SECTION -D-

ABSOLUTE TIME CONSTRAINTS ON DEFORMATION AND ACCOMPANYING METAMORPHISM FROM IN-SITU ELECTRON MICROPROBE DATING OF MONAZITE IN THE ROBERTSON RIVER METAMORPHICS, NE AUSTRALIA
Figure 1. Location map showing major regional geological features and the area in which detailed work was done outlined by a box (Compiled from Withnall 1985).
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Figure 3. a) Sketches of the oriented rock sample marked and cut into a horizontal slab, from which b) multiple-vertical thin sections are cut from a horizontal rock slab. The FIA (foliation intersection/inflection axis preserved within porphyroblasts) is determined where the asymmetry of the inclusion trails changes c) when viewed from one direction.
Figure 4. Photomicrographs showing the structural features and their interpretations, observed in the matrix and within porphyroblasts; a) garnet (Grt) porphyroblast with sigmoidal type inclusion trails representing pre-$S_1$, wrapped by andalusite (And) overgrowing $S_{1'}$, that continues through to main foliation $S_{1/2}$ and sillimanite (Sill) plus biotite (Bt) overprinting early phases; b) staurolite (St) porphyroblast replaced by andalusite in the matrix with $S_1$ preserved as a crenulation hinge within the staurolite and $S_{1/2}$ as the predominant foliation; c) andalusite replacing an older staurolite generation that overgrew $S_{1'}$ and younger staurolite generation overgrew $S_{1/2}$. $S_3$ and $S_4$ represent a crenulated foliation and steep cleavage respectively; d) garnet porphyroblast containing staircase inclusion trails, truncated by the matrix foliations. $S_2$ is preserved in the strain shadow of the garnet and away from the porphyroblast it decrenulates and rotate towards $S_{1/2}$ that is overprinted by $S_3$; e) staurolite porphyroblast overgrew $S_{1/2}$ $S_2$ preserved within the porphyroblast as the steep crenulation cleavage was destroyed in the matrix because of the reactivation; f) textural relationship showing the replacement of staurolite by prograde muscovite and the overprinting of garnet and andalusite by sillimanite plus biotite. The plates at left lower corners of photos show the sample number and vertical thin section directions around compass.
Figure 5. a) Rose diagrams showing the orientations of total FIA, b) FIA1 (ENE-WSW), FIA2 (E-W) and FIA3 (N-S) in garnet porphyroblasts, and c) FIA2 (E-W), FIA3 (N-S) and FIA4 (NE-SW) in staurolite porphyroblasts across the study area. See Table 1 for the FIA data.
Figure 6. Compositional zoning profiles ($X_{\text{Mn}}$, $X_{\text{Ca}}$, $X_{\text{Mg}}$, $X_{\text{Fe}}$ and $X_{\text{Fe}}/(\text{Fe+Mg})$) of garnet porphyroblasts in sample mc135 (a) and mc137 (b). In mc135 the garnet shows a lack of zoning as indicated by a flattened $X_{\text{Mn}}$ profile, whereas in mc137 the garnet preserves growth zoning.
Figure 7. Pseudosection (a) displaying the mineral stability fields, with respect to the bulk composition of mc137 (core-gr1 in (c)). The isopleths of $X_{\text{Mn}}$, $X_{\text{Ca}}$ and $X_{\text{Fe}}$ (b) derived from the probe analysis of the core and median of a garnet are calculated and then plotted based on the compositions (c) estimated using the fractionation method of Evans (2004).
**Absolute Time Constraints on Deformation and Metamorphism**

**M. CHAN**

A) Time-constraints on deformation and metamorphism.

B) Table showing XFe, 2 sigma, XCa, 2 sigma, XMn, 2 sigma values.

C) Bulk Rock Compositions (mol proportions; SiO2 free).

<table>
<thead>
<tr>
<th></th>
<th>Core (gr1)</th>
<th>Median (gr20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$_2$O$_3$</td>
<td>47.66</td>
<td>48.16</td>
</tr>
<tr>
<td>FeO</td>
<td>21.24</td>
<td>20.51</td>
</tr>
<tr>
<td>MnO</td>
<td>0.40</td>
<td>0.24</td>
</tr>
<tr>
<td>MgO</td>
<td>14.53</td>
<td>14.71</td>
</tr>
<tr>
<td>CaO</td>
<td>2.94</td>
<td>2.85</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>4.91</td>
<td>5.01</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>8.33</td>
<td>8.51</td>
</tr>
<tr>
<td>SUM</td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>
Figure 8. Backscatter images show the monazite grains and also their locations (a-e) from sample mc152. The numbered circular spots represent the locations of analyses presented in Table 4.
**Absolute Time Constraints on Deformation and Metamorphism**

M. CIHAN

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**Mean = 1512 ± 15 [0.97%] 95% conf.**

Wtd by data-pt errs only, 0 of 6 rej.

MSWD = 0.44, probability = 0.82

**Mean = 1584 ± 16 [1.0%] 95% conf.**

Wtd by data-pt errs only, 0 of 5 rej.

MSWD = 0.64, probability = 0.63

**Mean = 1598 ± 15 [1.0%] 95% conf.**

Wtd by data-pt errs only, 0 of 5 rej.

MSWD = 0.52, probability = 0.40

**Mean = 1606 ± 23 [1.5%] 95% conf.**

Wtd by data-pt errs only, 0 of 5 rej.

MSWD = 0.90, probability = 0.46

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**Mean = 1589 ± 17 [1.1%] 95% conf.**

Wtd by data-pt errs only, 0 of 7 rej.

MSWD = 2.4, probability = 0.024

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a) [Image of rock sample with annotations]

b) [Image of rock sample with annotations]

c) [Image of rock sample with annotations]

d) [Image of rock sample with annotations]
Figure 9. a) Weighted average plot of 9 individual monazite ages with 95% confidence level for rock sample mc152; b) Probability density curve suggests three distinct age populations.
Absolute Time Constraints on Deformation and Metamorphism

Mean = 1551 ± 27 [1.7%] 95% conf. by data-pt only, 0 of 9 rej.
MSWD = 23, probability = 0.000

Age ±2 σ fraction ±2 σ
1508.5 8.3 0.22 0.31
1559.5 7.9 0.33 0.39
1589.8 9.5 0.45 ---
relative misfit = 0.318
Figure 10. Backscatter images show the monazite grains and also their locations (a-b) from sample mc135. The numbered circular spots represent the locations of analyses presented in Table 4.
Figure 11. a) Weighted average plot of 6 individual monazite ages with 95% confidence level for rock sample mc135; b) Probability density curve suggests two distinct age populations.
Mean = 1573 ± 23 (1.5%) 95% conf.
Wtd by data-pnt errs only. 0 of 6 rej.
MSWD = 7.0; probability = 0.000

<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>±2σ</th>
<th>Fraction</th>
<th>±2σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1557.2</td>
<td>9.2</td>
<td>0.51</td>
<td>0.58</td>
</tr>
<tr>
<td>1595.8</td>
<td>11</td>
<td>0.49</td>
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</tr>
</tbody>
</table>

Relative misfit = 0.693
Figure 12. Backscatter electron images show the monazite grains and also their locations (a-d) from sample mc137. The numbered circular spots represent the locations of analyses presented in Table 4.
**Absolute Time Constraints on Deformation and Metamorphism**  

**M. CHAN**

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**a)**

Mean = 1586 ± 22 [1.4%] 2σ  
Wtd by data-pt errs only, 0 of 5 rej.  
MSWD = 1.6, probability = 0.16

**b)**

Mean = 1581 ± 19 [1.2%] 2σ  
Wtd by data-pt errs only, 0 of 7 rej.  
MSWD = 0.63, probability = 0.71

**c)**

Mean = 1564 ± 20 [1.3%] 2σ  
Wtd by data-pt errs only, 0 of 6 rej.  
MSWD = 1.7, probability = 0.14

**d)**

Mean = 1599 ± 17 [1.1%] 2σ  
Wtd by data-pt errs only, 0 of 9 rej.  
MSWD = 1.5, probability =
Figure 13. a) Weighted average plot of 7 individual monazite ages with 95% confidence level for rock sample mc137; b) Probability density curve suggests a single age group.
**Absolute Time Constraints on Deformation and Metamorphism**

**M. CHAN**

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**Diagram a)**

Graph showing data points with error bars. The mean is indicated at 1574 ± 16 Ma, and the 95% confidence interval is also shown.

**Diagram b)**

Graph showing the relative probability distribution function for different age ranges. The table below summarizes the data:

<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>±2 σ</th>
<th>fraction</th>
<th>±2 σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1567.8</td>
<td>13</td>
<td>0.70</td>
<td>0.69</td>
</tr>
<tr>
<td>1596</td>
<td>26</td>
<td>0.30</td>
<td></td>
</tr>
</tbody>
</table>

The relative misfit is 0.976.
Figure 14. Backscatter images show the monazite grains and also their locations (a-b) from sample mc133. The numbered circular spots represent the locations of analyses presented in Table 4.
**Absolute Time Constraints on Deformation and Metamorphism**  

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**a)**

![Image a]

**b)**

![Image b]
Figure 15. a) Weighted average plot of 5 individual monazite ages with 95% confidence level for rock sample mc133; b) Probability density curve suggests normal distribution of a single age population.
**Absolute Time Constraints on Deformation and Metamorphism**

**Diagram a)**
- Data-point error symbols are 2σ.
- Mean = 1524.1 ± 6.3 [0.42%] 95% conf.
- MSWD = 1.18, probability = 0.32

**Diagram b)**
- Age (Ma) vs. Relative probability
- Table:
<table>
<thead>
<tr>
<th>Age</th>
<th>±2 σ</th>
<th>Fraction</th>
<th>±2 σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1520.8</td>
<td>10</td>
<td>0.53</td>
<td>0.86</td>
</tr>
<tr>
<td>1529.7</td>
<td>14</td>
<td>0.47</td>
<td>---</td>
</tr>
</tbody>
</table>
- Relative misfit = 0.991
Figure 16. a) Weighted average plot of 27 individual monazite ages with 95% confidence level from all rock samples; b) Probability density curve suggests three distinct age populations.
ABSOLUTE TIME CONSTRAINTS ON DEFORMATION AND METAMORPHISM

M. CHAN

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<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>±2σ</th>
<th>fraction</th>
<th>±2σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1518</td>
<td>5.6</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td>1559.3</td>
<td>6.3</td>
<td>0.37</td>
<td>0.25</td>
</tr>
<tr>
<td>1592.2</td>
<td>6.9</td>
<td>0.38</td>
<td>---</td>
</tr>
</tbody>
</table>

relative misfit = 0.468

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Data-point error symbols are 2σ.

Mean = 1551 ± 12 [0.8%] 95% conf. Wtd. by data-pt errs only, 0 of 27 rej.

MSWD = 14, probability = 0.000
Figure 17. Sketch showing decrenulation of early-formed differentiated crenulation cleavage. Progressive synthetic shearing parallel to S_2 switches to progressive antithetic shearing along S_1-S_{1/2} across a boundary between reactivated and non-reactivated zones; thereby early deformation partitioning domains (progressive shearing and progressive shortening) are locally destroyed.
Figure 18. P-T-D-t diagram that shows clockwise loop overprinted by gently sloping path with increasing pressure and temperature. O₁-O₄ stands for deformation periods characterized by NNW-SSE, N-S, E-W and NW-SE, respectively. M₁ represents early medium pressure-temperature metamorphism, followed by retrogressive metamorphism, M₂, which are overprinted by low pressure-high temperature metamorphism, M₃.