PROCEEDINGS OF THE

DENVER MUSEUM OF NATURE & SCIENCE

SERIES 4, NUMBER 1, OCTOBER 1, 2001

FOSSIL FLORA AND STRATIGRAPHY OF THE FLORISSANT FORMATION, COLORADO

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1.

STRATIGRAPHIC SUMMARY AND ^{40}AR/^{39}AR GEOCHRONOLOGY OF THE FLORISSANT FORMATION, COLORADO

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ABSTRACT—The Florissant Formation is a heterolithic accumulation of shale, tuffaceous mudstone and siltstone, tuff, and arkosic and volcaniclastic sandstone and conglomerate. The name Florissant Formation redefines the former designation of the Florissant Lake Beds. The formation is divided into six informal units, including, from bottom to top: the lower shale, lower mudstone, middle shale, caprock conglomerate, upper shale, and upper pumice conglomerate. Fossil mammals include the co-occurrence of the horse *Mesohippus* and large brontotheres, indicating that the age of the formation is Chadronian.

Single-crystal ^{40}Ar/^{39}Ar analyses of sanidine from pumice in sandstone and debris flow deposits of the upper Florissant Formation yield a mean age of 34.07 ± 0.10 Ma. Although the pumice fragments are reworked and do not represent a primary volcanic deposit, their abundance and the unimodality of sanidine ages suggest that 34.07 ± 0.10 Ma is a good estimate for the depositional age of the Florissant Formation. The sanidine age data do not support derivation of the Florissant Formation pumice fragments from any of the catastrophic caldera eruptions that produced ignimbrite deposits in the region. Possible sources for the pumice fragments include early eruptive phases of the 33.5 Ma Mount Aetna caldera or late eruptive phases of the 34.3 Ma Grizzly Peak caldera in the Sawatch Range of central Colorado.

KEY WORDS: Florissant Formation, lithostratigraphy, biostratigraphy, ^{40}Ar/^{39}Ar geochronology

The Florissant "Lake Beds" contains one of the most important fossil flora and insect fauna of the western United States. It has been known as an important fossil location since the 1870s, but the details of its stratigraphy and radiometric age have been uncertain until recent findings. The only previously published radiometric age is a K/Ar analysis of sanidine from the formation by Epis and Chapin (1975) that yielded an age of 34.9 Ma (adjusted to modern decay constants of Steiger and Jaeger 1977). The present report redefines the Florissant Lake Beds as the Florissant Formation, summarizes the lithostratigraphy and biostratigraphy of the formation, and documents new single-crystal ^{40}Ar/^{39}Ar dating of several units within the formation. The area of study includes Florissant Fossil Beds National Monument and outcrops near the town of Florissant, Colorado (Fig. 1).

Methods

The new stratigraphic interpretations are a result of the mapping of four formations and six subdivisions of the Florissant Formation in an area extending from the town of Florissant to the monument. The outcrops of the formation are scattered and discontinuous; therefore, the stratigraphic sequence and the estimate of 74 m for the total thickness of the formation were determined from careful mapping and section measuring. Thirteen stratigraphic sections were described, eleven in the monument and two outside the monument. The distribution of the stratigraphic units and locations of important outcrops and dated rock samples are shown in Figure 1 and Table 1.

For ^{40}Ar/^{39}Ar dating analyses, samples of unweathered, unaltered pumice-rich sandstone or debris

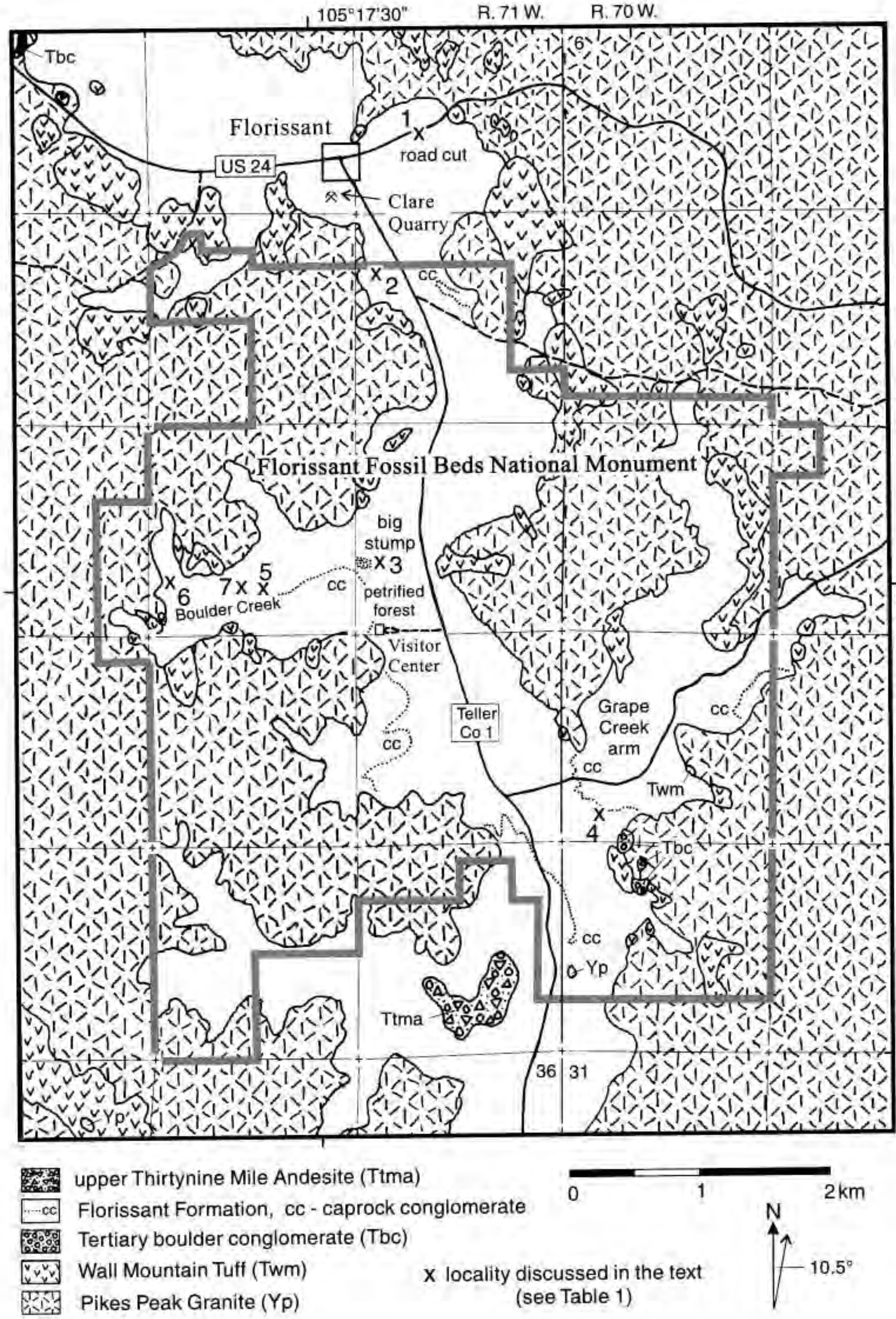

FIGURE 1. Bedrock geologic map and geographic features of the area surrounding Florissant Fossil Beds National Monument. The margins of the Florissant Formation outline the original paleovalley.

flow materials were collected from four localities in the Florissant Formation (Table 2). Sanidine separates were prepared from each sample and irradiated in the Ford Reactor at the University of Michigan. Single-crystal laser-fusion analyses were performed at the New Mexico Geochronology Research Laboratory at New Mexico Tech, Socorro, New Mexico. Details of sample preparation procedures, irradiation, $^{40}Ar/^{39}Ar$ analyses, and age calculations are provided in the footnote to Table 2. Table 2 summarizes weighted mean ages obtained from the five samples, and analytical data from individual crystals are given in Table 3.

Geologic Setting

There are four formal stratigraphic units represented by the rocks in the Florissant area. These include the Pikes Peak Granite, the Wall Mountain Tuff, the Florissant Formation, and breccias of the Thirtynine Mile Andesite. A fifth informal unit, herein assigned to Tertiary boulder conglomerate, occurs in the paleovalley. These units are in the composite section shown in Figure 2.

The oldest rocks in the monument are part of the Pikes Peak Granite, a pink to reddish-tan, medium to coarse-grained, biotitic or biotite-hornblende granite and quartz monzanite (Wobus and Epis 1978). The radiometric age of this granite is 1080 Ma (Wobus 1994). Late Eocene streams cut a long dendritic valley into this granite in which volcanic rocks and sediments later accumulated. Local relief on this unconformity is as great as 300 m near the southern end of the paleovalley. The granite is exposed as boulders, tors, and ridges on the flanks of the paleovalley.

TABLE 1. Locations of measured sections and radiometrically dated sanidine samples in the Florissant Formation.

Map. Loc.#	*Name*	*Features*	*Public Land Survey Location*	*UTM Location, NAD 27, Zone 13S*
1	Florissant road cut	Complete sequence of the lower shale unit, base of lower mudstone unit.	SW¼ SW¼ NE¼ SW¼ sec. 1, T. 13 S., R. 71 W.	475532mE 4310802mN el. 8223 ft
2	Monument N	Thickest sequence of the lower mudstone unit, capped by the middle shale.	N½ SW¼ NW¼ sec. 12, T. 13 S., R. 71 W.	475204mE 4309757mN el. 8301 ft
3	big stump	Thickest section of the caprock conglomerate, complete sequence of the middle shale unit.	SW¼ NW¼ SW¼ sec. 13, T. 13 S., R. 71 W.	475241mE 4307547mN el. 8321 ft
4	Gregory trench	Complete sequence of the middle shale unit. Site of paleobotanical work of Gregory (1994) and palynological work of Wingate and Nichols (2001).	Center, E½ SW¼ SW¼ sec. 19, T. 13 S., R. 70 W.	476920mE 4305596mN el. 8501 ft
5	lower Boulder Creek	Complete sequence of the upper shale unit, sanidine samples TF3 and TF4.	NW¼ SW¼ SE¼ sec. 14, T. 13 S., R. 71 W.	474395mE 4307349mN el. 8364 ft
6	upper Boulder Creek	Exposures of the upper pumice conglomerate unit, sanidine sample TF5.	NW¼ SW¼ SW¼ sec. 14, T. 13 S., R. 71 W.	473636mE 4307281mN el. 8479 ft
7	nm782	Sanidine sample nm782 from the lower part of the upper pumice conglomerate unit. From ledge halfway up the slope.	NE¼ SE¼ SW¼ sec. 14, T. 13 S., R. 71 W.	474118mE 4307328mN el. 8399 ft

TABLE 2. Summary of $^{40}Ar/^{39}Ar$ single-crystal laser-fusion results from Florissant Formation sanidines.

Sample	*Unit*	*n*	*K/Ca*	*±2s*	*Age*	*±2s*
TF5	tuff in upper pumice conglomerate unt	19	43.5	17.4	34.01	0.13
nm782	pumice-rich facies of upper pumice conglomerate unit	10	42.8	9.4	34.07	0.09
TF4	tuff in upper shale unit	19	45.1	5.9	34.14	0.08
TF3	sanidine crystals in caprock conglomerate unit	18	47.0	11.3	34.03	0.09
mean of samples		4			34.07	0.13
mean of all crystals		66			34.07	0.10

NOTES: n = number of individual crystals analyzed (SCLF); K/Ca = molar ratio calculated from K-derived ^{39}Ar and Ca-derived ^{37}Ar.

METHODS: Sample preparation of sanidine-crushing, LST heavy liquid, Franz, HF.

IRRADIATION: Five hours in vacuo, H-5 position, Ford Nuclear Reactor, University of Michigan.

NEUTRON FLUX MONITOR: Sample FC-1 of interlaboratory standard Fish Canyon Tuff sanidine with an assigned age of 27.84 Ma (Deino and Potts 1990), relative to Mnhb-1 at 520.4 Ma (Samson and Alexander 1987); samples and monitors irradiated in alternating holes in machined Al discs.

LABORATORY: New Mexico Geochronology Research Laboratory, Socorro, NM.

INSTRUMENTATION: Mass Analyzer Products 215-50 mass spectrometer on line with automated, all-metal extraction system.

HEATING: 10W continuous CO^2 laser.

REACTIVE GAS CLEANUP: SAES GP-50 getters operated at 20 °C and ~450 °C; 1 to 2 minutes.

ERROR CALCULATION: All errors reported at ± 2 sigma, mean ages calculated using inverse variance weighting of Samson and Alexander (1987).

DELAY CONTRANT AND ISOTOPIC ABUNDANCES: Steiger and Jaeger (1977).

ANALYTICAL PARAMETERS: Electron multiplier sensitivity = 1 to 3 x 10^{-17} moles/pA; typical system blanks were 470, 3, 0.6, 3, 3.0 x 10^{-18} moles (laser) and at 470, 3, 0.6, 3, 3.0 (furnace) at masses 40, 39, 38, 37, 36, respectively; J-factors determined to a precision of ± 0.2 percent using SCLF of 4 to 6 crystals from each of 4 to 6 radial positions around irradiation vessel. Correction factors for interfering nuclear reactions, determined using K-glass and CaF_2 ($^{40}Ar/^{39}Ar$) K = 0.00020 ± 0.0003; ($^{36}Ar/^{37}Ar$) Ca = 0.00026 ± 0.00002; and ($^{39}Ar/^{37}Ar$) Ca = 0.00070 ± 0.00005.

The Wall Mountain Tuff is the oldest Tertiary rock within the monument. This tuff is a rhyolitic ignimbrite that weathers into brownish-gray to dark gray, subangular blocks. It rests unconformably on the irregular erosion surface cut into the Pikes Peak Granite. The tuff mantles the sides of the paleovalley because it was emplaced by a thick pyroclastic flow that draped the welded tuff over the local topography. The tuff was also eroded prior to the deposition of the other Tertiary units. Accordingly, the thickness of the tuff varies considerably, with a maximum preserved thickness being about 15 m. The age of the Wall Mountain Tuff is 36.73 Ma ± 0.07 (average of two $^{40}Ar/^{39}Ar$ ages reported by McIntosh and Chapin 1994).

A limited exposure of Tertiary boulder conglomerate overlies the Pikes Peak Granite and the Wall Mountain Tuff on the southeast side of the monument (NE¼ NW¼ sec. 30, T. 13 S., R. 70 W., Fig. 1). This conglomerate contains huge boulders of granite as large as 5.8 m in maximum diameter. The largest boulders are typically near the top of the exposures, suggesting a crude inverse grading. The conglomerate contains cobbles and boulders of granite, gneiss, schist, welded tuff derived from the Wall Mountain Tuff, and scattered fragments of silicified wood. Niesen (1969) and Wobus and Epis (1978) did not recognize the volcanic clasts in this boulder conglomerate and mapped these conglomerates as Echo Park Alluvium. The Echo Park Al-

TABLE 3. $^{40}Ar/^{39}Ar$ single-crystal sanidine laser-fusion analytical data for Florissant samples.

TF5, J = 0.000773567 ± 0.13%, D = 1.0066 ± 0.0019, NM-17, Lab# = 1671
TF5, J = 0.000773567 ± 0.13%, D = 1.0073 ± 0.0015, NM-17, Lab# = 2045

ID	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_{K}$ (x 10^{-15} mol)	K/Ca	%$^{40}Ar^*$	Age (Ma)	±2s (Ma)
05	24.47	0.023	0.1487	8.94	41.4	99.7	33.75	0.15
01	24.50	0.0119	0.1011	12.5	43.0	99.8	33.81	0.15
07	24.52	0.0107	0.1494	8.11	47.6	99.7	33.81	0.15
02	24.54	0.0111	0.2029	19.9	46.1	99.7	33.82	0.15
13	24.51	0.0107	0.0948	8.96	47.6	99.8	33.82	0.15
04	24.53	0.0119	0.1481	6.56	42.7	99.7	33.83	0.16
17	24.61	0.0127	0.1256	10.00	40.2	99.8	33.95	0.13
03	24.62	0.0114	0.1466	10.0	44.8	99.8	33.96	0.15
09	24.63	0.0111	0.1055	8.16	45.8	99.8	33.98	0.15
06	24.64	0.0122	0.1418	4.29	41.9	99.8	33.98	0.15
11	24.70	0.0119	0.2910	2.54	42.9	99.6	34.00	0.17
18	24.68	0.0122	0.1765	3.94	41.8	99.7	34.02	0.15
19	24.72	0.0386	0.3181	6.89	13.2	99.6	34.02	0.15
08	24.67	0.0122	0.1322	13.4	41.9	99.8	34.03	0.15
20	24.76	0.0104	0.0865	10.8	49.1	99.8	34.17	0.13
15	24.82	0.0107	0.0663	9.41	47.6	99.8	34.26	0.15
12	24.86	0.0094	0.1155	4.61	54.1	99.8	34.29	0.14
16	24.85	0.0089	−0.0577	3.29	57.2	100.0	34.35	0.18
14	24.90	0.0134	−0.1451	2.58	38.1	100.1	34.45	0.16
Weighted mean ± S & A err (n = 19)					43.5 ± 17.4		34.01	0.13

nm782, J = 0.000788491 ± 0.13%, D = 1.0066 ± 0.0019, NM-17, Lab# = 1669

ID	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_{K}$ (x 10^{-15} mol)	K/Ca	%$^{40}Ar^*$	Age (Ma)	±2s (Ma)
05	24.12	0.0114	0.2680	11.4	44.7	99.6	33.86	0.15
03	24.16	0.0123	0.1457	12.9	41.6	99.7	33.96	0.15
01	24.27	0.0156	0.4179	6.77	32.6	99.4	34.00	0.16
06	24.22	0.0108	0.1457	12.5	47.1	99.7	34.04	0.15
02	24.26	0.0113	0.2558	11.8	45.3	99.6	34.05	0.15
10	24.25	0.0108	0.1733	12.8	47.4	99.7	34.07	0.15
07	24.27	0.0114	0.1587	3.51	44.7	99.7	34.11	0.16
04	24.29	0.0116	0.1918	12.8	43.8	99.7	34.13	0.15
09	24.31	0.0115	0.1285	12.6	44.4	99.8	34.17	0.15
08	24.43	0.0139	0.2479	13.9	36.6	99.6	34.29	0.15
Weighted mean ± S & A err (n = 10)					42.8 ± 9.4		34.07	0.12

TF4, J = 0.000775805 ± 0.13%, D = 1.0066 ± 0.0019, NM-17, Lab# = 1670
TF4, J = 0.000775805 ± 0.13%, D = 1.0073 ± 0.0015, NM-17, Lab# = 2046

ID	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_{K}$ (x 10^{-15} mol)	K/Ca	%$^{40}Ar^*$	Age (Ma)	±2s (Ma)
04	24.54	0.0117	0.2360	5.13	43.7	99.6	33.90	0.16
17	24.55	0.0109	0.1949	12.6	46.9	99.7	33.94	0.13

(continues)

(Table 3 continued)

ID	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_{K}$ (x 10^{-15} mol)	K/Ca	%$^{40}Ar^{*}$	Age (Ma)	±2s (Ma)
18	24.57	0.0112	0.1837	8.89	45.5	99.7	33.97	0.14
09	24.57	0.0111	0.1568	10.5	45.9	99.7	33.98	0.15
07	24.55	0.0110	−0.0417	3.00	46.6	100.0	34.04	0.16
01	24.60	0.0117	0.0797	15.2	43.7	99.8	34.05	0.15
02	24.60	0.0117	0.0432	11.5	43.7	99.9	34.06	0.15
08	24.61	0.0111	0.0639	8.84	46.1	99.8	34.07	0.15
06	24.63	0.0112	0.0543	4.96	45.7	99.9	34.10	0.16
05	24.67	0.0114	0.0888	1.99	44.7	99.8	34.07	0.15
13	24.70	0.0099	0.0927	6.83	51.4	99.8	34.18	0.14
12	24.71	0.0115	0.1135	12.3	44.3	99.8	34.19	0.14
20	24.81	0.0135	0.4028	3.90	37.7	99.4	34.21	0.15
14	24.71	0.0118	0.0503	10.4	43.2	99.9	34.21	0.13
03	24.74	0.0111	0.0573	9.54	46.2	99.9	34.25	0.16
10	24.75	0.0105	0.0810	7.09	48.6	99.8	34.26	0.16
19	24.81	0.0115	0.2445	8.28	44.3	99.6	34.28	0.14
15	24.80	0.0106	0.0080	5.38	48.3	99.9	34.35	0.14
11	24.96	0.0127	0.1256	4.03	40.3	99.8	34.53	0.15
Weighted mean ± S & A err (n = 19)					45.1 ± 5.9		34.14	0.12

TF3, J = 0.000787189 ± 0.13%, D = 1.0066 ± 0.0019, NM-17, Lab# = 1672
TF3, J = 0.000780139 ± 0.13%, D = 1.0073 ± 0.0015, NM-17, Lab# = 2044

ID	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_{K}$ (x 10^{-15} mol)	K/Ca	%$^{40}Ar^{*}$	Age (Ma)	±2s (Ma)
09	24.06	0.0112	0.4452	3.00	45.4	99.4	33.64	0.22
10	24.02	0.0118	0.1549	4.26	43.4	99.7	33.71	0.16
01	26.37	0.0117	8.009	30.0	43.5	91.0	33.75	0.19
06	24.14	0.0115	0.3195	4.52	44.4	99.5	33.81	0.25
03	24.12	0.0115	0.1377	29.4	44.2	99.8	33.85	0.15
17	24.42	0.0112	0.1196	14.9	45.4	99.8	33.98	0.13
08	24.28	0.0107	0.3463	11.4	47.6	99.5	33.98	0.21
18	24.46	0.0111	0.1926	19.0	46.1	99.7	34.00	0.14
02	24.33	0.0111	0.4597	13.4	46.0	99.4	34.01	0.18
05	24.28	0.0112	0.2243	8.54	45.7	99.7	34.03	0.19
04	24.25	0.0112	0.1320	23.2	45.5	99.8	34.04	0.16
12	24.53	0.0114	0.3178	14.2	44.6	99.5	34.04	0.13
07	24.32	0.0107	0.2913	34.6	47.5	99.6	34.07	0.16
11	24.58	0.0110	0.3468	11.3	46.5	99.5	34.10	0.13
13	24.56	0.0087	0.1370	2.25	58.6	99.8	34.16	0.19
16	24.63	0.0106	0.2848	3.81	48.3	99.6	34.19	0.15
19	24.64	0.0128	0.2427	15.1	39.9	99.6	34.23	0.14
14	24.81	0.0080	0.3457	6.72	64.2	99.5	34.42	0.15
Weighted mean ± S & A err (n = 18)					47.0 ± 11.3		34.03	0.13

Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interfering reactions.
Individual analyses show analytical error only; mean age errors also include error in J and irradiation parameters.
Analyses in italics are excluded from mean age calculations.
Correction factors:

$(^{39}Ar/^{37}Ar)_{Ca} = 0.00067 \pm 0.0000$
$(^{36}Ar/^{37}Ar)_{Ca} = 0.00026 \pm 0.0000$
$(^{38}Ar/^{39}Ar)_{K} = 0.0119$
$(^{40}Ar/^{39}Ar)_{K} = 0.0260 \pm 0.0020$

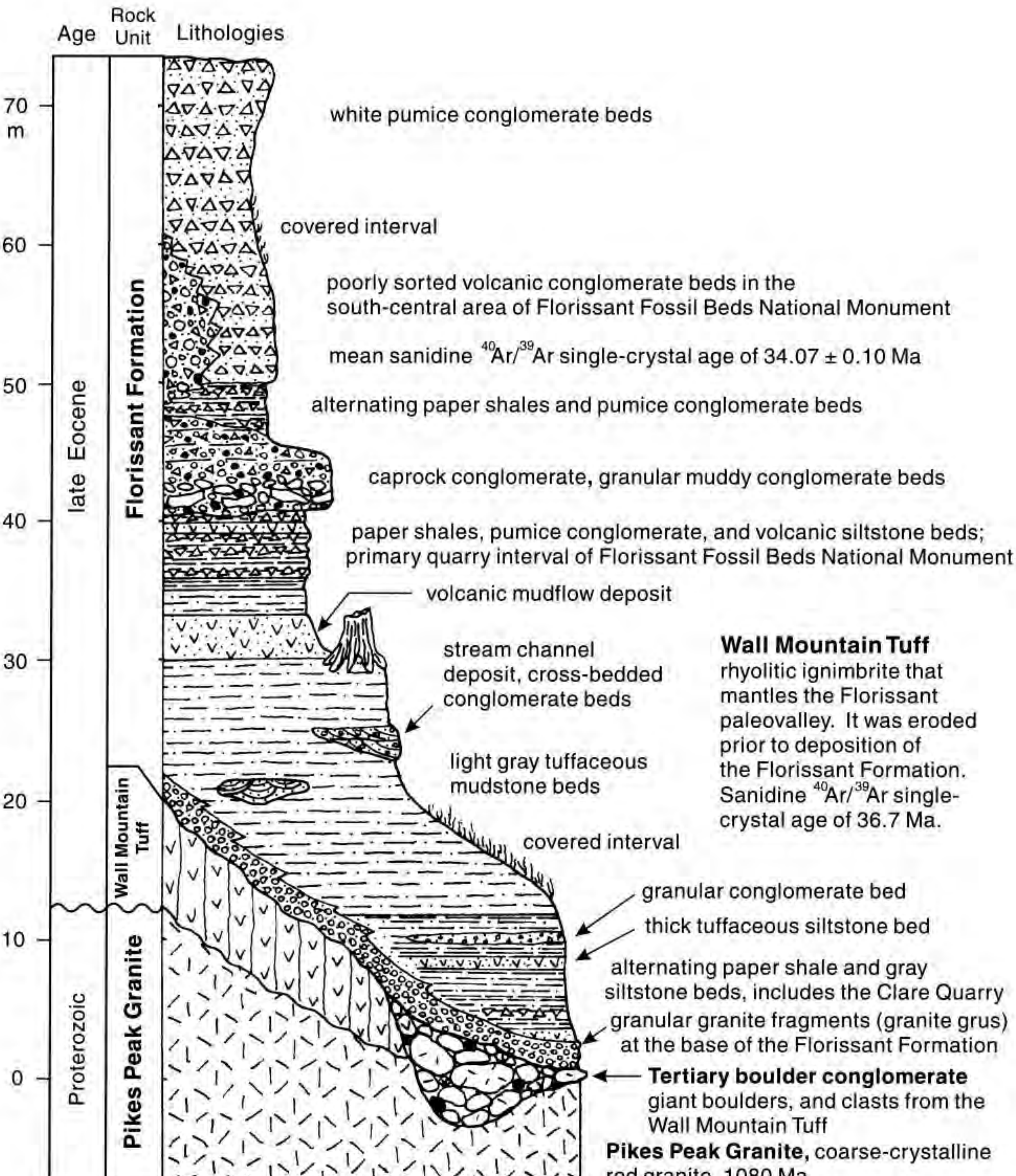

FIGURE 2. Generalized sequence of rock units in the Florissant paleovalley.

luvium is older than the Wall Mountain Tuff and does not contain clasts of welded tuff (Epis and Chapin 1975). However, the boulder conglomerate beds in the monument are equivalent to the Tallahassee Creek Conglomerate, which also contains clasts of the Wall Mountain Tuff. A small exposure of the Tertiary boulder conglomerate also occurs near the bottom of the paleovalley along Twin Creek (NE¼ NW¼ sec. 3, T. 13 S., R. 71 W., Fig. 1).

The Florissant paleovalley was episodically dammed by volcaniclastic debris flows (lahars) derived from the Thirtynine Mile volcanic field to the southwest (Fig. 3). These lahar deposits are poorly sorted, brown to purple, muddy breccias that contain intermediate volcanic clasts and granite fragments. They are part of the Thirtynine Mile Andesite of Wobus and Epis (1978). Their margins progressed northward in the paleovalley, reaching the south end of the monument by the end of lacustrine deposition of the Florissant Formation. These lahar deposits acted as dams to the Florissant valley drainage, creating the ancient Florissant lakes. The upper andesitic breccias from the Thirtynine Mile volcanic field covered the paleovalley sequence, and are preserved at the top of the butte south of the monument (SE¼ sec. 25, T. 13 S., R. 71W.)

Lithostratigraphy of the Florissant Formation

The primary fossil-bearing unit in the area is the Florissant Formation. This unit was named the Florissant Lake Beds by Cross (1894) and this designation has been used by subsequent workers (Niesen 1969; Wobus and Epis 1978). However, the unit contains many mudstone, sandstone, and conglomerate beds that were deposited by streams. The name Florissant Lake Beds does not conform to the modern criteria set forth by the North American Commission on Stratigraphic Nomenclature (1983, Article 22d) that states depositional environments should not be used in the definition of a lithostratigraphic unit. Thus, we redefine the name of the formation as the Florissant Formation.

The Florissant Formation contains a wide variety of lithologies, including arkosic granule conglomerate, volcaniclastic conglomerate, pumice conglomerate, sandstone, tuffaceous mudstone and siltstone, carbonaceous shale, and papery diatomaceous shale (McLeroy and Anderson 1966). The formation includes sediment derived from upstream sources (indicated primarily by metamorphic clasts), local sources (indicated by granite clasts), and volcanic sediments primarily derived from the Thirtynine Mile volcanic field. The formation was deposited on an erosional surface that cut the Pikes Peak Granite and the Wall Mountain Tuff. The formation contains six informal units (Fig. 4), which include (from bottom to top) the lower shale, the lower mudstone, the middle shale, the caprock conglomerate, the upper shale, and the upper pumice conglomerate. Previous stratigraphic work in the monument by Murphey (1992) and Evanoff and Murphey (1994) referred to the lower mudstone, middle shale, caprock conglomerate, upper shale, and upper pumice conglomerate by the alphanumeric designation Tf^1, Tf^2, Tf^3, Tf^4, and Tf^5, respectively. These alphanumeric unit names were used for classification of mapped outcrops in the monument, and were not intended to be used outside the monument.

The lower shale unit is characterized by alternating tuffaceous siltstone and paper shale beds. The paper shales consist of alternating laminae of diatomite and volcanic ash altered to smectite clays (O'Brien et al. 1998). Thin pumice conglomerate, pumiceous sandstone, and granular conglomerate with granite and volcanic clasts are also scattered throughout the unit. This unit is exposed only near the base of the paleovalley sequence north of the monument. It is exposed in the road cut east of the town of Florissant and at the Clare Quarry south of the town (Fig. 1). The greatest thickness of the lower shale unit is 11.4 m as exposed in the Florissant road cut (Fig. 1, Table 1, Locality 1) where the unit overlies a thin sequence of granular arkosic conglomerate beds and a tuffaceous mudstone containing pumice and granite granules (Fig. 4). The shale beds not only contain plants and insects, but most of the fish and almost all of the bird fossils known from the Florissant Formation. The pollen of the lower shale unit from the Florissant road cut has been described by Leopold and Clay-Poole (2001). The lower shale unit represents deposition in an early expansion of the Florissant lake.

The lower mudstone unit is a sequence of gray tuffaceous mudstone beds, muddy pumiceous conglomerate beds, and rare cross-bedded sandstone and conglomerate ribbons, overlain by a thick, structureless to weakly horizontally bedded, tuffaceous sandy mudstone. The fossilized *Sequoia* and angiosperm stumps (see Gregory-Wodzicki 2001; Wheeler 2001) in the "petrified forest" area of the monument are at the base and are surrounded by these upper sandy mudstone beds. Most of the fossil mammals of the Florissant Formation occur in the mudstone beds below the level of the bases of the stumps. The thickest exposed sequence of

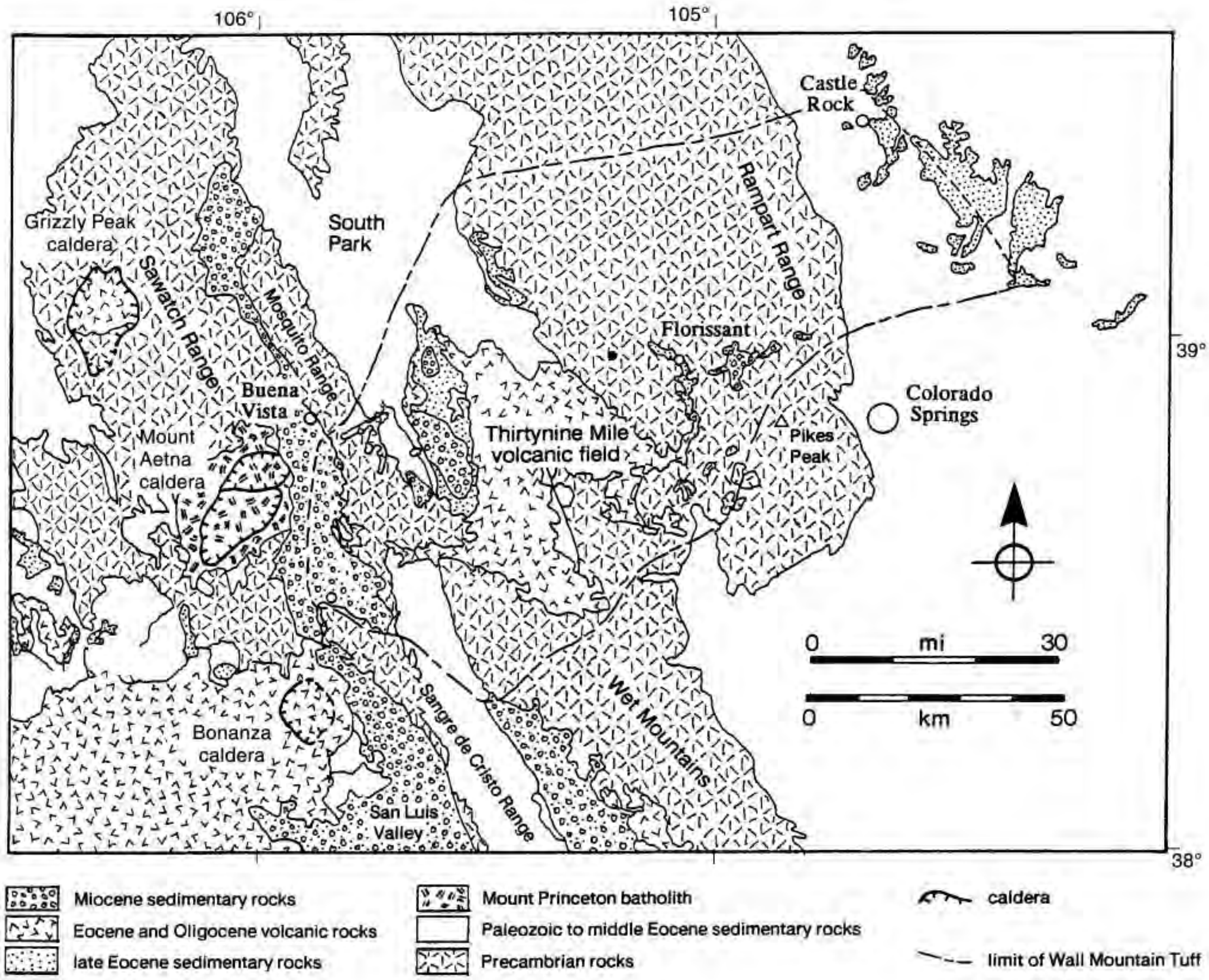

FIGURE 3. Regional map of central Colorado emphasizing Cenozoic geologic features.

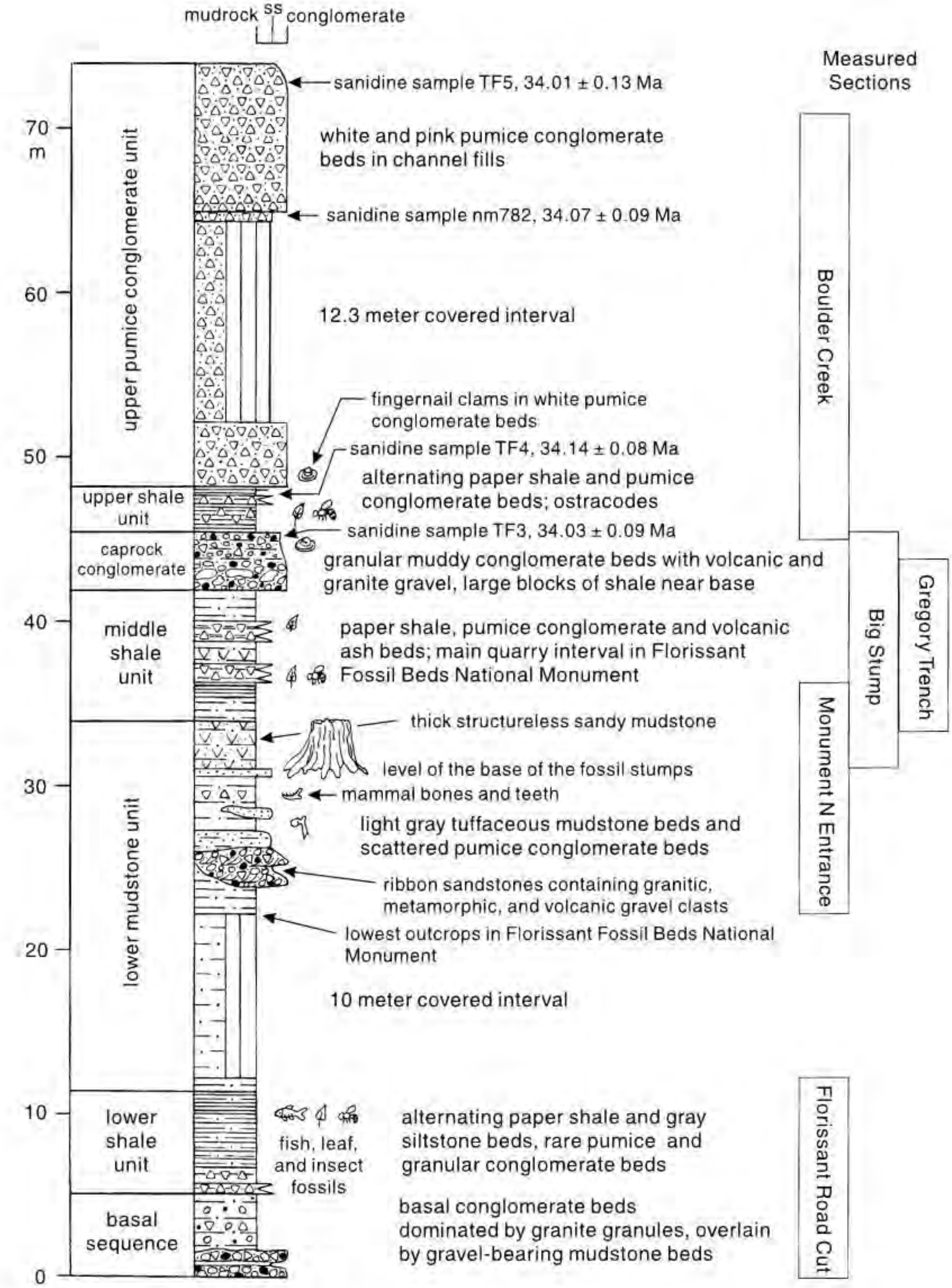

FIGURE 4. Informal subdivisions of the Florissant Formation. This sequence is compiled from the various measured sections at Localities 1–5 as shown in Figure 1 and listed in Table 1. The vertical bars on the right show the vertical range of the stratigraphic sections listed in Table 1.

the lower mudstone unit is 10.4 m near the north entrance road of the monument (Figs. 1, 4, Table 1, Locality 2). The base of the mudstone unit is not exposed in the monument, but is exposed near the top of the Florissant road cut section (Fig. 1, Locality 1). The elevation differences and regional dips of the formation suggest that the unit has an additional thickness of about 10 m. Trough cross-bed sets in the rare sandstone ribbon bodies in this unit show paleocurrent flow directions to the south within a trunk stream flowing down the axis of the main valley. The upper structureless sandy mudstone was deposited as a mudflow that buried the forest in the valley. Its upper part was reworked into horizontal beds by the redevelopment of the Florissant lake.

The middle shale unit (Fig. 4) is characterized by platy to papery shale beds interbedded with thin pumiceous conglomerate beds. The shale beds are also interbedded with scattered blocky to platy tuffaceous mudstone and siltstone beds, tuffs, and pumiceous sandstone beds. McLeroy and Anderson (1966) and O'Brien et al. (1998) studied the laminations in the papery shale beds and found them to be composed of alternating laminae of diatomite and smectite clay. The middle shale unit has a maximum thickness of 9 m in the center of the paleovalley axis. It is best exposed around the hill near the "big stump" (Fig. 1, Table 1, Locality 3) and at the mouth of the Grape Creek arm of the paleovalley (Fig. 1, Table 1, Locality 4). The transition from shale to granitic granular conglomerate beds on the edge of the paleovalley occurs at the mouth of the Grape Creek arm. Rare bones of mammals occur in the granite conglomerate lateral to the middle shale unit south of the Grape Creek arm. Most of the famous fossil plant and insect localities in the monument are from within this unit, but fish, mollusks, and ostracodes are very rare. Gregory (1994) studied the leaves and Wingate and Nichols (2001) studied the pollen in the middle shales at the mouth of Grape Creek (Fig. 1, Locality 4). The middle shales are lacustrine and record an episode of volcanic activity with the addition of pumice beds in the upper two thirds of the unit (see Wingate and Nichols 2001).

A widespread tuffaceous volcaniclastic conglomerate overlies the middle shale unit. This conglomerate is known in the monument as the "caprock" because it caps ridges and benches above the main fossil-producing shale beds (Figs. 2, 4). The clasts in the caprock conglomerate include abundant granite granules and numerous pebbles to granules of intermediate volcanic rocks. It is crudely graded, with pebbles and scattered cobbles or boulders at the base and muddy sandstone at the top. Bedding changes from primarily structureless at the base to horizontally bedded at the top. Vertical tubes representing water-escape structures occur in the middle part of this unit. Freshwater fingernail clams locally occur in the upper half of the unit. The unit is thickest in the central axial valley in the monument, but thins toward the north and northeast in the axial valley and up the tributary valleys. Just north of the monument, the caprock conglomerate pinches out. The thickest exposure of the caprock conglomerate is on the "big stump" hill (Fig. 1, Table 1, Locality 3) where it is 7.3 m thick. This conglomerate was initially a lahar deposit that entered the Florissant lake and was later reworked by lacustrine processes.

The upper shale unit (Fig. 4) is composed primarily of brownish-gray paper shale and secondarily of blocky mudstone and pumice conglomerate. Fossils are locally abundant in the shale, and include plants, insects, fish scales, and ostracodes. In the monument, the upper shale unit is thickest in the mouths of the western tributary valleys where it ranges from 3.6 to 5.6 m thick. The most complete exposures are along the Boulder Creek (Fig. 1, Table 1, Locality 5). Wingate and Nichols (2001) studied the pollen of this unit at this location. In the northwest corner of the monument where the caprock conglomerate is not present, the upper shale unit overlies the middle shale unit. Lithologically, the upper and middle shale units are similar, but the upper shale unit typically contains abundant ostracodes and numerous fingernail clam shells, unlike the middle shale unit. The upper shales represent lacustrine deposition after the influx of the caprock lahar deposits.

The upper pumice conglomerate unit (Fig. 4) consists of pumice-rich, white sandstone and conglomerate that are structureless near the base and cross-bedded near the top. The pumice fragments are typically granular and white with scattered pink clasts. The pumice conglomerate beds are exposed only at the head of the western tributary valleys of the main paleovalley, where they are as much as 22.8 m thick. Where the contact between the upper shales and the pumice conglomerate beds is exposed, the two units interfinger. The best exposures of the upper pumice conglomerate are north of the Boulder Creek (Fig. 1, Table 1, Localities 6, 7). The lower part of the pumice conglomerate unit was deposited in the Florissant lake, as indicated by locally abundant fingernail clam shells. The upper cross-bedded conglomerate beds represent deposition by streams flowing down the tributary valleys.

Mammalian Biostratigraphy of the Florissant Formation

The mammal fossils of the Florissant Formation provide biostratigraphic correlation with upper Eocene deposits of the Great Plains (Evanoff and deToledo 1999). The lower mudstone unit contains the mandible of the horse *Mesohippus* sp., the bones of a small artiodactyl (*Leptomeryx*? sp.), and the tooth fragments of large brontotheres. The arkosic conglomerate adjacent to the middle shale unit has produced the bones of oreodont artiodactyls and brontotheres. Other mammals reported from the formation include the oreodont *Merycoidodon* sp. (MacGinitie 1953), an unidentified rhinoceros, and the mouse opossum (*Peratherium*). Of these, only the mouse opossum has been described in detail (as *Peratherium* near *P. huntii;* Cope, see Gazin 1935). The co-occurrence of a large brontothere, *Mesohippus*, and *Merycoidodon* indicates a Chadronian age for the formation (Wood et al. 1941). These mammals indicate that the Florissant Formation correlates with the Chadron Formation of the White River Group of the Great Plains.

$^{40}Ar/^{39}Ar$ Geochronology of the Florissant Formation

Laser-fusion analyses of a total of sixty-six individual sanidine crystals from four pumiceous samples of the upper Florissant Formation (Fig. 5, Table 3) yielded high-precision single-crystal ages ranging from 33.64 ± 0.22 Ma to 34.53 ± 0.15 Ma (all errors reported at ±2 sigma). Radiogenic yields generally ranged from 99.5 to 100 percent, indicative of minimal alteration or adhering matrix. K/Ca values (calculated from K-derived ^{39}Ar and Ca-derived ^{37}Ar) cluster tightly near a value of 45, suggesting minimal compositional variation among the crystals. Weighted mean ages calculated for each of the four samples (Table 2) all agree within error, and do not show a systematic variation with stratigraphic sequence, suggesting that the sanidine-bearing pumice was derived from a single eruption or closely spaced series of eruptions. The weighted mean of the four sample ages (34.07 ± 0.12 Ma) agrees closely with the weighted mean age of all sixty-six sanidine crystals (34.07 ± 0.10 Ma); we consider the latter to be the best estimate for the eruption age of silicic pumice in the Florissant Formation. The range in ages shown by the entire population of sixty-six individual crystals is somewhat greater than that typically observed in sanidine crystals from individual ignimbrites (e.g., McIntosh and Chamberlin 1994), but the distribution of ages is unimodal and approximately Gaussian (Fig. 5). This age variation among crystals may be related to minor effects of melt inclusions in the sanidine crystals, but may also reflect some small variation in age of eruptions that produced the pumice clasts.

It is considered likely that the Florissant Formation was deposited soon after eruption of the 34.07 ± 0.10 Ma pumice clasts. Although the Florissant Formation lacks definite primary volcanic deposits, such as ignimbrites or pyroclastic fall deposits, several features are consistent with deposition penecontemporaneous with eruption. This interpretation is supported by the close agreement in age of the four stratigraphically distributed samples, the abundance of sanidine-bearing pumice of this age, the unimodal distribution of the single-crystal ages and K/Ca ratios, and the lack of any significantly older or younger pumice fragments.

Eruptive Source of Pumice and Ash in the Florissant Formation

The eruptive source of the silicic pumice and ash in the Florissant Formation is uncertain. Lithologically similar nonwelded pumiceous ignimbrites and reworked sedimentary deposits are present in the Antero Tuff, erupted from the Mount Aetna caldera and exposed in the Thirtynine Mile volcanic field to the south and west of Florissant (Fig. 3). However, sanidine from Antero Tuff has a measurably younger age (33.78 ± 0.09 Ma) than the Florissant Formation sanidine, and significantly higher K/Ca ratios (68.1 ± 16.4) per McIntosh (unpubl. data). The Grizzly Peak caldera (Fig. 3) is another potential source for the Florissant Formation pumice, but no outflow ignimbrites have been identified, and sanidine from samples of the Grizzly Peak intracaldera ignimbrite are older (34.31 ± 0.09 Ma) than the Florissant Formation sanidine, and also have higher K/Ca ratios (84.4 ± 6.2 Ma) per McIntosh (unpubl. data). Given available data, three possible sources for the 34.07 ± 0.10 Ma Florissant Formation pumice can be suggested: (1) early, pre-ignimbrite eruptions from the 33.8 Mount Aetna caldera, (2) late, post-ignimbrite eruptions from the 34.3 Ma Grizzly Peak caldera, or (3) eruption of local rhyolite domes in the vicinity of Florissant. Geologic mapping in the Florissant area has not identified any rhyolitic domes in the appropriate 34 Ma age range, although it is possible that such domes were present but are now eroded or covered.

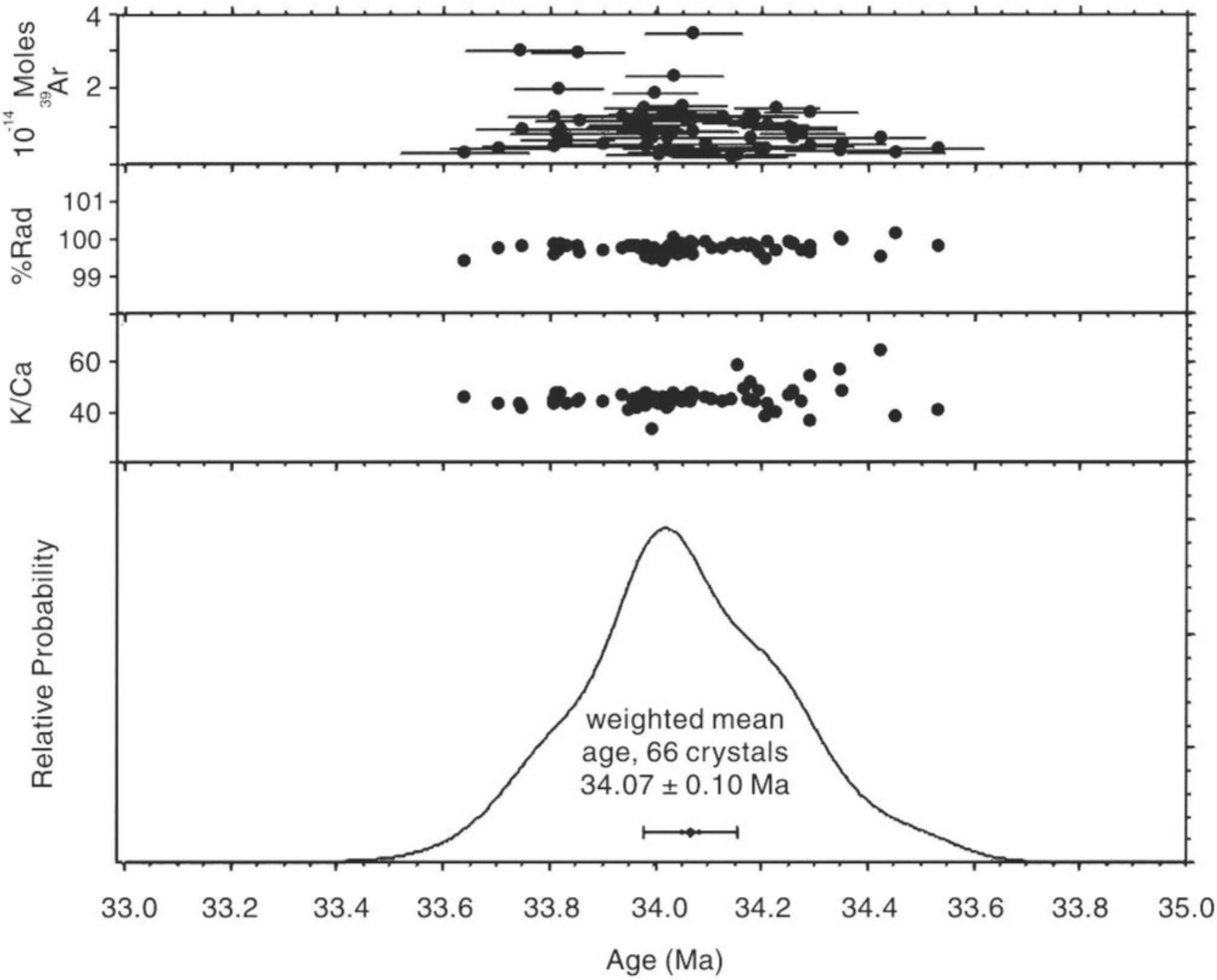

FIGURE 5. Ideogram (age probability diagram; Deino and Potts 1992) of single-crystal laser-fusion results of sanidine from the Florissant Formation.

Conclusions

The Florissant Formation is a heterolithic assemblage of shale, tuffaceous mudstone and siltstone, arkosic and volcaniclastic sandstone, and conglomerate. The formation was deposited within a valley that drained to the south. The valley was episodically blocked by lahar deposits, which eventually extended at least to the monument. The Florissant Formation records two episodes of lake formation. The first lacustrine episode is represented by the lower shale unit. These lower lacustrine deposits were separated from the middle lacustrine shale beds by a fluvial unit (the lower mudstone unit). The caprock conglomerate divides the upper lake sequence into two shale sequences within most of the monument area. The lacustrine deposits were eventually buried first by pumice gravel and then by additional laharic breccias from the Thirtynine Mile volcanic field. Post-Oligocene erosion has exposed the formation such that much of its present distribution reflects the original extent of the paleovalley fill.

The $^{40}Ar/^{39}Ar$ age of 34.07 ± 0.10 Ma of the Florissant Formation places its age within the latest Eocene. The current widely accepted age of the Eocene/Oligocene boundary is at 33.7 Ma $\pm$ 0.5 Ma, based on the age of the boundary stratotype in the northern Apennine Mountains of Italy (Montanari et al. 1988). McIntosh et al. (1992) have suggested a younger age for the boundary (near 33.4 Ma) based on calibrating the geomagnetic polarity time scale using $^{40}Ar/^{39}Ar$ dated ignimbrites in Colorado, New Mexico, and west Texas. Both ages for the boundaries place the Florissant Formation in the latest Eocene. The presence of large brontotheres also suggests a latest Eocene age for the formation because brontotheres became extinct at or very near the Eocene/Oligocene boundary in the Great Plains (Obradovich et al. 1995).

Acknowledgments

The first and third authors thank Johann Burgert, Rena Brill, Karolyn Darrow, Kentaro Doi, Boyce Drummond, Peter deToledo, and Debra Krumm for their help in the field. Access and support for this study have been provided by superintendents Dale Ditmanson and Jean Rodeck, head rangers Margaret A. Johnston and Tom Ulrich, and monument paleontologists Dr. Robert Cushman and Dr. Herbert Meyer, all previously or currently working at Florissant Fossil Beds National Monument. Funding for the fieldwork for the original stratigraphic study was provided by the University of Colorado Museum in Boulder.

The second author thanks Chuck Chapin and Kate Gregory-Wodzicki for introducing him to Florissant and the Thirtynine Mile volcanic field. We appreciate the assistance of Lisa Peters and Richard Esser in the New Mexico Geochronology Research Lab. The $^{40}Ar/^{39}Ar$ dating work was supported in large part by funding from the New Mexico Bureau of Mines and Mineral Resources.

Debra Hanneman, Herbert Meyer, and Doug Nichols reviewed the manuscript and provided many helpful suggestions for improvements.

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