Fission-track Analysis of Apatite and Zircon from Grand Canyon, Arizona

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Abstract: Fission-track analyses of apatite and zircon from two traverses in Grand Canyon provide information on the Cenozoic history of this part of the Colorado Plateau. Apatite ages from samples collected at river level show a gradual increase in age from Lees Ferry (~38 Ma) downriver to Diamond Creek (~80 Ma). However, there are deviations from this general trend across major structures. This indicates that there has been tilting of the blocks during uplift of the region during the Tertiary. A second traverse is a vertical profile along the North Kaibab and Bright Angel Trails from Grand Canyon Village on the South Rim to Phantom Ranch and part way up the north side. The apatite ages from this profile range from ~130 Ma at the rim to ~60 Ma near the river. Zircon ages at river level are all about 1000 Ma indicating that the rocks in the deepest part of the canyon have never been heated above ~200°C for the last 1 Ga. The fission-track data indicate two periods of uplift and cooling in the canyon: the first in the early Tertiary related to the Laramide orogeny, and a second period beginning in the middle Tertiary.

This report combines the results of two separate studies and it is largely based on an earlier paper (Naeser and others, 1989) that was presented without analytical data. One study (Table 1, CWN and DPE) involves rocks collected at river level between Lees Ferry and Diamond Creek. The second study (Table 2, IRD, TAD, and PFG) involves rocks sampled along a traverse extending from the South Rim of the canyon at Grand Canyon Village to the bottom of the canyon at Phantom Ranch. The purpose of these studies was to determine the thermal and tectonic history of Grand Canyon through fission-track analysis. If the thermal history can be constrained, it may then be possible to better understand the timing of events that led to the formation of the Colorado Plateau and, by inference, the excavation of Grand Canyon.

Two periods of Cenozoic uplift are recognized in the geologic record in the Grand Canyon region. Compressional events of Late Cretaceous and early Tertiary age (Laramide orogeny) originating from the west led to formation of the major monoclines and plateau upwarps of the Grand Canyon region (Hunt, 1956, 1969, 1974; Lucchitta, 1979; Young, 1979, 1987). The central plateau had yet to be subjected to strong regional uplift. The central Colorado Plateau remained low compared to the country to the southwest at least until the Eocene (Young, 1987). The Colorado Plateau then was eventually uplifted and became an area of positive relief relative to the country to the south of the Colorado Plateau.

Hunt (1974) reviewed two major theories concerning the development of the Colorado River and Grand Canyon. One theory proposed that the Colorado River and Grand Canyon are as old as early Miocene (Hunt, 1956, fig. 59), whereas a Pliocene age for the time of canyon-cutting is proposed in the other theory (Blackwelder, 1934).

Fission-track Dating

Apatite fission-track ages can be used to constrain times and rates of uplift (e.g., Naeser and others, 1983; Gleadow and Fitzgerald, 1987; Dokka and others, 1986). Fission tracks disappear at elevated temperatures through a process known as track annealing. Over the periods of time that are usually required for geological processes (>10^5 years), total annealing of fission tracks in apatite will take place at temperatures between 100 and 150°C (Naeser, 1979, 1981). The temperature for total annealing depends on the cooling rate and the composition of the apatite.

Measured apatite fission-track ages will always be either equal to (for samples that cooled quickly through their closure temperature) or greater than (for unannealed or mixed-age samples) the age of the last uplift or cooling event. Thus, the youngest apatite age obtained from a series of samples from the same structural block is a maximum age for the event that brought those samples to the surface.

The fission-track annealing properties of zircon are less well known. Fission tracks in zircon are more resistant to annealing than those in apatite. Several estimates have been made for the closure temperature for zircon; Harrison and others (1979) estimated ~175°C and Hurford (1986) estimated 240 ± 50°C. For the purposes of this paper a closure temperature for zircon of 200°C is used.

Results and Discussion

Apatite Data

Apatite from 26 samples from Grand Canyon was dated by the fission-track method. The analytical data for these apatites are in Tables 1 and 2. Fission-track lengths were not measured in the apatite samples reported in Table 1. Table 3 shows the distance downriver for the apatite samples and either the formation name or rock type collected. Figure 1 shows the fission-track ages of apatite separated from rocks collected at or near the river from Lees Ferry to Diamond Creek, a river distance of 364 km. Figure 2 shows the apatite fission-track ages determined on samples collected along the Kaibab and Bright Angel Trails. The sample closest to the river from this second data set is also shown on Figure 1. The rocks sampled for each data set include Phanerozoic and middle Proterozoic sedimentary rocks, and igneous and metamorphic rocks of late Early Proterozoic age.

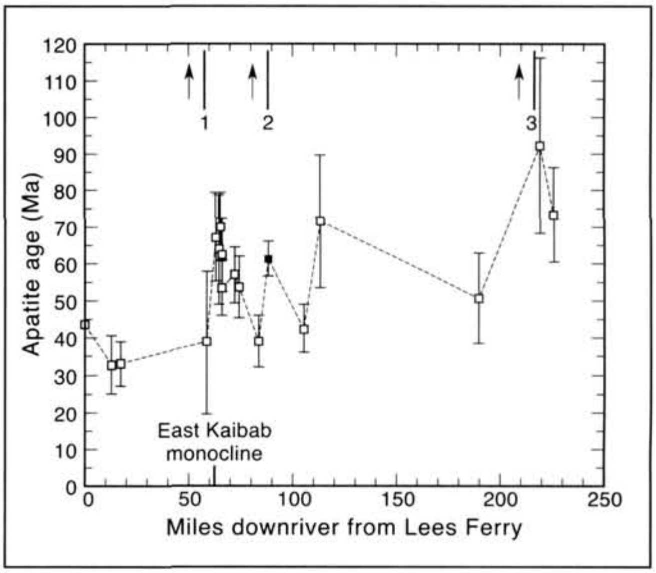

Figure 1. Apatite fission-track ages along the Colorado River in Grand Canyon between Lees Ferry and Diamond Creek. The black square is the lowest elevation closest to Phantom Ranch sample from Table 2 (GC-8). (1) Palisade Fault (strand of the Butte Fault), (2) Bright Angel Fault, and (3) Hurricane Fault. Arrows indicate sense of last movement on faults.

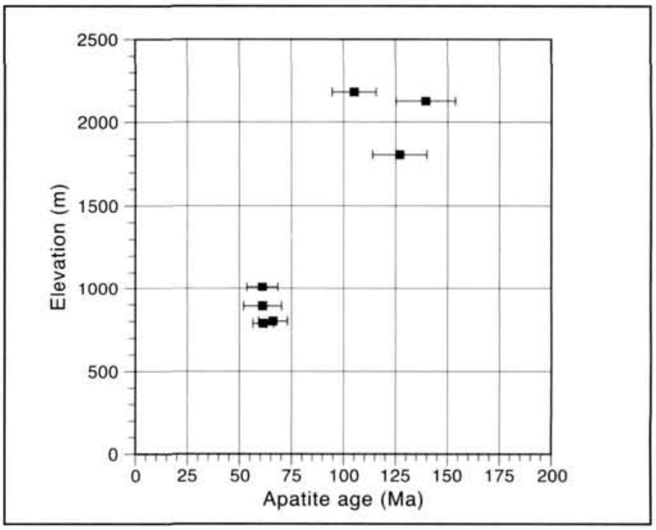

Figure 2. Apatite fission-track ages collected along a vertical traverse down the Kaibab Trail from Grand Canyon Village to the junction of Bright Angel and Phantom Creeks and part way up the Bright Angel Trail on the north side of the river. Error bars are ± 2σ.

The data collected at river level (Figure 1) show a general trend of increasing age with distance downriver. The youngest ages are found between Lees Ferry and the junction of the Colorado and Little Colorado Rivers. The ages along this reach of the river average 35 Ma. The oldest ages are found in the lower part of the canyon beyond river mile 219 (km 352). In this part of the canyon between the Hurricane Fault and Diamond Creek the apatite ages average 82 Ma. Within this overall trend of increasing age with distance downriver, deviations occur when some of the major structures are crossed. A significant age discontinuity occurs between the junction of the Little Colorado River and the Colorado River and the Palisades Fault, the eastern boundary fault of the East Kaibab monocline. All ages upstream of the junction are <45 Ma. In contrast, five samples immediately downriver from the junction have apatite ages that average 63.4 ± 11 Ma (± 2σ) A similar shift in ages occurs when the Bright Angel and Hurricane Faults are crossed, though the data are sparse for the Hurricane Fault. The discordant ages (Figure 1) obtained from the eastern side of the East Kaibab moncline, and a series of progressively younger ages obtained downstream from and west of the moncline, indicate that the East Kaibab moncline formed, uplifted, and cooled at the time of Laramide folding. Strata on the west sides of the Bright Angel and Hurricane Faults also are inferred to have been topographically elevated at this time relative to strata on the east sides of these faults. These data indicate differential uplift (tilting) within each block.

Sample No.	Miles down river	Mineral	Number of grains	ρ_s x 10^6 t/cm^2	Fossil tracks counted	ρ_i x 10^6 t/cm^2	Induced tracks counted	Neutron dose x 10^{15} t/cm^2	Tracks counted	Age Ma ± 2σ
78N3	0.0	APATITE	6	0.668	294	7.59	1669	8.35	2941	43.9 ± 5.8
78N4	12.5	APATITE	6	0.407	81	6.11	608	8.28	2941	32.9 ± 7.9
78N5	17.0	APATITE	6	0.869	157	12.87	1162	8.20	2941	33.1 ± 5.8
78N6	58.8	APATITE	1	0.430	20	2.70	125	8.13	2941	38.8 ± 19
80N1	63.0	ZIRCON	6	39.300	1786	11.70	266	5.22	1890	972 ± 135
80N1	63.0	APATITE	6	0.914	182	4.19	417	5.18	1890	67.3 ± 12
80N2	64.0	ZIRCON	6	34.700	1894	9.31	254	5.15	1890	1057 ± 150
80N3	64.5	ZIRCON	6	41.730	1897	11.48	261	5.11	1890	1032 ± 143
80N3	64.5	APATITE	6	0.689	102	3.25	241	5.08	1890	64.0 ± 15
78N8	65.4	APATITE	6	1.220	311	8.37	1065	8.05	2941	70.0 ± 9.4
78N9	65.7	APATITE	6	2.030	188	15.44	715	7.98	2941	62.5 ± 10
82N1	66.0	APATITE	7	1.010	312	5.07	786	4.52	3187	53.5 ± 7.4
78N10	67.0*	APATITE	1	1.900	35	12.60	119	7.90	2941	69.1 ± 27
78N11	69.5*	APATITE	6	0.780	236	5.95	896	7.83	2941	61.4 ± 9.3
82N4	72.0	APATITE	6	1.360	359	6.40	844	4.50	3187	57.0 ± 7.5
78N12	74.0	APATITE	6	0.920	227	7.96	976	7.75	2941	53.7 ± 8.2
78N13	83.8	APATITE	4	1.230	160	12.43	935	7.68	2941	39.2 ± 6.9
78N15	105.0	APATITE	6	0.758	207	8.08	1104	7.60	2941	42.5 ± 6.6
80N6	113.3	APATITE	6	0.485	101	2.02	210	5.01	1890	71.7 ± 18
78N19	189.6	APATITE	6	0.274	90	2.37	390	7.38	2941	50.8 ± 12
80N10	219.2	ZIRCON	6	35.280	1176	8.28	147	4.98	1890	1090 ± 200
80N10	219.2	APATITE	6	0.391	96	1.25	153	4.95	1890	92.3 ± 24
78N20	225.7	APATITE	6	0.864	188	5.12	557	7.30	2941	73.3 ± 13

Ages calculated using $\lambda_f = 7.03 \times 10^{17}$ yr^{1}

Ages determined prior to adoption of the Zeta method of calibration.

*Samples 78N10 (1400 m) and 78N11 (2120 m) north and south of the river respectively, at these at these river miles

Table 1. Fission-track ages from along the Colorado River in the Grand Canyon, Arizona, from Lees Ferry to Diamond Creek

Sample no.	Elevation meters	Length $\mu m \pm \sigma$	Number of grains	ρ_s x 10^6 t/cm^2	Fossil tracks counted	ρ_i x 10^6 t/cm^2	Induced tracks counted	Dosimeter density x 10^6 t/cm^2	Tracks counted	Age Ma ± 2σ
CG-1	1814	11.9 ± 2.6	23	1.930	682	3.02	1066	11.3	5181	126.9 ± 13.0
GC-5	1006	12.4 ± 1.7	19	0.581	324	2.01	1123	12.0	5181	60.9 ± 7.8
GC-6	896	12.0 ± 2.2	20	0.149	251	5.06	853	11.7	5181	61.0 ± 9.0
GC-7	805	--	20	1.070	533	3.39	1685	11.8	5181	66.2 ± 6.8
GC-8	792	12.6 ± 2.0	21	0.654	930	2.28	3237	12.1	5181	61.3 ± 4.8
GC-9	2192	11.5 ± 2.8	25	1.920	709	2.79	1029	11.5	5181	139 ± 14.2
GC-10	2134	11.7 ± 3.3	21	2.180	636	4.24	1238	11.6	5181	105 ± 11.0

Samples GC-6 and GC-7 were collected along the Bright Angel Trail, remaining samples collected along Kaibab Trail.

Ages calculated using a Z value of 355 for glass SRM 612

Table 2. Fission-track ages and lengths for apatite collected along Kaibab and Bright Angel trails.

Sample No.	Miles down river	Formation or rock type
78N3	0.0	CHINLE FM.
78N4	12.5	ESPLANADE FM.
78N5	17.0	ESPLANADE FM.
78N6	58.8	TAPEATS FM.
80N1	63.0	DOX FM.
80N2	64.0	DOX FM.
80N3	64.5	DOX FM.
78N8	65.4	DOX FM.
78N9	65.7	DOX FM.
82N1	66.0	DOX FM.
78N10	67.0*	TAPEATS FM.
78N11	69.5*	TAPEATS FM.
82N4	72.0	DOX FM.
78N12	74.0	DOX FM.
78N13	83.8	VISHNU SCHIST
78N15	105.0	RUBY GRANITE
80N6	113.3	ELVES CHASM GNEISS
78N19	189.6	GRANITE
80N10	219.2	GRANITE
78N20	225.7	GRANITE

*See footnote Table 1

Table 3. Distance down river from Lees Ferry of sample sites with formation name or rock type for samples dated in the river level sampling part of this study

Sample number1	Mean elevation meters	Length µm	Standard error of mean	Standard deviation	Range µm
GC-10	2192	11.66	0.33	3.27	2-18
GC-9	2134	11.47	0.28	2.82	2-16
GC-1	1814	11.86	0.24	2.59	2-16
GC-5	1006	12.40	0.29	1.77	7-16
GC-6	896	11.98	0.22	2.21	4-16
GC-8	792	12.64	0.20	1.95	7-17

1/ GC-10 and -9 from Permian Kaibab Limestone; GC-1 from Pennsylvanian-early Permian Supai Group; GC-5, -6, and -8 from Precambrian basement

Table 4. Confined fission-track lengths in apatite, Kaibab Trail, Grand Canyon, Arizona

A definite change in age with elevation is shown in the traverse that extends from the rim to the river (Figure 2). The apatite ages from the upper Paleozoic strata average 124 ± 34 Ma (± 2σ). The average age for the four apatite concentrates separated from the Precambrian basement in the vicinity of Phantom Ranch is 62.4 ± 5.2 Ma (± 2σ). A classical interpretation of this limited data set would be that detrital apatites dated from the upper Paleozoic strata had undergone partial track annealing and that apatites from the basement had been totally annealed prior to Laramide upwarping. Then, with moderate uplift of the Colorado Plateau and development of the monoclines during the Laramide (latest Cretaceous-early Paleocene) the rocks of the Grand Canyon region cooled, "freezing in" the age of the Laramide uplift. The younger ages <40 Ma indicate a second period of uplift and cooling in the Eocene.

The fission-track length data from the vertical traverse (Table 4), however, reveal a different story. The length distributions are similar to the patterns determined for apatites from the other basement and sedimentary rocks (Gleadow and others, 1986). The short mean track lengths in all of the samples (~12 µm) and the presence of short tracks (<10 µm) indicate a complex thermal history for these rocks. The ages of individual grains from the Paleozoic samples show excessive scatter (all failed the chi-square test) indicating the possibility of a non-uniform-age population. The apatites from the Paleozoic section underwent partial annealing prior to Laramide uplift and that the apatites from Phantom Ranch were totally annealed at the same time. If the apatites from the Paleozoic section had been totally annealed, the ages from the individual grains would represent a single uniform population. The presence of individual tracks in apatite from the Precambrian basement with lengths between 4 and 10 µm (Table 4) indicates that the basement remained at a temperature that allowed some track annealing to continue to take place after the initial uplift and cooling during the Laramide. The final cooling occurred during a second episode of uplift and erosion in the middle or late Tertiary. The increase in the mean track length with decreasing elevation is consistent with this interpretation of the data. Apatite fission-track ages of ~40 Ma in other parts of Grand Canyon indicate that this second event is late Eocene or younger in age.

Zircon Data

Four zircon separates from Grand Canyon were also dated (Table 1). Three were from middle Proterozoic sedimentary rocks collected between river miles 63 and 65 (km 101 and 105) and one was from a sample of a Precambrian granitic rock collected near river mile 220 (km 354). The fission-track ages of the zircons from the four Precambrian rocks are concordant, and they average 1038 ± 80 Ma (± 2σ) These ages indicate that the maximum temperature reached by rocks presently exposed at river level in Grand Canyon has not exceeded ~200°C in the last 1000 Ma.

Conclusions

Fission-track ages of ~1000 Ma obtained from zircons from Precambrian rocks now exposed at river level indicate that these rocks have been at temperatures of ~<200°C for the last 1000 Ma. Fission-track data on detrital apatite crystals separated from Pennsylvanian and Permian strata at the rim near Grand Canyon Village indicate that these rocks have never been buried to sufficiently high temperatures for the fission tracks to have been totally annealed. Therefore the maximum temperature must have been less than 100°C. Rocks presently exposed at river level between Lees Ferry and the Hurricane Fault were all in the zone of total track annealing, for apatite, prior to the onset of Laramide tectonism at the end of the Cretaceous Period. This suggests temperatures >100°C for these rocks prior to the initiation of Laramide uplift, following which they underwent an initial cooling. Because apatite ages from near Phantom Ranch are mixed (average = 62.4 ± 5.2 Ma), initiation of the Laramide uplift and folding occurred shortly before 62.4 Ma. Moderate Laramide uplift only served to cool these rocks over a period during which some annealing still was taking place. By contrast, abruptly different cooling ages across the East Kaibab monocline and the Bright Angel and Hurricane Faults, suggest the moncline and the west sides of the faults were elevated during Laramide compression, allowing these rocks to cool.

This second episode of uplift occurred after middle Eocene time, and brought the rocks up to a temperature zone during which no significant annealing took place. The minimum cooling ages obtained in Marble Canyon and eastern Grand Canyon, in the range of 35 to 40 Ma, appear to generally correspond with the Eocene time of regional uplift of the plateau inferred for the time of cutting of the Mogollon Rim and Grand Canyon. Rocks at river level west of the Hurricane Fault were not totally annealed prior to the episode of Laramide uplift and cooling, suggesting a relatively attenuated section of strata near the present western margin of the Colorado Plateau.

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