Division of Geological & Geophysical Surveys

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**APATITE FISSION TRACK DATA, ALASKA HIGHWAY CORRIDOR,
MOUNT HAYES QUADRANGLE, ALASKA**

by

Diana N. Solie, Paul O'Sullivan, Melanie Werdon, and Richard Lessard

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APATITE FISSION TRACK DATA, ALASKA HIGHWAY CORRIDOR, MOUNT HAYES QUADRANGLE, ALASKA

by

Diana N. Solie¹, Paul O'Sullivan², Melanie Werdon¹, and Richard Lessard¹

ABSTRACT

Two plutonic igneous rock samples were collected from opposite sides of the Sand Lake fault on Macomb Plateau in the Mount Hayes quadrangle, Alaska and analyzed for apatite fission-tracks. The results show a pooled fission-track age difference of over 10 Ma between the samples. Modelling suggests that timing of uplift/cooling on the northwest side began $\geq 33.3 \pm 2.4$ Ma and on the southeast side began $\geq 59.5 \pm 4.4$ Ma.

INTRODUCTION

The Alaska Division of Geological & Geophysical Surveys conducted a multi-year project studying the geology and geologic hazards along the Alaska Highway corridor between 2006 and 2010. As part of the bedrock-geologic mapping, samples were collected for geochronologic analyses using $^{40}\text{Ar}/^{39}\text{Ar}$, apatite fission-track and U/Pb dating techniques. Summaries of analytical results appear on bedrock-geologic maps, which are being published in three segments. In the western-most segment, between Delta Junction and Dot Lake, two rock samples were collected for apatite fission-track analysis. This report supplies the data for the apatite fission-track analyses. Sample coordinates are given in NAD27 (North American Datum of 1927) decimal degrees, and will be shown on the bedrock geologic map for this segment of the corridor project (Werdon and others, 2014 in press). The two samples from Segment 1 of the Alaska Highway corridor project were submitted to the Apatite to Zircon, Inc. (A2Z) laboratory, where apatite fission-track analysis was done by Paul O'Sullivan in 2008. The resulting data, excerpted from the laboratory report, are given below and in Appendices A and B. Laboratory procedures are described in Appendix C.

Sample 07MBW1007A was collected from the northwest side of the Sand Lake fault on Macomb Plateau (Werdon and others, 2014 in press). It is a megacrystic alkali feldspar biotite granodiorite with about 7% biotite. Sample 07RL485A is very coarse-grained biotite granite from the southeast side of the Sand Lake fault on Macomb Plateau. Sand Lake fault is a linear northeast-trending fault that transects the corridor, and is clearly evident as a linear feature in airborne magnetic and electromagnetic resistivity surveys (Burns and others, 2006). No evidence of geologically recent movement has been observed along the trace of the fault (Carver and others, 2008). The purpose of these samples, in conjunction with $^{40}\text{Ar}/^{39}\text{Ar}$ analyses from both sides of the Sand Lake fault, is to provide information about the time and rate of uplift on both sides of the fault.

SAMPLE LISTING

Table 1 contains a listing of the samples submitted for analysis, the number assigned to each sample in the A2Z laboratory, the amount of apatite isolated from each sample, the number of grain mounts prepared for each sample, and the quality of the apatite grains obtained for analysis.

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TABLE 1: LISTING OF THE SAMPLES SUBMITTED FOR APATITE FISSION-TRACK ANALYSIS

Sample Number	A2Z Sample Number	Latitude	Longitude	Apatite observed	Grain Mounts Prepared	Apatite Quality: 1=poor, 10=excellent
07MBW1007A	880-20	63.6313	-144.7647	1000s (excellent yield)	1	6
07RL485A	880-21	63.6266	-144.6690	1000s (excellent yield)	1	6

DATA RESULTS

The geologic history implications of the apatite fission-track data are summarized in Table 2. The apatite fission-track age data are summarized in Table 3. The apatite fission-track length data are summarized in Table 4.

TABLE 2: GEOLOGICAL HISTORY IMPLICATIONS OF FISSION-TRACK DATA

Sample Number	A2Z Sample Number	Age of Oldest Apatite Fission Track (Ma)	Timing of Initiation of Uplift/Cooling (Ma)	EasyR _o (%)
07MBW1007A	880-20	33.3±2.4 Ma	≥33.3±2.4 Ma	Not applicable
07RL485A	880-21	59.5±4.4 Ma	≥59.5±4.4 Ma	Not applicable

TABLE 3: SUMMARY OF THE APATITE FISSION-TRACK DATA

Sample Number	A2Z Sample Number	Grains (dmnl)	Dpar (μm)	Dper (μm)	N _s (tracks)	Area Analyzed (cm ²)	Σ(PQ) cm ²	1σ Σ(PQ) cm ²	ξ_{fms}	1σ ξ_{fms}	⁴³ Ca(apatite) ²⁹ Si(zircon) bkg:sig (dmnl)	²³⁸ U (dmnl)	Q (dmnl)	Pooled Fission-Track Age (Ma)
Age Standards														
Durango	DR06	492	1.52	0.29	3091	2.27E-02	7.117E-04	1.335E-06	14.5149	0.2625	2.565E-02	2.166E-03	0.9665	31.4±0.8
Interior Alaska														
07MBW1007A	880-20	32	1.29	0.28	251	6.63E-04	4.14E-05	1.29E-06	10.8562	0.2383	2.31E-02	1.27E-02	0	32.9±2.4
07RL485A	880-21	23	1.28	0.29	269	5.11E-04	2.89E-05	8.28E-07	10.6314	0.2332	3.50E-02	6.89E-02	0.017	49.2±3.5

TABLE 4: SUMMARY OF APATITE FISSION-TRACK LENGTH DATA (IN MICRONS) FOR ALL APATITE GRAINS COMBINED

Sample Number	Length Standards		Interior Alaska	
			07MBW1007A	07RL485A
A2Z Sample Number	Durango-D (31.4 Ma)	Fish Canyon Tuff (27.8 Ma)	880-20	880-21
Tracks (N=)	138	130	125	101
Mean, Error (μm)	14.59$\pm$0.08	15.01$\pm$0.09	14.16$\pm$0.16	13.60$\pm$0.18
Standard Deviation (μm)	0.98	1.02	1.83	1.84
Dpar (μm)	1.87	2.36	1.3	1.26
Dper (μm)	0.22	0.46	0.2	0.17
0-4 (μm)	-	-	-	-
4-5 (μm)	-	-	1	-
5-6 (μm)	-	-	-	-
6-7 (μm)	-	-	-	-
7-8 (μm)	-	-	-	1
8-9 (μm)	-	-	1	-
9-10 (μm)	-	-	3	4
10-11 (μm)	-	-	1	5
11-12 (μm)	1	1	9	10
12-13 (μm)	5	3	6	11
13-14 (μm)	28	16	25	22
14-15 (μm)	60	46	31	20
15-16 (μm)	32	39	40	24
16-17 (μm)	10	23	8	4
17-18 (μm)	2	2	-	-

FISSION-TRACK DATA INTERPRETATION

The following pages show how the model results appear when they are loaded into the quantitative modeling program HeFTy (©2004-2012 Apatite to Zircon, Inc. and Richard A. Ketcham). Using this program, it is possible to test alternative thermal histories for each sample while maintaining the analytical results as a background for guidance. HeFTy implements various laboratory calibrations of the behavior of fission tracks in apatite in response to heating and cooling histories. Full details concerning these calibrations and the various uses of HeFTy are publicly available (Carlson and others, 1999; Donelick and others, 1999; Ketcham and others, 1999; Ketcham and others, 2007). For each sample modeled, fission-track ages and track length distributions were calculated for a series of 20,000 randomly generated temperature histories. These randomly generated temperature histories were constrained to be geologically reasonable, where possible, by independently known information such as the intrusion age and present-day geological temperature for each sample. A temperature history was deemed acceptable (i.e., *Acceptable Fit*; solutions within the green band) when both the model fission-track age and the model fission track length distribution matched their measured counterparts with a level of confidence of 0.05 or greater. A temperature history was deemed good (i.e., *Good Fit*; solutions within the magenta band) when both the model fission-track age and model fission-track length distribution matched their counterparts with a level of confidence of 0.50 or greater.

KNOWN PARAMETERS AND ASSUMPTIONS

Client Sample Number	07MBW1007A
A2Z Sample Number	880-20
Kinetic Parameter Modeled	Dpar (μm)
Stratigraphic Age (Ma)	Jurassic (~150 Ma)
Present-day Temperature (°C)	0°C Assumed
Timing of Uplift/Cooling (Ma)	Assumed to be <65 Ma

IMPLICATIONS OF THE FISSION TRACK DATA

Age of Oldest Fission Track (Ma) (formed during cooling below elevated paleotemperatures)	33.3±2.4 Ma
Timing of Initiation of Uplift/Cooling (Ma)	≥33.3±2.4 Ma

KNOWN PARAMETERS AND ASSUMPTIONS

Client Sample Number	07RL485A
A2Z Sample Number	880-21
Kinetic Parameter Modeled	Dpar (μm)
Stratigraphic Age (Ma)	Jurassic (~150 Ma)
Present-day Temperature (°C)	0°C Assumed
Timing of Uplift/Cooling (Ma)	Assumed to be <65 Ma

IMPLICATIONS OF THE FISSION TRACK DATA

Age of Oldest Fission Track (Ma) (formed during cooling below elevated paleotemperatures)	59.5±4.4 Ma
Timing of Initiation of Uplift/Cooling (Ma)	≥59.5±4.4 Ma

BIBLIOGRAPHY

- Burns, L.E., Fugro Airborne Surveys Corp., and Stevens Exploration Management Corp., 2006, Line, grid, and vector data, and plot files for the airborne geophysical survey of the Alaska Highway corridor, east-central Alaska: Fairbanks, Alaska Division of Geological & Geophysical Surveys Geophysical Report 2006-6, 1 DVD
- Burtner, R.L., Nigrini, A., and Donelick, R.A., 1994, Thermochronology of Lower Cretaceous source rocks in the Idaho–Wyoming thrust belt: *American Association of Petroleum Geologists Bulletin*, v. 78, n. 10, p. 1,613–1,636.
- Carver, G.A., Bemis, S.P., Solie, D.N., and Obermiller, K.E., 2008, Active and potentially active faults in or near the Alaska Highway corridor, Delta Junction to Dot Lake, Alaska: Alaska Division of Geological & Geophysical Surveys Preliminary Interpretive Report 2008-3D, 32 p.
- Carlson, W.D., Donelick, R.A., and Ketcham, R.A., 1999, Variability of apatite fission track annealing kinetics I: Experimental results: *American Mineralogist*, v. 84, p. 1,213–1,223.
- Donelick, R.A., Ketcham, R.A., and Carlson, W.D., 1999, Variability of apatite fission track annealing kinetics II: Crystallographic orientation effects: *American Mineralogist*, v. 84, p. 1,224–1,234.
- Donelick, R.A. and Miller, D.S., 1991, Enhanced TINT fission track densities in low spontaneous track density apatites using ^{252}Cf -derived fission fragment tracks—A model and experimental observations: *Nuclear Tracks and Radiation Measurements*, v. 18, p. 301–307.
- Donelick, R.A., O’Sullivan, P.B., and Ketcham, R.A., 2005, Apatite fission-track analysis: *Reviews in Mineralogy and Geochemistry*, v. 58, p. 49–94.
- Hasebe, N., Barbarand, J., Jarvis, K., Carter, A., and Hurford, A.J., 2004, Apatite fission-track chronometry using laser ablation ICP-MS: *Chemical Geology*, v. 207, p. 135–145.
- Ketcham, R.A., Donelick, R.A., and Carlson, W.D., 1999, Variability of apatite fission track annealing kinetics III: Extrapolation to geological time scales: *American Mineralogist*, v. 84, p. 1,235–1,255.
- Ketcham, R.A., Carter, A.C., Donelick, R.A., Barbarand, J., and Hurford, A.J., 2007, Improved modeling of fission-track annealing in apatite: *American Mineralogist*, v. 92, p. 799–810.
- Weldon, M.B., Solie, D.N., Newberry, R.J., Freeman, L.K., Lessard, R.R., and Elliott, B.A., 2014 in press, Bedrock-geologic map, Alaska Highway corridor, Gerstle River to Dot Lake, Alaska: Alaska Division of Geological & Geophysical Surveys, Report of Investigations 2014-XX., 1 sheet, scale 1:63,360.

APPENDIX A: APATITE FISSION-TRACK AGE DATA

07MBW1007A:

880-20																	
Grain Number	Natural Tracks	Area (cm ² cm)	238U/43Ca (dmnls)	1 sigma (dmnls)	43Ca back:sig	238U back:sig	232Th back:sig	147Sm back:sig	FT Age (Ma)	1 sigma (Ma)	Etch Figures	Dpar (microns)	Dper (microns)	Uranium (ppm)	Thorium (ppm)	Samarium (ppm)	Pit Depth (microns)
1	12	2.91E-05	1.37E-01	1.12E-02	1.62E-02	7.08E-04	4.76E-04	4.94E-04	16.27	4.89	3	1.13	0.21	71.72	250.56	1106.00	11.12
4	3	1.16E-05	1.92E-02	1.86E-03	2.00E-02	4.28E-03	1.44E-02	5.17E-03	72.51	42.48	2	1.37	0.38	10.01	26.41	339.59	11.12
5	4	1.70E-05	1.50E-02	2.21E-03	2.05E-02	2.16E-03	7.04E-03	2.22E-03	84.90	44.31	1	1.34	0.31	7.81	24.37	355.92	10.47
6	7	2.18E-05	5.23E-02	6.21E-03	1.84E-02	2.28E-04	4.83E-03	3.31E-03	33.17	13.16	1	1.25	0.10	27.32	63.99	429.37	11.30
7	1	9.71E-06	1.94E-02	1.80E-03	2.09E-02	4.02E-03	8.67E-03	3.12E-03	28.77	28.90	1	1.24	0.21	10.13	31.96	408.13	10.40
8	6	2.91E-05	3.79E-02	2.95E-03	2.05E-02	3.92E-03	2.57E-03	1.26E-03	29.44	12.25	2	1.03	0.28	19.79	46.80	438.30	10.70
10	10	1.46E-05	5.94E-02	1.11E-02	2.10E-02	1.24E-02	3.84E-03	3.38E-03	62.42	22.96	1	1.23	0.21	31.05	93.48	489.85	10.47
12	10	1.94E-05	1.11E-01	8.88E-03	2.36E-02	9.63E-03	8.04E-04	8.80E-04	25.14	8.22	2	1.48	0.39	57.97	214.37	898.02	8.67
13	27	2.33E-05	1.52E-01	1.45E-02	2.22E-02	4.84E-04	1.05E-03	1.03E-03	41.31	8.92	1	1.46	0.43	79.28	229.43	1078.10	9.66
14	8	1.94E-05	3.62E-02	4.34E-03	2.40E-02	8.45E-03	1.35E-02	6.52E-03	61.43	22.97	2	1.25	0.29	18.93	44.89	428.40	9.49
16	6	1.21E-05	1.35E-01	1.32E-02	2.50E-02	1.77E-03	1.20E-02	5.08E-03	19.80	8.32	1	1.43	0.30	70.69	38.09	414.29	8.89
17	6	9.71E-06	2.58E-02	3.20E-03	4.01E-02	1.84E-01	2.23E-02	6.92E-03	128.93	55.09	2	1.44	0.41	13.46	27.93	414.79	5.76
18	3	2.91E-05	3.17E-02	2.97E-03	1.74E-02	4.33E-02	9.13E-03	5.17E-03	17.59	10.29	1	1.40	0.23	16.58	42.78	348.00	12.32
19	3	1.16E-05	2.83E-02	1.62E-03	2.18E-02	4.13E-03	7.73E-03	3.20E-03	49.13	28.52	1	1.24	0.20	14.81	39.39	436.89	10.37
20	7	3.40E-05	4.77E-02	2.76E-03	2.10E-02	2.26E-03	4.33E-03	2.42E-03	23.39	8.96	2	1.20	0.39	24.93	54.55	448.61	10.35
21	2	9.71E-06	2.34E-02	1.71E-03	1.92E-02	2.38E-02	7.81E-03	3.11E-03	47.53	33.80	1	1.31	0.26	12.25	45.57	527.14	11.81
22	12	1.21E-05	8.91E-02	9.59E-03	2.25E-02	8.65E-04	2.09E-03	1.74E-03	59.99	18.53	1	1.18	0.21	46.52	107.80	596.69	10.52
23	12	1.75E-05	3.47E-02	3.11E-03	2.42E-02	1.99E-03	7.95E-03	4.49E-03	106.63	32.32	3	1.17	0.38	18.11	47.34	384.75	10.28
24	16	3.11E-05	3.20E-02	2.34E-03	2.58E-02	1.73E-03	6.40E-03	3.96E-03	86.72	22.67	2	1.28	0.29	16.73	57.32	426.17	9.15
25	16	4.85E-05	4.78E-02	4.88E-03	2.25E-02	4.77E-02	6.16E-03	4.80E-03	37.30	10.10	2	1.43	0.34	24.99	63.92	377.22	10.51
26	6	1.55E-05	7.95E-02	7.32E-03	1.91E-02	3.60E-03	1.70E-03	1.96E-03	26.31	11.03	1	1.17	0.31	41.54	143.76	572.21	12.07
28	0	4.37E-05	2.25E-03	1.91E-04	2.35E-02	9.19E-03	2.30E+00	3.31E-01	0.00	81.86	1	1.10	0.11	1.17	0.14	4.38	9.80
29	5	2.43E-05	2.50E-02	2.01E-03	2.32E-02	0.00E+00	5.29E-03	2.54E-03	44.54	20.26	1	1.79	0.27	13.07	33.88	323.49	10.25
30	5	2.43E-05	2.51E-02	2.34E-03	2.10E-02	6.86E-04	3.36E-03	2.49E-03	44.33	20.27	1	1.28	0.30	13.13	56.76	352.03	11.74
31	22	2.18E-05	1.22E-01	9.25E-03	2.43E-02	3.29E-03	3.23E-03	3.35E-03	44.70	10.16	2	1.40	0.29	63.67	183.62	815.40	9.88
33	5	2.43E-05	2.21E-02	2.26E-03	2.43E-02	6.42E-03	6.80E-03	2.25E-03	50.40	23.15	1	1.19	0.18	11.55	25.60	354.97	9.76
34	7	1.94E-05	4.15E-01	5.48E-02	2.61E-02	3.04E-03	8.56E-04	1.40E-03	4.72	1.89	1	1.25	0.31	216.64	399.66	1124.90	9.51
35	3	1.94E-05	2.37E-02	2.26E-03	2.40E-02	5.77E-03	1.22E-02	4.64E-03	35.31	20.68	1	1.40	0.27	12.37	28.83	348.10	10.14
37	8	1.75E-05	3.61E-02	2.59E-03	2.58E-02	2.35E-03	1.19E-02	5.59E-03	68.42	24.73	1	1.34	0.20	18.87	41.59	407.23	9.53
38	8	1.94E-05	3.40E-02	2.66E-03	2.37E-02	2.32E-03	5.06E-03	2.63E-03	65.38	23.71	2	1.33	0.42	17.78	50.20	444.99	10.28
39	9	1.36E-05	1.13E-01	1.06E-02	2.25E-02	1.09E-03	1.15E-03	1.16E-03	31.68	10.99	1	1.24	0.21	59.13	178.89	814.47	10.42
40	2	9.71E-06	9.69E-03	1.71E-03	3.55E-02	1.28E-02	2.86E-02	7.01E-02	114.43	83.44	1	1.10	0.26	5.06	27.88	52.31	7.10
	Mean	Dpar	=	1.29													
	Mean	Dper	=	0.28													
	Modified	Zeta	=	10.856+/-	0.238												
	Mean	29Si	b:s	=	0.023												
	Mean	43Ca	b:s	=	0.023												
	Mean	238U	b:s	=	0.013												
	Number	of	grains=	32													
	Chi-square	=	104.6														
	Chi-square prob=		0.0000														
	Pooled	Age	(Ma)	=	32.9+/-	2.4											

07RL485A:

880-21																	
Grain Number	Natural Tracks	Area (cm ² cm)	238U/43C (dmnls)	1 sigma (dmnls)	43Ca back:sig	238U back:sig	232Th back:sig	147Sm back:sig	FT Age (Ma)	1 sigma (Ma)	Etch Figures	Dpar (microns)	Dper (microns)	Uranium (ppm)	Thorium (ppm)	Samarium (ppm)	Pit Depth (microns)
1	15	2.33E-05	5.93E-02	4.49E-03	1.91E-02	4.52E-04	2.71E-03	1.70E-03	57.44	15.51	2	1.09	0.32	31.64	112.55	825.32	11.52
2	8	2.91E-05	3.22E-02	1.85E-03	2.10E-02	6.15E-02	2.37E-02	7.85E-03	45.21	16.22	2	1.18	0.16	17.17	45.75	636.74	10.79
3	17	2.04E-05	4.31E-02	2.56E-03	2.55E-02	3.02E-02	2.20E-02	9.39E-03	102.03	25.57	1	1.37	0.22	22.99	65.36	706.50	10.23
4	8	2.38E-05	2.49E-02	1.53E-03	2.59E-02	3.42E-03	2.42E-02	5.82E-03	71.32	25.64	1	1.16	0.41	13.30	29.24	559.76	9.64
5	21	1.94E-05	1.18E-01	1.53E-02	3.42E-02	2.77E-03	1.53E-03	1.40E-03	48.39	12.32	1	1.25	0.37	63.14	308.37	1555.50	6.71
6	9	2.43E-05	3.46E-02	2.93E-03	2.62E-02	8.87E-04	3.30E-03	1.30E-03	56.70	19.54	1	1.28	0.24	18.46	59.62	694.35	8.93
7	7	1.75E-05	5.72E-02	5.36E-03	4.04E-02	3.85E-02	1.23E-02	1.03E-02	37.10	14.47	1	1.45	0.43	30.53	175.42	963.90	5.94
8	17	2.33E-05	6.45E-02	3.33E-03	2.52E-02	7.15E-03	2.40E-03	2.03E-03	59.84	14.90	2	1.46	0.33	34.42	151.19	821.93	9.90
10	11	3.88E-05	2.47E-02	1.28E-03	2.52E-02	4.33E-02	2.56E-02	1.07E-02	60.57	18.58	2	1.34	0.38	13.20	49.57	548.79	9.52
11	4	1.16E-05	4.64E-02	3.17E-03	2.14E-02	9.13E-03	6.61E-03	2.76E-03	39.18	19.79	2	1.36	0.19	24.77	73.45	808.84	10.85
12	14	2.91E-05	6.67E-02	6.70E-03	2.29E-02	1.78E-02	3.29E-03	1.87E-03	38.17	10.93	2	1.35	0.30	35.60	109.12	883.84	10.60
13	15	2.04E-05	8.26E-02	7.27E-03	2.42E-02	8.16E-02	2.83E-03	2.00E-03	47.19	12.92	1	1.11	0.26	44.05	159.31	1035.10	9.46
14	16	1.70E-05	7.07E-02	6.65E-03	2.23E-02	1.30E-01	4.92E-03	3.36E-03	70.39	18.87	1	1.40	0.21	37.73	135.73	916.21	10.36
15	4	1.21E-05	6.69E-02	7.48E-03	2.28E-02	0.00E+00	2.01E-03	1.14E-03	26.13	13.40	2	1.12	0.28	35.70	107.45	870.11	10.25
16	8	2.91E-05	2.60E-02	3.22E-03	2.00E-02	1.80E-01	2.74E-02	1.10E-02	55.94	20.99	1	1.03	0.21	13.86	50.93	581.68	11.44
18	1	9.71E-06	3.29E-02	4.02E-03	2.46E-02	3.23E-03	4.73E-03	1.98E-03	16.64	16.77	1	1.34	0.23	17.53	66.80	734.56	10.34
19	6	4.37E-06	4.76E-02	8.11E-03	2.18E-02	2.72E-01	2.26E-02	2.08E-02	151.62	67.15	2	1.32	0.22	25.38	139.24	697.67	11.36
20	8	2.91E-05	4.23E-02	8.44E-03	2.71E-01	6.14E-01	8.47E-01	3.11E-01	34.41	13.99	1	1.50	0.41	22.57	65.20	816.50	9.89
21	20	3.11E-05	4.54E-02	5.43E-03	2.30E-02	2.91E-03	4.08E-03	1.98E-03	74.97	19.08	0	0.00	0.00	24.21	82.22	777.85	10.90
22	12	2.43E-05	2.85E-02	3.56E-03	2.23E-02	8.78E-04	7.80E-03	2.92E-03	91.69	28.92	1	1.18	0.25	15.18	46.82	574.99	10.97
23	28	2.91E-05	1.41E-01	1.81E-02	2.29E-02	3.97E-02	2.75E-03	2.40E-03	36.18	8.31	1	1.39	0.41	75.13	257.24	1354.80	11.25
24	13	2.43E-05	9.57E-02	9.59E-03	2.50E-02	5.92E-04	1.58E-03	1.18E-03	29.69	8.78	3	1.22	0.34	51.05	163.06	1002.60	9.68
25	7	1.94E-05	6.77E-02	9.48E-03	1.70E-02	4.40E-02	2.75E-02	2.22E-02	28.26	11.41	0	0.00	0.00	36.09	151.52	863.64	14.26
Mean		Dpar	=	1.28													
Mean		Dper	=	0.29													
Modified		Zeta	=	10.631+/-	0.233												
Mean		29Si	b:s	=	0.035												
Mean		43Ca	b:s	=	0.035												
Mean		238U	b:s	=	0.069												
Number of		grains=		23													
Chi-square =				38.3													
Chi-square prob=				0.0170													
Pooled Age		(Ma)	=	49.2+/-	3.5												

APPENDIX B: APATITE FISSION-TRACK LENGTH DATA

07MBW1007A

880-20

Track Number	Length (microns)	Etch Figures	Dpar (microns)	Dpar (microns)	Angle to c-axis (degrees)
1	14.41	2	1.28	0.11	79.21
2	12.23	2	1.11	0.02	56.66
3	15.76	2	1.05	0.21	63.41
4	11.02	2	1.15	0.20	90.00
5	14.31	2	1.15	0.20	33.96
6	13.21	4	1.11	0.09	62.50
7	15.33	1	1.19	0.18	48.23
8	14.65	1	1.37	0.14	76.12
9	15.45	2	1.11	0.18	13.70
10	15.99	2	1.37	0.15	40.86
11	14.39	2	1.37	0.15	49.45
12	14.07	2	1.37	0.15	31.48
13	13.22	2	1.12	0.24	60.08
14	13.05	2	1.12	0.24	66.19
15	13.84	2	0.90	0.12	84.36
16	14.63	2	0.90	0.12	45.95
17	15.40	2	1.15	0.16	47.79
18	13.90	1	1.40	0.25	63.52
19	13.92	2	1.38	0.25	56.85
20	12.48	2	1.38	0.25	72.98
21	14.52	2	1.34	0.10	60.89
22	14.88	2	1.34	0.10	31.47
23	15.88	2	1.52	0.16	57.96
24	15.20	2	1.52	0.16	40.42
25	9.01	2	1.52	0.16	83.87
26	16.91	2	1.52	0.16	58.15
27	16.68	2	1.52	0.16	54.46
28	14.84	2	1.52	0.16	79.32
29	14.55	2	1.12	-0.02	61.20
30	16.14	2	1.12	-0.02	63.97
31	15.37	2	1.12	-0.02	28.40
32	13.74	2	1.19	0.21	54.47
33	11.69	2	1.15	-0.00	68.44
34	15.07	2	1.19	0.21	62.95
35	12.39	1	1.25	0.11	62.63
36	14.71	1	1.25	0.11	33.62
37	13.06	3	1.23	0.30	73.49
38	13.32	3	1.23	0.30	55.71
39	13.03	3	1.23	0.30	73.20
40	15.42	3	1.23	0.30	35.18
41	15.37	4	1.71	0.25	29.49
42	13.72	4	1.19	0.12	60.33
43	4.80	4	1.19	0.12	74.70
44	15.69	4	1.19	0.12	74.67
45	13.74	4	1.33	0.20	72.06
46	16.30	4	1.33	0.20	9.11
47	11.56	2	1.37	0.23	84.85
48	12.83	2	1.37	0.23	33.46
49	14.63	2	1.37	0.23	36.34
50	12.77	2	1.37	0.23	73.44
51	14.81	2	1.37	0.23	52.09
52	15.55	2	1.32	0.38	56.24
53	15.38	2	1.32	0.38	23.35
54	15.81	2	1.32	0.38	36.46
55	15.88	2	1.32	0.38	34.56
56	15.40	2	1.48	0.12	50.23
57	16.02	2	1.48	0.12	45.17
58	13.09	2	1.48	0.12	85.26
59	15.97	2	1.48	0.12	10.30
60	14.45	3	1.38	0.40	52.52
61	15.52	3	1.38	0.40	36.99
62	16.03	2	1.39	0.19	70.12
63	11.32	1	1.50	0.25	60.43
64	13.73	1	1.50	0.25	37.76
65	15.32	1	1.50	0.25	34.22
66	14.08	1	1.57	-0.03	52.20
67	14.57	1	1.57	-0.03	89.75
68	14.61	1	1.57	-0.03	51.01
69	14.17	2	1.06	0.18	79.34
70	11.15	3	1.34	0.15	82.63
71	15.01	3	1.34	0.15	51.72

72	15.31	1	1.76	0.39	34.08
73	15.61	3	1.14	0.21	52.65
74	13.48	3	1.14	0.21	60.39
75	14.39	3	1.14	0.21	57.30
76	15.37	3	1.14	0.21	85.97
77	15.76	3	1.14	0.21	0.37
78	14.27	3	1.14	0.21	50.74
79	15.11	2	0.87	0.51	67.61
80	13.52	3	1.00	0.18	84.62
81	15.89	3	1.00	0.18	32.14
82	14.90	3	1.18	0.21	77.31
83	13.35	3	1.18	0.21	82.05
84	15.94	3	1.18	0.21	51.56
85	15.43	3	1.18	0.21	41.33
86	14.64	2	1.27	0.16	62.77
87	15.30	2	1.27	0.16	24.74
88	13.34	2	1.27	0.16	56.70
89	13.72	2	1.53	0.20	75.13
90	14.92	2	1.10	0.15	50.64
91	14.83	3	1.26	0.25	30.63
92	14.32	2	1.34	0.33	33.23
93	13.01	2	1.34	0.33	50.34
94	14.18	4	1.53	0.21	63.07
95	15.65	4	1.53	0.21	22.29
96	15.53	4	1.53	0.21	39.46
97	15.10	4	1.45	0.28	51.38
98	14.17	4	1.45	0.28	38.23
99	14.36	4	1.45	0.28	83.29
100	13.61	4	1.45	0.28	37.63
101	14.85	4	1.45	0.28	52.05
102	11.12	3	1.39	0.21	41.28
103	11.69	3	1.39	0.21	77.48
104	14.00	3	1.39	0.21	67.72
105	13.90	3	1.28	0.25	77.05
106	15.90	3	1.19	0.34	42.99
107	15.34	3	1.19	0.34	23.49
108	15.72	3	1.19	0.34	51.81
109	16.07	3	1.19	0.34	51.77
110	13.98	3	1.28	0.11	84.33
111	15.56	3	1.28	0.11	49.41
112	13.80	4	1.25	0.14	65.34
113	11.44	4	1.25	0.14	89.45
114	8.69	4	1.25	0.14	59.00
115	15.83	4	1.25	0.14	25.65
116	9.76	4	1.25	0.14	69.61
117	16.48	4	1.25	0.14	50.57
118	15.84	2	1.30	0.39	57.28
119	12.87	2	1.46	0.09	78.66
120	10.48	2	0.93	0.04	72.18
121	9.86	2	1.44	0.21	52.53
122	11.63	2	1.44	0.21	68.80
123	14.19	2	1.44	0.21	48.77
124	15.75	2	1.44	0.21	17.83
125	13.36	2	1.07	0.05	71.39

Mean Dpar = 1.30

Mean Dper = 0.20

Mean length (um)= 14.16+/- 0.16

Std. Dev. (um)= 1.83

Skewness = -1.77

Kurtosis = 4.92

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880-21

Track Number	Length (microns)	Etch Figures	Dpar (microns)	Dpar (microns)	Angle to c-axis (degrees)
1	13.29	2	1.19	0.07	69.45
2	13.85	2	1.19	0.07	35.98
3	13.03	2	1.17	0.29	44.20
4	14.71	2	1.40	0.02	56.02
5	12.17	2	1.40	0.02	36.75
6	15.53	2	1.40	0.02	27.12
7	13.42	3	1.27	0.05	36.27
8	14.29	2	1.05	0.21	37.47
9	14.57	2	1.27	0.21	35.72
10	15.29	2	1.27	0.21	25.42
11	13.81	2	1.25	0.14	76.80
12	12.74	2	1.05	0.31	72.06
13	15.34	4	1.06	0.15	56.49
14	14.32	4	1.06	0.15	34.53
15	15.97	2	1.30	0.20	45.12
16	14.74	3	1.40	0.23	78.00
17	16.07	3	1.40	0.23	18.22
18	13.05	2	1.15	0.09	75.66
19	12.13	3	1.28	0.20	66.78
20	15.80	3	1.28	0.20	39.79
21	15.71	3	1.28	0.20	32.80
22	16.11	3	1.28	0.20	15.41
23	15.03	3	1.45	0.23	22.47
24	14.86	3	1.45	0.23	53.91
25	13.60	3	1.15	0.24	81.04
26	16.42	3	1.15	0.24	25.79
27	9.65	3	1.15	0.24	77.96
28	15.39	3	1.15	0.24	51.93
29	12.88	3	1.21	0.12	64.94
30	14.52	3	1.21	0.12	12.20
31	15.41	3	1.21	0.12	68.68
32	16.37	2	1.33	0.14	39.09
33	12.60	4	1.30	0.12	31.73
34	15.57	4	1.30	0.12	40.11
35	15.90	2	1.54	0.28	42.34
36	13.49	2	1.54	0.28	62.88
37	14.77	2	1.54	0.28	25.28
38	11.87	2	1.46	0.10	63.34
39	11.03	2	1.27	0.25	71.97
40	7.49	2	1.27	0.25	89.05
41	11.42	2	0.93	0.20	85.08
42	11.98	2	1.19	0.10	49.45
43	12.10	2	1.19	0.10	49.78
44	13.83	1	1.19	0.16	35.14
45	13.24	1	1.19	0.16	63.75
46	12.49	2	1.33	0.23	66.74
47	14.04	2	1.17	0.19	55.41
48	11.02	2	1.17	0.19	56.64
49	12.74	2	1.17	0.19	70.79
50	10.74	3	1.07	0.20	58.19
51	14.39	3	1.07	0.20	28.47
52	13.51	2	1.46	0.19	51.62
53	14.69	2	1.46	0.19	72.54
54	13.60	2	1.46	0.19	56.49
55	13.75	2	1.46	0.19	67.95
56	14.91	2	1.01	0.11	59.68
57	14.09	2	1.01	0.11	31.86
58	10.76	2	1.01	0.11	72.27
59	11.32	2	1.26	0.23	59.15
60	13.84	2	1.26	0.09	60.81
61	12.04	2	1.26	0.09	65.49
62	13.67	2	1.26	0.09	12.82
63	9.58	2	1.26	0.09	62.24
64	14.22	2	1.26	0.09	78.10
65	14.44	2	1.26	0.09	56.36
66	12.21	2	1.26	0.09	53.35
67	14.50	2	1.26	0.09	41.38
68	15.06	3	1.31	0.09	84.25
69	14.64	3	1.31	0.09	52.54
70	11.41	3	1.31	0.09	45.01
71	13.71	2	1.26	0.21	56.12
72	15.24	2	1.26	0.21	8.45
73	11.18	2	1.26	0.21	62.25
74	15.34	2	1.26	0.21	57.10

75	12.42	2	1.26	0.21	85.28
76	15.05	2	1.26	0.21	17.40
77	15.49	2	1.26	0.05	58.95
78	13.23	2	1.26	0.05	33.41
79	13.75	3	1.00	0.04	43.33
80	13.69	2	1.31	0.26	65.77
81	15.19	2	1.31	0.26	18.46
82	11.97	2	1.31	0.26	49.51
83	15.47	2	1.31	0.26	10.74
84	13.63	2	1.31	0.26	62.84
85	15.94	2	1.31	0.26	32.74
86	9.96	3	1.34	0.19	80.41
87	11.26	3	1.34	0.19	73.71
88	10.99	3	1.34	0.19	53.24
89	15.11	3	1.34	0.19	29.92
90	13.10	3	1.34	0.19	54.94
91	14.48	3	1.34	0.19	53.05
92	15.00	3	1.34	0.19	30.77
93	9.63	4	1.39	0.37	61.37
94	14.43	3	1.30	0.29	72.59
95	10.55	2	1.25	0.05	83.22
96	15.70	2	1.25	0.05	21.62
97	15.91	2	1.25	0.05	7.67
98	14.37	2	1.25	0.05	21.92
99	13.12	3	1.13	0.28	35.79
100	10.22	3	1.13	0.28	83.89
101	15.37	3	1.13	0.28	46.04

Mean Dpar = 1.26

Mean Dper = 0.17

Mean length (um)= 13.60+/- 0.18

Std. Dev. (um)= 1.84

Skewness = -0.75

Kurtosis = 0.08

APPENDIX C: FISSION-TRACK LABORATORY PROCEDURES

GENERAL

Laboratory procedures (mineral separation and grain mounting) were performed at the Apatite to Zircon, Inc (A2Z). facilities located in Viola, Idaho. Paul B. O'Sullivan at the A2Z office located in Moscow, Idaho performed analytical procedures. All laser ablation of samples for age analyses were performed under the direction of Paul B. O'Sullivan using the facilities available at the Washington State University School of Earth and Environmental Sciences GeoAnalytical Laboratory in Pullman, Washington.

A general discussion of the methods undertaken to process and analyze samples by A2Z is presented below. Please see Donelick and others (2005), for a complete and detailed discussion of these particular methods and their justification.

SAMPLE PREPARATION AND MEASUREMENT FEASIBILITY ASSESSMENT

Each sample was reduced to sand-sized particles using a jaw-crusher, sieved through a 300 μm mesh, washed in water to remove clay-sized particles, and dried at room temperature. After drying, any apatite initially present in each sample was isolated using standard gravimetric and magnetic mineral separation techniques.

For each sample subjected to apatite fission-track analysis (AFT), at least one 1cm^2 apatite grain mount, consisting of some quantity of apatite grains immersed in epoxy resin, was prepared. Each grain mount was subsequently cured at 90°C for 1 hour. Once cured, each grain mount was polished to a glass-like finish to expose internal surfaces of the apatite grains present. After polishing, the apatite grain mounts were immersed in 5.5N HNO_3 for 20.0 seconds (± 0.5 seconds) at 21°C ($\pm 1^\circ\text{C}$) to reveal all natural fission tracks that intersected the respective polished apatite grain surface.

The feasibility of measurement of the apatite fission-track parameters (i.e., grain ages and track lengths) was assessed by quickly scanning the polished and etched grain mount to determine if any dateable apatite grains were present. If more than one dateable grain was observed during this quick scan, measurement of the fission-track parameters was considered feasible.

GENERALIZED FISSION-TRACK PROCEDURES - AFT

For AFT analysis, the polished grain mounts were first immersed in 5.5N HNO_3 for 20.0 seconds (± 0.5 seconds) at 21°C ($\pm 1^\circ\text{C}$) to reveal only the natural fission tracks intersecting the grain surfaces (**Figure C.1**).

FIGURE C.1. BEFORE AND AFTER IMAGES OF APATITE GRAINS SUBJECTED TO ^{252}Cf -DERIVED FISSION-FRAGMENT IRRADIATION. UPPER IMAGES ARE AT 625X MAGNIFICATION; LOWER IMAGES ARE OF THE SAME GRAIN AT 1562X MAGNIFICATION. NOTE THE OBVIOUS INCREASE IN CONFINED TRACKS FOR LENGTH MEASUREMENT. THE LARGE PIT REPRESENTS A LASER ABLATION PIT CREATED DURING LA-ICP-MS ANALYSIS FOR AFT AGE DATING.

The mounts were then scanned to search for suitable apatite grains for age dating and those grain locations digitally recorded. For each suitable grain, representative kinetic parameters (D_{par}) were measured, and the natural fission-track densities were counted. These grain localities were then revisited using the LA-ICP-MS where spot analyses to determine the concentration of U were completed on the identical areas of each grain from which the natural fission-track densities were first counted. The grain mounts were then irradiated with approximately 10^7 tracks/cm² fission fragments from a 50 μCi (activity as of July, 1996) ^{252}Cf source in a vacuum chamber. Irradiated grain mounts were then re-immersed in 5.5N HNO_3 for 20.0 seconds (± 0.5 seconds) at 21°C ($\pm 1^\circ\text{C}$) to reveal any horizontal, confined fission tracks, and the track lengths were then measured (**Figure C.1**).

During analyses, all fission-track kinetic-parameter measurements, spontaneous track counts and confined track-length measurements were completed using unpolarized light at 2000x magnification (100x dry objective, 1.25x projection tube, 16x oculars). When possible, each AFT analysis includes either 40 single-grain ages and 200 confined track length measurements.

KINETIC CLASSIFICATION OF EACH APATITE GRAIN

It is well known that apatite fission track ages and total etched fission track lengths are strongly correlated with the solubility of their host apatite grain in samples that have experienced significant residence time at temperatures

above approximately 70°C (see Burtner and others, 1994; U.S. Patent Number 5,267,274; Australian Patent Number 658,800). The parameter used to quantify solubility is termed *Dpar* in this report. *Dpar* refers to the maximum diameter of fission track etch pits parallel to the crystallographic c-axis at their intersection with the polished and etched apatite surface (**Figure C.2**).

Fission tracks in apatite grains exhibiting the smallest *Dpar* values usually anneal more quickly than fission tracks in apatite grains having larger *Dpar* values. In an apatite grain having a *Dpar* value near 1.50 µm (a typical fluorine-rich apatite), fission tracks generally do not survive geological heating above about 100°C. On the other hand, in an apatite grain having a *Dpar* value near 3.00 µm (a typical chlorine-rich apatite), fission tracks may survive geological heating above 150°C.

For each apatite grain from which fission-track data were measured, between one and four etch pit diameters were measured and an arithmetic mean *Dpar* value calculated from these individual values.

FIGURE C.2. REFLECTED LIGHT PHOTOMICROGRAPHS TAKEN AT 1562.5X MAGNIFICATION OF TWO APATITE CRYSTALS THAT EXHIBIT VERY DIFFERENT *DPAR* VALUES (SEE TEXT). BOTH APATITE CRYSTALS WERE ETCHED IN 5.5N HNO₃ FOR 20.0 SECONDS (± 0.5 SECONDS) AT 21°C (± 1°C). (a) *DPAR*=1.83 µm (APATITE FROM DURANGO, MEXICO ([F]=3.33 WT.%, [CL]=0.43 WT.%). (b) *DPAR*=4.99 µm (APATITE FROM BAMBLE, NORWAY ([F]=0.08 WT.%, [CL]=6.37 WT.%).

FISSION-TRACK AGE MEASUREMENT FOR APATITE

Natural fission tracks form as a result of the spontaneous nuclear fission of trace amounts of ²³⁸U within an apatite grain. Using a modified version of the radioactive decay equation, the fission-track age of an apatite grain can be calculated using the ratio of the number of fission tracks intersecting the surface over a unit area in the grain to the amount of ²³⁸U present in the grain.

Spontaneous tracks were first counted on suitable grain surfaces using unpolarized light at 2000x magnification. A laser ablation inductively coupled plasma-mass spectrometer (LA-ICP-MS) was then used to determine the ²³⁸U concentrations by measuring the ratio of ²³⁸U to ⁴³Ca, from the exact regions on the individual grains from which the spontaneous tracks were initially counted (see Hasebe and others, 2004; Donelick and others, 2005). All LA-ICP-MS analyses were carried out at the GeoAnalytical Laboratory, Washington State University in Pullman, Washington, using the conditions and parameters outlined in **Table C.2**.

The fundamental assumption is made that Ca occurs in stoichiometric amounts in all apatite grains analyzed by the LA-ICP-MS. The isotope ⁴³Ca is used as the indicator of the volume of apatite ablated. Samples are ablated in a helium atmosphere to reduce condensation and elemental fractionation.

Spot analyses, with the laser centered on a fixed point, were used (see **Figure C.1**). A total of 30 scans for ^{238}U , ^{232}Th , ^{147}Sm and ^{43}Ca were performed for each spot analyzed. Of these scans, approximately 10 were performed while the laser was warming up and was blocked from contacting the grain surface. During this time, background counts were collected. Once the laser was permitted to hit the grain surface, a cylindrical pit was excavated to a depth beyond which uranium did not contribute fission tracks to the etched grain surface. Between 15 and 20 scans performed during pit excavation were required to reach this depth. The depths of a representative number of these pits were measured and the $^{238}\text{U}/^{42}\text{Ca}$ value for the pit as a whole was determined based on the weighted mean of the $^{238}\text{U}/^{43}\text{Ca}$ value for individual scans relative to the depths from which the ablated material was derived.

TABLE C.2. ICP-MS AND LASER OPERATING CONDITIONS AND DATA ACQUISITION PARAMETERS.

ICP-MS: operating conditions	
Instrument	Finnigan Element II Magnetic Sector ICP-MS
Forward power	1.25 kW
Reflected power	<5 W
Plasma gas	Ar
Coolant flow	15 l/min
Carrier flow	1.0 l/min (Ar) 0.8 l/min (He) – optimized daily
Auxiliary flow	0.9 l/min
ICP-MS: acquisition parameters	
Dwell time	18 milliseconds per peak point
Points per peak	4
Mass window	5%
Scans	30
Data acquisition time	22 sec
Data acquisition mode	electronic scanning
Isotopes measured	^{43}Ca (apatite) or ^{29}Si (zircon), ^{238}U , ^{232}Th , and ^{147}Sm
Laser: operating conditions	
Laser type	New Wave UP213 (Nd: YAG)
Wavelength	213 nm
Laser mode	Q switched
Laser output power	8 J/cm
Laser warm up time	6 sec
Shot repetition rate	5 Hz
Sampling scheme	spot (16 μm apatite, 12 μm zircon)

The fission track ages and errors were calculated using: (a) the ratio of the density of natural fission tracks present in the grain to the amount of ^{238}U present, and (b) a modified version of the radioactive decay equation that includes a LA-ICPMS zeta calibration factor (see equations 1b for age equation and 2b for error calculation in Donelick and others, 2005). This zeta calibration factor is determined for each sample analyzed during each LA-ICP-MS session by analyzing the U:Ca ratio of an apatite calibration standard with known age at the beginning and end of each session on the LA-ICP-MS. The apatite standard used is Durango apatite, 30.6 ± 0.3 Ma.

FISSION-TRACK LENGTH MEASUREMENT FOR APATITE

The total etched length of a natural fission track in apatite is a strong indicator of the integrated thermal history that the track has experienced. Fission tracks form continuously through time at a rate determined solely by the concentration of ^{238}U in the host apatite grain. As such, the distribution of fission-track lengths in an apatite

contains abundant information about the time-temperature path experienced by the apatite, particularly the cooling history since the time of peak temperature.

Following age analysis, apatite mounts were then irradiated using fission fragments from a ^{252}Cf source in a vacuum chamber in order to enhance the number of confined tracks available for measurement (e.g. Donelick and Miller, 1991; Donelick and others, 2005). Donelick and Miller (1991) demonstrated that irradiating apatite grains with ^{252}Cf -derived fission fragments could yield a 20-fold increase in the number of available fission tracks for length measurement (**Figure C.3**).

FIGURE C.3. TRANSMITTED LIGHT PHOTOMICROGRAPHS TAKEN AT 1562.5X MAGNIFICATION OF TWO APATITE CRYSTALS FROM THE SAME SAMPLE THAT EXHIBIT LOW NATURAL FISSION-TRACK DENSITIES. (a) NOT IRRADIATED WITH ^{252}Cf FISSION FRAGMENTS (ARROW INDICATES A NATURAL FISSION TRACK).

The ^{252}Cf -irradiated grain mounts were then re-etched using the same formula as before in order to reveal horizontal, confined fission tracks within the apatite grains. Only natural, horizontal, confined fission tracks in apatite with clearly visible ends were considered candidates for length measurement. The length and crystallographic orientation of each fission track was determined using a digitizing tablet interfaced with a personal computer. The precision of each track length is estimated to be $\pm 0.20\ \mu\text{m}$; the precision of each track angle to the crystallographic c-axis is estimated to be ± 2 degrees.