APATITE FISSION TRACK ANALYSIS (AFTA®) OF A MINERALISED DYKE SAMPLE FROM THE STORM GOLD DEPOSIT, NEVADA

GEOTRACK REPORT #949
A research report prepared for Rick Trotman, Centre for Research in Economic Geology, University of Nevada, Reno

Report prepared by: I. R. Duddy

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EXECUTIVE SUMMARY

Introduction and Objectives

This research report describes AFTA® Apatite Fission Track Analysis of a single mineralised dyke sample from the Storm Gold Deposit, Nevada. The sample and supporting information were provided by Rick Trotman, Centre for Research in Economic Geology, University of Nevada, Reno.

AFTA data have been used to identify, characterise and quantify any episodes of heating and cooling which have affected this sample. Quantitative thermal history constraints including paleotemperature estimates and timing of thermal episodes obtained from the AFTA are summarised in Table i while a schematic illustration of the reconstructed thermal history is presented in Figure i. The conclusions of this work are summarised in the Executive Summary, with detailed discussion including Tables and Figures provided in Text. Supporting information is provided in Appendix A, with the AFTA data presented in Appendix B.

SUMMARY CONCLUSIONS

1. Kinetic modelling of the AFTA results from sample GC949-1 (R021) indicate that the apatite in this sample has retained fission tracks for between 8 and 20 Myr (±95% confidence interval), i.e., since the Early to Late Miocene (Table i). A back-up sample was also supplied (source number R035), but this was not processed given the acceptable yield of apatite obtained from sample GC949-1 (Table A.1, Appendix A).

2. This Early to Late Miocene timing is significantly younger than 37 Ma (Eocene), the youngest age considered likely by the client for the intrusion age of this dyke into the Silurian-Devonian aged host rocks. The client also indicates that the dyke could be as old as Jurassic (162 Ma), but as the AFTA age is much younger than either of these two possible intrusion ages, the exact age of the dyke within this range has no effect on the interpretation of the AFTA results.
3. There are a number of possible interpretations of the AFTA results obtained from sample GC949-1. For example, it is possible that the AFTA results reflect cooling following an Early to Late Miocene mineralising episode involving temperatures $>105^\circ\text{C}$. On the other hand, it is also possible that the results indicate a regional cooling episode that affected both the mineralised dykes and host rocks, perhaps reflecting simple exhumation.

4. Texturally the apatite analysed from this sample appears to be largely of secondary origin (i.e. not primary igneous apatite from the dyke). Therefore, it is also possible that the thermal history constraints revealed by AFTA indicate the time at which this secondary apatite crystallised, which may, or may not, be unrelated to the time of mineralisation. Without information on the thermal history of the broader region, the implications of the Early to Late Miocene timing revealed by AFTA for the age of mineralisation remain equivocal.

**RECOMMENDATIONS**

5. It is recommended that AFTA is carried out on additional samples unrelated to mineralised dykes in order to provide a regional thermal history framework in which the AFTA results from this sample can be better understood.
Table i: Paleotemperature analysis summary: AFTA data from a mineralised dyke sample, Nevada (Geotrack Report 949)

<table>
<thead>
<tr>
<th>Geotrack sample no</th>
<th>Depth (m)</th>
<th>Stratigraphic age (Ma)</th>
<th>Present temperature (°C)</th>
<th>Maximum paleotemperature °¹</th>
<th>Onset of cooling °¹</th>
<th>Maximum paleotemperature °¹</th>
<th>Onset of cooling °¹</th>
<th>Equivalent Vitrinite Reflectance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC 949-1 (R021)</td>
<td>?</td>
<td>37</td>
<td>30</td>
<td>-</td>
<td>-</td>
<td>&gt;105</td>
<td>20 to 8</td>
<td>&gt;0.61</td>
</tr>
</tbody>
</table>

°¹ The client has indicated a Silurian-Devonian age for the host rock of this mineralised dyke sample with possible intrusion age for the dyke of Jurassic (162 Ma) or Eocene (37 Ma). For the purpose of the Default Thermal History assessment we have assumed an Eocene age (37 Ma), but this assumption has no material effect on the interpretation as the apatite fission track age of the sample is significantly younger than all of the potential “initial” ages of the sample – see text.

°² Present temperature supplied by client - Appendix A.

°³ Thermal history interpretation of AFTA data is based on an assumed heating rate of 1°C/Myr and a cooling rate of 10°C/Myr (see Section 2). Quoted ranges for paleotemperature and onset of cooling correspond to ±95% confidence limits. Conditions shown in italics represent events allowed though not definitely required by the AFTA data.

°⁴ Integrated AFTA timing constraints based on overlap of timing constraints obtained from individual samples assuming they represent coherent, regionally significant thermal episodes – see Figure i.
The AFTA and results from a single mineralised dyke sample (GC949-1) reported in this study indicate that the sample cooled through a paleotemperatures of 105°C at some time between 20 and 8 Ma (±95% confidence interval; Table i). However, the implications of this time of cooling for the age of mineralisation remains equivocal without information on the thermal history of the broader region. Thus, it is possible that the AFTA timing constraint represents the time of mineralisation of the dyke, or alternatively it may indicate a time of cooling due to regional exhumation.

There is some textural evidence which suggests that the apatite analysed from sample GC949-1 may be wholly of secondary origin. If this is case, the AFTA results may not provide any paleotemperature constraints, but may simply indicate that the secondary apatite crystallised at some time between 20 and 8 Ma. Further samples, including samples of the host rocks away from any mineralised dykes, are required to assess the full significance of the AFTA results in this sample.
1. Introduction

1.1 Aims and objectives

This research report describes AFTA® Apatite Fission Track Analysis of a single mineralised dyke sample from the Storm Gold Deposit, Nevada. The sample and supporting information were provided by Rick Trotman, Centre for Research in Economic Geology, University of Nevada, Reno.

The principle objective of this study was to use AFTA to determine the timing and magnitude of the maximum paleotemperature reached by the mineralized dyke sample.

AFTA data have been used to identify, characterise and quantify any episodes of heating and cooling which have affected this sample.

Quantitative thermal history constraints including paleotemperature estimates and timing of thermal episodes obtained from the AFTA are summarised in Table i while a schematic illustration of the reconstructed thermal history is presented in Figure i. The conclusions of this work are summarised in the Executive Summary, with detailed discussion including Tables and Figures provided in Text. Supporting information is provided in Appendix A, with the AFTA data presented in Appendix B.

1.2 Report structure

The main conclusions of this report are provided in the Executive Summary, where a summary of the thermal history interpretation of AFTA data in the mineralised dyke sample is provided in Table i. Figure i provides a schematic illustration of the reconstructed thermal history derived from the AFTA results.

Introductory aspects of the report are dealt with in Section 1, including comments on data quality. Section 2 briefly explains the principles of interpretation of AFTA and VR data (also see Appendix C). Section 3 presents a detailed discussion if the AFTA results principally as a series of Tables and Figures, and includes recommendations for further work to improve the understanding of the timing of mineralisation.

Supporting information and data are provided in four Appendices (A, B, C and D). Appendix A presents details of the two samples supplied for AFTA, including the yield of apatite obtained from the primary sample (GC949-1, source no. R021), which are summarised in Table A.1. A back-up sample was also supplied (R035; source no. R035), but this sample was not processed given the acceptable yield of...
apatite obtained from sample GC949-1 (Table A.1, Appendix A). This Table also contains information on the yields and quality of detrital apatite obtained after mineral separation. Appendix A also contains all supporting geological information. Sample preparation and analytical procedures for AFTA are described in Appendix B, followed by the presentation of all AFTA data, including raw track counts, fission track ages and the chlorine contents of dated grains. Appendix C outlines the principles employed in interpreting the AFTA data in terms of thermal history. Appendix D discusses the principles involved in integrating AFTA and VR data to provide coherent thermal history interpretations.

1.3 Data quality

AFTA data

The AFTA data generated for this report from the mineralised dyke sample are generally of fair quality, mainly due to the fair apatite yield (Table A.1, Appendix A) and the variable quality of the apatite recovered from sample GC949-1 (R021). Although more than 150 grains of apatite were obtained from the minerals separation, most of the grains were small composite grains of secondary apatite containing abundant inclusions which made track recognition and counting impossible. In the final analysis, three grain mounts were made of apatites from sample GC949-1, resulting in fission track age determinations on 12 grains and 24 confined track length measurements (Tables B.1 and B.2, Appendix B). Petrographic observations suggest that all of the grains in which fission track ages and lengths were measured are likely to be of secondary origin, with no convincing primary igneous apatites recovered (See Section 3).

Overall, the fission track data are regarded as providing a reliable thermal history interpretation in terms of the stated uncertainties.

1.4 Apatite Compositions

The annealing kinetics of fission tracks in apatite are affected by chemical composition, specifically the Cl content, as explained in more detail in Appendix C. For this study, chlorine compositions were determined for all individual apatite grains analysed for this study (i.e. all grains in which fission track ages were determined and/or lengths were measured). Knowledge of chlorine contents is essential in interpreting AFTA data, and provides both improved accuracy and precision in establishing the time and magnitude of thermal events.
The measured ranges of chlorine contents of dated grains and/or grains used for confined track length measurements are shown in histogram format in the Fission Track Age Data Sheets at the end of Appendix B. Table B.3 (Appendix B) contains single grain fission track age and track length data collected into discrete compositional groups, on the basis of the chlorine contents of the grains from which the data were derived. In addition, plots of single grain age versus weight % chlorine are shown in the Fission Track Age Data Sheets, which also list the chlorine contents of individual age grains.

In each sample, the measured distribution of compositions has been employed in extracting thermal history information from the AFTA data, using methods outlined in Appendix C.
2. Interpretation strategy

2.1 Thermal history interpretation of AFTA data

Basic principles

Interpretation of AFTA data in this report begins by assessing whether the fission track age and track length data in each sample could have been produced if the sample has never been hotter than its present temperature at any time since deposition. To this end, we consider a "Default Thermal History" for each sample, which forms the basis of interpretation. Default Thermal Histories throughout a well are derived from the stratigraphy of the preserved sedimentary section, combined with constant values for paleogeothermal gradient and paleo-surface temperature which are adopted from present-day values. For outcrop samples, the Default Thermal Histories simply represent long-term residence at the prevailing surface temperature.

Using this history, AFTA parameters are predicted for each sample. If the measured data show a greater degree of fission track annealing (in terms of either fission track age reduction or track length reduction) than expected on the basis of this history, the sample must have been hotter at some time in the past. In this case, the AFTA data are analysed to provide estimates of the magnitude of the maximum paleotemperature in that sample, and the timing of cooling from the thermal maximum.

Because of the possible presence of tracks inherited from sediment source terrains, it is possible that track length data might show definite evidence that the sample has been hotter in the past (since deposition) while fission track ages are still greater than predicted from the Default Thermal History (which only refers to tracks formed after deposition). Similarly in samples in which all or most fission tracks were totally annealed in a paleo-thermal episode, and which have subsequently been cooled and then reburied, fission track age data might show clear evidence of exposure to higher temperatures in the past while track length data may be dominated by the present-day thermal regime and will not directly reveal the paleo-thermal effects. In circumstances such as these, evidence from either track length or fission track age data alone is sufficient to establish that a sample has been hotter in the past.

As AFTA data provide no information on the approach to a thermal maximum, they cannot independently constrain the heating rate and a value must therefore be assumed in order to interpret the data. The resulting paleotemperature estimates are therefore conditional on this assumed value. AFTA data do provide some control on
the history after cooling from maximum paleotemperatures, through the lengths of tracks formed during this period.

Wherever possible, data from each sample are normally interpreted in terms of two episodes of heating and cooling, using assumed heating and cooling rates during each episode. The maximum paleotemperature is assumed to be reached during the earlier episode. The timing of the onset of cooling and the peak paleotemperatures during the two episodes are varied systematically, and by comparing predicted and measured parameters the range of conditions which are compatible with the data can be defined. One additional episode during the cooling history is the limit of resolution from typical AFTA data. Alternatively, if the data can be explained by a single episode of heating and cooling, then a heating rate is assumed and the range of values of maximum paleotemperature and the time of cooling is defined as before.

If AFTA data show a lower degree of fission track annealing (age and/or length reduction) than expected on the basis of the Default Thermal History, this either suggests present temperatures may be overestimated or temperatures have increased very recently. In such cases, the data may allow a more realistic estimate of the present temperature, or an estimate of the time over which temperatures have increased.

AFTA data are predicted using a multi-compositional kinetic model for fission track annealing in apatite developed by Geotrack, described in more detail in Appendix C.

**Specific to this report**

For all samples analysed for this report, chlorine content has been determined in every apatite grain analysed (i.e., for both fission track age and track length measurement), as explained in more detail in Appendix A. For rigorous thermal history interpretation the age and length data have been grouped into 0.1 wt% Cl divisions (see Table B.3, Appendix B).

In this report, AFTA data in all samples have been interpreted using a heating rate of 1°C/Ma and a cooling rate of 10°C/Ma. All paleotemperature estimates are conditional on the assumed rates. For the kinetics characterising AFTA, increasing or decreasing heating rates by an order of magnitude is equivalent to raising or lowering the required maximum paleotemperature by about 10°C.
3. Thermal history interpretation of AFTA data in a mineralised dyke sample

3.1 Introduction and background information

A single mineralised dyke sample (GC949-1; R021) from the Storm Gold Deposit, Nevada, was subjected to AFTA.

The client indicates that the intrusion age of the dyke is most likely Eocene (37 Ma) or Jurassic (162 Ma) and it intrudes host rocks of Silurian-Devonian age. The present temperature of the sample is assumed to be 30°C (client estimate).

3.2 Thermal history interpretation of AFTA data

Introduction

Fission track age and mean track length data in samples analysed from this well are summarised in Table 3.1 and plotted as a function of depth and present temperature in Figure 3.1. In this plot, the fission track age data are contrasted with the variation of stratigraphic age through the section. The variation of fission track age and length versus depth predicted from the Default Thermal Histories (see Section 2.1) for the well are also shown in Figure 3.1, for selected apatite chlorine contents. Table 3.1 summarises the values of mean length and fission track age predicted from the Default Thermal History for the sample. These values take into account the range of chlorine contents measured in the sample (see Age data sheet, p.B.16, Appendix B).

Qualitative interpretation of the AFTA data

The measured fission track age of the sample is significantly younger than expected from the Default Thermal History for this sample and the corresponding mean track lengths are less than predicted, as shown in Figure 3.1. This pattern of fission track age and track length provides prima facie evidence that either this sample has cooled from maximum paleotemperature higher than the present temperature of 30°C at some time since the Eocene (this applies if the apatite was present in the sample in the Eocene), or that the apatite in this sample has crystallised/precipitated at some time since the Eocene.

Note that for the purposes of interpretation of the AFTA data an Eocene age (37 Ma) has been chosen as the original intrusion age of the dyke (Section 3.1), as this provides the most conservative interpretation framework. In fact, since the apatite fission track age of the sample is much younger than the Eocene, the exact age of the
dyke within the Eocene to Jurassic range has no effect on the interpretation of the AFTA results.

Qualitative interpretation of the AFTA data, in terms of evidence that the samples may have been hotter in the past is summarised in Table 3.2.

**Timing and magnitude of maximum paleotemperatures from AFTA**

Following the strategy outlined in Section 2.1, quantitative interpretation of the AFTA data sample GC949-1 from the Storm Gold Deposit, in terms of estimates of the magnitude and timing of maximum paleotemperatures, is summarised in Table 3.3.

In summary, kinetic modelling of the AFTA results from sample GC949-1 (R021) indicate that the apatite in this sample has retained fission tracks for between 8 and 20 Myr (±95% confidence interval), i.e., since the Early to Late Miocene (Table 3.3).

If the apatite was present in this sample in the Eocene (37 Ma), then the AFTA results also indicate that the sample cooled from >105°C at some time between 20 and 8 Ma (Early to Late Micoene).

Some geological implications and alternative explanations of the AFTA results are discussed in Section 3.3.

The thermal history interpretation of the AFTA data in sample GC949-1 from the Storm Gold Deposit is summarised in Table i.

### 3.3. Geological implications of the AFTA results

There are a number of possible interpretations of the AFTA results obtained from the mineralised dyke sample GC949-1 (R021).

Assuming for the moment that the apatite analysed was present in the sample in the Eocene, the AFTA results indicate that it cooled through 105°C at some time between 20 and 8 Ma (±95% confidence interval), as discussed above. In this context, this episode may reflect cooling following a mineralising episode at this time.

However, as we have no AFTA constraints on the regional thermal history, we cannot be certain that the AFTA results from sample GC949-1 do not reflect a regional cooling episode related, for example, to a Early to Late Miocene episode of uplift and erosion (exhumation), instead of a localised mineralising event.
Alternatively, as noted above, textural observations suggest that the apatite analysed is of secondary origin (see Figure 3.2), and therefore we cannot be certain that the apatite was present in the sample in the Eocene. Thus, it is possible that the apatite was precipitated in this sample at a temperature much lower than 105°C, and that the fission track results simply indicate that 8 to 20 Myr has elapsed since the apatite crystallised. Again, the AFFA results alone provide no information on whether this time relates to economic mineralisation, but petrographic studies may be able to elucidate this.

3.4. Recommendations for further work

The interpretation of AFTA results obtained in this study has provided reliable timing constraints on a key aspect of the thermal history of a mineralised dyke sample. A number of interpretations are possible from the results, however, and it is recommended that AFTA is carried out on additional samples unrelated to mineralised dykes. With this strategy the regional cooling history could be established, providing a regional thermal history framework in which the AFTA results from this mineralised sample can be more accurately interpreted.

Specific sampling strategies and costings to address this issue can be provided on request.
Table 3.1: Summary of apatite fission track data, “Mineralised Dyke” sample, Nevada (Geotrack Report #949)

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Source Number</th>
<th>Present temperature*1 (°C)</th>
<th>Stratigraphic age (Ma)</th>
<th>Mean track length (µm)</th>
<th>Predicted mean track length*2 (µm)</th>
<th>Fission track age (Ma)</th>
<th>Predicted fission track age*2 (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC949-1</td>
<td>R021</td>
<td>30</td>
<td>37</td>
<td>13.39 ± 0.43</td>
<td>14.3</td>
<td>13.7 ± 2.3</td>
<td>36</td>
</tr>
<tr>
<td>GC949-2</td>
<td>R035</td>
<td>30</td>
<td>37</td>
<td>Not processed</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*1 A present-day temperature estimate of 30°C has been supplied for this sub-surface sample (Appendix A).

*2 Values predicted from the Default Thermal History (Section 2.1); i.e. assuming that each sample is now at its maximum temperature since deposition. The values refer only to tracks formed after deposition. Samples may contain tracks inherited from sediment provenance areas. Calculations refer to apatites within the measured compositional range for each sample, as discussed in Appendix A.

*3 The client has indicated a Silurian-Devonian age for the host rock of this mineralised dyke sample with possible intrusion age for the dyke of Jurassic (162 Ma) or Eocene (37 Ma). For the purpose of the Default Thermal History assessment we have assumed an Eocene Age (37 Ma), but this assumption has no material effect on the interpretation as the apatite fission track age of the sample is significantly younger than all of the potential “initial” ages of the sample – see text.

Note: All depths quoted are TVD with respect to KB.
### Table 3.2: Summary of thermal history interpretation of AFTA data in a “Mineralised Dyke” sample, Nevada (Geotrack Report #949).

<table>
<thead>
<tr>
<th>Sample no. Depth (m)</th>
<th>Sample type</th>
<th>Present temp</th>
<th>Strat. Unit</th>
<th>Strat. Age</th>
<th>Do AFTA data require revision of the present temp.?</th>
<th>Evidence of higher temperatures in the past from length data?</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC949-1 (R021)</td>
<td>Core sample</td>
<td>30°C</td>
<td>Mineralised Dyke</td>
<td>Eocene, or older &gt;37 Ma</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Depth not known</td>
<td></td>
<td></td>
<td></td>
<td>The mean track length is ~0.9 µm shorter than that predicted on the basis of the Default Thermal History. Kinetic modelling of the AFTA parameters through likely thermal history scenarios shows that the measured lengths can be explained only by higher paleotemperatures after deposition, and not by inheritance of short tracks from the source terrain.]</td>
<td>The central fission track age and most single grain ages are significantly younger than expected on the basis of the Default Thermal History providing clear evidence for post-depositional temperatures higher than the revised present temperature.]</td>
<td>The fission track age and track length data in this sample show that the sample has been hotter in the past.</td>
</tr>
<tr>
<td>GC949-2 (R035)</td>
<td>Core sample</td>
<td>30°C</td>
<td>Mineralised Dyke</td>
<td>Eocene, or older &gt;37 Ma</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: Interpretation of AFTA data is based on comparison of measured AFTA parameters with values predicted from the "Default Thermal History" (Section 2.1). The predicted values for each sample are summarised in Table 3.1, and refer only to tracks formed after deposition. Samples may also contain tracks inherited from sediment provenance areas, which must be allowed for in interpreting the data. Calculations refer to apatites with the compositional range measured in each sample, as explained in Appendix A.
### Table 3.3: Estimates of timing and magnitude of elevated paleotemperatures AFTA data in a “Mineralised Dyke” sample, Nevada (Geotrack Report #949).

<table>
<thead>
<tr>
<th>Sample Details</th>
<th>Paleo-thermal constraints</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Event</strong></td>
<td><strong>Maximum paleo-temperature (°C)</strong></td>
<td><strong>Onset Of Cooling (Ma)</strong></td>
</tr>
<tr>
<td>GC949-1</td>
<td>Single</td>
<td>&gt;105</td>
</tr>
</tbody>
</table>

Good quality AFTA data based on 13 age grains and 24 confined track length measurements (see Age versus Cl plot, data sheet, p. B.16, Appendix B). Kinetic modeling of the data indicates that cooling through a maximum paleotemperature >105°C occurred at some time between 20 and 8 Ma (Early to Late Miocene), as listed at left, and illustrated in Figure i. This timing is significantly younger than 37 Ma (Eocene), the youngest age considered likely by the client for the intrusion age of the dyke. Without information on the thermal history of the broader region, the implications of this time of cooling on the age of mineralisation remains equivocal. It is possible that 20 to 8 Ma represents the time of mineralisation of the dyke, or alternatively it may indicate the time of cooling due to regional exhumation. In addition, the apatite from this sample appears to be largely of secondary origin (i.e. not primary igneous apatite from the dyke), and it may be that the thermal history constraints revealed by AFTA indicate the time at which this secondary apatite crystallised, and which is unrelated to the gold mineralisation.

It is recommended that AFTA is carried out on samples unrelated to mineralized dykes in order to provide a regional thermal history framework in which the AFTA results from this sample can be better understood.

**Equivalent VR from AFTA: >0.61%**
The AFTA-derived maximum paleotemperature constraint of >105°C predicts an equivalent VR level >0.61%. No measured VR data are available at this depth for direct comparison with AFTA.

All thermal history constraints are based on assumed heating rates of 1°C/Ma and cooling rates of 10°C/Ma.
Events shown in italics are not required by the AFTA data, though they are allowed within the limits shown.
Mineralised Dyke Sample (GC949-1, R021)

Figure 3.1: AFTA parameters plotted against relative stratigraphic position for a mineralised dyke sample, GC949-1. The stratigraphic age is also shown, as the solid line in the central panel. A present-day temperature of 30°C has been assume for the sample. Coloured lines show the pattern of fission track age and mean track length predicted (for apatites containing 0.0-0.1, 0.4-0.5, 0.9-1.0 and 1.5-1.6 wt% Cl) from the Default Thermal History (see Section 2.1) based on the thermal structure reported above.

The measured apatite fission track age is significantly younger than predicted from the Default Thermal History for the entire range of Cl contents and the mean track length is shorter than predicted. This pattern is consistent with this sample cooling from maximum paleotemperatures higher than the present temperature of 30°C at some time since the Eocene – see text for a detailed explanation.
Figure 3.2: Representative photomicrographs of apatite grains recovered from sample GC949-1 (R021). Grain shapes suggest these apatites are of secondary origin.

Image 1: GC949-1, Slide 1: Grain 5, width of field of view = 195 µm
Image 2: GC949-1, Slide 1: Grain 15, width of field of view = 390 µm
Image 3: GC949-1, Slide 1: Grain 29, width of field of view = 195 µm
Image 4: GC949-1, Slide 1: Grain 30, width of field of view = 195 µm
Image 5: GC949-1, Slide 2: Grain 5, width of field of view = 390 µm
Image 6: GC949-1, Slide 2: Grain 15, width of field of view = 390 µm
Image 7: GC949-1, Slide 2: Grain 17, width of field of view = 390 µm
Image 8: GC949-1, Slide 2: Grain 29, width of field of view = 390 µm
Image 9: GC949-1, Slide 2: Grain 33, width of field of view = 390 µm
Some References


APPENDIX A

Sample Details, Geological Data and Apatite Compositions

A.1 Sample details

Two core samples of mineralised dykes from the Storm Gold Deposit Nevada, together with supporting information were supplied by Rick Trotman (University of Nevada, Reno) for AFTA® Apatite Fission track Analysis.

Only one sample (GC949-1; R021) was processed through the mineral separation procedures to recover apatite, with the other sample (GC949-2; R035) retained as a back-up in case of a poor apatite yield. Sample GC949-1 contained sufficient apatite for AFTA analysis as summarised in Table A.1 and the overall data quality is regarded as high as a result of the fair apatite yield. Details of all AFTA samples, including stratigraphic ages and estimates of present temperature for each sample, are also summarised in Table A.1. Details of present temperatures are discussed below. Basic AFTA data are summarised in Tables B.1 and B.2 (Appendix B), and are broken down into discrete compositional groups in Table B.3.

No vitrinite reflectance determinations were carried out for this research study.

A.2 Stratigraphic details

Details of the stratigraphic age of the samples were provided by the client, as summarised in Table A.1.

An Eocene (37 Ma) intrusion age is assumed for both mineralised dyke samples as summarised in Table A.1. In fact, the client indicated that the intrusion age of the dyke might be either Eocene (37 Ma) or Jurassic (162 Ma), but given the AFTA results obtained, assuming intrusion ages in this range has no influence on the outcome of the AFTA thermal history results. The client also indicated a Silurian-Devonian stratigraphic age for the host rocks, but again, given the AFTA results obtained from sample GC949-1, this age has no influence on the thermal history interpretation.

Thus, any slight errors in the estimated chronometric ages of each sample are not expected to affect the thermal history interpretation of either the AFTA data to any significant degree.
A.3 Present temperatures

In application of any technique involving estimation of paleotemperatures, it is critical to control the present temperature profile, since estimation of maximum paleotemperatures proceeds from determining how much of the observed effect can be explained by the magnitude of present temperatures.

In this case, the client has provided estimated present-day temperatures for each core sample of 30°C (Table A.1). As long as the actual present-day temperature for sample GC949-1 (R021) is less than ~60°C, this assumption will have no significant effect on the interpretation of the AFTA results.

A.4 Apatite Grain morphologies

The majority of grains analysed from these samples from the sample GC949-1 (R021) were euhedral in shape, and other consisted of aggregates of euhedral grains. These petrographic characteristics suggest many, if not all, grains are of secondary origin, precipitated in the samples at some time during, or since dyke intrusion. Some apatite grains images are provided in the text.

A.5 Apatite compositions

The annealing kinetics of fission tracks in apatite are affected by chemical composition, specifically the Cl content, as explained in more detail in Appendix C. In all samples collected for this study, Cl contents were measured in all apatite grains analysed (i.e. for both fission track age determination and track length measurement), and the measured compositions in individual grains have been employed in interpreting the AFTA data, using methods outlined in Appendix C.

Chlorine contents were measured using a fully automated Jeol JXA-5A electron microprobe equipped with a computer controlled X-Y-Z stage and three computer controlled wavelength dispersive crystal spectrometers, with an accelerating voltage of 15kV and beam current of 25nA. The beam was defocussed to 20 µm diameter to avoid problems associated with apatite decomposition, which occur under a fully focussed 1 µm - 2 µm beam. The X-Y co-ordinates of dated grains within the grain mount were transferred from the Autoscan Fission Track Stage to a file suitable for direct input into the electron microprobe. The identification of each grain was verified optically prior to analysis. Cl count rates from the analysed grains were converted to wt% Cl by reference.
to those from a Durango apatite standard (Melbourne University Standard APT151) analysed at regular intervals. This approach implicitly takes into account atomic number absorption and fluorescence matrix effects, which are normally calculated explicitly when analysing for all elements. A value of 0.43 wt% Cl was used for the Durango standard, based on repeated measurements on the same single fragment using pure rock salt (NaCl) as a standard for chlorine. This approach gives essentially identical results to Cl contents determined from full compositional measurements, but has the advantage of reducing analytical time by a factor of ten or more.

Lower limits of detection for chlorine content have been calculated for typical analytical conditions (beam current, counting time, etc.) and are listed in Table A.4. Errors in wt% composition are given as a percentage and quoted at 1σ for chlorine determinations. A generalised summary of errors for various wt% chlorine values is presented in Table A.5.

Specific to this report

Cl contents in individual grains are listed in the Fission Track Age Data Sheet in Appendix B, together with histograms of Cl contents in individual samples and plots of fission track age against Cl content. Table B.3 (Appendix B) contains fission track age and length data grouped into 0.1 wt% Cl intervals on the basis of chlorine contents of the grains from which the data are derived.

All of the apatite grains analysed from mineralised dyke sample GC949-1 show a very narrow range of Cl, varying from 0 to <0.1wt%. In our experience, this pattern is consistent with a secondary origin for the analysed apatites, although primary igneous apatite cannot be ruled out on this basis. Typical histograms of apatite compositions are shown in Figure C.4b, Appendix C.
Table A.1: Details of fission track samples and apatite yields - outcrop samples from Storm Gold Deposit, Nevada, USA (Geotrack Report #949)

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Source #</th>
<th>Stratigraphic Subdivision</th>
<th>Stratigraphic age (Ma)</th>
<th>Raw weight (g)</th>
<th>Washed weight (g)</th>
<th>Apatite yield *1</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC949-1</td>
<td>R021</td>
<td>EOCENE</td>
<td>37</td>
<td>-</td>
<td>-</td>
<td>fair</td>
</tr>
<tr>
<td>GC949-2</td>
<td>R035</td>
<td>EOCENE</td>
<td>37</td>
<td>-</td>
<td>Not Processed</td>
<td></td>
</tr>
</tbody>
</table>

*1 Yield based on quantity of mineral suitable for age determination. Excellent: >20 grains; Good: 15-19 grains; Fair: 10-14 grains; Poor: 5-9 grains; Very Poor: <5 grains.
Table A.2: Lower Limits of Detection for Apatite Analyses (Geotrack Report #949)

<table>
<thead>
<tr>
<th>Element</th>
<th>LLD (95% c.l.) (wt%)</th>
<th>LLD (95% c.l.) (ppm)</th>
<th>LLD (99% c.l.) (wt%)</th>
<th>LLD (99% c.l.) (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl</td>
<td>0.01</td>
<td>126</td>
<td>0.02</td>
<td>182</td>
</tr>
</tbody>
</table>

Table A.3: Per cent errors in chlorine content (Geotrack Report #949)

<table>
<thead>
<tr>
<th>Chlorine content (wt%)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>9.3</td>
</tr>
<tr>
<td>0.02</td>
<td>8.7</td>
</tr>
<tr>
<td>0.05</td>
<td>7.3</td>
</tr>
<tr>
<td>0.10</td>
<td>6.1</td>
</tr>
<tr>
<td>0.20</td>
<td>4.7</td>
</tr>
<tr>
<td>0.50</td>
<td>3.2</td>
</tr>
<tr>
<td>1.00</td>
<td>2.3</td>
</tr>
<tr>
<td>1.50</td>
<td>1.9</td>
</tr>
<tr>
<td>2.00</td>
<td>1.7</td>
</tr>
<tr>
<td>2.50</td>
<td>1.5</td>
</tr>
<tr>
<td>3.00</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Errors quoted are at 1σ. See Appendix A for more details.
APPENDIX B

Sample Preparation, Analytical Details and Data Presentation

B.1 Sample Preparation

Core and outcrop samples are crushed in a jaw crusher and then ground to sand grade in a rotary disc mill. Cuttings samples are washed and dried before grinding to sand grade. The ground material is then washed to remove dust, dried and processed by conventional heavy liquid and magnetic separation techniques to recover heavy minerals. Apatite grains are mounted in epoxy resin on glass slides, polished and etched for 20 sec in 5M HNO₃ at 20°C to reveal the fossil fission tracks.

After etching, all mounts are cut down to 1.5 x 1 cm, and cleaned in detergent, alcohol and distilled water. The mounts are then sealed in intimate contact with low-uranium muscovite detectors within heat-shrink plastic film. Each batch of mounts is stacked between two pieces of uranium standard glass, which has been prepared in similar fashion. The stack is then inserted into an aluminium can for irradiation.

After irradiation, the mica detectors are removed from the grain mounts and standard glasses and etched in hydrofluoric acid to reveal the fission tracks produced by induced fission of $^{235}$U in the apatite and standard glass.

B.2 Analytical Details

Fission track ages

Fission track ages are calculated using the standard fission track age equation using the zeta calibration method (equation five of Hurford and Green, 1983), viz:

$$ F.T. \text{AGE} = \frac{1}{\lambda_D} \ln \left[ 1 + \left( \frac{\zeta \lambda_D \rho_s g \rho_D}{\rho_i} \right) \right] $$  \hspace{1cm} B.1

where:

- $\lambda_D$ = Total decay constant of $^{238}$U ($= 1.55125 \times 10^{-10}$)
- $\zeta$ = Zeta calibration factor
- $\rho_s$ = Spontaneous track density
- $\rho_i$ = Induced track density
- $\rho_D$ = Track density from uranium standard glass
- $g$ = A geometry factor ($= 0.5$)
Fission track ages are determined by the external detector method or EDM (Gleadow, 1981). The EDM has the advantage of allowing fission track ages to be determined on single grains. In apatite, tracks are counted in 20 grains from each mount wherever possible. In those samples where the desired number is not present, all available grains are counted, the actual number depending on the availability of suitably etched and oriented grains. Only grains oriented with surfaces parallel to the crystallographic c-axis are analysed. Such grains can be identified on the basis of the etching characteristics, as well as from morphological evidence in euhedral grains. The grain mount is scanned sequentially, and the first 20 suitably oriented grains identified are analysed.

Tracks are counted within an eyepiece graticule divided into 100 grid squares. In each grain, the number of spontaneous tracks ($N_s$) within a certain number of grid squares ($N_a$) is recorded. The number of induced tracks ($N_i$) in the corresponding location within the mica external detector is then counted. Spontaneous and induced track densities ($\rho_s$ and $\rho_i$, respectively) are calculated by dividing the track counts by the total area counted, given by the product of $N_a$ and the area of each grid square (determined by calibration against a ruled stage graticule or diffraction grating). Fission track ages may be calculated by substituting track counts ($N_s$ and $N_i$) for track densities ($\rho_s$ and $\rho_i$) in equation B.1, since the areas cancel in the ratio.

Translation between apatite grains in the grain mount and external detector locations corresponding to each grain is carried out using Autoscan™ microcomputer-controlled automatic stages (Smith and Leigh Jones, 1985). This system allows repeated movement between grain and detector, and all grain locations are stored for later reference if required.

Neutron irradiations are carried out in a well-thermalised flux (X-7 facility; Cd ratio for Au ~98) in the Australian Atomic Energy Commission's HIFAR research reactor. Total neutron fluence is monitored by counting tracks in mica external detectors attached to two pieces of Corning Glass Works standard glass CN5 (containing ~11 ppm Uranium) included in the irradiation canister at each end of the sample stack. In determining track densities in external detectors irradiated adjacent to uranium standard glasses, 25 fields are normally counted in each detector. The total track count ($N_D$) is divided by the total area counted to obtain the track density ($\rho_D$). The positions of the counted fields are arranged in a 5 x 5 grid covering the whole area of the detector. For typical track densities of between ~5 x 10^5 and 5 x 10^6, this is a convenient arrangement to sample across the detector while gathering sufficient counts to achieve a precision of ~±2% in a reasonable time.
A small flux gradient is often present in the irradiation facility over the length of the sample package. If a detectable gradient is present, the track count in the external detector adjacent to each standard glass is converted to a track density ($\rho_D$) and a value for each mount in the stack is calculated by linear interpolation. When no detectable gradient is present, the track counts in the two external detectors are pooled to give a single value of $\rho_D$, which is used to calculate fission track ages for each sample.

A Zeta calibration factor ($\zeta$) has been determined empirically for each observer by analysing a set of carefully chosen age standards with independently known K-Ar ages, following the methods outlined by Hurford and Green (1983) and Green (1985).

All track counting is carried out using Zeiss(R) Axioplan microscopes, with an overall linear magnification of 1068 x using dry objectives.

For further details and background information on practical aspects of fission track age determination, see e.g. Fleischer, Price and Walker (1975), Naeser (1979) and Hurford (1986).

**Track length measurements**

For track length studies in apatite, the full lengths of "confined" fission tracks are measured. Confined tracks are those which do not intersect the polished surface but have been etched from other tracks or fractures, so that the whole length of the track is etched. Confined track lengths are measured using a digitising tablet connected to a microcomputer, superimposed on the microscope field of view via a projection tube. With this system, calibrated against a stage graticule ruled in 2 $\mu$m divisions, individual tracks can be measured to a precision of $\pm 0.2$ $\mu$m. Tracks are measured only in prismatic grains, characterised by sharp polishing scratches with well-etched tracks of narrow cone angle in all orientations, because of the anisotropy of annealing of fission tracks in apatite (as discussed by Green et al. 1986). Tracks are also measured following the recommendations of Laslett et al. (1982), the most important of which is that only horizontal tracks should be measured. One hundred tracks are measured whenever possible. In apatite samples with low track density, or in those samples in which only a small number of apatite grains are obtained, fewer confined tracks may be available. In such cases, the whole mount is scanned to measure as many confined tracks as possible.

**Integrated fission track age and length measurement**

Fission track age determination and length measurement are now made in a single pass of the grain mount, in an integrated approach. The location of each grain in which
tracks are either counted or measured is recorded for future reference. Thus, track length measurements can be tied to age determination in individual grains. As a routine procedure we do not measure the age of every grain in which lengths are determined, as this would be much too time-consuming. Likewise we do not only measure ages in grain in which lengths are measured, as this would bias the age data against low track density grains. Nevertheless, the ability to determine the fission track age of certain grains from which length data originate can be a particularly useful aid to interpretation in some cases. Grain location data are not provided in this report, but are available on request.

B.3 Data Presentation

**Fission track age data**

Data sheets summarising the apatite fission track age data, including full details of fission track age data for individual apatite grains in each sample, together with the primary counting results and statistical data, are given in the following pages. Individual grain fission track ages are calculated from the ratio of spontaneous to induced fission track counts for each grain using equation B.1, and errors in the single grain ages are calculated using Poissonian statistics, as explained in more detail by Galbraith (1981) and Green (1981). All errors are quoted as ±1σ throughout this report, unless otherwise stated.

The variability of fission track ages between individual apatite grains within each sample can be assessed using a chi-squared (χ²) statistic (Galbraith, 1981), the results of which are summarised for each sample in the data sheets. If all the grains counted belong to a single age population, the probability of obtaining the observed χ² value, for ν degrees of freedom (where ν = number of crystals -1), is listed in the data sheets as P(χ²) or P(chi squared).

A P(χ²) value greater than 5% can be taken as evidence that all grains are consistent with a single population of fission track age. In this case, the best estimate of the fission track age of the sample is given by the "pooled age", calculated from the ratio of the total spontaneous and induced track counts in all grains analysed. Errors for the pooled age are calculated using the "conventional" technique outlined by Green (1981), based on the total number of tracks counted for each track density measurement (see also Galbraith, 1981).

A P(χ²) value of less than 5% denotes a significant spread of single grain ages, suggesting real differences exist between the fission track ages of individual apatite
grains. A significant spread in grain ages can result either from inheritance of detrital grains from mixed source areas (in sedimentary rocks), or from differential annealing in apatite grains of different composition, within a narrow range of temperature.

Calculation of the pooled age inherently assumes that only a single population of ages is present, and is thus not appropriate to samples containing a significant spread of fission track ages. In such cases Galbraith, has recently devised a means of estimating the modal age of a distribution of single grain fission track ages which is referred to as the "central age". Calculation of the central age assumes that all single grain ages belong to a Normal distribution of ages, with a standard deviation (σ) known as the "age dispersion". An iterative algorithm (Galbraith and Laslett, 1993) is used to provide estimates of the central age with its associated error, and the age dispersion, which are all quoted in the data sheets. Note that this treatment replaces use of the "mean age", which has used been in the past for those samples in which P(χ²)<5%. For samples in which P(χ²)>5%, the central age and the pooled age should be equal, and the age dispersion should be less than ~10%.

Table B.1 summarises the fission track age data in apatite from each sample analysed.

**Construction of radial plots of single grain age data**

Single grain age data are best represented in the form of radial plot diagrams (Galbraith, 1988, 1990). As illustrated in Figure B.1, these plots display the variation of individual grain ages in a plot of y against x, where:

\[ y = \frac{(z_j - z_o)}{\sigma_j} \quad x = \frac{1}{\sigma_j} \]  

and;

- \( z_j \) = Fission track age of grain j
- \( z_o \) = A reference age
- \( \sigma_j \) = Error in age for grain j

In this plot, all points on a straight line from the origin define a single value of fission track age, and, at any point, the value of x is a measure of the precision of each individual grain age. Therefore, precise individual grain ages fall to the right of the plot (small error, high x), which is useful, for example, in enabling precise, young grains to be identified. The age scale is shown radially around the perimeter of the plot (in Ma). If all grains belong to a single age population, all data should scatter between \( y = +2 \) and \( y = -2 \), equivalent to scatter within ±2σ. Scatter outside these boundaries shows a significant spread of individual grain ages, as also reflected in the values of P(χ²) and age dispersion.
In detail, rather than using the fission track age for each grain as in equation B.2, we use:

\[
    z_j = \frac{N_{sj}}{N_{ij}} \quad \sigma_j = \{1/N_{sj} + 1/N_{ij}\} \quad \text{B.3}
\]

as we are interested in displaying the scatter within the data from each sample in comparison with that allowed by the Poissonian uncertainty in track counts, without the additional terms which are involved in determination of the fission track age (\(\rho_D\), \(\zeta\), etc).

Zero ages cannot be displayed in such a plot. This can be achieved using a modified plot, (Galbraith, 1990) with:

\[
    z_j = \arcsin \left( \frac{N_{sj} + 3/8}{N_{sj} + N_{ij} + 3/4} \right) \quad \sigma_j = \frac{1}{2} \sqrt{\left\{ \frac{1}{N_{sj} + N_{ij}} \right\}} \quad \text{B.4}
\]

Note that the numerical terms in the equation for \(z_j\) are standard terms, introduced for statistical reasons. Using this arc-sin transformation, zero ages plot on a diagonal line which slopes from upper left to lower right. Note that this line does not go through the origin. Figure B.2 illustrates this difference between conventional and arc-sin radial plots, and also provides a simple guide to the structure of radial plots.

Use of arc-sin radial plots is particularly useful in assessing the relative importance of zero ages. For instance, grains with \(N_s = 0, N_i = 1\) are compatible with ages up to \(~900\) Ma (at the 95% confidence level), whereas grains with \(N_s = 0, N_i = 50\) are only compatible with ages up to \(~14\) Ma. The two data would readily be distinguishable on the radial plot as the 0,50 datum would plot well to the right (high x) compared to the 0,1 datum.

In this report the value of \(z\) corresponding to the stratigraphic age of each sample (or the midpoint of the range where appropriate) is adopted as the reference value, \(z_0\). This allows rapid assessment of the fission track age of individual grains in relation to the stratigraphic age, which is a key component in the interpretation of AFTA data, as explained in more detail in Appendix C.

Note that the x axis of the radial plot is normally not labelled, as this would obscure the age scale around the plot. In general labelling is not considered necessary, as we are concerned only with relative variation within the data, rather than absolute values of precision.
Radial plots of the single grain age data in apatite from each sample analysed in this report are shown on the fission track age data summary sheets at the end of this Appendix. Use of radial plots to provide thermal history information is explained in Appendix C and Figure C.7.

**Track length data**

Distributions of confined track lengths in apatite from each sample are shown as simple histograms on the fission track age data summary sheets at the end of this Appendix. For every track length measurement, the length is recorded to the nearest 0.1 µm, but the measurements have been grouped into 1 µm intervals for construction of these histograms. Each distribution has been normalised to 100 tracks for each sample to facilitate comparison. A summary of the length distribution in each sample is presented in Table B.2, which also shows the mean track length in each sample and its associated error, the standard deviation of each distribution and the number of tracks (N) measured in each sample. The angle which each confined track makes with the crystallographic c-axis is also routinely recorded, as is the width of each fracture within which tracks are revealed. These data are not provided in this report, but can be supplied on request.

**Breakdown of data into compositional groups**

In Table B.3, AFTA data are grouped into compositional intervals of 0.1 wt% Cl width. Parameters for each interval represent the data from all grains with Cl contents within each interval. Also shown are the parameters for each compositional interval predicted from the Default Thermal History (see Section 2.1). These data form the basis of interpretation of the AFTA data, which takes full account of the influence of Cl content on annealing kinetics, as described in Appendix C. Distributions of Cl contents in all apatites analysed from each sample (i.e. for both age and length determinations) are shown on the fission track age data summary sheets at the end of this Appendix.

**Plots of fission track age against Cl content for individual apatite grains**

Fission track ages of single apatite grains within individual samples are plotted against the Cl content of each grain on the fission track age data summary sheets at the end of this Appendix. These plots are useful in assessing the degree of annealing, as expressed by the fission track age data. For example, if grains with a range of Cl contents from zero to some upper limit all give similar fission track ages which are significantly less than the stratigraphic age, then grains with these compositions must have been totally annealed. Alternatively, if fission track age falls rapidly with decreasing Cl content, the sample displays a high degree of partial annealing.
B.4  A note on terminology

Note that throughout this report, the term "fission track age" is understood to denote the parameter calculated from the fission track age equation, using the observed spontaneous and induced track counts (either pooled for all grains or for individual grains). The resulting number (with units of Ma) should not be taken as possessing any significance in terms of events taking place at the time indicated by the measured fission track age, but should rather be regarded as a measure of the integrated thermal history of the sample, and should be interpreted in that light using the principles outlined in Appendix C. Use of the term "apparent age" is not considered to be useful in this regard, as almost every fission track age should be regarded as an apparent age, in the classic sense, and repeated use becomes cumbersome.
References


### Table B.1: Apatite fission track analytical results - samples from Storm Gold Deposit, Nevada, USA (Geotrack Report #949)

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Number of grains</th>
<th>$\rho_D$ (Ns) x10^6/cm²</th>
<th>$\rho_s$ (Ni) x10^6/cm²</th>
<th>$\rho_i$ (Ni) x10^6/cm²</th>
<th>Uranium content (ppm)</th>
<th>$P(\chi^2)$ (%)</th>
<th>Age dispersion (%)</th>
<th>Fission track age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dyke samples</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GC949-1</td>
<td>13</td>
<td>1.045 (1668)</td>
<td>0.410 (58)</td>
<td>6.621 (938)</td>
<td>72</td>
<td>4</td>
<td>33</td>
<td>12.7 ± 1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13.7 ± 2.4*</td>
</tr>
</tbody>
</table>

$\rho_s$ = spontaneous track density; $\rho_i$ = induced track density; $\rho_D$ = track density in glass standard external detector. Brackets show number of tracks counted. $\rho_D$ and $\rho_i$ measured in mica external detectors; $\rho_s$ measured in internal surfaces.

*Central age, used where sample contains a significant spread of single grain ages ($P(\chi^2)<5\%$). Errors quoted at 1σ.

Ages calculated using dosimeter glass CN5, with a zeta of 392.9 ± 7.4 (Analyst: M. Moore) for sample 1.
Table B.2: Length distribution summary data - samples from Storm Gold Deposit, Nevada, USA (Geotrack Report #949)

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Mean track length (µm)</th>
<th>Standard deviation (µm)</th>
<th>Number of tracks (N)</th>
<th>Number of tracks in Length Intervals (µm)</th>
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<tbody>
<tr>
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<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20</td>
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</tr>
<tr>
<td>dyke samples</td>
<td></td>
<td></td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>GC949-1</td>
<td>13.39 ± 0.43</td>
<td>2.11</td>
<td>- - - - - - - - 1 - 3 3 2 5 7 1 - 2 - -</td>
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Track length measurements by: M. Moore for samples; 1
### Table B.3: AFTA Data in Compositional Groups - (Geotrack Report #949)

<table>
<thead>
<tr>
<th>Cl Wt %</th>
<th>Default fission track age* (Ma)</th>
<th>Measured fission track age (Ma)</th>
<th>Error P (χ²)</th>
<th>Number of grains</th>
<th>Default fission track length* (µm)</th>
<th>Mean Track length (µm)</th>
<th>Error in length (µm)</th>
<th>Std deviation (µm)</th>
<th>Number of lengths</th>
<th>Number of grains</th>
</tr>
</thead>
<tbody>
<tr>
<td>dyke samples</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>949-1†</td>
<td>36</td>
<td>13.7</td>
<td>2.4</td>
<td>4.4</td>
<td>13</td>
<td>14.3</td>
<td>13.4</td>
<td>0.4</td>
<td>2.1</td>
<td>24</td>
</tr>
<tr>
<td>0.0 - 0.1</td>
<td>36</td>
<td>13.6</td>
<td>2.4</td>
<td>4.4</td>
<td>13</td>
<td>14.3</td>
<td>13.4</td>
<td>0.4</td>
<td>2.1</td>
<td>24</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Fission Track Age and Mean Track Length predicted from the Default Thermal History (i.e. if the sample has not been hotter in the past)
†Combined data for all compositional groups
Estimates \( z_i \)
Standard errors \( \sigma_i \)
Reference value \( z_o \)
Standardised estimates \( y_i = (z_i - z_o) / \sigma_i \)
Precision \( x_i = 1 / \sigma_i \)

**PLOT** \( y_i \) against \( x_i \)

Slope of line from origin through data point
\[
= \frac{y_i}{x_i}
\]
\[
= \frac{(z_i - z_o) / \sigma_i}{1 / \sigma_i}
\]
\[
= z_i - z_o
\]

**Key Points:**

Radial lines emanating from the origin correspond to fixed values of \( z \)

Data points with higher values of \( x_i \) have greater precision.

Error bars on all points are the same size in this plot.

**Figure B.1** Basic construction of a radial plot. In AFTA, the estimates \( z_i \) correspond to the fission track age values for individual apatite grains. Any convenient value of age can be chosen as the reference value corresponding to the horizontal in the radial plot. Radial lines emanating from the origin with positive slopes correspond to fission track ages greater than the reference value. Lines with negative slopes correspond to fission track ages less than the reference value.
Normal radial plot (equations B.2 and B.3)

Arc-sin radial plot (equations B.2 and B.4)

Figure B.2  Simplified structure of Normal and Arc-sin radial plots.
### Fission Track Age Data Sheets - Glossary

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>( N_s )</td>
<td>Number of spontaneous tracks in ( N_a ) grid squares</td>
</tr>
<tr>
<td>( N_i )</td>
<td>Number of induced tracks in ( N_a ) grid squares</td>
</tr>
<tr>
<td>( N_a )</td>
<td>Number of grid squares counted in each grain</td>
</tr>
<tr>
<td>RATIO</td>
<td>( N_s/N_i )</td>
</tr>
<tr>
<td>U (ppm)</td>
<td>Uranium content of each grain (= U content of standard glass * ( \rho_i/\rho_D ))</td>
</tr>
<tr>
<td>Cl (wt%)</td>
<td>Weight percent chlorine content of each grain</td>
</tr>
<tr>
<td>( \rho_s )</td>
<td>Spontaneous track density ( \rho_s = N_s/(N_a \times \text{area of basic unit}) )</td>
</tr>
<tr>
<td>( \rho_i )</td>
<td>Induced track density ( \rho_i = N_i/(N_a \times \text{area of basic unit}) )</td>
</tr>
<tr>
<td>F.T. AGE</td>
<td>Fission track age, calculated using equation B.1</td>
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### Key to Figures:

<table>
<thead>
<tr>
<th>A</th>
<th>Radial plot of single grain ages</th>
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<tbody>
<tr>
<td></td>
<td><em>(See Figures B.1 and B.2 for details of radial plot construction)</em></td>
</tr>
<tr>
<td>B</td>
<td>Distribution of Cl contents in apatite grains</td>
</tr>
<tr>
<td>C</td>
<td>Single grain age vs weight % Cl for individual apatite grains</td>
</tr>
<tr>
<td>D</td>
<td>Distribution of confined track lengths</td>
</tr>
</tbody>
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### GC949-1 Apatite

**Counts by:** MEM

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<tr>
<th>Slide ref</th>
<th>Current grain no</th>
<th>(N_s)</th>
<th>(N_i)</th>
<th>(N_a)</th>
<th>(\rho_s)</th>
<th>(\rho_i)</th>
<th>RATIO</th>
<th>U (ppm)</th>
<th>Cl (wt%)</th>
<th>F.T. AGE (Ma)</th>
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<tbody>
<tr>
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<td>3</td>
<td>0</td>
<td>3</td>
<td>30</td>
<td>0.000E+00</td>
<td>1.589E+05</td>
<td>0.000</td>
<td>1.7</td>
<td>0.00</td>
<td>0.0 ± 171.3</td>
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<td>G1006-1</td>
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<td>3</td>
<td>14</td>
<td>28</td>
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<td>7.945E+05</td>
<td>0.214</td>
<td>8.7</td>
<td>0.00</td>
<td>43.8 ± 27.9</td>
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<tr>
<td>G1006-1</td>
<td>11</td>
<td>5</td>
<td>89</td>
<td>10</td>
<td>7.945E+05</td>
<td>1.414E+07</td>
<td>0.056</td>
<td>154.3</td>
<td>0.00</td>
<td>11.5 ± 5.3</td>
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<tr>
<td>G1006-1</td>
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<td>5</td>
<td>46</td>
<td>4</td>
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<td>1.827E+07</td>
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<td>199.4</td>
<td>0.00</td>
<td>22.3 ± 10.5</td>
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<td>3</td>
<td>173</td>
<td>18</td>
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<td>0.00</td>
<td>37.9 ± 18.5</td>
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<td>15</td>
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<td>4.343E+06</td>
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<td>15.0 ± 9.0</td>
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<td>28</td>
<td>2.838E+05</td>
<td>4.143E+06</td>
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<td>45.2</td>
<td>0.00</td>
<td>14.0 ± 6.5</td>
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<td>15</td>
<td>167</td>
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<td>1.490E+06</td>
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<td>3.531E+05</td>
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<td>0.049</td>
<td>78.6</td>
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<td>10.1 ± 7.3</td>
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<tr>
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<td>5</td>
<td>101</td>
<td>15</td>
<td>5.297E+05</td>
<td>1.070E+07</td>
<td>0.050</td>
<td>116.2</td>
<td>0.00</td>
<td>10.2 ± 4.7</td>
</tr>
</tbody>
</table>

\[\chi^2 = 21.459\] with 12 degrees of freedom

\[P(\chi^2) = 4.4\%\]

**Age Dispersion** = 33.498\%

**\(N_s / N_i\)** = 0.062 ± 0.008

**Mean Ratio** = 0.080 ± 0.017

**Area of basic unit** = 6.293E-07 cm\(^2\)

Ages calculated using a zeta of 392.9 ± 7.4 for CN5 glass

\[\rho_D = 1.045E+06\text{cm}^{-2}\] ND = 1668

\[\rho_D\] interpolated between top of can; \(\rho_D = 1.045E+06\text{cm}^{-2}\) ND = 822

bottom of can; \(\rho_D = 1.075E+06\text{cm}^{-2}\) ND = 846

**POOLED AGE** = 12.7 ± 1.8 Ma

**CENTRAL AGE** = 13.7 ± 2.4 Ma

### Diagrams

**A:**

![Graph A](image1)

**B:**

![Graph B](image2)

**C:**

![Graph C](image3)

**D:**

![Graph D](image4)

Mean track length 13.39 ± 0.43 \(\mu\text{m}\) Std. Dev. 2.11 \(\mu\text{m}\) 24 tracks
APPENDIX C

Principles of Interpretation of AFTA Data in Sedimentary Basins

C.1 Introduction

Detrital apatite grains are incorporated into sedimentary rocks from three dominant sources - crystalline basement rocks, older sediments and contemporaneous volcanism. Apatites derived from the first two sources will, in general, contain fission tracks when they are deposited, with AFTA parameters characteristic of the source regions. However, apatites derived from contemporaneous volcanism, or from rapidly uplifted basement, will contain no tracks when they are deposited. For now, we will restrict discussion to this situation, and generalise at a later point to cover the case of apatites which contain tracks that have been inherited from source regions.

C.2 Basic principles of Apatite Fission Track Analysis

Fission tracks are trails of radiation damage, which are produced within apatite grains at a more or less constant rate through geological time, as a result of the spontaneous fission of $^{238}\text{U}$ impurity atoms. Therefore, the number of fission events which occur within an apatite grain during a fixed time interval depends on the magnitude of the time interval and the uranium content of the grain. Each fission event leads to the formation of a single fission track, and the proportion of tracks which can intersect a polished surface of an apatite grain depends on the length of the tracks. Therefore, the number of tracks which are etched in unit area of the surface of an apatite grain (the "spontaneous track density") depends on three factors - (i) The time over which tracks have been accumulating; (ii) The uranium content of the apatite grain; and, (iii) The distribution of track lengths in the grain. In sedimentary rocks which have not been subjected to temperatures greater than $\sim$50°C since deposition, spontaneous fission tracks have a characteristic distribution of confined track lengths, with a mean length in the range 14-15 µm and a standard deviation of $\sim$1 µm. In such samples, by measuring the spontaneous track density and the uranium content of a collection of apatite grains, a "fission track age" can be calculated which will be equal to the time over which tracks have been accumulating. The technique is calibrated against other isotopic systems using age standards which also have this type of length distribution (see Appendix B).
In samples which have been subjected to temperatures greater than ~50°C after deposition, fission tracks are shortened because of the gradual repair of the radiation damage which constitutes the unetched tracks. In effect, the tracks shrink from each end, in a process which is known as fission track "annealing". The final length of each individual track is essentially determined by the maximum temperature which that track has experienced. A time difference of an order of magnitude produces a change in fission track parameters which is equivalent to a temperature change of only ~10°C, so temperature is by far the dominant factor in determining the final fission track parameters. As temperature increases, all existing tracks shorten to a length determined by the prevailing temperature, regardless of when they were formed. After the temperature has subsequently decreased, all tracks formed prior to the thermal maximum are "frozen" at the degree of length reduction they attained at that time. Thus, the length of each track can be thought of as a maximum-reading thermometer, recording the maximum temperature to which it has been subjected.

Therefore, in samples for which the present temperature is maximum, all tracks have much the same length, resulting in a narrow, symmetric distribution. The degree of shortening will depend on the temperature, with the mean track length falling progressively from ~14 µm at 50°C, to zero at around 110°-120°C - the precise temperature depending on the timescale of heating and the composition of the apatites present in the sample (see below). Values quoted here relate to times of the order of 10^7 years (heating rates around 1 to 10°C/Ma) and average apatite composition. If the effective timescale of heating is shorter than 10^7 years, the temperature responsible for a given degree of track shortening will be higher, depending in detail on the kinetics of the annealing process (Green et al., 1986; Laslett et al., 1987; Duddy et al., 1988; Green et al., 1989b). Shortening of tracks produces an accompanying reduction in the fission track age, because of the reduced proportion of tracks which can intersect the polished surface. Therefore, the fission track age is also highly temperature dependent, falling to zero at around 120°C due to total erasure of all tracks.

Samples which have been heated to a maximum paleotemperature less than ~120°C at some time in the past and subsequently cooled will contain two populations of tracks, and will show a more complex distribution of lengths and ages. If the maximum paleotemperature was less than ~50°C then the two components will not be resolvable, but for maximum paleotemperatures between ~50° and 120°C the presence of two components can readily be identified. Tracks formed prior to the thermal maximum will all be shortened to approximately the same degree (the precise value depending on the maximum paleotemperature), while those formed during and after cooling will be longer, due to the lower prevailing temperatures. The length distribution in such
samples will be broader than in the simple case, consisting of a shorter and a longer component, and the fission track age will reflect the amount of length reduction shown by the shorter component (determined by the maximum paleotemperature).

If the maximum paleotemperature was sufficient to shorten tracks to between 9 and 11 µm, and cooling to temperatures of ~50°C or less was sufficiently rapid, tracks formed after cooling will have lengths of 14-15 µm and the resulting track length distribution will show a characteristic bimodal form. If the maximum paleotemperature was greater than ~110 to 120°C, all pre-existing tracks will be erased, and all tracks now present will have formed after the onset of cooling. The fission track age in such samples relates directly to the time of cooling.

In thermal history scenarios in which a heating episode is followed by cooling and then temperature increases again, the tracks formed during the second heating phase will undergo progressive shortening. The tracks formed prior to the initial cooling, which were shortened in the first heating episode, will not undergo further shortening until the temperature exceeds the maximum temperature reached in the earlier heating episode. (In practice, differences in timescale of heating can complicate this simple description. In detail, it is the integrated time-temperature effect of the two heating episodes which should be considered.) If the maximum and peak paleotemperatures in the two episodes are sufficiently different (>~10°C), and the later peak paleotemperature is less than the earlier maximum value, then the AFTA parameters allow determination of both episodes. As the peak paleotemperature in the later episode approaches the earlier maximum, the two generations of tracks become increasingly more difficult to resolve, and when the two paleotemperatures are the same, both components are shortened to an identical degree and all information on the earlier heating phase will be lost.

No information is preserved on the approach to maximum paleotemperature because the great majority of tracks formed up to that time have the same mean track length. Only those tracks formed in the last few per cent of the history prior to the onset of cooling are not shortened to the same degree (because temperature dominates over time in the annealing kinetics). These form a very small proportion of the total number of tracks and therefore cannot be resolved within the length distribution because of the inherent spread of several µm in the length distribution.

To summarise, AFTA allows determination of the magnitude of the maximum temperature and the time at which cooling from that maximum began. In some circumstances, determination of a subsequent peak paleotemperature and the time of cooling is also possible.
C.3 Quantitative understanding of fission track annealing in apatite

Annealing kinetics and modelling the development of AFTA parameters

Our understanding of the behaviour of fission tracks in apatite during geological thermal histories is based on study of the response of fission tracks to elevated temperatures in the laboratory (Green et al., 1986; Laslett et al., 1987; Duddy et al., 1988; Green et al., 1989b), in geological situations (Green et al., 1989a), observations of the lengths of spontaneous tracks in apatites from a wide variety of geological environments (Gleadow et al., 1986), and the relationship between track length reduction and reduction in fission track age observed in controlled laboratory experiments (Green, 1988).

These studies resulted in the capability to simulate the development of AFTA parameters resulting from geological thermal histories for an apatite of average composition (Durango apatite, ~0.43 wt% Cl). Full details of this modelling procedure have been explained in Green et al. (1989b). The following discussion presents a brief explanation of the approach.

Geological thermal histories involving temperatures varying through time are broken down into a series of isothermal steps. The progressive shortening of track length through sequential intervals is calculated using the extrapolated predictions of an empirical kinetic model fitted to laboratory annealing data. Contributions from tracks generated throughout the history (remembering that new tracks are continuously generated through time as new fissions occur) are summed to produce the final distribution of track lengths expected to result from the input history. In summing these components, care is taken to allow for various biases which affect revelation of confined tracks (Laslett et al., 1982). The final length reduction of each component of tracks is converted to a contribution of fission track age, using the relationship between track length and density reduction determined by Green (1988). These age contributions are summed to generate the final predicted fission track age.

This approach depends critically on the assumption that extrapolation of the laboratory-based kinetic model to geological timescales, over many orders of magnitude in time, is valid. This was assessed critically by Green et al. (1989b), who showed that predictions from this approach agree well with observed AFTA parameters in apatites of the appropriate composition in samples from a series of reference wells in the Otway Basin of south-east Australia (Gleadow and Duddy, 1981; Gleadow et al., 1983; Green et al., 1989a). This point is illustrated in Figure C.1. Green et al. (1989b) also quantitatively assessed the errors associated with extrapolation of the Laslett et al. (1987) model from...
laboratory to geological timescales (i.e. precision, as opposed to accuracy). Typical levels of precision are \( \sim 0.5 \, \mu m \) for mean lengths \( \ll 10 \, \mu m \), and \( \sim 0.3 \, \mu m \) for lengths \( \gg 10 \, \mu m \). These figures are equivalent to an uncertainty in estimates of maximum paleotemperature derived using this approach of \( \sim 10^\circ C \). Precision is largely independent of thermal history for any reasonable geological history. Accuracy of prediction from this model is limited principally by the effect of apatite composition on annealing kinetics, as explained in the next section.

**Compositional effects**

Natural apatites essentially have the composition \( \text{Ca}_5(\text{PO}_4)_3(\text{F,OH,Cl}) \). Most common detrital and accessory apatites are predominantly Fluor-apatites, but may contain appreciable amounts of chlorine. The amount of chlorine in the apatite lattice exerts a subtle compositional control on the degree of annealing, with apatites richer in fluorine being more easily annealed than those richer in chlorine. The result of this effect is that in a single sample, individual apatite grains may show a spread in the degree of annealing (i.e. length reduction and fission track age reduction). This effect becomes most pronounced in the temperature range 90 - 120\(^\circ C\) (assuming a heating timescale of \( \sim 10 \, \text{Ma} \)), and can be useful in identifying samples exposed to paleotemperatures in this range. At temperatures below \( \sim 80^\circ C \), the difference in annealing sensitivity is less marked, and compositional effects can largely be ignored.

Our original quantitative understanding of the kinetics of fission track annealing, as described above, relates to a single apatite (Durango apatite) with \( \sim 0.43 \, \text{wt}\% \) Cl, on which most of our original experimental studies were carried out. Recently, we have extended this quantitative understanding to apatites with Cl contents up to \( \sim 3 \, \text{wt}\% \). This new, multi-compositional kinetic model is based both on new laboratory annealing studies on a range of apatites with different F-Cl compositions (Figure C.2), and on observations of geological annealing in apatites from a series of samples from exploration wells in which the section is currently at maximum temperature since deposition. A composite model for Durango apatite composition was first created by fitting a common model to the old laboratory data (from Green et al., 1986) and the new geological data for a similar composition. This was then extended to other compositions on the basis of the multi-compositional laboratory and geological data sets. Details of the multi-compositional model are contained in a Technical Note, available from Geotrack in Melbourne.
The multi-compositional model allows prediction of AFTA parameters for any Cl content between 0 and 3 wt%, using a similar approach to that used in our original single composition modelling, as outlined above. Then, for an assumed or measured distribution of Cl contents within a sample, the composite parameters for the sample can be predicted. The range of Cl contents from 0 to 3 wt% spans the range of compositions commonly encountered, as discussed in the next section.

Predictions of the new multi-compositional model are in good agreement with the geological constraints on annealing rates provided by the Otway Basin reference wells, as shown in Figure C.3. However, note that the AFTA data from these Otway Basin wells were among those used in construction of the new model, so this should not be viewed as independent verification, but rather as a demonstration of the overall consistency of the model.

**Distributions of Cl content in common AFTA samples**

Figure C.4a shows a histogram of Cl contents, measured by electron microprobe, in apatite grains from more than 100 samples of various types. Most grains have Cl contents less than ~0.5 wt%. The majority of grains with Cl contents greater than this come from volcanic sources and basic intrusives, and contain up to ~2 wt% Cl. Figure C.4b shows the distribution of Cl contents measured in randomly selected apatite grains from 61 samples of "typical" quartzo-feldspathic sandstone. This distribution is similar to that in Figure C.4a, except for a more rapid fall-off as Cl content increases. Apatites from most common sandstones give distributions of Cl content which are very similar to that in Figure C.4b. Volcanogenic sandstones typically contain apatites with higher Cl contents, with a much flatter distribution for Cl contents up to ~1.5%, falling to zero at ~2.5 to 3 wt%, as shown in Figure C.4c. Cl contents in granitic basement samples and high-level intrusives are typically much more dominated by compositions close to end-member Fluorapatite, although many exceptions occur to this general rule.

Information about the spread of Cl contents in samples analysed in this report can be found in Appendix A.

**Alternative kinetic models**

Recently, both Carlson (1990) and Crowley et al. (1991) have published alternative kinetic models for fission track annealing in apatite. Carlson's model is based on our laboratory annealing data for Durango apatite (Green et al., 1986) and other (unpublished) data. In his abstract, Carlson claims that because his model is "based on explicit physical mechanisms, extrapolations of annealing rates to the lower temperatures and longer timescales required for the interpretation of natural fission track
length distributions can be made with greater confidence than is the case for purely empirical relationships fitted to the experimental annealing data". As explained in detail by Green et al. (1993), all aspects of Carlson's model are in fact purely empirical, and his model is inherently no "better" for the interpretation of data than any other. In fact, detailed inspection shows that Carlson's model does not fit the laboratory data set at all well. Therefore, we recommend against use of this model to interpret AFTA data.

The approach taken by Crowley et al. (1991) is very similar to that taken by Laslett et al., (1987). They have fitted models to new annealing data in twoapatites of different composition - one close to end-member Fluorapatite (B-5) and one having a relatively high Sr content (113855). The model developed by Crowley et al. (1991) from their own annealing data for the B-5 apatite gives predictions in geological conditions which are consistently higher than measured values, as shown in Figure C.5. Corrigan (1992) reported a similar observation in volcanogenic apatites in samples from a series of West Texas wells. Since the B-5 apatite is close to end-member Fluor-apatite, while the Otway Group apatites contain apatites with Cl contents from zero up to ~3 wt% (and the West Texas apatites have up to 1 wt%), the fluorapatites should have mean lengths rather less than the measured values, which should represent a mean over the range of Cl contents present. Therefore, the predictions of the Crowley et al. (1991) B-5 model appear to be consistently high.

We attribute this to the rather restricted temperature-time conditions covered by the experiments of Crowley et al. (1991), with annealing times between one and 1000 hours, in contrast to times between 20 minutes and 500 days in the experiments of Green et al. (1986). In addition, few of the measured length values in Crowley et al.'s study fall below 11 µm (in only five out of 60 runs in which lengths were measured in apatite B-5) and their model is particularly poorly defined in this region.

Crowley et al. (1991) also fitted a new model to the annealing data for Durango apatite published by Green et al. (1986). Predictions of their fit to our data are not very much different to those from the Laslett et al. (1987) model (Figure C.6). We have not pursued the differences between their model and ours in detail because the advent of our multi-compositional model has rendered the single compositional approach obsolete.

### C.4 Evidence for elevated paleotemperatures from AFTA

The basic principle involved in the interpretation of AFTA data in sedimentary basins is to determine whether the degree of annealing shown by tracks in apatite from a particular sample could have been produced if the sample has never been hotter than its present temperature at any time since deposition. To do this, the burial history derived
from the stratigraphy of the preserved sedimentary section is used to calculate a thermal history for each sample using the present geothermal gradient and surface temperature (i.e. assuming these have not changed through time). This is termed the "Default Thermal History". For each sample, the AFTA parameters predicted as a result of the Default Thermal History are then compared to the measured data. If the data show a greater degree of annealing than calculated on the basis of this history, the sample must have been hotter at some time in the past. In this case, the AFTA data are analysed to provide estimates of the magnitude of the maximum paleotemperature in that sample, and the time at which cooling commenced from the thermal maximum.

The degree of annealing is assessed in two ways - from fission track age and track length data. The stratigraphic age provides a basic reference point for the interpretation of fission track age, because reduction of the fission track age below the stratigraphic age unequivocally reveals that appreciable annealing has taken place after deposition of the host sediment. Large degrees of fission track age reduction, with the pooled or central fission track age very much less than the stratigraphic age, indicate severe annealing, which requires paleotemperatures of at least ~100°C for any reasonable geological time-scale of heating (>~1 Ma). Note that this applies even when apatites contain tracks inherited from source areas. More moderate degrees of annealing can be detected by inspection of the single grain age data, as the most sensitive (fluorine-rich) grains will begin to give fission track ages significantly less than the stratigraphic age before the central or pooled age has been reduced sufficiently to give a noticeable signal. Note that this aspect of the single grain age data can also be used for apatites which have tracks inherited from source areas. If signs of moderate annealing (from single grain age reduction) or severe annealing (from the reduction in pooled or central age) are seen in samples in which the Default Thermal History predicts little or no effect, the sample must have been subjected to elevated paleotemperatures at some time in the past. Figure C.7 shows how increasing degrees of annealing are observable in radial plots of the single grain fission track age data.

Similarly, the present temperature from which a sample is taken, and the way in which this has been approached (as inferred from the preserved sedimentary section), forms a basic point of reference for track length data. The observed mean track length is compared with the mean length predicted from the Default Thermal History. If the observed degree of track shortening in a sample is greater than that expected from the Default Thermal History (i.e. the mean length is significantly less than the predicted value), either the sample must have been subjected to higher paleotemperatures at some time after deposition, or the sample contains shorter tracks which were inherited from sediment source areas at the time the sediment was deposited. If shorter tracks were
inherited from source areas, the sample should still contain a component of longer tracks corresponding to the tracks formed after deposition. In general, the fission track age should be greater than the stratigraphic age. This can be assessed quantitatively using the computer models for the development of AFTA parameters described in an earlier section. If the presence of shorter tracks cannot be explained by their inheritance from source areas, the sample must have been hotter in the past.

C.5 Quantitative determination of the magnitude of maximum paleotemperature and the timing of cooling using AFTA

Values of maximum paleotemperature and timing of cooling in each sample are determined using a forward modelling approach based on the quantitative description of fission track annealing described in earlier sections. The Default Thermal History described above is used as the basis for this forward modelling, but with the addition of episodes of elevated paleotemperatures as required to explain the data. AFTA parameters are modelled iteratively through successive thermal history scenarios in order to identify thermal histories that can account for observed parameters. The range of values of maximum paleotemperature and timing of cooling which can account for the measured AFTA parameters (fission track age and track length distribution) are defined using a maximum likelihood-based approach. In this way, best estimates ("maximum likelihood values") can be defined together with ±95% confidence limits.

In samples in which all tracks have been totally annealed at some time in the past, only a minimum estimate of maximum paleotemperature is possible. In such cases, AFTA data provide most control on the time at which the sample cooled to temperatures at which tracks could be retained. The time at which cooling began could be earlier than this time, and therefore the timing also constitutes a minimum estimate.

Comparison of the AFTA parameters predicted by the multi-compositional model with measured values in samples which are currently at their maximum temperatures since deposition shows a good degree of consistency, suggesting the uncertainty in application of the model should be less than ±10°C. This constitutes a significant improvement over earlier approaches, since the kinetic models used are constrained in both laboratory and geological conditions. It should be appreciated that relative differences in maximum paleotemperature can be identified with greater precision than absolute paleotemperatures, and it is only the estimation of absolute paleotemperature values to which the ±10°C uncertainty relates.
C.10

Cooling history

If the data are of high quality and provided that cooling from maximum paleotemperatures began sufficiently long ago (so that the history after this time is represented by a significant proportion of the total tracks in the sample), determination of the magnitude of a subsequent peak paleotemperature and the timing of cooling from that peak may also be possible (as explained in Section C.2). A similar approach to that outlined above provides best estimates and corresponding ±95% confidence limits for this episode. Such estimates may simply represent part of a protracted cooling history, and evidence for a later discrete cooling episode can only be accepted if this scenario provides a significantly improved fit to the data. Geological evidence and consistency of estimates between a series of samples can also be used to verify evidence for a second episode.

In practise, most typical AFTA datasets are only sufficient to resolve two discrete episodes of heating and cooling. One notable exception to this is when a sample has been totally annealed in an early episode, and has then undergone two (or more) subsequent episodes with progressively lower peak paleotemperatures in each. But in general, complex cooling histories involving a series of episodes of heating and cooling will allow resolution of only two episodes, and the results will depend on which episodes dominate the data. Typically this will be the earliest and latest episodes, but if multiple cooling episodes occur within a narrow time interval the result will represent an approximation to the actual history.

C.6 Qualitative assessment of AFTA parameters

Various aspects of thermal history can often be assessed by qualitative assessment of AFTA parameters. For example, samples which have reached maximum paleotemperatures sufficient to produce total annealing, and which only contain tracks formed after the onset of cooling, can be identified from a number of lines of evidence. In a vertical sequence of samples showing increasing degrees of annealing, the transition from rapidly decreasing fission track age with increasing depth to more or less the same age over a range of depth denotes the transition from partial to total annealing of all tracks formed prior to the thermal maximum. In samples in which all tracks have been totally annealed, the single grain age data should show that none of the individual grain fission track ages are significantly older than the time of cooling, and grains in all compositional groups should give the same fission track age unless the sample has been further disturbed by a later episode. If the sample cooled rapidly to sufficiently low temperatures, little annealing will have taken place since cooling, and all grains will
give ages which are compatible with a single population around the time of cooling, as shown in Figure C.7.

Inspection of the distribution of single grain ages in partially annealed samples can often yield useful information on the time of cooling, as the most easily annealed grains (those richest in fluorine) may have been totally annealed prior to cooling, while more retentive (Cl-rich) compositions were only partially annealed (as in Figure C.7, centre). The form of the track length distribution can also provide information, from the relative proportions of tracks with different lengths. All of these aspects of the data can be used to reach a preliminary thermal history interpretation.

C.7  Allowing for tracks inherited from source areas

The effect of tracks inherited from source areas, and present at the time the apatite is deposited in the host sediment, is often posed as a potential problem for AFTA. However, this can readily be allowed for in analysing both the fission track age and length data.

In assessing fission track age data to determine the degree of annealing, the only criterion used is the comparison of fission track age with the value expected on the basis of the Default Thermal History. From this point of view, inherited tracks do not affect the conclusion: if a grain or a sample gives a fission track age which is significantly less than expected, the grain or sample has clearly undergone a higher degree of annealing than can be accounted for by the Default Thermal History, and therefore must have been hotter in the past, whether the sample contained tracks when it was deposited or not.

The presence of inherited tracks does impose a limit on our ability to detect post-depositional annealing from age data alone, as in samples which contain a fair proportion of inherited tracks, moderate degrees of annealing may reduce the fission track age from the original value, but not to a value which is significantly less than the stratigraphic age. This is particularly noticeable in the case of Tertiary samples containing apatites derived from Paleozoic basement. In such cases, although fission track age data may show no evidence of post-depositional annealing, track length data may well show such evidence quite clearly.

The influence of track lengths inherited from source areas can be allowed for by comparison of the fission track age with the value predicted by the Default Thermal History combined with inspection of the track length distribution. If the mean length is much less than the length predicted by the Default Thermal History, either the sample has been subjected to elevated paleotemperatures, sufficient to produce the observed degree of length reduction, or else the sample contains a large proportion of shorter
tracks inherited from source areas. However, in the latter case, the sample should give a pooled or central fission track age correspondingly older than the stratigraphic age, while the length distribution should contain a component of longer track lengths corresponding to the value predicted by the Default Thermal History. It is important in this regard that the length of a track depends primarily on the maximum temperature to which it has been subjected, whether in the source regions or after deposition in the sedimentary basin. Thus, any tracks retaining a provenance signature will have lengths towards the shorter end of the distribution where track lengths will not have "equilibrated" with the temperatures attained since deposition.

In general, it is only in extreme cases that inherited tracks render track length data insensitive to post-depositional annealing. For example, if practically all the tracks in a particular sample were formed prior to deposition, perhaps in a Pliocene sediment in which apatites were derived from a stable Paleozoic shield with fission track ages of ~300 Ma or more, the track length distribution will, in general, be dominated by inheritance, as only ~2% of tracks would have formed after deposition. Post-depositional heating will not be detectable as long as the maximum paleotemperature is insufficient to cause greater shortening than that which occurred in the source terrain. Even in such extreme cases, once a sample is exposed to temperatures sufficient to produce greater shortening than that inherited from source areas, the inherited tracks and those formed after deposition will all undergo the same degree of shortening, and the effects of post-depositional annealing can be recognised. In such cases, the presence of tracks inherited from source areas is actually very useful, because the number of tracks formed after deposition is so small that little or no information would be available without the inherited tracks.

C.8 Plots of fission track age and mean track length vs depth and temperature

AFTA data from well sequences are usually plotted as shown in Figure C.8. This figure shows AFTA data for two scenarios: one in which deposition has been essentially continuous from the Carboniferous to the present and all samples are presently at their maximum paleotemperature since deposition (Figure C.8a); and, one in which the section was exposed to elevated paleotemperatures prior to cooling in the Early Tertiary (Figure C.8b).

In both figures, fission track age and mean track length are plotted against depth and present temperature. Presentation of AFTA data in this way often provides insight into the thermal history interpretation, following principles outlined earlier in this Appendix.
In Figure C.8a, for samples at temperatures below ~70°C, the fission track age is either greater than or close to the stratigraphic age, and little fission track age reduction has affected these samples. Track lengths in these samples are all greater than ~13 µm. In progressively deeper samples, both the fission track age and mean track length are progressively reduced to zero at a present temperature of around 110°C, with the precise value depending on the spread of apatite compositions present in the sample. Track length distributions in the shallowest samples would be a mixture of tracks retaining information on the thermal history of source regions, while in deeper samples, all tracks would be shortened to a length determined by the prevailing temperature. This pattern of AFTA parameters is characteristic of a sequence which is currently at maximum temperatures.

The data in Figure C.8b show a very different pattern. The fission track age data show a rapid decrease in age, with values significantly less than the stratigraphic age at temperatures of ~40 to 50°C, at which such a degree of age reduction could not be produced in any geological timescale. Below this rapid fall, the fission track ages do not change much over ~1 km (30°C). This transition from rapid fall to consistent ages is diagnostic of the transition from partial to total annealing. Samples above the "break-in slope" contain two generations of tracks: those formed prior to the thermal maximum, which have been partially annealed (shortened) to a degree which depends on the maximum paleotemperature; and, those formed after cooling, which will be longer. Samples below the break-in slope contain only one generation of tracks, formed after cooling to lower temperatures at which tracks can be retained. At greater depths, where temperatures increase to ~90°C and above, the effect of present temperatures begins to reduce the fission track ages towards zero, as in the "maximum temperatures now" case.

The track length data also reflect the changes seen in the fission track age data. At shallow depths, the presence of the partially annealed tracks shortened prior to cooling causes the mean track length to decrease progressively as the fission track age decreases. However, at depths below the break in slope in the age profile, the track length increases again as the shorter component is totally annealed and so does not contribute to the measured distribution of track lengths. At greater depths, the mean track lengths decrease progressively to zero once more due to the effects of the present temperature regime.

Examples of such data have been presented, e.g. by Green (1989) and Kamp and Green (1990).
C.9 Determining paleogeothermal gradients and amount of section removed on unconformities

Estimates of maximum paleotemperatures in samples over a range of depths in a vertical sequence provides the capability of determining the paleogeothermal gradient immediately prior to the onset of cooling from those maximum paleotemperatures. The degree to which the paleogeothermal gradient can be constrained depends on a number of factors, particularly the depth range over which samples are analysed. If samples are only analysed over ~1 km, then the paleotemperature difference over that range may be only ~20 to 30°C. Since maximum paleotemperatures can often only be determined within a ~10°C range, this introduces considerable uncertainty into the final estimate of paleogeothermal gradient (see Figure C.9).

Another important factor is the difference between maximum paleotemperatures and present temperatures (“net cooling”). If this is only ~10°C, which is similar to the uncertainty in absolute paleotemperature determination, only broad limits can be established on the paleogeothermal gradient. In general, the control on the paleogeothermal gradient improves as the amount of net cooling increases. However, if the net cooling becomes so great that many samples were totally annealed prior to the onset of cooling - so that only minimum estimates of maximum paleotemperatures are possible - constraints on the paleogeothermal gradient from AFTA come only from that part of the section in which samples were not totally annealed. In this case, integration of AFTA data with VR measurements can be particularly useful in constraining the paleo-gradient.

Having constrained the paleogeothermal gradient at the time cooling from maximum paleotemperatures began, if we assume a value for surface temperature at that time, the amount of section subsequently removed by uplift and erosion can be calculated as shown in Figure C.10. The net amount of section removed is obtained by dividing the difference between the paleo-surface temperature \( T_s \) and the intercept of the paleotemperature profile at the present ground surface \( T_i \) by the estimated paleogeothermal gradient. The total amount of section removed is obtained by adding the thickness of section subsequently redeposited above the unconformity to the net amount estimated as in Figure C.10. If the analysis is performed using depths from the appropriate unconformity, then the analysis will directly yield the total amount of section removed.

Geotrack have developed a method of deriving estimates of both the paleogeothermal gradient and the net amount of section removed using estimated paleotemperatures.
derived from AFTA and VR. Perhaps more importantly, this method also provides rigorous values for upper and lower 95% confidence limits on each parameter. The method is based on maximum likelihood estimation of the paleogeothermal gradient and the surface intercept, from a table of paleotemperature and depth values. The method is able to accept ranges for paleotemperature estimates (e.g. where the maximum paleotemperature can only be constrained to between, for example, 60 and 90°C), as well as upper and lower limits (e.g. <60°C for samples which show no detectable annealing; >110°C in samples which were totally annealed). Estimates of paleotemperature from AFTA and VR may be combined or analysed separately. Some results from this method have been reported by Bray et al. (1992). Full details of the methods employed are presented in a confidential, in-house, Geotrack research report, copies of which are available on request from the Melbourne office.

Results are presented in two forms. Likelihood profiles, plotting the log-likelihood as a function of either gradient or section removed, portray the probability of a given value of gradient or section removed. The best estimate is given by the value of gradient or section removed for which the log-likelihood is maximised. Ideally, the likelihood profiles should show a quadratic form, and values of gradient or section removed at which the log-likelihood has fallen by two from the maximum value define the upper and lower 95% confidence limits on the estimates. An alternative method of portraying this information is a crossplot of gradient against section removed, in which values which fall within 95% confidence limits (in two dimensions) are contoured. Note that the confidence limits defined by this method are rather tighter than those from the likelihood profiles, as the latter only reflect variation in one parameter, whereas the contoured crossplot takes variation of both parameters into account.

It must be emphasised that this method relies on the assumption that the paleotemperature profile was linear both throughout the section analysed and through the overlying section which has been removed. While the second part of this assumption can never be confirmed independently, visual inspection of the paleotemperature estimates as a function of depth should be sufficient to verify or deny the linearity of the paleotemperature profile through the preserved section.

Results of this procedure are shown in this report if the data allow sufficiently well-defined paleotemperature estimates to justify use of the method. Where the AFTA data suggest that the section is currently at maximum temperature since deposition, or that the paleotemperature profile was non-linear, or where data are of insufficient quality to allow rigorous paleotemperature estimation, the method is not used.
References


Figure C.1a  Comparison of mean track length (solid circles) measured in samples from four Otway Basin reference wells (from Green et al., 1989a) and predicted mean track lengths (open diamonds) from the kinetic model of fission track annealing from Laslett et al. (1987). The predictions underestimate the measured values, but they refer to an apatite composition that is more easily annealed than the majority of apatites in these samples, so this is expected.

Figure C.1b  Comparison of the mean track length in apatites of the same Cl content as Durango apatite from the Otway Group samples illustrated in figure C.1a, with values predicted for apatite of the same composition by the model of Laslett et al. (1987). The agreement is clearly very good except possibly at lengths below ~10 µm.
**Figure C.2** Mean track length in apatites with four different chlorine contents, as a combined function of temperature and time, to reduce the data to a single scale. Fluorapatites are more easily annealed than chlorapatites, and the annealing kinetics show a progressive change with increasing Cl content.

**Figure C.3** Comparison of measured mean track length (solid circles) in samples from four Otway Basin reference wells (from Green et al, 1989a) and predicted mean track lengths (open diamonds) from the new multi-compositional kinetic model of fission track annealing described in Section C.3. This model takes into account the spread of Cl contents in apatites from the Otway Group samples and the influence of Cl content on annealing rate. The agreement is clearly very good over the range of the data.
Figure C.4  

a: Histogram of Cl contents (wt%) in over 1750 apatite grains from over 100 samples of various sedimentary and igneous rocks. Most samples give Cl contents below ~0.5 wt %, while those apatites giving higher Cl contents are characteristic of volcanogenic sandstones and basic igneous sources.

b: Histogram of Cl contents (wt%) in 1168 apatite grains from 61 samples which can loosely be characterised as "normal sandstone". The distribution is similar to that in the upper figure, except for a lower number of grains with Cl contents greater than ~1%.

c: Histogram of Cl contents (wt%) in 188 apatite grains from 15 samples of volcanogenic sandstone. The distribution is much flatter than the other two, with much higher proportion of Cl-rich grains.
Comparison of mean track length in samples from four Otway Basin reference wells (from Green et al. 1989a) and predicted mean track lengths from three kinetic models for fission track annealing. The Crowley et al. (1991) model relates to almost pure Fluorapatite (B-5), yet overpredicts mean lengths in the Otway Group samples which are dominated by Cl-rich apatites. The predictions of that model are therefore not reliable.

Comparison of mean track length in samples from four Otway Basin reference wells with values predicted from Laslett et al. (1987) and the model fitted to the annealing data of Green et al. (1986) by Crowley et al. (1991). The predictions of the two models are not very different.
C.21

Little or no post-depositional annealing (T<60°C)

Moderate post-depositional annealing (T~90°C)

Total post-depositional annealing (T>110°C)

Figure C.7

Radial plots of single grain age data in three samples of mid-Jurassic sandstone that have been subjected to varying degrees of post-depositional annealing prior to cooling at ~60 Ma. The mid-point of the stratigraphic age range has been taken as the reference value (corresponding to the horizontal).

The upper diagram represents a sample which has remained at paleotemperatures less than ~60°C, and has therefore undergone little or no post-depositional annealing. All single grain ages are either compatible with the stratigraphic age (within $y = \pm 2$ in the radial plot) or older than the stratigraphic age ($y_i > 2$).

The centre diagram represents a sample which has undergone a moderate degree of post-depositional annealing, having reached a maximum paleotemperature of around ~90°C prior to cooling. While some of the individual grain ages are compatible with the stratigraphic age (-2 $< y_i < +2$) and some may be significantly greater than the stratigraphic age ($y_i > 2$), a number of grains give ages which are significantly less than the stratigraphic age ($y < 2$).

The lower diagram represents a sample in which all apatite grains were totally annealed, at paleotemperatures greater than ~110°C, prior to rapid cooling at ~60 Ma. All grains give fission track ages compatible with a fission track age of ~60 Ma (i.e., all data plot within ±2 of the radial line corresponding to an age of ~60 Ma), and most are significantly younger than the stratigraphic age.
**MAXIMUM TEMPERATURES NOW**

Tertiary
Upper Cretaceous
Lower Cretaceous
Jurassic
Triassic
Permian
Carboniferous

**Figure C.8a** Typical pattern of AFTA parameters in a well in which samples throughout the entire section are currently at their maximum temperatures since deposition. Both the fission track age and mean track length undergo progressive reduction to zero at temperatures of ~100 - 110°C, the actual value depending on the range of apatite compositions present.

**HOTTER IN THE PAST**

Upper Cretaceous
Lower Cretaceous
Jurassic
Triassic
Permian
Carboniferous

**Figure C.8b** Typical pattern of AFTA parameters in a well in which samples throughout the section were exposed to elevated paleotemperatures after deposition (prior to cooling in the Early Tertiary, in this case). Both the fission track age and mean track length show more reduction at temperatures of ~40 to 50°C than would be expected at such temperatures. At greater depths (higher temperatures), the constancy of fission track age and the increase in track length are both diagnostic of exposure to elevated paleotemperatures. See Appendix C for further discussion.
Figure C.9  It is important to obtain paleotemperature constraints over as great a range of depths as possible in order to provide a reliable estimate of paleogeothermal gradient. If paleotemperatures are only available over a narrow depth range, then the paleogeothermal gradient can only be very loosely constrained.
If the paleogeothermal gradient can be constrained by AFTA and VR, as explained in the text, then for an assumed value of surface temperature, $T_s$, the amount of section removed can be estimated, as shown.

\[
\text{removed section (U)} = \frac{T_s - T_i}{(dT/dZ)_{\text{pal}}}
\]
APPENDIX D

Vitrinite Reflectance Measurements

D.1 Integration of vitrinite reflectance data with AFTA

Vitrinite reflectance is a time-temperature indicator governed by a kinetic response in a similar manner to the annealing of fission tracks in apatite as described in Appendix C. In this study, vitrinite reflectance data are interpreted on the basis of the distributed activation energy model describing the evolution of VR with temperature and time described by Burnham and Sweeney (1989), as implemented in the BasinMod™ software package of Platte River Associates. In a considerable number of wells from around the world, in which AFTA has been used to constrain the thermal history, we have found that the Burnham and Sweeney (1989) model gives good agreement between predicted and observed VR data, in a variety of settings.

As in the case of fission track annealing, it is clear from the chemical kinetic description embodied in equation 2 of Burham and Sweeney (1989) that temperature is more important than time in controlling the increase of vitrinite reflectance. If the Burham and Sweeney (1989) distributed activation energy model is expressed in the form of an Arrhenius plot (a plot of the logarithm of time versus inverse absolute temperature), then the slopes of lines defining contours of equal vitrinite reflectance in such a plot are very similar to those describing the kinetic description of annealing of fission tracks in Durango apatite developed by Laslett et al. (1987), which is used to interpret the AFTA data in this report. This feature of the two quite independent approaches to thermal history analysis means that for a particular sample, a given degree of fission track annealing in apatite of Durango composition will be associated with the same value of vitrinite reflectance regardless of the heating rate experienced by a sample. Thus paleotemperature estimates based on either AFTA or VR data sets should be equivalent, regardless of the duration of heating. As a guide, Table D.1 gives paleotemperature estimates for various values of VR for two different heating times.

One practical consequence of this relationship between AFTA and VR is, for example, that a VR value of 0.7% is associated with total annealing of all fission tracks in apatite of Durango composition, and that total annealing of all fission tracks in apatites of more Chlorine-rich composition is accomplished between VR values of 0.7 and ~0.9%.
Furthermore, because vitrinite reflectance continues to increase progressively with increasing temperature, VR data allow direct estimation of maximum paleotemperatures in the range where fission tracks in apatite are totally annealed (generally above ~110°C) and where therefore AFTA only provides minimum estimates. Maximum paleotemperature estimates based on vitrinite reflectance data from a well in which most AFTA samples were totally annealed will allow constraints on the paleogeothermal gradient that would not be possible from AFTA alone. In such cases the AFTA data should allow tight constraints to be placed on the time of cooling and also the cooling history, since AFTA parameters will be dominated by the effects of tracks formed after cooling from maximum paleotemperatures. Even in situations where AFTA samples were not totally annealed, integration of AFTA and VR can allow paleotemperature control over a greater range of depth, e.g. by combining AFTA from sand-dominated units with VR from other parts of the section, thereby providing tighter constraint on the paleogeothermal gradient.

References


Table D.1: Paleotemperature - vitrinite reflectance nomogram based on Equation 2 of Burnham and Sweeney (1989)

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