Inheritance and Pb-loss in Multiple Generations of Metamorphic Monazite: Thermodynamic and Kinetic Controls on Accessory Phase Behaviour at Ultra-High Temperature

Ian C. W. Fitzsimons*, Chris Clark, and Pete Kinny
The Institute for Geoscience Research, Department of Applied Geology, Curtin University of Technology, GPO Box U1987, Perth, WA 6845, Australia
I.Fitzsimons@curtin.edu.au

Summary

U-Pb isotopic analysis coupled with detailed petrography and yttrium mapping of monazite in ultra-high temperature migmatite indicate that some age domains record simple periods of monazite growth, and others reflect variable degrees of isotopic resetting during prograde and retrograde events. While the timing of high-temperature monazite growth is controlled broadly by the changing thermodynamic stability of different mineral assemblages in the bulk rock, the extent to which these ages are preserved or reset is controlled by kinetic effects.

Introduction

Monazite is the mineral chronometer of choice for metamorphic rocks. It has high U, Th, and Pb contents allowing for easy analysis and high precision ages. It grows at medium to high temperatures in many metapelitic lithologies, and can often be linked with reactions involving distinctive rock-forming minerals making it possible to directly correlate metamorphic pressure-temperature with time. Pre-metamorphic grains are often destroyed by prograde metamorphic reactions, limiting the extent of isotopic inheritance, and syn-metamorphic monazite is resistant to alteration during peak and retrograde metamorphism, limiting isotopic discordance.

Most monazite ages are derived by electron microprobe chemical dating, which is based on total U, Th and Pb contents and assumes isotopic concordance between the decay schemes, or secondary ion mass spectrometry, which collects a full isotopic data set and can assess isotopic discordance, but requires equipment that can be difficult and expensive to access.

Electron Microprobe Monazite Ages from the Madurai Block

Over 400 electron microprobe monazite ages have been determined for ultra-high-temperature (T>900 °C) metapelites of the Madurai Block of southern India (Fig. 1). These data define a broad age population between 450 and 800 Ma, which might reflect:

1) Imprecise measurement of a single monazite population;
2) Precise measurement of a protracted period of continuous monazite growth;
3) Variable isotope resetting of a single monazite population; or
4) Combination of (1) and (2) and (3) where analytical imprecision and isotopic resetting smooth the age data between multiple periods of monazite growth.

These possibilities lead to four interpretations for the 530 Ma mode of the age distribution:

1) The true age of the only period of monazite growth;
2) The time of maximum monazite growth;
3) The time of maximum isotopic resetting; or
4) An apparent age that does not correlate with any specific geological event.

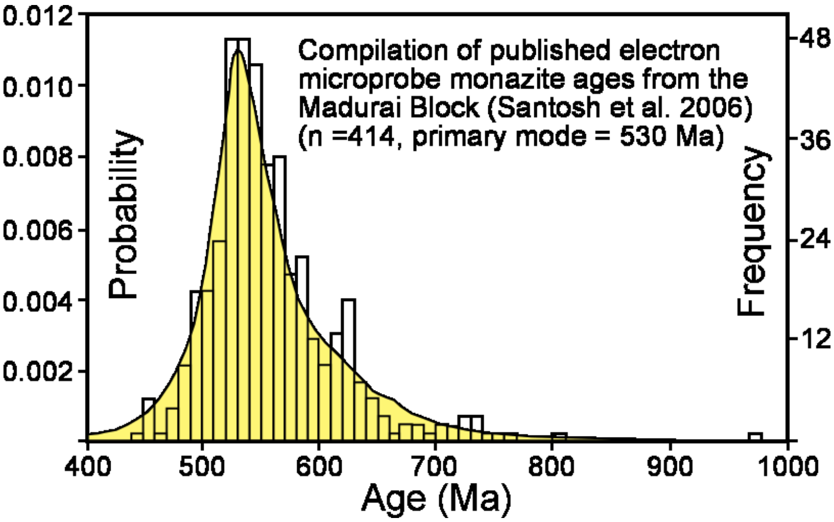

Figure 1: Compilation of electron-probe monazite ages for the Madurai Block (Santosh et al. 2006), shown as a frequency histogram in bins of 10 Myr and a probability density distribution.

Petrography of a Pelitic Migmatite from Usilampatti

We selected a sample of pelitic migmatite from Usilampatti for detailed investigation to assess the meaning of age data from the Madurai Block. This sample has melanosome comprising resorbed relics of garnet enclosed by coarse intergrowths of ilmenite-spinel-cordierite-monazite. These latter phases have polygonal grain boundaries and are interpreted as having equilibrated texturally and chemically during garnet breakdown as a result of decompression at temperatures close to the metamorphic peak. A later stage of hydrous retrogression is recorded by cordierite, which has undergone widespread alteration. Yttrium maps show cores of high-yttrium monazite, which presumably grew early in the rock's history before garnet was stabilized, and lower-yttrium monazite that grew or recrystallized during garnet breakdown at peak temperature conditions. There are distinct boundaries between the two types of monazite.

SHRIMP U-Pb Monazite Ages for Usilampatti

U-Pb isotopic analyses were made of 40 spots from 13 monazite grains in the Usilampatti migmatite using the Sensitive High-Resolution Ion MicroProbe (SHRIMP-II) at Curtin University. The location of the analysis points was selected to sample both high and low yttrium chemical domains. All analyses were processed and plotted as Wetherill Concordia diagrams (Fig. 2) using Isoplot v. 3 (Ludwig 2003). The data span an age range of 800-500 Ma and can be divided into four populations depicted with different colours on Figure 2.

There are two concordant populations, an older population of five analyses with a weighted mean ^{206}Pb/^{238}U age of 774±17 Ma (red points in Fig. 2) and a younger population of six analyses with a weighted mean ^{206}Pb/^{238}U age of 578±11 Ma (blue points in Fig. 2). The older ages are from high-Y cores interpreted as inherited monazite grains that pre-date ultra-high temperature metamorphism, while the younger ages are from low-Y monazite interpreted as having grown during ultra-high temperature metamorphism.

A spread of five analyses between 775 and 580 Ma (yellow points in Fig. 2) is within error of a discordia between the two concordant populations. It is unlikely that each of these ages is a distinct period of monazite growth, and yttrium maps suggest they are not mixed analyses that sampled multiple age domains but rather reflect variable degrees of Pb loss from older high-Y inherited monazite during ultra-high temperature metamorphism.

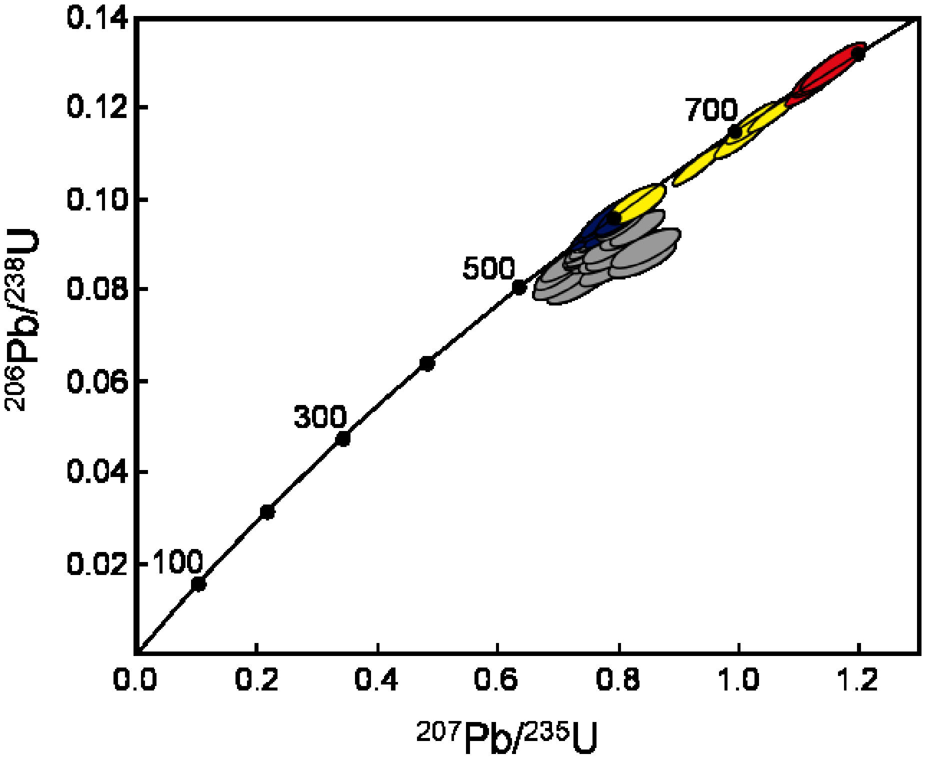

Figure 2: Wetherill concordia diagrams for U-Pb SHRIMP analyses of this study. Data ellipses are for ±1sigma uncertainties, and colours indicate four populations discussed in the text.

Most analyses (24 points, grey in Fig. 2) form a broad discordant population that overlaps with the younger concordant analyses and suggests isotopic disturbance of peak metamorphic monazite through a combination of radiogenic Pb loss and addition of common Pb. These analyses are from monazite with abundant fractures or adjacent to retrogressed cordierite, and we attribute this disturbance to retrograde fluid influx causing hydrous alteration of cordierite.

Conclusions

SHRIMP U-Pb data from Usilampatti reveal a broad spectrum of monazite ages reflecting pre-metamorphic inheritance, high-temperature monazite modification and growth, and retrograde isotopic disturbance. These data have a number of important implications for the interpretation of monazite isotopic data from granulite-facies rocks:

1) Pre-metamorphic monazite grains can preserve old concordant ages even after ultra-high-temperature metamorphism;
2) Pre-metamorphic grains can also yield discordant ages due to partial resetting of isotope systematics at ultra-high temperature conditions;
3) Whether or not pre-metamorphic monazite is reset under ultra-high temperature conditions will be controlled by factors such as grain size, microstructure, and petrographic setting relative to grain boundaries and any shielding phases; and
4) Monazite U-Pb isotope systematics can also be significantly disturbed by hydrothermal retrogression.

These effects will result in a broad spread of monazite age data, and the spread of SHRIMP ages observed in the single sample from Usilampatti matches the spread in electron microprobe ages reported for the entire terrane. This means that electron probe data faithfully record a real spread of apparent isotopic ages, but cannot resolve this age spectrum into meaningful geological events because they are based on elemental concentrations. Conversely, ion probe isotope data can identify discrete concordant populations, which coupled with petrographic and mineral chemical information can be used to date specific stages in the geological history. Importantly, the dominance of monazite affected by hydrous retrogression in the Usilampatti sample suggests that the mode of any age distribution (Fig. 3) will reflect complex kinetically-controlled processes of partial isotopic disturbance rather than indicate the age of a real geological event.

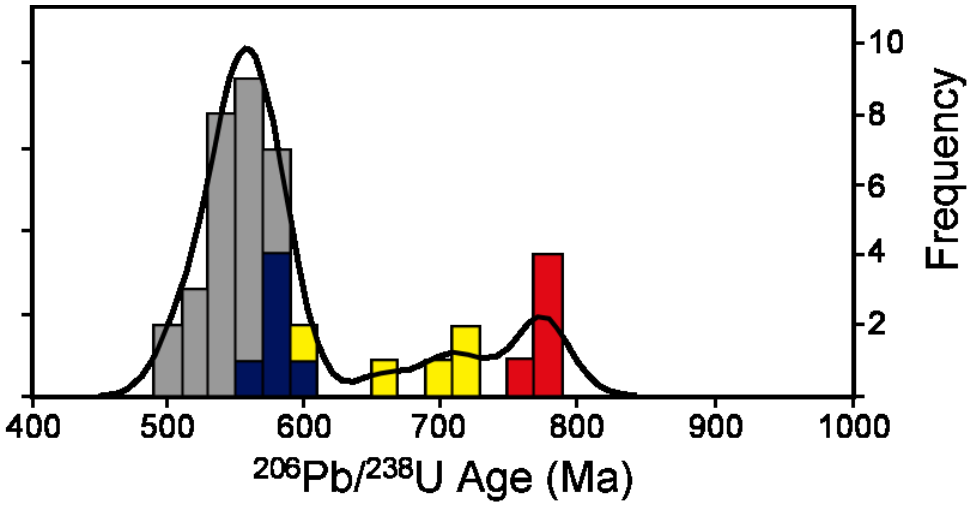

Figure 3: Histogram of SHRIMP $^{206}Pb/^{238}U$ ages for the Usilampatti migmatite shaded to match the four populations in Fig. 3. Also shown is a probability density distribution curve for the same data (black curve). Blue and red data on the histogram represent concordant populations that can be correlated with geological events. Yellow and grey data are discordant apparent ages. The mode of the apparently simple age spread between 500 and 600 Ma is dominated by grey data and has no geological meaning. It is likely that the 530 Ma mode in the regional data set of Fig. 1 has a similar origin.

Acknowledgements

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