Age of the plant-bearing tuffs of the John Day Formation at Fossil, Oregon, based upon $^{40}Ar/^{39}Ar$ single-crystal dating

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ABSTRACT

The age of the fossil plant locality in the town of Fossil, Oregon, is estimated based upon $^{40}Ar/^{39}Ar$ analysis of sanidine crystals from the fossil-bearing tuffaceous shale. The resulting date of 32.58±0.13 Ma provides a more reliable date for the locality than previous whole-rock K-Ar dates of the underlying basalt (29.7±1.6 Ma and 33.8±1.7 Ma). The new date confirms an early Oligocene age for the flora, shows that the assemblage is approximately coeval with that of the Bridge Creek flora at the Painted Hills locality, and indicates that hardwood deciduous forest similar to that found today in eastern North America and eastern Asia was established less than 1.5 million years following the Eocene-Oligocene transition.

INTRODUCTION

A well-known locality for fossil plants occurs in the lower part of the John Day Formation in the town of Fossil, Oregon. A general overview of the plant assemblage from this locality, including brief descriptions and illustrations of the characteristic species, was presented by Manchester and Meyer (1987). Many additional taxa have been collected subsequently, and the assemblage is now known to contain more than 65 plant species (Meyer and Manchester, in press) as well as skeletal remains of bat (Brown, 1959), salamander (Naylor, 1979), and frog (T. Dillhoff, T. Fremd, oral communication, 1994). The fossil leaves, cones, flowers, and fruits represent a hardwood deciduous forest similar in composition to present-day forests of temperate eastern North America and eastern Asia. Based upon floral similarities with other fossil assemblages of the John Day Formation, the Fossil locality has been assigned to the Bridge Creek flora and has been considered to be Oligocene (Brown, 1959; Manchester and Meyer, 1987), but direct radioisotopic data have only recently become available.

The fossils occur in tuffaceous lake sediments. In the summer of 1995, we collected a sample of the fossil-bearing tuff from the Wheeler High School locality for radioisotopic age determination. Relatively large euhedral sanidine crystals were isolated from the sample and then dated using the single-crystal laser-fusion $^{40}Ar/^{39}Ar$ dating method. Such age determinations, obtained directly from fossil-bearing rocks, provide an important link between biostratigraphic and radioisotopic geologic time scales. The purpose of this report is to summarize the $^{40}Ar/^{39}Ar$ dating technique, present age results, compare the results with earlier K-Ar dates, and discuss the relevance of the date to the fossil plant assemblage at Fossil.

$^{40}AR/^{39}AR$ DATING TECHNIQUE

The argon-argon ($^{40}Ar/^{39}Ar$) dating technique offers several advantages over conventional potassium-argon (K-Ar) dating (Maluski, 1989). Both methods rely on the natural radioactive decay of ^{40}K to ^{40}Ar (the half-life of ^{40}K is 1.25 Ga [giga-annum=10^9 years]). Assuming that all ^{40}Ar gas escaped from the volcanic melt prior to formation of sanidine crystals, any measurable ^{40}Ar gas found in the sanidine crystals of a rock sample may be attributed to the decay of ^{40}K. Accordingly, the ratio of parent ^{40}K to daughter ^{40}Ar can be measured and used to calculate the age of the rock. In the conventional K-Ar dating technique, K and Ar are measured on separate aliquots of sample. In the $^{40}Ar/^{39}Ar$ technique, the sample is irradiated with neutrons in a nuclear reactor, converting some of the K into ^{39}Ar, which then serves as a proxy for the K. The ratio of parent to daughter isotopes is then measured as the ratio of ^{39}Ar to ^{40}Ar in a single aliquot of sample. This approach allows ages to be measured far more precisely than the conventional K-Ar technique and uses much smaller sample sizes. Laser-heating enables precise ages to be measured on individual, sand-sized mineral grains, permitting identification and rejection of contaminant or altered grains. This method is known as single-crystal laser-fusion $^{40}Ar/^{39}Ar$ dating. One constraint of the $^{40}Ar/^{39}Ar$ dating technique is that all samples must be irradiated with "monitor" minerals of known age in order to accurately determine the flux of neutrons received.

METHODS

A crystal-rich sample of tuffaceous sediment bearing fossil leaf impressions was collected from the Wheeler High School fossil locality (SW¼NW¼ sec. 33, T. 6 S., R. 21 E.). The sample was prepared by crushing and sieving to 120-500 μ (micron), followed by ultrasonic cleaning in dilute (7-percent) hydrofluoric acid. A sanidine separate was produced, using a Franz magnetic separator, density liquids (nontoxic lithium metatungstate), and hand-picking. A 20-mg aliquot of the sanidine separate was packaged with flux monitors of Fish Canyon Tuff sanidine (27.84 Ma, relative to Mmhb-1 hornblende at 520.4 Ma; Samson and Alexander, 1987) and irradiated at the Texas A&M Nuclear Research Center for 14 hours.

$^{40}Ar/^{39}Ar$ analyses were performed at the New Mexico Geochronology Research Laboratory of the New Mexico Institute of Mining and Technology. This facility includes an MAP 215-50 mass spectrometer attached to a fully automated all-metal argon extraction system equipped with a 10-watt CO_2 laser. A total of 31 sanidine crystals from the sample and four to six sanidine crystals from each monitor were individually analyzed. Sanidine crystals were fused by CO_2 laser for 15 seconds; then reactive gases were removed with an SAES GP-50 getter prior to expansion into the mass spectrometer. Extraction line blanks during these analyses ranged from 5×10^{-17} to 2×10^{-16} moles ^{40}Ar and 5×10^{-19} to 2×10^{-18} moles ^{36}Ar. The neutron flux values (J-values) within irradiation packages were determined to a precision of ±0.25 percent by averaging results from six sanidine crystals from each sanidine monitor.

RESULTS AND DISCUSSION

Single-crystal laser-fusion results are summarized in Table 1 and Figure 1. The 31 analyzed crystals range in age from 32.30 to 33.04 Ma, with analytical precisions (±1 standard deviation) generally between ±0.09 and ±0.15 Ma. The K-Ca ratios of individual sanidine crystals (calculated from $^{37}Ar/^{39}Ar$ measurements) range from 22.4 to 39.4, consistent with their derivation from a single eruptive source. The mean age of 30 crystals (excluding crystal 5887–23, which, at 33.04 Ma, is slightly but distinctly older than the other crystals) is 32.58±0.13 Ma. This mean was calculated by equally weighting the values from each crystal, and the error is a simple ±1 standard deviation.

The resulting age of 32.58±0.13 Ma for the leaf-bearing tuff at Fossil provides a refinement over previous unpublished ages obtained for the locality. Our age falls between two whole-rock K-Ar ages presented in a master's thesis by Riseley (1989) from an andesitic basalt immediately underlying the tuffaceous shales. These ages, from Geochron Laboratories, were 29.7±1.6 Ma and 33.8±1.7 Ma. A suite of ten crystals extracted from the same tuff as that treated in the present paper gave a slightly younger $^{40}Ar/^{39}Ar$ age of 32.24±0.18 Ma in an earlier un-

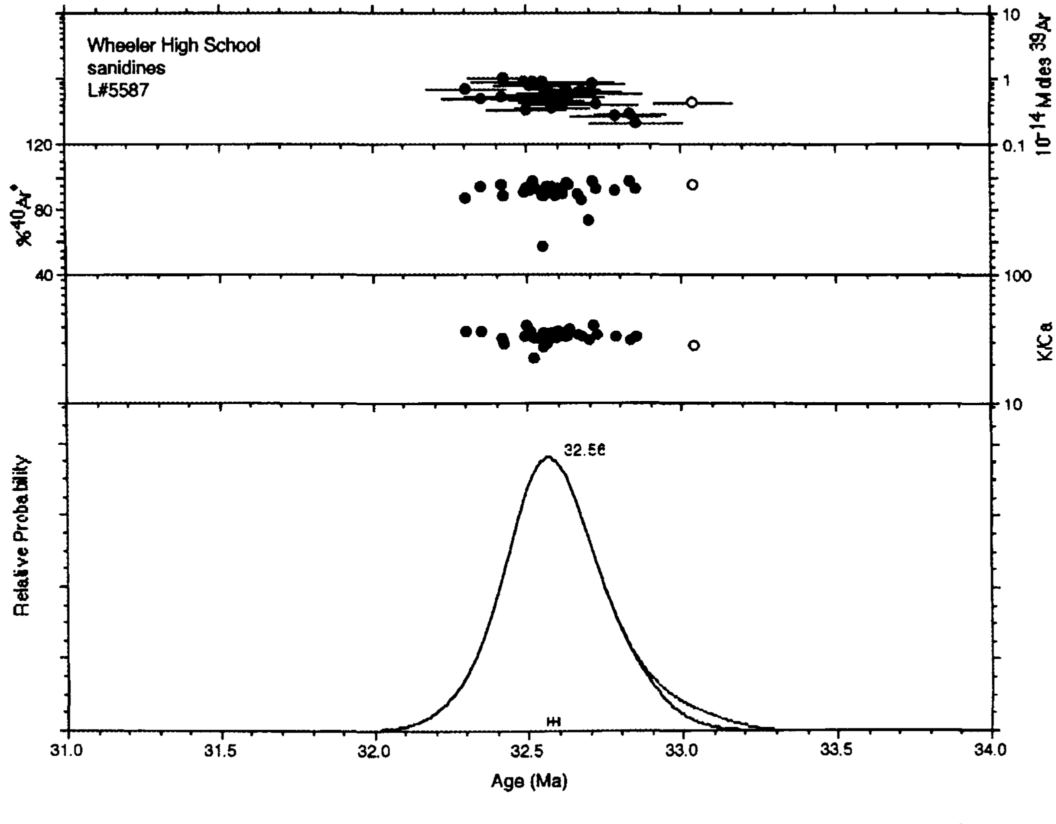

Figure 1. Single-crystal laser-fusion results from sanidines from Wheeler High School sample. Values plotted versus age are signal size in moles ^{39}Ar, radiogenic yield, K-Ca ratio, and relative probability. Analyses used in the mean age calculation are shown as solid circles, and the one analysis excluded from the mean is shown by an open circle. Age uncertainty of each analysis (±1 standard deviation) is shown as horizontal bars on age versus moles ^{39}Ar. The relative probability curve, or ideogram, is the sum of the gaussian probabilities of the individual age determinations.

Table 1. *Single-crystal laser-fusion $^{40}Ar/^{39}Ar$ results. All ages of single sanidine crystals. Errors expressed as ±1 σ. Results in italics excluded from mean values*

Run ID no.	^{40}Ar/^{39}Ar	^{37}Ar/^{39}Ar	^{36}Ar/^{39}Ar	^{39}K moles	K/CA	%^{40}Ar*	Age (Ma)	± Err
5587-20	14.41	1.43E-02	6.39E-03	6.9E-15	35.6	86.9	32.30	0.11
5587-32	13.38	1.41E-02	2.83E-03	4.9E-15	36.2	93.8	32.35	0.11
5587-25	13.26	1.63E-02	2.34E-03	5.2E-15	31.4	94.8	32.42	0.10
5587-40	14.33	1.77E-02	5.96E-03	9.8E-15	28.8	87.7	32.43	0.10
5587-37	13.96	1.55E-02	4.63E-03	8.8E-15	33.0	90.2	32.49	0.10
5587-39	13.56	1.29E-02	3.25E-03	3.3E-15	39.4	92.9	32.50	0.11
5587-28	13.52	1.40E-02	3.12E-03	4.9E-15	36.5	93.2	32.51	0.10
5587-10	13.86	1.49E-02	4.28E-03	7.5E-15	34.2	90.9	32.51	0.10
5587-33	12.92	1.59E-02	1.05E-03	8.6E-15	32.0	97.6	32.52	0.09
5587-36	13.19	2.29E-02	1.99E-03	8.6E-15	22.3	95.6	32.52	0.09
5587-04	13.66	1.64E-02	3.57E-03	8.0E-15	31.2	92.3	32.53	0.09
5587-07	22.16	1.44E-02	3.23E-02	8.8E-15	35.4	57.0	32.55	0.21
5587-30	14.30	1.89E-02	5.69E-03	8.1E-15	26.9	88.2	32.55	0.11
5587-03	14.28	1.56E-02	5.63E-03	5.7E-15	32.8	88.4	32.56	0.11
5587-22	13.51	1.79E-02	3.02E-03	4.5E-15	28.6	93.4	32.56	0.10
5587-02	13.43	1.47E-02	2.73E-03	6.1E-15	34.8	94.0	32.58	0.09
5587-27	13.41	1.47E-02	2.65E-03	3.4E-15	34.8	94.2	32.58	0.10
5587-35	14.45	1.63E-02	6.14E-03	5.6E-15	31.3	87.5	32.59	0.11
5587-31	13.72	1.39E-02	3.66E-03	4.2E-15	36.6	92.1	32.60	0.11
5587-34	14.19	1.56E-02	5.24E-03	3.9E-15	32.7	89.1	32.62	0.12
5587-38	13.21	1.55E-02	1.92E-03	6.9E-15	32.8	95.7	32.63	0.09
5587-06	13.33	1.39E-02	2.30E-03	5.3E-15	36.8	94.9	32.64	0.10
5587-09	14.27	1.52E-02	5.44E-03	6.0E-15	33.5	88.7	32.66	0.11
5587-01	14.72	1.57E-02	6.94E-03	6.3E-15	32.6	86.1	32.68	0.11
5587-08	17.40	1.65E-02	1.60E-02	5.8E-15	30.9	72.8	32.70	0.15
5587-21	13.01	1.29E-02	1.10E-03	8.0E-15	39.5	97.5	32.71	0.09
5587-26	13.74	1.50E-02	3.58E-03	4.1E-15	34.0	92.3	32.73	0.12
5587-05	13.96	1.56E-02	4.23E-03	2.8E-15	32.8	91.1	32.79	0.13
5587-29	13.05	1.64E-02	1.08E-03	2.8E-15	31.0	97.6	32.84	0.10
5587-24	13.73	1.56E-02	3.38E-03	2.0E-15	32.7	92.7	32.85	0.13
5587-23	*13.47*	*1.84E-02*	*2.26E-03*	*4.2E-15*	*27.7*	*95.1*	*33.04*	*0.11*

Mean values: n=30; K/Ca=33.0±3.5; age=32.58±0.13

Analytical parameters: Mass discrimination=1.005±0.002; $^{39}Ar_{Ca}/^{37}Ar_{Ca}$=0.0007±0.0005; $^{36}Ar_{Ca}/^{37}Ar/_{Ca}$=0.00026±0.00002; $^{38}Ar_K/^{39}Ar_K$=0.0119; $^{40}Ar_K/^{39}Ar_K$=0.0002±0.0003; J-value=0.001442918±0.000002. Decay constants from Steiger and Jager (1977).

published analysis (Brent Turrin, written communication to Manchester, 1989).

The new age of 32.58±0.13 Ma is consistent with those obtained for rocks associated with the classic locality of the Bridge Creek flora at the Painted Hills Unit of John Day Fossil Beds National Monument. Evernden and others (1964) published K-Ar ages of 31.8 and 32.3 Ma (corrected to decay constants of Steiger and Jager, 1977) based upon sanidine crystals from tuffs and whole-rock analysis of basalt, respectively. More recently, ^{40}Ar/^{39}Ar ages of 32.99±0.11 Ma and 32.66±0.03 Ma were obtained from a biotite tuff 3–5 m stratigraphically below the leaf-bearing tuffs at Painted Hills and from a tuff situated well above the leaf beds, respectively (C. Swisher *in* Bestland and Retallack, 1994); Bestland and others, 1994; Retallack and others, 1996).

The new radiometric data indicate that the Bridge Creek flora, represented by temperate forest assemblages at Fossil, Painted Hills, and various other sites in north-central Oregon (Meyer and Manchester, in press), are early Oligocene in age. Swisher has obtained a radiometric age of 33.62±0.19 for the "slanting leaf beds" on Iron Mountain (Retallack and others, 1996). With the Eocene/Oligocene boundary now placed at about 34.0 million years (Swisher and Prothero, 1990; Berggren and others, 1992), these ages show that the Bridge Creek flora, as known at Fossil, Painted Hills, and Iron Mountain, is representative of the forest that had developed within 0.3–1.5 million years following the Eocene-Oligocene transition.

ACKNOWLEDGMENTS

This research was funded in part by grant EAR 9506727 from the National Science Foundation to S.R. Manchester. Thanks are owed to the citizens of Fossil, Oregon, for keeping the Wheeler High School locality open for public fossil collecting. Critical comments on the original paper were kindly provided by Jeff A. Myers and Wesley Wehr.

(Continued on page 20)

OREGON GEOLOGY

published by the
Oregon Department of Geology and Mineral Industries

VOLUME 59, NUMBER 1 JANUARY/FEBRUARY 1997

IN THIS ISSUE:

OREGON GEOLOGY

(ISSN 0164-3304)

VOLUME 59, NUMBER 1 JAN./FEB. 1997

Published bimonthly in January, March, May, July, September, and November by the Oregon Department of Geology and Mineral Industries. (Volumes 1 through 40 were entitled *The Ore Bin*.)

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Cover photo

Slab of shale with fossil plant remains from the locality at Fossil, Oregon, at 85 percent of natural size. Impressions include leaves of *Juglans, Porrotia, Paracarpinus, Alnus*, and *Quercus*, fruit valves of *Craigia*, and an *Acer* samara. Specimen collected 1988 and housed at Florida Museum of Natural History, Gainesville, Florida. Article beginning on next page dates locality at about 32.6 million years.

In memoriam: John Eliot Allen

He was one of the "grand old men" of Oregon geology, well known as geologist, teacher, and author.

John Eliot Allen began his professional career in 1935 as a ranger-naturalist at Crater Lake National Park. In 1937, he became part of the beginnings of the Oregon Department of Geology and Mineral Industries, first as a "Field Geologist," finally as "Chief Geologist." He was one of three geologists with a doctoral degree (along with Wallace D. Lowry and Ewart M. Baldwin) whose simultaneous departure for better positions in industry or the academic world hit the agency hard in 1947.

John Eliot Allen, 1908–1996

Aside from his regular duties, field mapping continued to be a favorite occupation of his until 1954, and he conducted field studies in California, Washington, Nevada, New Mexico, Arizona, and Pennsylvania as well as in Oregon. His last geologic quadrangle map was produced on airphoto mosaics—"perhaps the first time they had been used that way," he wrote in his autobiography. (A brief summary appeared in *Oregon Geology* in the May 1994 issue.)

He guided the first steps of the Portland State University Geology Department, building its program and serving as its head for 18 years, from 1956 to 1974. For his outstanding and enthusiastic teaching, the National Association of Geology Teachers honored him with the Neil Miner Award in 1972. In his lectures, he was using a multimedia approach already in the 1960s. In 1995, he received a Presidential Citation from Portland State University for his "outstanding service and dedication."

When he retired from teaching in 1974, he concentrated on writing about geology for the lay reader. PSU commented on this start of his "third career" with the words, "And he has yet to slow down." The latest of his hundreds of articles and books is reviewed on page 21 of this issue.

John Eliot Allen died November 17, 1996, at age 88. He never slowed down. ☐