# The long-term burial and exhumation history of basement blocks in the footwall of the Wasatch fault, Utah

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# ABSTRACT

Thermochronologic studies of the Santaquin and Farmington Canyon crystalline basement complexes, exposed in the footwall of the Wasatch fault in Utah, provide rare opportunities to investigate the long-term tectonic, burial, and exhumation history of this region. Both complexes underwent amphibolite-facies meta-morphism at ~1700 Ma, followed by a complex pressure-temperature-time history. By 740–770 Ma, exhumation had brought both complexes to the surface from a depth of ~9–10 km (3–3.5 kbar), followed by reburial by passive margin, Oquirrh Basin, and foreland basin sedimentation from Neoproterozoic through early Cretaceous time.

The final structural pathway to present-day surface exposure of both complexes began in early Cretaceous time, with crustal contraction along the Sevier belt and resultant structural stacking. Structural breaching of the thrust culminations and final cooling of the crystalline complexes occurred as a result of Tertiary through Holocene extension and accompanying normal faulting.

Inferred exhumation rates for the last 10–15 my are on the order of 0.3–0.6 mm/yr, although recent slip rates across the Wasatch fault appear to be several times higher. This suggests that: (1) periods of enhanced slip on the Wasatch fault from Miocene to present time may have been punctuated by periods of quiescence; and (2) the fault now may be experiencing an episode of rapid slip. Alternatively, strain may have been partitioned into multiple fault strands at a boundary between the Provo and Nephi segments.

KEY WORDS: Wasatch fault, thermochronology, Farmington Canyon complex, Santaquin complex.

# INTRODUCTION

Exposures of Precambrian crystalline rocks are sparse in the Basin and Range province and Colorado Plateau, limiting our ability to assess the region's long-term tectonic history. Fortunately, at a few localities on or near the Basin and Range– Colorado Plateau transition, blocks of basement have been tectonically exhumed, including rocks of the Farmington Canyon complex, Santaquin complex, Mineral Mountains, and Beaver Dam Mountains (Fig. 1). Careful analyses of these exposures of basement rock provide a rare opportunity to better understand the geologic history of the region, extending into Precambrian time.

Numerous studies have examined the thermal and exhumation history of the footwall of the Wasatch fault over discrete time intervals, particularly through Miocene to recent time. For example, exhumation during Basin and Range extension (<17 Ma) has been considered in detail (e.g., Naeser et al., 1983; Parry and Bruhn, 1987; Kowallis et al., 1990; Ehlers et al., 2003; and Armstrong et al., 2003, 2004). Recently, attention has been paid to



**Figure 1, facing page.** Index map showing location of Farmington Canyon and Santaquin complexes in Utah, with insets of geologic maps (after Ludington et al., 2005) of these localities and ticks representing UTM coordinates (zone 12N) in meters. Other basement exposures include: *BDM*, Beaver Dam Mountains; *LW*, Little Willow Formation; *ARG*, Albion/Raft River/Grouse Creek Ranges; *ORC*, Owiyukuts/Red Creek Quartzite; and *UU*, Uncompahgre uplift. White star in inset map for Farmington Canyon complex shows location of Mineral Mountains.

orogenic collapse after the Sevier orogeny but prior to Basin and Range extension (see Constenius, 1996; and Constenius et al., 2003 for review). In contrast to these previous studies, the purpose of this paper is to examine the thermal history of the Santaquin and Farmington Canyon complexes in order to summarize the tectonic history of the crust of northern and central Utah over the last 1700 my, essentially since the time of crust formation.

# **GEOLOGIC SETTING**

Of the basement rocks exposed in Utah (Fig. 1), only those of the Raft River–Grouse Creek Ranges are most clearly Archean (Nelson et al., 2002; Premo et al., 2008). For example, basement rocks in the Mineral Mountains are Proterozoic (~1720 Ma; e.g., Aleinikoff et al., 1986), and rocks in the Beaver Dam Mountains have similar ages (Nelson et al., 2007). Until recently, the Farmington Canyon complex (FCC) was considered Archean on the basis of apparent inheritance of zircon in U–Pb isotope ages, Nd-isotope model ages, and <sup>87</sup>Sr/<sup>86</sup>Sr data (e.g., Hedge et al., 1983). However, recent re-examination of geochronology of the FCC strongly suggests that it was first metamorphosed at ~1700–1800 Ma (Nelson et al., 2002 and 2007).

The Santaquin complex (SC) is a small, ~4-km<sup>2</sup> exposure of igneous and metamorphic rocks (Fig. 1)(Nelson et al., 2002). On the west, it is bounded by a major strand of the Wasatch fault, which in turn defines the eastern boundary of the Basin and Range province. On the east, the SC is overlain by the Neoproterozoic Big Cottonwood Formation, with their contact defining a nonconformity roughly equivalent to the Great Unconformity of the Grand Canyon. The SC and overlying strata are structurally the lowest units of a major Sevier thrust sheet. The major foliation of the SC, and contacts between it and the overlying Big Cottonwood Formation, are commonly but not universally sub-parallel to bedding. Even where there is clear discordance, usually it is not pronounced. Assuming no post-metamorphic rotation of the SC until after the deposition of overlying strata, the net principal stresses may have been nearly vertical, producing the foliation over time.

The FCC (Fig. 1) exposes a much larger area of basement rocks (>300 km<sup>2</sup>) in two main bodies: (1) Antelope Island in the Great Salt Lake (55 km<sup>2</sup>), west of the Wasatch fault; and (2) the northern Wasatch Mountains, in the immediate footwall of the Wasatch fault (260 km<sup>2</sup>). Precambrian basement on Antelope Island is dominated by gneisses with subordinate metamorphosed ultramafic rock, granite, and pegmatite (Yonkee et al., 2000). FCC rocks of the Wasatch Mountains include amphibolite, schist, gneiss, migmatite, and pegmatite, and they are present in the footwall of the Wasatch fault from Bountiful to Ogden, Utah (Bryant, 1984). Excellent reviews of the geology of the FCC were provided by Bryant (1988) and Yonkee et al. (2000).

Like the SC, the FCC is separated from much younger sedimentary rocks by major nonconformities. On Antelope Island, the FCC is overlain by the Neoproterozoic Mineral Fork and Kelly Canyon Formations, as well as the Cambrian Tintic Quartzite (a silica-cemented sandstone). In the immediate footwall of the Wasatch fault, the FCC is overlain by the Tintic Quartzite to the north. However, over a large area, the FCC is directly overlain by the Paleocene– Eocene Wasatch Formation.

# METHODS

One hornblende sample (KNC7396-1) from the SC was incrementally heated at the University of Alaska Fairbanks by laser, with gases analyzed using a VG3600 noble-gas mass spectrometer for <sup>40</sup>Ar/<sup>39</sup>Ar analysis. A biotite sample from the same rock was incrementally heated by laser at New Mexico Tech, with extracted gases analyzed using a MAP215-50 noble-gas mass spectrometer for <sup>40</sup>Ar/<sup>39</sup>Ar analysis. Results are reported in Table 1. Fission-track ages, including track-length distributions, were determined at Brigham Young University and New Mexico Tech. Results are reported in Table 2. All other radiometric ages discussed in this paper were assembled from the literature.

#### Table 1A. Analytical data for sample KNC7396-1 hornblende.

Laser	Cumulative	40Ar/ <sup>39</sup> Ar	+/-	37Ar/ <sup>39</sup> Ar	+/-	36Ar/ <sup>39</sup> Ar	+/-	% Atm.
(mW)	39Ar	measured		measured		measured		40Ar
150	0.0004	1.10	0.12	0.0276	0.0282	-0.00335	0.00549	-92.9
300	0.0009	47.36	0.54	1.2505	0.0336	0.08798	0.00628	54.7
450	0.0015	160.61	3.35	2.6800	0.0685	0.23121	0.00746	42.4
600	0.0025	267.18	1.83	2.9999	0.0358	0.21850	0.00488	24.1
750	0.0039	174.85	1.71	3.7724	0.0532	0.12739	0.00420	21.4
900	0.0060	140.12	1.71	2.3786	0.0371	0.06975	0.00177	14.6
1050	0.0081	167.79	1.57	2.3061	0.0287	0.07022	0.00136	12.3
1250	0.0115	145.77	36.98	2.7007	0.0237	0.09055	0.00102	18.2
1350	0.0149	131.51	1.10	2.1994	0.0187	0.04306	0.00075	9.6
1500	0.0228	13.03	13.38	2.1201	0.0102	0.01229	0.00034	26.7
2000	0.1202	146.97	1.07	3.6931	0.0047	0.00218	0.00005	0.2
2500	0.3997	156.51	0.46	4.3117	0.0064	0.00163	0.00003	0.1
8500	1.0000	157.83	1.02	4.4849	0.0290	0.00133	0.00001	0.0
Integrated		155.13	0.65	4.3110	0.0172	0.00289	0.00002	0.3
Laser	Ca/K	+/-	Cl/K	+/-	$40 {\rm Ar}^{*/^{39}} {\rm Ar}_{\rm K}$	+/-	Age	+/-
(mW)							(Ma)	(Ma)
150	0.051	0.052	0.0009	0.0024	2.06	1.63	-36.5	27.5
300	2.296	0.062	0.0290	0.0023	21.44	1.86	-3250.6	26.5
450	4.926	0.126	0.0645	0.0024	92.62	2.58	3176.9	23.6
600	5.515	0.066	0.1107	0.0021	203.21	1.96	3138.9	11.5
750	6.939	0.098	0.0861	0.0019	137.80	1.80	2092.8	13.4
900	4.371	0.068	0.0554	0.0010	119.84	1.54	1387.2	12.3
1050	4.238	0.053	0.0552	0.0010	147.40	1.43	1598.3	10.2
1250	4.964	0.044	0.0555	0.0009	119.39	37.05	1383.6	298.0
1350	4.041	0.034	0.0258	0.0005	119.10	1.02	1381.2	8.2
1500	3.895	0.019	0.0259	0.0004	9.55	13.39	158.2	211.2
2000	6.793	0.009	0.0593	0.0001	146.93	1.07	1594.8	7.7

0.0001

0.0003

0.0002

156.76

158.20

155.00

Integrated Notes:

2500

8500

Age of standard was 523.1 Ma. Weighted average J from standars =9.573e-03±3.952e-5.

0.012

0.053

0.032

0.0688

0.0715

0.0689

Total uncertainty for the 8500 mW heating step is ±8.3 Ma.

7.934

8.253

7.932

Simulation modeling was employed: (1) as a metric to determine concordance between individual ages; and (2) to estimate mean cooling rates and associated uncertainties from closure temperatures and ages. The random-number generation feature of EXCEL was used to create synthetic data sets of 1000 normally distributed individual ages and closure temperatures. These data were then employed to calculate 1000 individual cooling rates, from which a mean value and one standard deviation of uncertainty could be determined.

This study also relies on chemical, electronmicroprobe, and isotopic studies for the SC and FCC, as reported by Barnett et al. (1993), Nelson et al. (2002; GSA Data Repository item 2002097), and Armstrong et al. (2004; GSA Data Repository item 2004064). Stratigraphic thicknesses reported by Hintze (1993) also were employed to estimate reheating by burial.

0.46

1.02

0.65

1664.7

1678.9

1637.3

3.2

7.0

6.4

# RESULTS

#### **Mineral Ages**

<sup>40</sup>Ar/<sup>39</sup>Ar ages of amphibole and biotite, U/Pb ages (zircon and monazite), as well as fission track ages of apatite and zircon record the times at which rocks of the SC cooled through a range of closure

Tal	ble	1 <b>B</b> .	Anal	vtical	data i	for samp	le KNC	7396-1	biotite.
				-					

ID	Power (Watts)	40Ar/39Ar	<sup>37</sup> Ar/ <sup>39</sup> Ar	<sup>36</sup> Ar/ <sup>39</sup> Ar (x 10 <sup>-3</sup> )	<sup>39</sup> Ar <sub>K</sub> (x 10 <sup>-15</sup> mol)	K/Ca	$^{40}{ m Ar}^{*}$ (%)	<sup>39</sup> Ar (%)	Age (Ma)	±1s (Ma)
				(x 10 )	(x 10 1101)					
KNC7396-1,A8:12	8, Biotite,0.80mg,	J=0.016485796±	0.09%, D=1.00	78±0.0014, NM	-128, Lab#=51520-	-01				
A	1	21.92	0.1878	3.977	7.07	2.7	94.7	2.2	531.3	1.3
В	2	47.03	0.0621	1.370	10.0	8.2	99.2	5.4	1029.7	1.9
С	2	74.68	0.0192	0.6894	14.5	26.5	99.7	10.0	1446.5	2.0
D	3	76.32	0.0137	0.4526	33.2	37.3	99.8	20.5	1469.1	2.0
E	3	75.39	0.0102	0.2470	29.4	49.9	99.9	29.8	1457.6	2.2
F	4	73.47	0.0120	0.2631	26.7	42.4	99.9	38.2	1431.9	2.2
G	4	72.21	0.0187	0.2759	21.3	27.4	99.9	45.0	1414.8	2.3
Н	5	73.77	0.0244	0.2748	17.9	20.9	99.9	50.7	1436.0	2.0
Ι	5	76.48	0.0322	0.2955	16.3	15.8	99.9	55.8	1471.9	1.8
J	6	78.38	0.0403	0.3353	16.9	12.7	99.9	61.2	1496.7	2.0
K	6	79.94	0.0444	0.2134	17.3	11.5	99.9	66.6	1517.3	1.8
L	7	79.41	0.0508	0.2199	22.2	10.1	99.9	73.7	1510.4	2.5
М	8	77.98	0.0644	0.2348	17.9	7.9	99.9	79.3	1491.9	2.3
Ν	10	71.07	0.0899	0.2081	19.9	5.7	99.9	85.6	1399.7	2.8
0	25	76.23	0.1031	0.1624	45.4	4.9	100.0	100.0	1469.2	2.0
Integrated age ± 1s			n=15		316.1	10.8			1453.0	1.8
Plateau ± 1s		no plateau								

Notes:

Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interfering reactions.

Errors quoted for individual analyses include analytical error only, without interfering reaction or J uncertainties.

Integrated age calculated by summing isotopic measurements of all steps.

Integrated age error calculated by quadratically combining errors of isotopic measurements of all steps.

Isotopic abundances after Steiger and Jäger (1977).

Total 40K decay constants after Min et al. (2000).

Ages calculated relative to FC-2 Fish Canyon Tuff sanidine interlaboratory standard at 28.201 Ma

Decay Constant (LambdaK (total)) = 5.463e-10/a

Correction factors:

 $\begin{array}{l} ({}^{_{39}}Ar/{}^{_{37}}Ar)_{_{Ca}}=0.0007\pm5e\text{--}05\\ ({}^{_{56}}Ar/{}^{_{37}}Ar)_{_{Ca}}=0.00027\pm1e\text{--}05 \end{array}$ 

temperatures. That information permitted us to develop a thermal history for the SC and FCC when combined with existing data and field relations.

Because the argon data will be discussed in comparison with U/Pb zircon data, it is necessary to consider intercalibrations of the methods. Kuiper et al. (2008) suggested that <sup>40</sup>Ar/<sup>39</sup>Ar ages determined relative to Fish Canyon Tuff (FC) sanidine should use an age for the sanidine of 28.201 Ma and the <sup>40</sup>K totaldecay constant from Min et al. (2000) of 5.463 x 10<sup>-10</sup> yr<sup>-1</sup>. Hornblende ages from Nelson et al. (2002) were determined relative to FC, with an assigned age of 27.84 Ma, using the decay constant reported by Steiger and Jaeger (1977). Recalculation of the 1623and 1657-Ma reported ages yields ages of 1645 and 1679 Ma, respectively. We report the results of a third hornblende (KNC7396-1 hornblende; Fig. 2) that yield an age of 1679 ±7 Ma when recalculated for the decay constant from Min et al. (2000) and using an age for MMhb-1 (523.1 Ma) that is compatible with a Fish Canyon sanidine age of 28.201 Ma. This age is based on the last step, which released 60 percent of the gas.

Intersample discordances of the SC for hornblende probably are due to variable closure temperatures arising from low cooling rates and crystallographic differences among amphiboles. These results are consistent with cooling through about  $500^{\circ} \pm 50^{\circ}$ C between 1680 to 1645 Ma. For purposes of calculating cooling rates, we used a weighted mean age of 1675  $\pm$  18 Ma.

Biotite KNC7396-1 from a schist within the SC yields a disturbed spectrum (Fig. 2). The complexity probably results from combined effects of alteration and <sup>39</sup>Ar-recoil redistribution (cf. Lo and Onstott, 1989). This sample has a total-gas age of  $1453 \pm 1.8$  Ma. However, visual inspection of this age spectrum clearly indicates that the true uncertainty of this biotite is significantly greater than the 1.8 Ma cited, as individual ages vary between about 1400 and 1520 Ma.

To better estimate uncertainty in the age of this sample, we have neglected the first two steps, which are significantly younger and probably reflect alteration and <sup>39</sup>Ar-recoil loss. This produces a weighted mean age of 1468 ± 11 Ma. For purposes of calculat-

 $<sup>({}^{38}</sup>Ar/{}^{39}Ar)_{K} = 0.00027$  $({}^{38}Ar/{}^{39}Ar)_{K} = 0.0125$ 

 $<sup>({}^{40}\</sup>text{Ar}/{}^{39}\text{Ar})_{\text{K}} = 0.02495 \pm 0.00025$ 

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Grain #	Spontaneous	Spontaneous	Induced	Induced	Age
	Track Counts	Track Density	Track Counts	Track Density	(Ma)
		(10 <sup>6</sup> tr/cm <sup>2</sup> )		(10 <sup>6</sup> tr/cm <sup>2</sup> )	
100	30	1	55	1.83	27
101	17	0.85	10	0.5	84
102	5	0.21	9	0.38	28
103	19	0.32	30	0.5	31
104	6	0.25	5	0.21	59
105	12	0.33	9	0.25	66
105a	. 11	0.44	8	0.32	68
108	60	1.2	86	1.72	35
109	31	1.03	23	0.77	67
111	13	0.27	17	0.35	38
112	7	0.12	34	0.57	10
114	3	0.05	32	0.53	5
115	2	0.03	14	0.23	7
116	7	0.14	16	0.32	22
117	10	0.27	13	0.36	38
118	39	0.39	37	0.37	52
119	29	0.29	31	0.31	46
120	45	0.45	44	0.44	51
121	46	0.46	46	0.46	49
122	62	0.62	64	0.64	48
Weighted	454	0.41	583	0.52	39
Average					

Table 2A. Apatite fission track data for sample DM-1a.

Reactor run #10-18-00-7, zeta = 1.20 x 10<sup>4</sup>, mica detector track density = 8.263 tr/cm<sup>2</sup> for NBS-963

ing a cooling rate (see below), the small difference in the two ages is relatively unimportant. The difference in the uncertainty is large, however, and the 11-Ma figure probably is a better approximation of true uncertainty. In either event, an age of 1450 to 1470 Ma approximates the time of passage through ~300°  $\pm$  50° C and is consistent with many biotite ages from the southwestern U.S.A. (e.g., Shaw et al., 2005).

Fission-track ages have been determined for three apatite samples from the SC (60 Ma, mafic syenite; 38.5 Ma, schist; and 47.4 Ma, gneiss), whereas a single zircon from gneiss yielded an age of 443.5 Ma (Fig. 3; Table 2). Apatite ages are somewhat discordant, presumably due to differences in annealing properties between apatites of different composition, and they record cooling through temperatures on the order of 80°–110° C (Wagner and Van Den Haute, 1992). As discussed below, two samples were analyzed further for track-length distributions.

#### **Peak Metamorphic Conditions**

Barnett et al. (1993), based on mineral thermometry, reported peak metamorphic conditions of about 680° C for the FCC just east of the Wasatch fault, and between 700°–780° C at Antelope Island. We performed reconnaissance thermobarometric studies on the SC. Garnet-biotite thermometry (Holdaway et al., 1997) on crystal rims in contact or nearly in contact, coupled with garnet-biotite-plagioclase-quartz barometry (Hoisch, 1990) on garnet schist indicate that metamorphic conditions of 3 kbar and at least 600° C were attained in the SC. The temperature calculated from a randomly selected pair of garnet and biotite cores is

Grain #	Spontaneous	Spontaneous	Induced	Induced	Age
	Track Counts	Track Density	Track Counts	Track Density	(Ma)
		(10 <sup>6</sup> tr/cm <sup>2</sup> )		(10 <sup>6</sup> tr/cm <sup>2</sup> )	
1	9	0.28	4	0.13	111
2	15	0.94	8	0.5	93
5	5	0.31	7	0.44	35
6	2	0.1	4	0.2	25
6a	. 2	0.1	3	0.15	33
7	8	0.32	9	0.36	44
13	11	0.22	7	0.14	77
19	15	0.43	10	0.29	74
20	24	0.89	20	0.74	59
21	13	0.54	11	0.46	58
27	30	0.94	25	0.78	59
29	14	0.56	17	0.68	41
30	18	1	12	0.67	74
31	36	1	30	0.83	59
36	9	0.56	7	0.44	63
48	18	0.6	10	0.33	89
51	5	0.42	4	0.33	62
52	3	0.17	4	0.22	37
59	4	0.25	3	0.19	66
60	22	0.92	21	0.88	52
Weighted	454	0.53	583	0.44	60
Average	2				

Table 2B. Apatite fission track data for sample 99HS-127b.

Reactor run #10-18-00-2, zeta =  $1.20 \times 10^4$ , mica detector track density =  $8.263 \text{ tr/cm}^2$  for NBS-963

closer to 700° C, however, suggesting that some retrograde re-equilibration may have occurred. Plagioclasehornblende thermometry (Holland and Blundy, 1994) and barometry (Schmidt, 1992) on amphibolite yield, respectively, a temperature of  $672^\circ \pm 15^\circ$  C and  $3.6 \pm$ 0.3 kbar. Temperature estimates from hornblende in amphibolite alone are considerably lower, averaging about 540° ± 8° C, although pressure estimates fall within a similar range of 3.6–4.2 kbar (Zenk and Schulz, 2004).

# THERMAL HISTORY OF WASATCH FRONT

#### Introduction

Mineral ages, combined with estimated closure temperatures and mineral thermometry, provide

estimates of time and temperature, with associated uncertainties, of discrete points along thermal-history curves. Some mineral-age information, especially fission-track-length distributions in apatite, may be used to help interpret the low-temperature (<150° C) part of the time-temperature-history curve. Finally, the burial and removal of known, or estimated, overburden due to sedimentation and exhumation can be combined with reasonable estimates of geothermal gradients to provide other limits on the thermal history.

In the present section, we combine these data types to produce an integrated view of the thermal history of the SC. We then compare this record with a similar history for the FCC to examine local and regional differences along the strike of the Wasatch fault.

no. of grains	rs x10 <sup>5</sup> t/cm <sup>2</sup>	ri x 10 <sup>6</sup> t/cm <sup>2</sup>	rd x 10 <sup>5</sup> t/cm <sup>2</sup>	central age (Ma±1 s.e.)	$P(c)^2$
20	3.61	4.2	1.1586	47.4±3.5	55
	-312	-1813	-4600	apatite	
15	3.69	1.03	2.8647	443.5±29.2	85
	-2420	-339	-4600	zircon	

Table 2C. Apatite fission track data for paragneiss sample KNC7396-1.

rs=spontaneous track density

ri=induced track density (reported induced track density is twice the measured density)

rd= track density in muscovite detector covering CN-6 (1.05 ppm) or CN-5 (10 ppm); reported value determined from interpol figures in parentheses are: no. of tracks counted for ages and fluence calibration, or no. of tracks measured for lengths s.e.=standard error

 $P(c)^2 = chi$ -squared probability

 $l_f = 1.551 \times 10^{10} yr^{-1}, g=0.5$ 

zeta = 4772 ± 340 (apatite); 449 ± 49 (zircon)

mean track lengths not corrected for bias (Laslett et al., 1982)

#### Santaquin Complex

Thermochronologic studies allow us to summarize the thermal history of the SC over nearly 1700 my of Earth history (Fig. 4*A*). Mafic syenite has a U–Pb zircon (upper intercept) age of  $1673 \pm 12$  Ma (Nelson et al., 2002), which we interpret to approximate the time of emplacement. Because the mafic syenite is undeformed, however, the metamorphism of the amphibolites and schists it intrudes had already occurred by that time. Microprobe ages of monazite (Nelson et al., 2002) from schist in the SC record a mean age (n=12) of  $1704 \pm 91$  Ma. This age has large uncertainty, but the central tendency in the data may be meaningful.

The U–Pb zircon age of mafic syenite is concordant with a weighted mean  ${}^{40}\text{Ar}/{}^{39}\text{Ar}$  age for SC amphibolite, making it impossible to calculate a cooling rate (Table 3). We note that igneous amphibole from the mafic syenite is slightly younger than the U/ Pb age for this sample (1673 ± 12 Ma vs. 1645 ± 5 Ma), and that could indicate cooling on the order of ~7° C/my over this interval.

Biotite cooled through  $300^{\circ} \pm 50^{\circ}$  C at  $1466 \pm 11$  Ma. Thus, simulation modeling indicates a cooling rate of  $1^{\circ} \pm 0.4^{\circ}$  C/my following the closure of hornblende (Table 3). A primary purpose for calculating a cooling rate through this interval is to provide some sense of the overall uncertainty in cooling-rate calculations.

As mentioned, a value of  $1466 \pm 11$  Ma is similar to many biotite argon ages from the southwest-

ern U.S.A. Details of the thermal history between ~1680 and ~1460 Ma are not known, and they may not represent simple, constant cooling. For example, we cannot determine if these rocks cooled well below 300° C during the Paleoproterozoic and then were reheated during Mesoproterozoic time. Regardless of the path, it appears that the SC was at nearly 300° C at ca. 1450–1470 Ma and thus at a mid-crustal position.

Because Neoproterozoic strata (Big Cottonwood Formation) overlie the SC (Fig. 1), it must have been at the surface prior to deposition. Although Ehlers and Chan (1999) suggested a depositional age of ~900 Ma for the Big Cottonwood Formation, more recent work strongly suggests an age of 770 to 740 Ma (Dehler et al., 2001 and 2005), as based on interpretation that the Chuar Group, upper Uinta Mountain Group, and Big Cottonwood Formation are correlative. By simulation modeling, this implies an overall cooling rate of ~0.4°  $\pm$  0.1° C/my since the time of closure of hornblende.

It is important to emphasize that this cooling rate is a *mean* value derived over a protracted period (~900 my). Excursions in the cooling rate, including possible reheating events to <300° C cannot be discerned. The most that can be concluded is that the SC was at ~500° C at ~1680 Ma, ~300° C at ~1460 Ma, and at the surface between about 770 to 740 Ma.

Deposition of the Big Cottonwood Formation marks a fundamental shift from exhumation of the



**Figure 2.** Release spectra for hornblende and biotite from samples of Santaquin complex.

SC basement to burial related to development of a passive margin along the western edge of North America. The passive margin developed between 850 and 600 Ma (e.g., Stewart, 1976; Stewart and Suczek, 1977; Armin and Mayer, 1983; Bond et al., 1985; Harper and Link, 1986; Park et al., 1995; Bond, 1997; and Wingate et al., 1998). Hintze (1993) reported that the Neoproterozoic Big Cottonwood Formation in the Santaquin area is -300-m thick, although recent mapping by BYU field-school students reveals it to be only 100–150-m thick immediately above most of the SC, where it is overlain by the Cambrian Tintic Quartzite. Other Neoproterozoic units, as well as greater accumulations of the Big Cottonwood Formation, are found in the vicinity of the SC. Neoproterozoic units also occur along the Wasatch Front, where cumulative thicknesses reach several hundred to several thousand meters (Hintze, 1993). Thus, it is possible that the SC was buried and nearly exhumed again by the time of deposition of the early Cambrian Tintic Quartzite.

The SC area is located along the Wasatch line, which approximates the average position of the paleoshoreline throughout much of the early Paleozoic. With exception of the Devonian Fitchville Dolomite, middle Paleozoic strata are missing, possibly representing another episode of partial re-exhumation, perhaps related to the Stansbury uplift (Teichert, 1959; Rigby, 1959; and Hintze, 1993).

Beginning in the late Mississippian, sedimentation and subsidence rates increased as the Oquirrh





**Figure 3.** Radial plots (cf. Galbraith, 1990) for multi-grain, fission-track ages from apatite samples of Santaquin complex are a convenient way to illustrate degrees of uncertainty for individual samples. Although only a single age for each sample is shown, these plots graphically represent fission-track ages of individual grains by a line connecting the origin and each point to an age indicated on the arc. The further a point is from the origin, the more precise it is.

Basin developed, resulting in deposition of a minimum of 4500–5000 m of Mississippian through Permian strata near the SC (Hintze, 1993).

Within this context, two paths exist for reheating the SC following development of the unconformity between basement rocks and the Big Cottonwood Formation (Fig. 4*A*). The first path is constrained by



Figure 4. Summary thermal histories for: A, Santaquin complex; and B, Farmington Canyon complex. See text for discussion.

a single zircon fission-track age (444  $\pm$  29 Ma; Table 2*C*). Assuming an annealing temperature of 200°  $\pm$  25° C for zircon, a simulation model for reheating the SC, beginning with deposition of the Big Cottonwood Formation to 444 Ma, gives a mean heating rate of 0.6°  $\pm$  0.1° C/my.

Although we have no objective basis for discarding this fission-track age, a second path is favored because it is based on the observed geologic record. The bars constraining this path (Fig. 4A) represent estimated thermal conditions at the end of the Cambrian, Mississippian, Permian, and Jurassic Periods, as based upon reported cumulative variability in stratigraphic thicknesses in the Santaquin area (Hintze, 1993) multiplied by assumed end-member 20° C/km and 30° C/km isotherms. It should be noted that, for some units, only a minimum thickness is known; the uncertainty in temperature due to burial increases due to accumulating error.

Owing to constraints imposed by fission-tracklength modeling (discussed below), our preferred reheating path passes through the lower end of the bars in Figure 4A. This path also results in an overall re-heating of ~ $0.3^{\circ}$  C/my to a temperature of ~200° C between deposition of the Big Cottonwood Formation, the end of the Jurassic Period, and onset of the Sevier orogeny. Simulation modeling is difficult to apply in this case owing to large uncertainties in stratigraphic thicknesses and unknown past geothermal gradients. Stratigraphic thicknesses also indicate that heating should have accelerated after the end of the Mississippian Period due to formation of the Oquirrh Basin.

The SC is carried in the hanging wall of the Charleston–Nebo salient, an element of the Sevier fold-thrust belt, that stratigraphic evidence suggests developed from Albian through late middle Eocene time (ca. 100 to 40 Ma; Jefferson, 1982; Lawton, 1985; Mitra and Sussman, 1997; Constenius et al., 2003; DeCelles, 2004; Horton et al., 2004). Other studies proposed initial displacement of the Charleston–Nebo salient to be older (e.g., Schwans 1995 and Currie 1997). However, for purposes of the present study, we have assumed a local age of 100 Ma for initiation of the Sevier orogeny, accompanying a reburial temperature of about 200° C.

After burial in the Oquirrh Basin, a great thickness of clastic sediments was shed from the Sevier

Table 3. Cooling rate estimates and associated uncertainties for selected time intervals for the SC.

Constraint	Thermal Range	Temporal Range	Cooling Rate	Comment
	°C		°C/Ma	
U/Pb zircon-	700±50 <sup>2</sup> to	1673±12 <sup>2</sup> to	not applicable	Concordant ages
40Ar/39Ar	$500+50^{2}$	1675+18 <sup>1,2</sup>		indicating rapid
amphibolite	900±90	10/ 9110		cooling.
40Ar/39Ar	500±50 <sup>2</sup> to	1675±18 <sup>2</sup> to	1±0.4	Average rate over
amphibolite to	$300+50^{2}$			long period of
<sup>40</sup> Ar/ <sup>39</sup> Ar biotite	500290			time. May
ni, ni biotite				neglect
				considerable
		1466±11 <sup>2</sup>		detail.
<sup>40</sup> Ar/ <sup>39</sup> Ar biotite to	300±50 <sup>2</sup> to 20	1466±11 <sup>2</sup> to	0.4±0.1	Average rate over
erosion to the				long period of
surface				time. Almost
				certainly neglects
				considerable
		755±15 <sup>3</sup>		detail.
reburial to zircon	20 to 225±25	755±15 <sup>3</sup> to	0.7±0.1	
fission-track age		444±29 <sup>2</sup>		

<sup>1</sup>weighted mean age of 3 amphibole samples for the SC. Two were published in Nelson et al. (2002) and the remaining age is reported in Table 1.

<sup>2</sup>employed a normal distribution in simulation model <sup>3</sup>employed a uniform distribution in simulation model

orogen in Cretaceous through early Tertiary time and preserved in east-central Utah. This material represents detritus resulting from denudation of the orogen and partial exhumation of the SC at an overall cooling rate of ~2° C/my to the present. Post-Sevier cooling probably was controlled by two tectonic events: (1) exhumation by incorporation of the SC into the Charleston–Nebo thrust system; and (2) as discussed below, subsequent Paleogene orogenic extensional collapse and later Basin and Range extension. We note, however, that although the local evidence for the Paleogene event is compelling (e.g., Constenius, 1996), its presence is not obvious in our cooling curves.

Wedge-top foreland-basin deposits of the late Paleocene North Horn, early Eocene Flagstaff, and Miocene Moroni Formations rest with angular unconformity on erosionally truncated, hanging-wall strata (Witkind and Weiss, 1991). Thus, there was a long interval of exhumation caused by structural shortening and concomitant erosional denudation from Campanian through late Paleocene time (ca. 80-55 Ma; Constenius et al., 2003). The wedgetop strata are thin (<150 m). However, there may have been modest burial reheating of the SC by materials deposited in the Moroni-Tintic volcanic belt that are now eroded. Additional evidence for possible shallow reburial is discussed below for fission-track models.

Externally derived geological constraints have been refined by inverse models of fission-tracklength distributions in apatite (Ketcham et al., 2000) to provide additional limits and detail regarding the thermal history between 200 and 0 Ma (Fig. 5). Fission-track models should be, and indeed are, consistent with known and inferred geological events and conditions of the past.

Five constraints were imposed on the models to obtain good fits to track-length distributions; optimized models for both samples suggest similar thermal histories. All five constraints were derived from geological evidence independent of the modeling.

The first constraint, consistent with the time-temperature history proposed in Figure 4A, was picked at a temperature of ~200° ±5° C at 200 Ma. It permits the model to match a prominent node of short track lengths at about 9 µm in both samples via a protracted dwell time in the partial-annealing zone. The second constraint was imposed at 100 Ma with temperatures between ~200° C and 225° C, representing the onset of tectonic and erosional exhumation of the Sevier orogen. This temperature range is toward the low end as inferred from cumulative stratigraphic thicknesses, but its choice improved the model fit. In this sense, the fission-track models help reduce uncertainty in this particular constraint.

The third constraint was placed at 60 Ma and at temperatures between ~100° C and 125° C, corresponding to the end of an erosional event that locally removed all upper Paleozoic and Mesozoic strata. Again, field evidence for this event is deposition of Tertiary strata (North Horn Formation) directly on Mississippian strata in the mountain block east of the SC (Fig. 1). The fourth constraint, placed at a moderately higher temperature, permits some reburial by Tertiary



**Figure 5.** Summary of fission-track models for two apatite samples (sample names indicated on figs.) from Santaquin complex. Uncertainty envelopes and best fits (dashed lines) are shown. Vertical bars and associated numbers represent imposed time-temperature constraints as discussed in text.

strata prior to onset of Basin and Range extension at about 17 Ma. Note, however, that although this constraint was placed at 20 Ma, the best-fit models for both samples imply Basin and Range exhumation began at 10–15 Ma. Finally, the last constraint is imposed at 6.4 Ma and ~70° C through the U/ Th-He age reported by Armstrong et al. (2004) for the SC.

In summary, independent geological constraints augmented and refined by best-fit fission-track models indicate the following: (1) the onset of cooling due to rapid erosion accompanying Sevier tectonism began at ~90  $\pm$  10 Ma and occurred at an inferred rate of 4.5°-5.3° C/my until some time between 85 and 60 Ma; and (2) slight to modest reburial and accompanying reheating (0.5°– 0.7° C/my) is inferred beginning 60–85 Ma, continuing until onset of Basin and Range extension at ~10–15 Ma (however, it is not clear whether the reheating was real or simply an artifact of constraints imposed on the model); and (3) cooling by Basin and Range exhumation, by contrast, has been rapid, occurring at apparent rates of ~8.8°–11.5° C/my. Assuming end-member geothermal gradients of 20° C/km and 30° C/km, Basin and Range cooling rates correspond to long-term, vertical-slip rates of 0.29 to 0.58 mm/yr, assuming that cooling kept pace with uplift.

SC slip rates may represent minimum values as the Wasatch fault bifurcated near the SC (Fig. 1). Much of the exhumation of the SC, however, clearly was accomplished along strands that bound the SC to the west. For example, near the mouth of Santaquin Canyon, the Pennsylvanian–Permian Oquirrh Formation is juxtaposed against the SC, representing as much as ~9 km of stratigraphic separation.

The Wasatch fault is segmented (Fig. 1), and each segment traditionally has been considered to have acted independently (Machette et al., 1986 and 1987). This assumption, however, has been questioned over million-year time scales (Armstrong et al., 2004). It is instructive to compare denudation rates among segments. Similar to the SC on the northern Nebo segment of the Wasatch fault, other geologists have inferred increased denudation rates in the last several million years for other segments. For example, Naeser et al. (1983) inferred rates of 0.8 to 0.4 mm/yr over the last 5 and 10 my, respectively, for the Weber segment near the FCC. Rates of 0.20 to 0.76 mm/ year have been inferred for the Salt Lake segment over the same interval (Kowallis et al., 1990; Evans et al., 1985; and Parry and Bruhn, 1987; Armstrong et al., 2000; Armstrong et al., 2004).

#### **Farmington Canyon Complex**

It is possible to construct a similar cooling curve for the FCC on the basis of existing data and employing a similar approach to the SC (Fig. 4*B*). Barnett et al. (1993) reported U/Pb results for monazite samples from the FCC that are nearly concordant (~1700 Ma intercept) and yield  $^{207}$ Pb/ $^{206}$ Pb ages ranging from 1640 to 1720 Ma. Thermobarometry indicates temperatures as high as 700° C. Hornblendes from amphibolite record  $^{40}$ Ar/ $^{39}$ Ar cooling ages ranging from 1586 to 1656 Ma (Barnett et al., 1993). Using the midpoint of these age ranges suggests an overall cooling rate on the order of 3.5° C/my, similar to the peak cooling rate of 4° C/my inferred for the SC following peak metamorphic conditions.

Two biotite <sup>40</sup>Ar/<sup>39</sup>Ar samples reported by Barnett et al. (1993), similar to the Santaquin samples, are disturbed, with total-gas ages on the order of 1060 and 550 Ma, respectively. The 550 Ma sample cannot represent cooling through ~300° C, because the FCC was at the surface in early Cambrian time (it is unconformably overlain by Cambrian rocks as well as the Neoproterozoic strata on Antelope Island; Doelling et al., 1990; Fig. 1). The 1060-Ma sample is also difficult to interpret with confidence, but it could reflect cooling through the 300° C isotherm, yielding a cooling rate of 0.3°–0.4° C/my.

Alternatively, the biotites could exhibit alteration, or perhaps they were reheated during Phanerozoic time sufficiently to wholly or partially reset them. Existing FCC biotite ages probably provide little additional detail to the thermal history of this body.

Because the FCC on Antelope Island is nonconformably overlain by Neoproterozoic strata, it must have reached the surface by 740–700 Ma. The total thickness of Neoproterozoic strata in the region suggests that some reburial and exhumation occurred. Nevertheless, the FCC may have remained near the surface until after deposition of the Cambrian Tintic Quartzite, which extensively overlies the unit in the footwall of the Wasatch fault (Bryant, 1984).

Burial of the FCC by Cambrian through Jurassic sediments probably produced a concaveupward heating curve similar to the SC, with a mean overall heating rate of between 0.4° and 0.6° C/my. Since the FCC also is in a Sevier thrust sheet, at least locally, it too probably was cooled by erosion that accompanied the Sevier orogeny. Unlike the SC, however, the FCC was at the surface between Paleocene and Eocene time, as Tertiary strata (Wasatch Fm.) also nonconformably overlie the FCC in many areas (Bryant, 1984; Fig. 1). Exhumation from Cretaceous to Paleocene time corresponds to a cooling rate of 1.8° to 2.9° C/my.

The extent of reburial during and after deposition of the Wasatch Formation and the Tertiary volcanic rocks (Norwood Tuff) is uncertain, but it may have included as much as 2.4 km of overburden. Through Miocene to recent time (i.e., over the last 5 to 10 my), however, Naeser et al. (1983) inferred denudation rates of 0.8 to 0.4 mm/yr, corresponding to bracketed cooling rates of 8° to 24° C/my for 20° and 30° C/km isothermal gradients.

### A Composite View

An important component of the present study is to examine coherence of the thermal history recorded in these two basement complexes within the context of our understanding of the regional geological history. That way, the strength of the thermochronologic underpinnings can be evaluated for other regions in which the geological history is less well known.

We recognize five general episodes in the thermal history of basement rocks in the immediate footwall of the Wasatch fault that can be correlated to specific tectonic episodes (Fig. 4). The first is Paleoproterozoic orogenesis, reflected in peak metamorphic temperatures at about 1700 Ma, believed to be associated with accretion of island-arc material (SC) and deformation of a passive-margin sequence (FCC) along the southern boundary of the Archean Wyoming province (e.g., Nelson et al., 2002). This was followed by a period of rapid, post-orogenic cooling to below about 500° C by ~1650 Ma.

Second, during Meso- and much of Neoproterozoic time, the net erosional effect was to exhume midcrustal rocks prior to burial by the Big Cottonwood complex after 770 Ma. Details of this exhumation are unknown, but long-term tectonic stability and associated gradual denudation of the orogen is plausible. During that time, Rodinia was assembled, as well as encompassing two episodes of anorogenic magmatism and accompanying metamorphism (e.g., Karlstrom and Humphrey, 1998; and Ferguson et al., 2004), although these episodes are not clearly recognized at either locality.

Third, the Neoproterozoic strata deposited atop basement rocks near the Wasatch fault require that crystalline rocks had been exhumed. The Big Cottonwood Formation, which overlies the SC, was deposited along a new passive margin as it formed during breakup of Rodinia between 850 and 600 Ma (e.g., Stewart, 1976; Stewart and Suczek, 1977; Armin and Mayer, 1983; Bond et al., 1985; Harper and Link, 1986; Park et al., 1995; Bond, 1997; and Wingate et al., 1998). That was followed by deposition of thick sequences of Paleozoic passive-margin sediments. On Antelope Island, the Neoproterozoic Mineral Fork Formation, a unit slightly younger than the Big Cottonwood Formation, overlies the basement of the FCC. We speculate that deep erosion and surface exposure of these basement complexes during late Precambrian time not only was facilitated by post-accretionary exhumation, but it also experienced rift-flank uplift during breakup of Rodinia.

The fourth event, peak reheating by burial, may have been terminated by rapid erosion during the Sevier orogeny at about 100 Ma. That was followed by the fifth event, recorded in post-Sevier tectonic collapse of the fold and thrust belt, followed in turn by Basin and Range extension. Constenius et al. (2003), for example, attributed collapse of the fold-and-thrust belt to gravitational spreading of an over-thickened crust. As noted above, however, fission-track models are consistent with a minor episode of reburial by Tertiary deposits that were largely removed between the Sevier Orogeny (100 to 70 Ma) and advent of Basin and Range extension (<17 Ma). Paleogene gravitational collapse of the Sevier orogen is well documented, but unfortunately this event remains outside the resolution of our time-temperature curves (e.g., Figs. 4 and 5). Basin and Range extension is the proximate cause for exposures of basement rocks in the footwall of the Wasatch fault, and well-documented, Quaternary fault scarps attest to the fact that the fault is still active (UGS, 2002; Gilbert, 1928).

# Slip Rates Over Divergent Time Scales

Our analysis cannot add new insight to decadal-(as measured by GPS) or millennial- (fault-trench measurements) scale studies. Such work typically suggests Holocene slip rates >1 mm/yr. For example, Friedrich et al. (2003) estimated Holocene slip at 1.7  $\pm$  0.5 mm/yr, compared to a rate of ~0.6 mm/ yr from 10 Ma to 6 ka. This is at the high end of rates deduced by us, as well as by Armstrong et al. (2000). It is clear that episodes of high slip on timescales of  $10^4$  yr are masked at timescales >10<sup>5</sup> years.

# CONCLUSIONS

The SC and its relationship to adjacent rock bodies and geologic structures provides a rare glimpse into the geologic history of central Utah over the last 1700 million years. Located along the Wasatch line, it provides particular insight to geologic history of a long-lived crustal boundary (Nelson and Harris, 2001). As such, the results obtained for the SC emphasize the value to future investigations of basement rocks elsewhere.

Isotopic constraints place the age of crust formation and accompanying amphibolite-facies metamorphism at ~1700 Ma. The SC records an extensive thermal history from 1700 Ma to late Quaternary slip on the Wasatch fault (Figs. 4A and 5). Following initial metamorphism, plutonism, and accretion, the crust cooled slowly, presumably driven by erosional exhumation, because Neoproterozic strata of the Big Cottonwood Formation unconformably overlie the crystalline rocks. Regional stratigraphic thicknesses and constraints imposed on fission-track models require re-burial of the SC to depths of several kilometers, with corresponding temperatures of ~200° C from Neoproterozoic through onset of the Sevier orogeny. Burial and reheating were accelerated during Mississippian through Permian time due to deep, rapid burial in the Oquirrh Basin. Commencing at ~100 Ma, the SC began an episode of erosional exhumation as it became incorporated into thrust sheets of the Charleston-Nebo salient. Erosion and extensional collapse of the Sevier orogen, followed by Basin and Range extension, produced an overall cooling rate of nearly 2° C/my.

Fission-track data and constraints imposed on fission-track models provide additional detail regarding the post-Sevier thermal history. They specifically indicate a pulse of rapid cooling after thrusting, followed by a period of stasis or slight reheating until Basin and Range extension initiated another episode of rapid cooling. Cooling rates converted into denudation rates are on the order of 0.3 to 0.6 mm/yr over the last 10–15 my. However, estimates of Quaternary slip along the fault are even higher, on the order of 1 to 3 mm/yr. This suggests that the Wasatch fault may have experienced periods of rapid slip (like the present), punctuated by periods of relative quiescence.

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