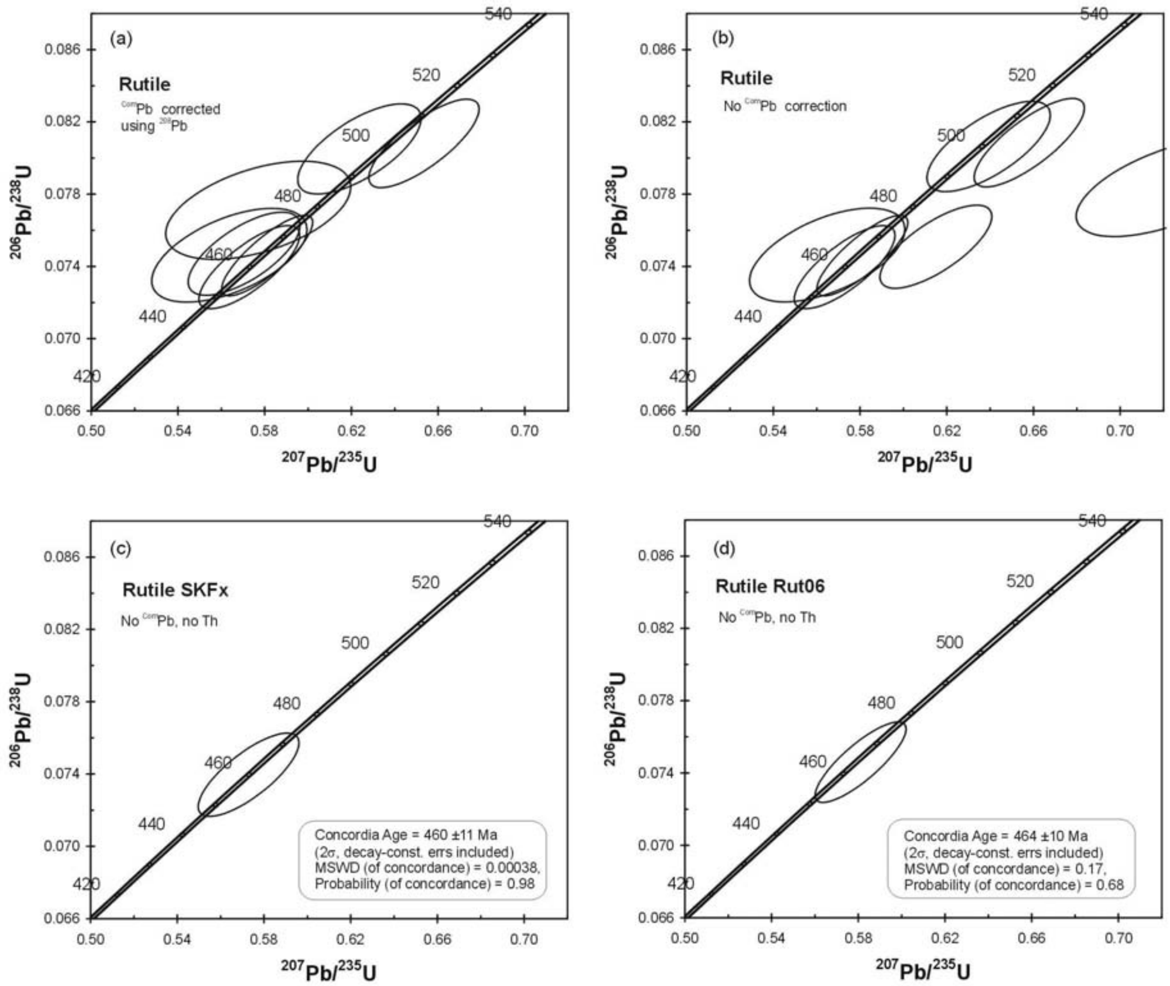


Fig. 37: U-Pb isotopic data for rutile from Allanite Skarn (JB05-37)

Rutile U-Pb data were corrected for common lead using ^{208}Pb instead of ^{204}Pb because of the total absence of thorium. The correction is a lot more accurate and some rutile grains had even no detectable ^{208}Pb; (a) represents all corrected analyses and (b) the uncorrected ones for comparison. (c) The best concordant rutile with absence of common Pb gives a 460 ± 11 Ma. (d) Similar grain with slightly lower concordance probability.

The U-Pb T_C of rutile is estimated at 600-640°C. The 460 Ma age indicates the onset of the cooling (<600°C) for the rock assemblage. Some of the larger rutile give older ages (~500 Ma) recording probably the peak of the Delamerian orogeny (>600°C). Rutile is not recording any Pb-loss during the Mesozoic-Paleozoic (unlike allanite, zircon and thorite).

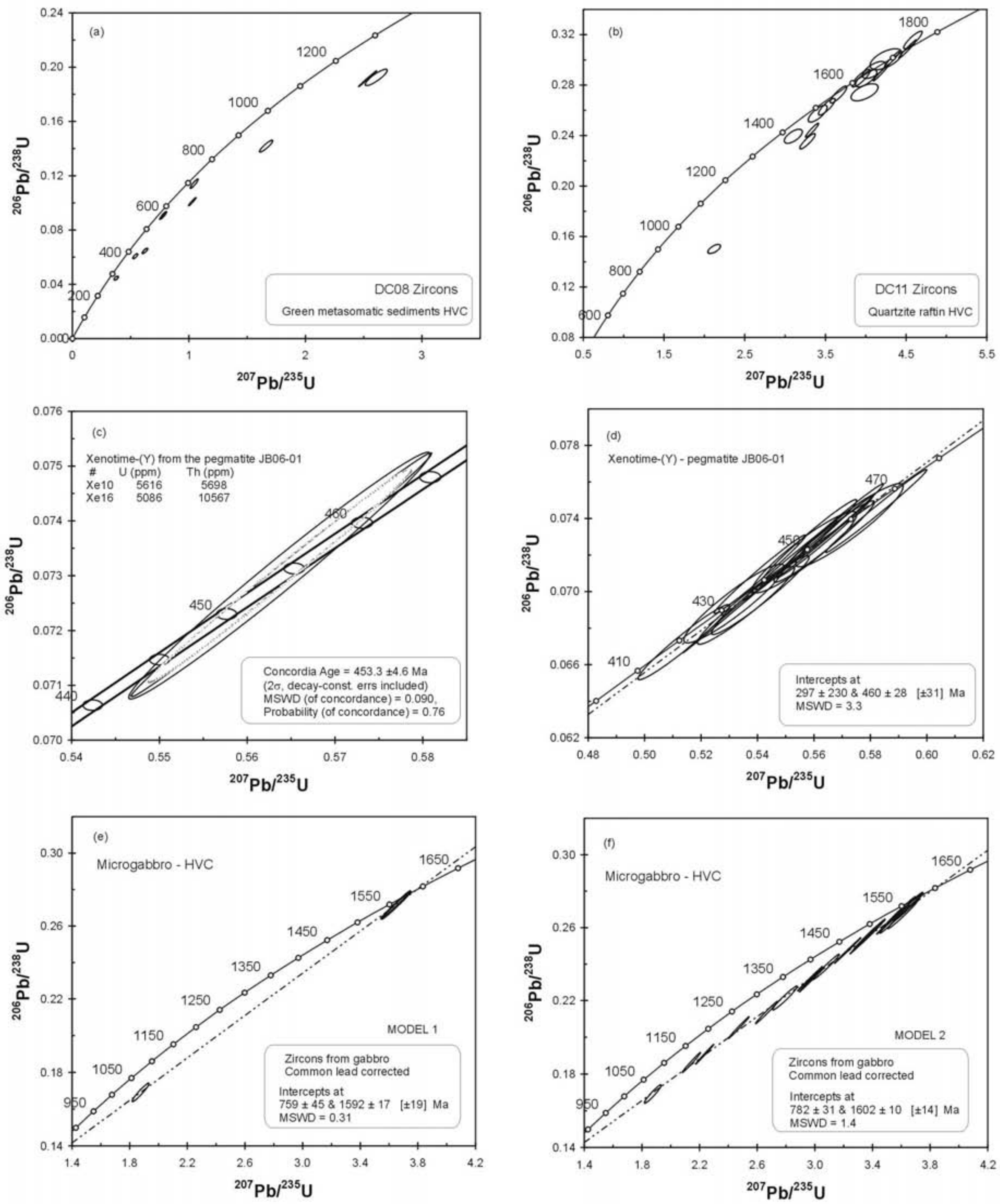


Fig. 38: U-Pb isotopic data for diverse rocks from Hidden Valley Complex (A)

(a) Zircons from a characteristic green metasomatic sediment (shale) from the central HVC; all zircons are discordant. (b) Detrital zircons from a pure quartzite block floating in the HVC: the ages can be divided into ~1580 Ma and a 1650-1750 Ma groups, suggesting that the rock belongs to the Mesoproterozoic "Freeling Heights Quartzite" formation; the discordant zircons draw a trend towards a Paleozoic thermal/hydrothermal event. (c) Xenotime from a large granitic pegmatite in Hidden Valley North (JB06-01): the best crystal gives a perfectly concordant 453 ± 4.6 Ma age. (d) Xenotimes from the same sample draw a trendthat can be interpreted as a younger partial Pb loss. (e) Zircons from a microgabbroic intrusion in the HVC (north), the zircons are essentially rounded have been interpreted as inherited; the first Discordia (e) only uses the extreme values. (f) Same sample with all zircons plotted; the calculated Discordia indicates a 782 ± 31 Ma lower intercept.

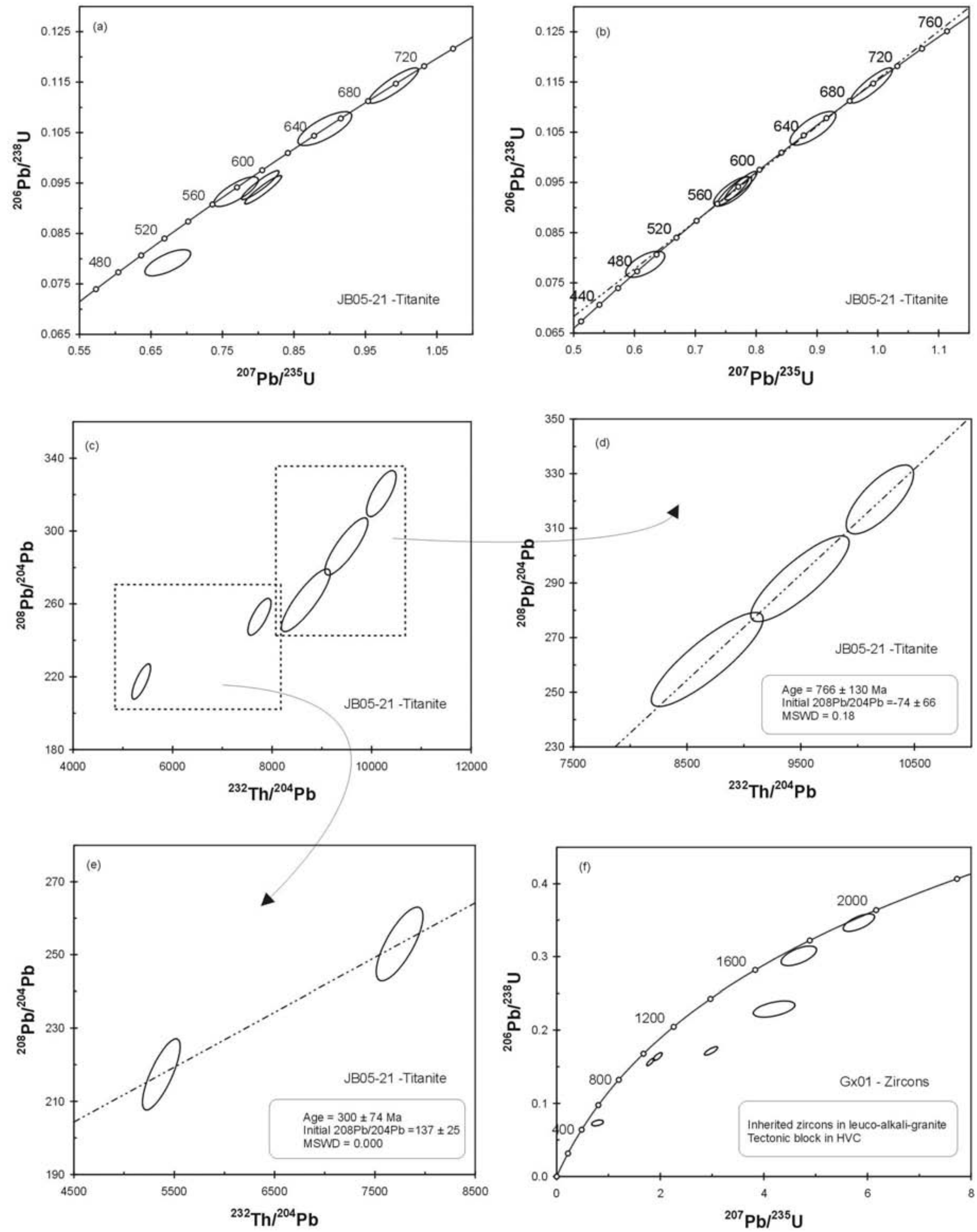


Fig. 39: U-Pb isotopic data for diverse rocks from Hidden Valley Complex (B)

(a-e) Titanite from the central HVC; the titanite appears in a metasomatic marble rock with nearby soda-rich pegmatite intrusions. (a) All titanite grains without common lead correction. (b) Same with ^{204}Pb minimised. (c, d, e) Th-Pb isochrones are drawn on two separate crystals (d) & (e); both isochrones suggest titanite has undergone some in-situ radiogenic Pb diffusion (strongly radiogenic initial lead compositions). Concordant U-Pb analyses indicate titanite went through maintained high temperature and had its structure partly open during the period 600-700 Ma. (f) Zircons from the alkali granite GX01, in direct contact with a large gabbro-diorite outcrop. Despite the absence of fully concordant zircons, it is noticeable the rock lacks of 1560-1650 Ma local granitic zircons.

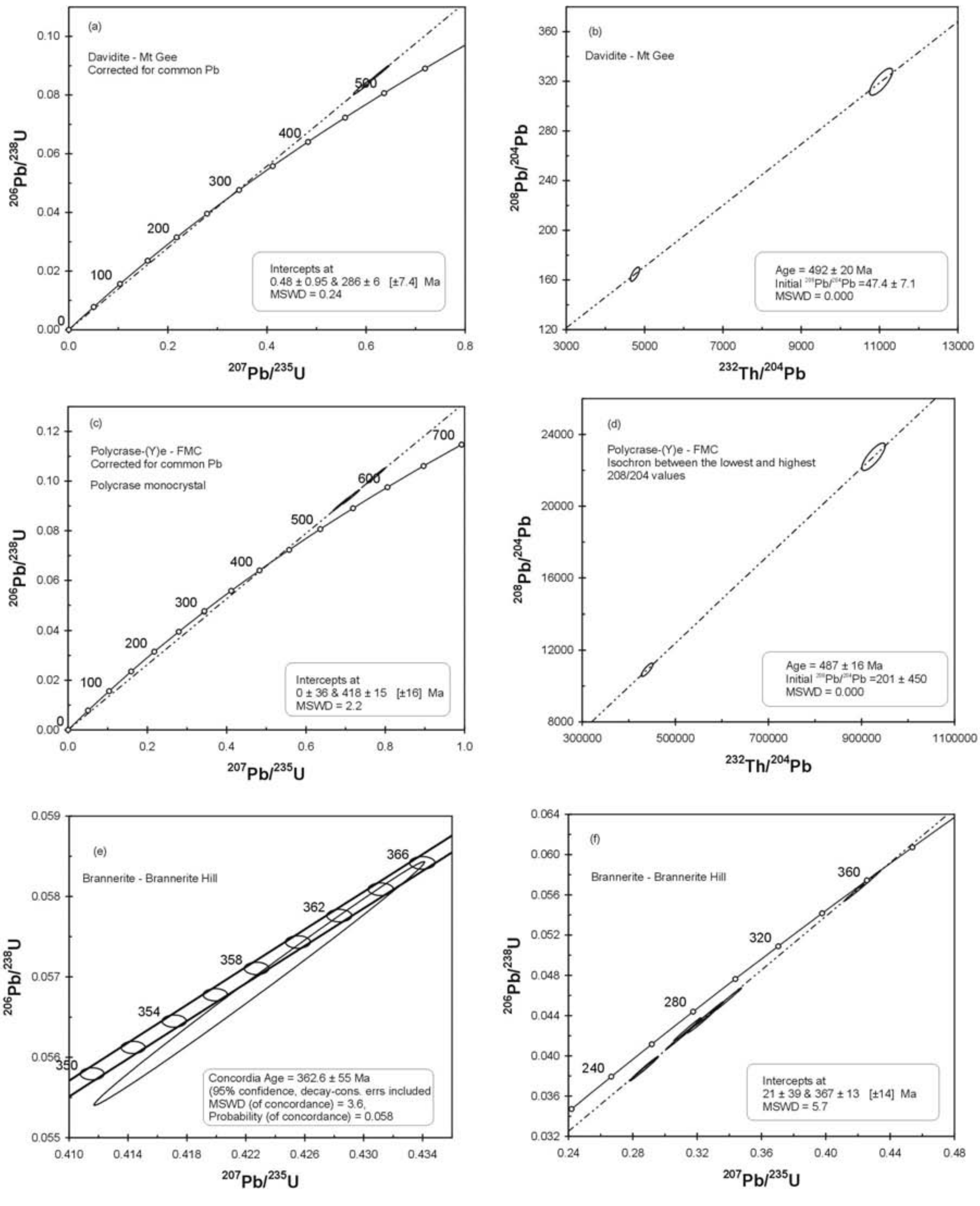


Fig. 40: U-Pb isotopic data for primary U-rich minerals – HVC – Paralana Plateau – Mt Gee

(a) Davidite from Mt Gee West (No.10); reverse discordant positions are interpreted to result from a uranium loss rather than a Pb loss, which is more stable in the davidite structure (Gong et al., 1995). (b) The composition of davidite also includes Th and common Pb; the 204-208-232 isochrone indicates a Delamerian ~490 Ma crystallisation age; a mixing between radiogenic Pb and an original common lead occurred; Th is thought to be more immobile than U in davidite, giving a stronger confidence in the isochrone age. Davidite was formed in a Delamerian pegmatite which was subjected to a major hydrothermal event around 286 ± 6 Ma ago (Mt Gee sinter) and the davidite structure lost some U at this time. (c, d) Polycrase-(Y) from the radioactive red gneiss from the migmatites has underwent through uranium loss around 400-430 Ma, leading to a reverse discordant age e) Brannerite from "Jacob", Brannerite Hill (HVC): best analysis giving near-concordant age (363 ± 55 Ma); (f) Discordia age of brannerite indicating a recent Pb loss and a Devonian (367 ± 13 Ma) age of crystallisation.

6 Mobility and timing of U, Th and REE

The petrogenesis of the exceptionally enriched Mesoproterozoic rocks in the MPD is discussed first, to the light of the mineralogical, geochemical and geological observations. The considerable amount of work dedicated to them justifies the presence of a special section in this chapter.

Following this, a synthesis of the diverse geochronological data acquired on the rocks and minerals will be discussed in the general context of the MPD. With a special regard to the U-Th-REE mobility but also in an integrated geological history; the new elements brought to the geological history will be introduced together with previous data in a chronological order. It is important to keep in mind the respective closure temperature (T_C) of the different mineral systems investigated and to clearly interpret them in their context.

6.1 Petrogenesis of the U- and Th-rich Yerila granite and related rocks in the MPD

Geochemical patterns of the Yerila granite are characteristic of the A-type granites (e.g., discrimination diagrams of Whalen *et al.,* 1987). The rocks have variable amounts of SiO_2 (65 to 75 wt%) and other major elements, especially because of the late-stage crystallisation of biotite. The rocks are either monzogranites or granites in the De la Roche classification (De La Roche et al. 1980). The CIPW normative composition of Yerila (YER-03) corresponds to granite under the Streckeisen classification. The composition is slightly peraluminous with an ASI index of 1.11.

The rock displays exceptional concentration in HFSE (REE, Zr, Th, Y and Nb) but also Ga and Zn. This character is present in all analysed samples. A typical composition has 160 ppm U, 500 ppm Th, 90 ppm Nb, 280 ppm Y, 1100 ppm Ce, and 700 ppm Zr.

Because of the metaluminous to slightly peraluminous compositions met in the Yerila granite, HFSE solubility in the melt was was controlled by fluorine (Pfeiffert *et al.*, 1996). The role of fluorine is demonstrated by its abundance in the mineral assemblage in both early and late mineral phases. The early crystallisation of a minor proportion of calcic amphibole variety (hastingsite) synchronously with some biotite (poikilitic texture) indicates that iron minerals remained essentially stable in the granitic melt. However, most of the biotite and potassic-hastingsite crystallized late in the sequence (i.e. post-stress) and bear numerous inclusions of radioactive minerals and fluorite. The compositions of both annite (Nachit *et al.* 1985) and potassic amphibole suggest they formed from a peralkaline (and K-rich) melt. Biotite concentrates where analysed separately and display high HFSE contents, with e.g.210 ppm U, 490 ppm Th, and 650 ppm Ce.

The overall HFSE abundance can be explained as a combination of (1) early magmatic minerals (chevkinite, fergusonite, euxenite, molybdenite, allanite and apatite) and (2) late-magmatic minerals (Allanite, Y-bearing Al-F-titanite, zircon, late-stage biotite with thorite, uraninite, uranothorite, bastnäsite, synchysite, Y-rich titanite, etc.).

To explain the changing compositions in the Yerila granite outcrops (especially in the proportion of biotite and allanite), we suggest that late-magmatic F-rich melts migrated toward to top of the intrusion and formed enhanced HFSE concentrations. The presence of REE-Ca fluorocarbonates indicates that some CO_2 was present in this late-magmatic fluids, unless a CO_2-, F-rich fluid phase unmixed and escaped outside the intrusion, as witnessed by late-stage calcite-fluorite veinlets (YER-5).

The global effect of the metasomatism on the original mineralogy can be summarised as: quartz and oligoclase disappearance, ilmenite oxidation and rimming by Y-bearing Al-F-titanite, introduction of late-stage biotite, late-stage zircons, remobilisation of early allanite and crystallisation of REE-Ca fluorocarbonates, oxidation of early magmatic sulphides (molybdenite, pyrite), second-stage Y-bearing apatite crystallisation.

The migration of the late-stage residual F-rich silicate melts toward the top of the Yerila intrusion, or the migration of unmixed F-rich fluid (highly evolved pegmatitic melt / aqueous or non-aqueous fluids exsolving from such fluid) (Veksler et al., 2002) can lead to the formation of mineralised rocks when adequate chemical or structural barriers were met (F trapped by Ca-rich assemblages). The calcsilicate rock assemblage studied (JB05-36-37) provides a good example of mineralisation caused by the reaction of Yerila-related metasomatic fluids with high Zr, Y, Th, U and REE with Ca-rich sediment close to the top of the intrusion. The lower Th/U ratio in this skarn assemblage (2.38) suggests that uranium was enriched in the metasomatic fluid phase. This final fluid is recorded by late crystallisation (post-allanite) of H_2O-rich Ca-rich uranothorite in the skarn.

Concerning the source of the Yerila intrusion, the problem is more complicated. The geochemistry indicates that Yerila is a A-type granite (Whalen *et al.*, 1987), which is consistent with the zircon typology (series 6 with D & P types) matched with alkaline/peralkaline series granites (Pupin, 1980; Barbarin, 1999). However, Zr/Hf ratio distribution in zircons is clearly indicating a crustal origin; zircons from rocks with only mantle or mainly mantle origins bear less than 11000 ppm HfO_2 (Pupin, 2000), whereas the higher 14000-20000 ppm HfO_2 from Yerila zircons indicates a crustal origin (either anatectic crustal granites, migmatites) or alkaline subsolvus magmas (Pupin, 2000). We finally retain an F-rich dry lower crustal source for Yerila, as suggested by Whalen *et al.* (1987) and in accordance with the Zr/Hf ratio of zircons. The extreme enrichment in F in the melt is responsible for the formation of both "alkaline" D-type zircons of Pupin (1980) and "peralkaline" F-rich annite composition of Nachit *et al.* (1985).

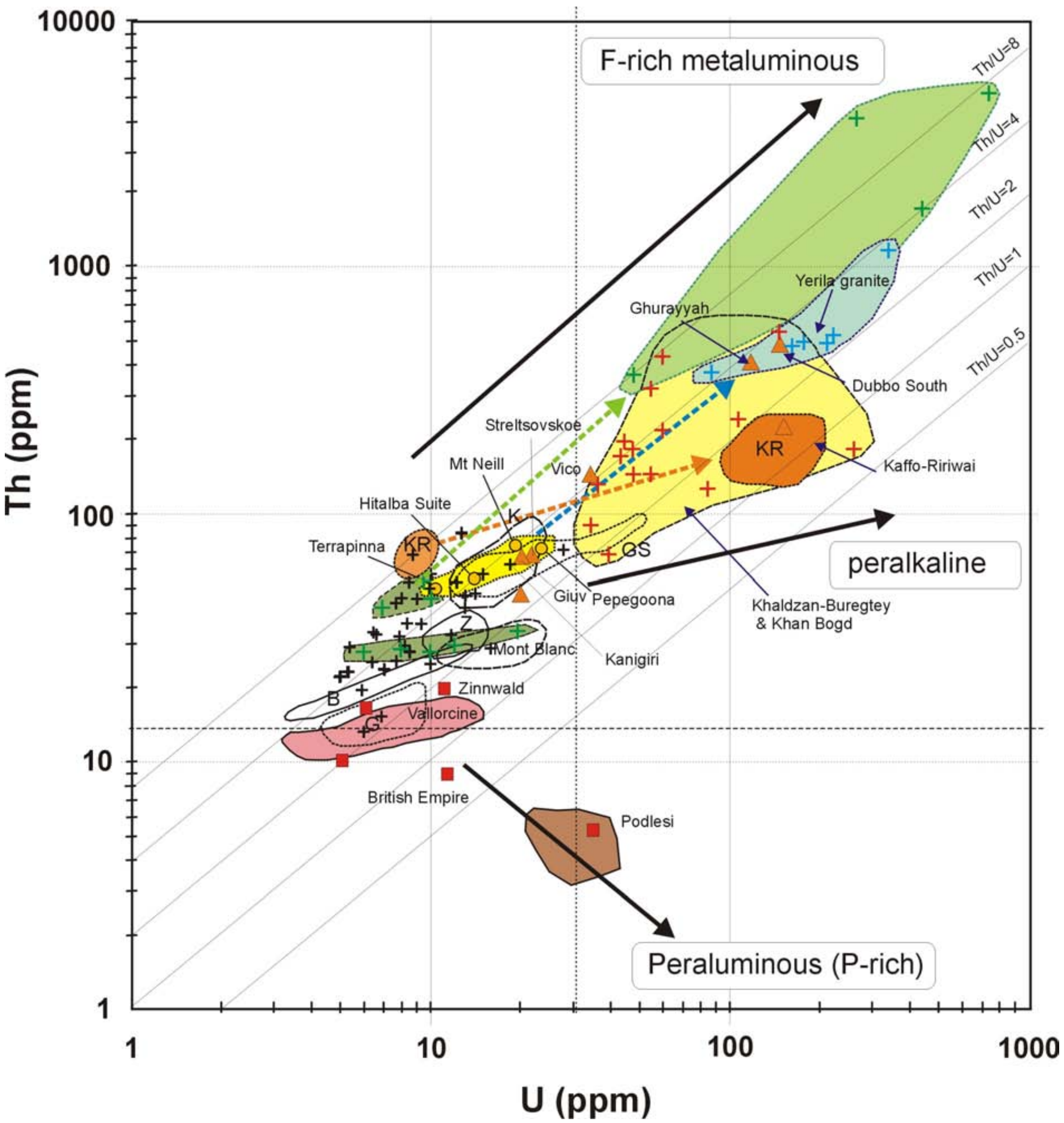


Fig. 41: Global comparison between MPD granites with possible Th-U enrichment processes

The MPD granites are reported in the dark yellow circle, including the Hitalba suite. The Yerila granite is shown in the light blue area with analyses reported as crosses. The olive coloured areas represent the Suzhou granite (China) and the green area its biotite-rich roofing, enriched in Zr, Th, U and REE. Both Yerila and Suzhou follow a similar trend, and display biotite concentrations with Th>Nb. The peralkaline rare metal granites reported (Khaldzan-Buregtey, Khan Bogd, Ghurayyah and Kaffo-Ririwai) illustrate the behaviour of Th-U in fractionated peralkaline melt; they systematically are enriched in Zr, Nb, Ta, Y, REE, Th, and U, with generally Nb>Th. Finally, the peraluminous granites can also develop a rare perphosphorous melt. It displays U>>Th. Otherwise same symbols as on Fig. 9.

6.2 New geochronological framework in the MPD and HSFE mobility

6.2.1 Paleoproterozoic

As mentioned earlier, Paleoproterozoic rocks have never been recognised in the MPD. The new geochronological elements of this study do not change this situation, but several detrital zircons measured in this study have revealed Paleoproterozoic ages: (1) FMC sediments from the Bottleneck Creek, (2) zircons from the Mawson Plateau sediments, (3) a leucogranitic body adjacent to a gabbro block in the HVC and (4) a single age population of zircons in a gabbro intrusion from the HVC. The sediments from FMC display a distinct population of subhedral zircons with ages between 1680 and 1740 Ma (Fig. 31a-c); these zircons are interpreted to originate from the Freeling Heights Quartzite Unit. The sediments from the Mawson Plateau also display a similar population. This new information is in agreement with zircon population studies made on the Freeling Heights Quartzite by Fanning *et al.* (2003). Zircons from a leucogranite from HVC are scarce due to the exceptionally low level of Zr. The youngest near-concordant zircons are Paleoproterozoic (1800-2000 Ma) and this underlines the absence of the "nearly always present 1550-1590" zircons. This could have an important consequence: some granitic melts issued from Paleoproterozoic crust could be present in the HVC; this result is subject to caution because of the small quantity of zircons analysed (10). The gabbro intrusion from the northern HVC reveals a single population of pink smoothed, probably magmatically resorbed zircons forming a Discordia line from 1602 ± 10 Ma toward 782 ± 31 Ma (Fig. 38e-f). We interpret that these zircons have crystallised at ~1602 Ma and therefore are just Paleoproterozoic. The lower intercept at 782 ± 31 Ma probably represents the age of the intrusion, recorded through the Pb loss during the assimilation of the zircons from a Paleoproterozoic crustal basement into the gabbro melt. This basement source is interpreted to have an anomalously low Th/U ratio (Th/U=2.68), according to the average concentrations of these elements in the measured zircons (790 ppm Th and 1850 ppm U). It is however impossible to deduct the concentration of these elements in their source-rock. Finally, I suggest that further works should be dedicated to the HVC and its unusual basement blocks, as this may lead to the discovery of the first Paleoproterozoic outcrops of the MPD.

6.2.2 Mesoproterozoic magmatism and postmagmatic metasomatism

Most of the basement of the MPD (>80%) is dated or attributed to the Mesoproterozoic. The rocks investigated during this research are categorized into (1) detrital sediments, (2) granites, (3) migmatitic gneisses and (4) metasomatic rocks (skarns, F-rich metasomatised rocks). The detrital sediments studied consist of a pure quartzite block from the HVC from which zircons from ~1580 to 1740 Mas were found; the quartzite can be compared to the Freeling Heights Quartzite Unit. Granitoids of the MPD have been divided into two suites by Stewart & Foden (2001): the Mt Neill suite (~1575 Ma) and the Moolawatana suite (~1560 Ma). All granites investigated for geochronology belong to the Moolawatana suite as defined in Figure 3. Because of the resolution of the LA-ICPMS technique employed, a clear distinction between the two suites is quite delicate. The Terrapinna granite from the MBI revealed concordant U-Pb ages at 1572 ± 15 Ma, in the incertitude range of the 1556 ± 4 Ma age of Thornton (1980). The Yerila granite was investigated on three different locations: the porphyritic Yerila type gives concordant zircons ages at 1521 ± 12 Ma. Allanite gives similar Th-Pb isochrone ages at 1542 ± 44 Ma. Zircons from albitised Yerila provides an upper intersect age of 1539 ± 10 Ma and further south, in the biotite-rich monazite-xenotime-bearing Yerila, zircons display ages at 1565 ± 6 Ma. The monazites populations from the same area display Mesoproterozoic ages, confirming that the monazite-xenotime paragenesis also formed around this period of time. Although thorite, uranothorite, uraninite are not providing any ages, they clearly crystallised together with zircon, allanite and other phases, as they frequently occur in them. Distinction between magmatic stages and late-magmatic metasomatism is made from the petrographical and mineralogical and geochemical observations: late biotite (fluor-annite) with numerous thorite, uraninite, zircon inclusions, oxidation of magmatic molybdenite, and oxidation-replacement of ilmenite by low-P (<6 kbar, >400 °C) Y-bearing Al-F-titanite and late-stage fluoro-carbonates of Ca and REE accompanied by fluorite veinlets. Finally, we find that REE, Th, U, Zr, Y and also Fe, Ti and Ca have been mobile throughout the Yerila intrusion until the late-stage cooling phase when the pluton reached shallow level in the crust (< 20 km). Associated F-rich fluids were responsible for further Th, U, Y and REE migration.

The Mesoproterozoic late-stage metasomatism associated to the Yerila-type intrusions was studied using an exoskarn formed near the intrusion contact in the Brindana Gorge area (northern MPI). Two minerals were dated in the Mesoproterozoic: zircon (1501 ± 6 Ma, 1501 ± 45 Ma) and a poor age obtained by Th-Pb isochrone on allanite-(Ce) (1381 ± 280 Ma). Minerals recognised to have formed together with allanite and zircons are: hastingsite, magnetite, fluorapatite, fluorite and uranothorite. The Zr-REE-Th-U signature of both Yerila in MBI and this skarn is identical and interpreted to be cogenetic. Other U-Pb minerals investigated in the skarn indicate later remobilisation or cooling ages. They are discussed after.

An additional sample revealed Mesoproterozoic ages: a cobble of U-Th-rich biotite-K-feldspar gneiss bearing some polycrase-(Y), found in the Bottleneck Creek, downstream the Paralana Plateau migmatitic units. The sample contains some discordant zircons defining intercept ages at 1544 ± 7 Ma, 99 ± 26 Ma. Most of the euhedral zircons from the same sample displayed Mesoproterozoic ages, defining a cluster of ages around 1560-1580 Ma and a minor population at 1520-1540 Ma (Fig. 31c). By analogy with the U-rich cobble, the average FMC zircon types and ages, and data from the Yerila granite and associated skarn, I interpret the U-rich migmatitic unit forming the Paralana Plateau area to be essentially composed of granites and metasomatic granites of the same nature and origins than the Yerila intrusion itself (see Fig. 4 part I).

If the age shift (~20 Ma) observed between the metasomatic zircons from the skarn (1501 ± 6 Ma) and the magmatic/late-magmatic zircons ages from the Yerila granite intrusions (1521 ± 12, 1539 ± 10 Ma, 1544 ± 7 Ma, 1565 ± 6 Ma) is confirmed, it may have important consequences for understanding the influence of these rocks on the entire MPD. The lack of relationship between the lithologies and the large radiometric anomaly in the northern MPI (Fig. 21) can only be explained by the impact of such F-rich metasomatism around Yerila-type intrusions.

6.2.3 Neoproterozoic rifting and alkaline metasomatism

The MPD region was subject to erosion and denudation of the basement between the Mesoproterozoic – Neoproterozoic era (1500 Ma to around 900-800 Ma). The end of this period is marked by mafic volcanism and intrusion as documented by Preiss (2000). The Wooltana Volcanics in the MPD were dated by Rb-Sr at ~ 830 Ma by Compston *et al.* (1966) and correlatively compared with the Gairdner Dike Swarm on the Gawler craton dated by U-Pb on baddeleyite at 827 ± 6 Ma (Wingate *et al.*, 1998). We provide here the first U-Pb dating on zircons from mafic intrusives from the MPD: a gabbro body from the northern HVC gives a Discordia age of 782 ± 31 Ma / 1602 ± 10 Ma (assimilated granitic zircons) whereas the main amphibolite dike from the MBI reveals some concordant U-Pb ages at 790 ± 14 Ma on cauliflower-shaped zircons. Both new ages are overlap within error.

In the central HVC, a scapolite marble with calcite veins was dated using titanite: all titanite crystals give concordant U-Pb isotopic ages in the range of 700 to 490 Ma with a cluster at 580 Ma. These ages are not primary and represent U-Pb diffusion (U-Pb Tc of titanite =680-700 °C) through high temperature metasomatism evidenced by scapolitisation. One Th-Pb isochrone obtained on a same zoned titanite indicate an age of 766 ± 130 Ma. We therefore interpret the scapolite marble to have formed by contact metamorphic with a nearby intrusion around 700-800 Ma and the local environment remained hot until 580 Ma. The context of a deepening rift seems to be the most adequate one for the HVC. This can also explain the strong metasomatic alteration found in HVC sediments, (vermiculite, tourmaline, phlogopite, tremolite, etc…), although the alteration could also have formed during the heat peak related to the BEG intrusion and its pegmatite spreading.

No evidence of U, REE or Th mobility was identified during this extended period. It appears quite important mention the dispersion of U, Th and REE through erosion from the time of the first exposure of the MPD granitoids until around 800. The Pandurra Formation on the Gawler craton or some undiscovered equivalents could have reconcentrated some of the dispersed uranium.

6.2.4 Delamerian orogeny, metamorphism and migmatitisation

The beginning of the Delamerian orogeny marks the end of the Adelaide Geosyncline sedimentation. The timing of the orogeny have been well-defined by diverse dating techniques, especially on granites intrusion (U-Pb on zircon) (Foden *et al.* 2006), but also on metamorphic assemblages (U-Pb on monazite) (Elburg *et al.* 2003). Most previous works used Rb-Sr and K-Ar methods on minerals that only recorded cooling ages and exhumation stage (erosion) (Foden *et al.* 2006). The duration of the orogeny has been defined between 514 ± 3 and 490 ± 3 Ma, followed by a "rapid uplift, cooling, and extension in association with post-tectonic magmatism" (Foden *et al.* 2006). Most of these information are however defined to the central or southern part of the Adelaide Geosyncline, only three Delamerian-related ages defined on pegmatites and small leucogranitic intrusions are reported, all using Sm-Nd or Sr-Rb isochrone methods: 496 ± 8, 506 ± 9 and 499 ± 12 Ma (Elburg *et al.* 2003). Additionally, a monazite provides a slightly discordant U-Pb age with 486.1 ± 7.2 Ma ($^{207}Pb/^{206}Pb$).

From the investigated rocks and minerals, we report a wide range of Delamerian-related ages for all the regions of the MPD. In the MBI, the regional monazite survey on the Yerila granite reveals a preponderance of Paleozoic ages. From the same survey, xenotime-monazite paragenesis associated to biotite is evidenced and large gem-quality xenotime-(Y) dated by LA-ICPMS: the crystals give excellent U-Pb concordant ages of 490.3 ± 4.2 Ma 495.5 ± 3.3 Ma. This provides a good quality age recording the peak of the Delamerian orogeny in the Yerila granite. Only a few hundreds of meters away, a rimed zircon from a pegmatite dike gives a two points Discordia with intercepts at 488 ± 32 and 1544 ± 17 Ma. Still from the Yerila granite area, a large uraninite inclusion (100 µm) from cracked zircons gives an EMPA U-Th-Pb age of 491 ± 20 Ma. Further south, monazites from both Four Mile Creek catchment and from the Mawson Plateau display a net dominance of Paleozoic ages. Some davidite-(La) from a pegmatite dike crosscutting the "Radium Creek Metamorphics" near Mount Gee gives a 492 ± 20 Ma using Th-Pb isochrone age. Polycrase-(Y) forming the main disseminated mineralisation in a gneissic biotite granite sample from the Paralana Plateau catchment gives a 487 ± 16 Ma using Th-Pb isochrone age. The davidite-(La) and polycrase-(Y) $^{207}Pb/^{206}Pb$ ages can be compared to the 485.6 ± 14.2 Ma $^{207}Pb/^{206}Pb$ age on U-Pb reverse discordant euxenite-samarskite from Radium Ridge Nr. 2 Workings (Elburg *et al.* 2003).

The presence of Delamerian monazites and xenotimes in the metamorphosed biotite-rich granitic Mesoproterozoic units from all over the MPD is now confirmed and this is the first evidence for a global redistribution of REE, Th, Y and U and this time. Most of these monazite occurrences were never dated. It is important to remember that some monazite concentrations reach a few percents in some localities (migmatitic gneisses of Paralana Plateau and Radium Ridge area). The Mount Gee mineralisations are monazite-hematite-rich in a brecciated complex basement and sediment mixing. Monazites from these mineralisations have high common lead content and display signs of complex remobilisations, as shown by a 539 ± 92 Ma $^{207}Pb/^{206}Pb$ age obtained by Elburg *et al.(* 2003).

In summary, there are many evidences that the Delamerian orogeny had a dramatic impact on the speciation and remobilisation of U, REE, Th, Y and Nb. A large range of primary U-Th-Y-Nb minerals have formed during this period. Concerning the mobility of these elements, there is no evidence for large-scale migration (> 1 km). The role of migmatitisation from Mesoproterozoic HFSE-rich granites to produce even richer concentrations is evidenced. Delamerian pegmatite generation was limited in the MPD and probably played a minor role for HFSE mobility.

6.2.5 Palaeozoic magmatism, hydrothermalism, brecciation and exhumation

Extension at the end of the Delamerian orogeny led to the intrusion of post-tectonic A-type granites (U-Pb zircons: 487-478 Ma) in the Southern Adelaide Fold belt (Foden *et al.* 2006). These intrusions related to mafic magmas reached shallow level in the already exhumed fold belt. Titanite (Tc = 680-700 °C) from a mafic enclave in one of these granites was dated using ^{238}U-^{206}Pb-^{204}Pb at 449 ± 5 Ma (Foden *et al.* 2006), an age approaching those obtained in the MPD on (1) monazites from the BEG (440.8 ± 1.8 to 443.5 ± 1.8 Ma) and (2) a titanite-diopside pegmatitic vein (442.3 ± 3.7 Ma) (Elburg *et al.* 2003). A multitude of K-Ar, Ar-Ar and Rb-Sr ages on minerals from the MPD are reported and giving cooling/exhumation ages from ~430 Ma to ~320 Ma (McLaren *et al.* 2002) (see synoptic summary on Fig. 4). Further investigation on monazites from the BEG by McLaren et al. (2006) provide a set of concordant SHRIMP U-Pb ages from 470 to 410 Ma. The weighed mean average is calculated at 442.7 ± 8.2 Ma.

We present here new zircons ages from the I-type BEG tail (456 ± 9 to 459 ± 9 Ma). Additionally, xenotime-(Y) from a zircon-free, muscovite-bearing granitic pegmatite related to BEG (S-type) gives perfectly concordant U-Pb ages at 453.3 ± 4.6 Ma. These ages should be considered as the best estimates for the age of the BEG intrusion and related pegmatites.

One problem immediately appears and requires an explanation: why do monazites from BEG give younger ages (4-10 Ma younger)? Several explanations can be given: (1) it could be related to the nature of the monazite, rich in Ca and common Pb as measured by EMPA in the monazites from the Mawson Plateau, leading to a poorly-closed mineral structure; (2) monazite ages are inappropriately used: we recalculated the ages from Elburg *et al.* (2003) and it appears that they are in fact discordant and probably not suitable for dating BEG. Monazites ages from McLaren *et al.* (2006) are also quite dispersed and we think that using the weighed mean average is inappropriate, because it includes different monazite types (discordant points, Delamerian and Mesoproterozoic inheritance and zoning); (3) the genesis of the BEG by anatexis took a long time and the S-type melt developed through a ~10 Ma period during which monazite crystallised. An argument favouring this last explanation is the MPD cooling ages under 400 °C (430-400 Ma) indicating that the BEG crystallised after the climax of the orogenesis, but before the main Silurian-Devonian exhumation period.

U-Pb rutile ages from the Brindana Gorge skarns provide some very good cooling ages for this area from the northern MPI; the 460 ± 11 to 464 ± 10 Ma are interpreted to correspond to the cooling time under 600-640 °C. This interpretation is in accordance with our retained model for the BEG age and intrusion.

We obtained additional geochronological data for the MBI: U-Pb on apatite (Tc=450 °C) at 400-430 Ma in the Terrapinna granite. This complements the 400 Ma cooling ages obtained on the Yerila biotite (annite) by Webb (1976), Tc = 320 °C.

Pegmatitic brannerite from Jacob in the HVC was dated using a set of analyses on a large crystal. They define a Discordia with intercepts at 367 ± 13 and 21 ± 39 Ma. The vein genesis is associated to a faulting period during which basement blocks from the HVC substratum where uplifted. The vein presents many vuggs that indicate a shallow depth of emplacement.

The pegmatitic davidite from Mt Gee West (492 ± 20 Ma, Th-Pb isochrone) records either (1) a major loss of its uranium content around 290 Ma or (2) a gain of radiogenic lead mobilised from uranium minerals around the same time, whereas already present lead and thorium were kept in the mineral structure. Thorite from skarns in the northern MBI is discordant and gives a $^{207}Pb/^{206}Pb$ apparent age of 284 ± 25 Ma, which coincides with the Discordia obtained using zircons (intercepts at 1501 ± 45 and 283 ± 99 Ma. All these Permian ages can be correlated to the Mt Gee hematitic breccia-hosted REE-U deposit which crosscuts some fluviatile paleochannel with a maximum age of 320 Ma (Brugger & Wulser *in prep*) and was estimated to have a Permian age of 300-250 Ma using paleomagnetism (Idnurm and Heinrich, 1993).

Finally, the U-Th-REE mobility during the post-Delamerian period has continued over a long period of time, because of the extremely long residence time of the Mesoproterozoic basement in high-T conditions. The generation of anatectic melts produced some magmatic biotite-rich formations, which are highly enriched in monazite, zircons and uranothorite. Uranium was locally reconcentrated in quartz-brannerite veins during some stages of faulting and brecciation associated to the tilting and uplifting of areas in the MPI. Uranium was again remobilised at and near Mt Gee during a final Permian epithermal event. Uranium migration during the Post-Delamerian Palaeozoic era is more selective, which contrasts with the previous period where uranium migrated together with other HFSE through F-rich fluids or migmatitic melts extraction; being separated from thorium through aqueous fluid migration.

6.2.6 Cretaceous-Cenozoic supergene uranium remobilisation

Supergene uranium mineralisations are widespread in the MPD. A detailed list of them can be found in Appendix II. The most common mineral in these concentrations is torbernite or metatorbernite. Only limited data on the geochronology can be found in the literature: a torbernite from Nr. 2 Radium Ridge occurrences gives a U-Pb ~3.3 Ma age (Elburg *et al.* 2003).

Our measurements on diverse minerals suggest U-Pb remobilisations during the Cenozoic (lower intercepts on brannerite at 21 ± 39 Ma, thorite) and maybe the Cretaceous for the MBI (lower intercepts at 144 ± 11 and 84 ± 27 Ma on zircons from Yerila area. The large population of the U-rich Mesoproterozoic zircons from the FMC can be used to draw a Discordia line with the intercepts at 1570 ± 11 & 138 ± 43 Ma, suggesting a significant loss of lead during Cretaceous; all these ages have to be used with extreme caution. Zircons from the polycrase-rich cobble give a lower intercept age of 99 ± 26 Ma also in accordance with the recent uranium loss recorded in the polycrase-(Y). All these ages indicate the MPD was exposed to alteration from the Cretaceous and significant amounts of uranium were released from the basement rocks from this period. We finally document the Pliocene ages on the Beverley uranium deposit hosted in the Miocene sands of the Namba formation: concordant U-Pb ages on carnotite and coffinite from 5.3 to 3.1 Ma (see part I). We cannot exclude some part of the mineralisation have occurred earlier.

GENERAL CONCLUSIONS

The Mount Painter Domain has been recognised as a highly uraniferous province for a long time. We documented most parts of the MPD aiming to understand the reasons for the presence of such concentrations of not only uranium, but also thorium and rare earth elements. During the field investigation period in 2005, we discovered a new uranium occurrence in the Hidden Valley Complex. This discovery represents a new type of mineralisation in the Mount Painter Domain: brannerite in veins. During the same year and only a few kilometres away the Four Mile uranium deposit was discovered. A review of the geological framework was the first step undertaken, helped by widespread geochronological determinations on different units and rocks. The second step was the characterisation of U, Th and REE speciation in these rocks, through an extensive mineralogical study.

The most important discoveries resulting from this research are listed below and their implications will be discussed for both metallogenetic and economic points of view:

- Recognition of the **importance of the Paleozoic magmatic-hydrothermal event for U metallogenesis**, first dating of many U-Th-REE-phases crystallised or remobilised from the Delamerian peak (~495 Ma) until Permian (~290 Ma). This favours protracted high-T conditions in the MPD with several faulting, cooling episodes responsible for U-Th-Y-rich vein generation, REE-U-Y breccia-hosted deposits, and shear-zone hosted Th-U-REE deposits.
- Recognition of a Mesoproterozoic **F-rich metasomatism late- to post-magmatic metasomatic process**, which controlled the first generation of REE-Th-U anomalous concentrations in the MPD.
- Successful **application of a new technique** for sediment provenance determination and dating using a combined typological/morphological study of zircons from detrital rocks followed by a selective U-Pb dating of a representative selection of all typological and morphological categories. The technique achieved a lot and has the potential for many avenues in future studies (geochronology, provenance studies and tracking/mapping metasomatism in large regions).
- Recognition of the necessary role played by the MPD in the **Beverley uranium deposit genesis.** REE-rich uranium source fingerprinted, mineralisation constrained to a shallowing lake shore environment during the Pliocene. This has major implications for future exploration around the MPD and for understanding the system at the nearby Four Mile uranium deposit.

Scope for future geological research:

- Recognition of metamorphic assemblages adequate for further PT-path determinations and MPD geological history reconstitution during the Delamerian orogeny: xenotime-monazite paragenesis (T, t) for using (Sm-Gm) and (U-Th-Pb) systems, spinel-sapphirine-corundum-rutile-zircons paragenesis (P, T, t) using Zr-in-rutile, Ti-in-zircon, U-Pb systems.
- Further geochronological constrains on detrital sediments of the MPD and Adelaide Geosyncline using the developed technique of combining zircon typology, morphology and selective dating by LA-ICPMS
- The first indices of a Paleoproterozoic basement in the MPD found in the Hidden Valley Complex should be followed up and confirmed by further research. It could give precious information on the origin of the Paleoproterozoic crust from which the U-Th-rich granites of the province were sourced.

Scope for future prospecting:

- The Mesoproterozoic late-magmatic to post-magmatic HSFE concentrations were localised in structural traps at or under the roof of the Yerila intrusion. For this reason, it seams reasonable to think the thickness and the shape of these enriched bodies should be assessed by drilling. The Ca-rich skarns found at the intrusion roofs are locally more enriched in uranium than the metasomatised granite (>200 ppm U) but are only one specific type of contact rock. A structural or chemical barrier with no or only little Ca will favour the crystallisation of thorite, uraninite and monazite instead of allanite. Concentrations of this type could have economic potential.
- The origin of the breccia-hosted Mt Gee REE-Th-U deposit is necessarily linked at some stages to the Mesoproterozoic metasomatic concentrations. It is important to understand how this remobilisation happened and what exactly concentrated or dispersed during the Paleozoic era. Further geochronological investigations could solve this question.

- The vicinity of the outcropping MPD played a key role in the Beverley genesis as evidenced by geochemistry and paleoenvironment reconstitution. We think that the shore-line of the lake Frome during the Cenozoic was the best metallotect and therefore, tracking the paleo-shoreline around the MPD will help targeting the best prospective areas for drilling. Concerning the Mesozoic, the post-glacial Upper Cretaceous sandstone especially could have a similar potential and detailed palynology and sedimentology could help defining this.
- The discovery of brannerite-rich veins along faults in the Eastern MPD confirms that uranium can be efficiently concentrated in structural elements. This new evidence opens the doors for prospecting Paleozoic, post-Delamerian fault zones in the MPD. Brannerite is also present in Mt Gee and such high-grade feeders could be discovered elsewhere.
- Mapping, mapping and mapping again! The best available “detailed” maps are at 1:50’000 scale. Most geological details like faults, shear zones and degree of metasomatism alteration need to be mapped at a better scale (1:10’000 ideally). The MPD has not revealed all its treasures!