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TIMING OF EMPLACEMENT OF THE SAPPHIRE-BEARING YOGO DIKE, LITTLE BELT MOUNTAINS, MONTANA

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Introduction

Most corundum deposits worldwide are found in alluvial deposits and their source is uncertain. However, a rare sapphire-bearing ultramafic dike is found in the northern Little Belt Mountains of central Montana. The Yogo dike, as it is known, is the world's only well-documented occurrence of mined gem-quality corundum associated with an igneous intrusion and is thus of economic importance. At the Yogo deposit, corundum is typically found as cornflower-blue stones and at one time, the Yogo sapphire field was described as "the most important gem locality in the United States" (Clabaugh, 1952, p. 6). The Yogo dike is thought to be Tertiary in age, mainly because of its compositional similarity to dated rocks elsewhere in the Little Belt Mountains, but the dike that hosts this unusual mineral deposit has not been isotopically dated. As part of an attempt to determine more precisely the timing, duration, and spatial migration of Late Cretaceous and Tertiary magmatic activity in central Montana using the high-precision $^{40}Ar/^{39}Ar$ dating technique, this report presents the first isotopic dates from the Yogo dike. Indeed, these are the first such dates reported from any of the rocks of the central Montana alkalic province (Chadwick, 1972).

Geology of the Yogo Dike

The Yogo dike is found along the northeastern flank of the Little Belt Mountains (Fig. 1), a basement-cored uplift that was structurally elevated during Laramide (Late Cretaceous-early Tertiary) contractional deformation. Because of its economic importance, the petrology and geochemistry of the dike have been the subject of numerous studies, the most important of which include Weed and Pirsson (1900), Clabaugh (1952), Meyer and Mitchell (1988), and Dahy (1991). A detailed, nontechnical description of the history and development of the deposit is given by Voynick (1985).

The dike cuts gently east-dipping Mississippian carbonate and clastic strata of the Madison and Big Snowy Groups (Clabaugh, 1952; Zimmerman, 1966; Dahy, 1991; Fig. 1). It strikes N 75° E, is nearly vertical, and extends in three distinct en echelon segments for a cumulative distance of about 8 km. The dike thickness ranges from 0.6 to 8 m and averages about 2.4 m (Clabaugh, 1952; Dahy, 1991). Locally, the dike consists of limestone breccia cemented by igneous rocks (Clabaugh, 1952; Dahy, 1991). A dike of similar composition and orientation is reported about 200 m to the north, although it apparently contains no sapphire (Weed and Pirsson, 1900; Clabaugh, 1952; Meyer and Mitchell, 1988). Recently, a number of other lamprophyric breccias have been found in the immediate vicinity of the Yogo dike (Dahy, 1991), but it is not clear whether these contain any sapphire.

The Yogo dike is a dark gray to green ultramafic lamprophyre that is composed of phenocrysts of pyroxene and phlogopite within a fine-grained groundmass (Clabaugh, 1952; Meyer and Mitchell, 1988). Clinopyroxene composes about 30 to 50 percent of the rock and is present as both euhedral phenocrysts and anhedral groundmass phases. The cores of large grains are typically diopsidic, whereas rims and small grains are enriched in FeO, Al, and Ti (Meyer and Mitchell, 1988). Euhedral to anhedral reddish-brown to colorless phlogopite comprises 20 to 30 percent of the rock and is generally chemically homogeneous; its chemical composition indicates that it may have crystallized at about 900°C (Meyer and Mitchell, 1988). The remainder of the rock consists of a matrix of Ti-rich magnetite, apatite, and a mesostasis of chlorite, serpentine, calcite, and rare potassium feldspar. Meyer and Mitchell (1988) note that analcime was not observed in their samples, but Dahy (1991) reports that the groundmass is composed primarily of analcime and that analcime is present as euhedral grains in ocelli. The dike contains angular xenoliths of limestone, fine-grained clastic rocks, and quartzofeldspathic basement gneiss, as well as cognate xenoliths. A number of rock names has been applied to the Yogo dike, including monchiquite, analcime basalt, minette, and ouachitite, but most recent workers consider the mineralogical and geochemical characteristics of the dike best to represent an ouachitite (Clabaugh, 1952; Rock, 1986; Meyer and Mitchell, 1988; Dahy, 1991).

Sapphire occurs in trace amounts throughout the Yogo dike. The sapphires were first noted in alluvial material in 1894 during placer gold mining but were soon determined to have come from the Yogo dike. Most (98%) of the sapphires are blue, but some show lilac or amethyst colors (Dahy, 1991). Sapphires found in situ are etched and commonly have a thin crust of spinel (Clabaugh, 1952; Dahy, 1991). The origin of the sapphires is unknown, but they are thought to be xenocrystic (Meyer and Mitchell, 1988). The recent discovery of a corundum-bearing gneiss xenolith within the dike, with sapphires that exhibit physical characteristics similar to those found in the dike, suggests that the dike sapphires may have originated from the assimilation of a corundum-bearing basement rock by the ultramafic magma (Dahy, 1991). None of the other igneous rocks in the Big Belt Mountains has been found to contain sapphires. The reason the Yogo dike contains sapphires, even though the rest of the igneous rocks of the Little Belt Mountains do not, remains enigmatic. Elsewhere in Montana, one, or possibly two, dikes near Helena and approximately 200 km southwest of the Yogo dike, have also been reported to contain sapphires (Clabaugh, 1952), but little is known regarding their age or chemical and compositional characteristics.

Methods and Results

Two phlogopite concentrates for $^{40}Ar/^{39}Ar$ dating were prepared from two different relatively fresh samples of the Yogo

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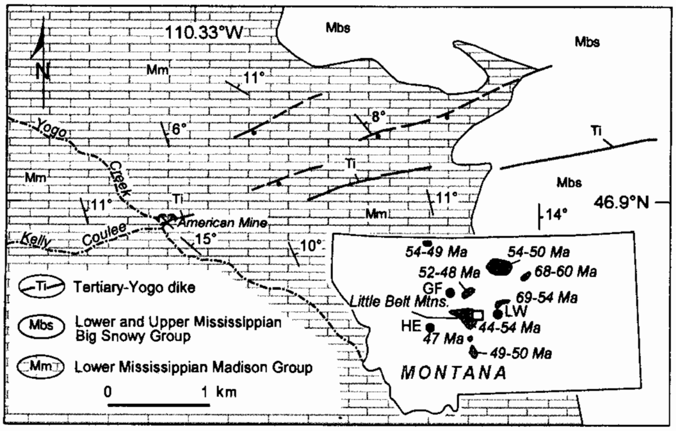

FIG. 1. Simplified geologic map of the Yogo dike, northeastern Little Belt Mountains, Montana (modified from Dahy, 1991). Inset shows the location of major uplifts in Montana that contain igneous rocks of the central Montana alkalic province. The square shows the approximate location of the study area. Also shown are K-Ar and ^{40}Ar/^{39}Ar dates from strongly alkaline mafic rocks (Marvin et al., 1973, 1980; Harlan, unpub. data). GF = Great Falls, HE = Helena, and LW = Lewiston, Montana.

dike from the American mine (sample location: 46.8717° N, 110.3406° W; Fig. 1). The concentrates were washed in 10 percent HCl in an ultrasonic bath to remove carbonate and were handpicked to remove grains that showed any evidence of incipient alteration. The separates were irradiated in the central thimble of the U.S. Geological Survey TRIGA reactor in two separate 30-h irradiations. Corrections for interfering isotopes produced during irradiation were made using ratios derived from potassium and calcium salts irradiated in each package. Neutron flux during irradiation was monitored using hornblende standard MMhb-1, which has a K-Ar age of 520.4 ± 1.7 Ma (Samson and Alexander, 1987). After irradiation, the samples were progressively degassed in a double-vacuum resistance furnace in a series of ten or twelve 20-min-long steps. Isotopic abundances of argon were measured using a mass spectrometer operated in the static mode. Apparent ages were calculated using the decay constants recommended by Steiger and Jäeger (1977). The determination of whether the individual age spectrum yielded a plateau was made using the criteria of Fleck et al. (1977), whereby a plateau is defined by two or more contiguous gas fractions that yield apparent ages which are statistically identical at the 95 percent confidence level (using the critical value test of Dalrymple and Lanphere, 1969) and which together constitute greater than 50 percent of the total ^{39}Ar$_K$ released in the incremental heating experiment. Plateau dates were calculated using a weighted mean, where weighting is by the inverse of the analytical variance (Taylor, 1992). A detailed description of analytical procedures similar to those used in this study is given by Tysdal et al. (1990, appendix 1).

^{40}Ar/^{39}Ar results from the phlogopite concentrate of sample YG91-1 from the Yogo ouachitite dike yielded a total gas date 48.61 ± 0.30 Ma (2σ; Table 1). Apparent ages calculated from low-temperature steps (700°–900°C) are somewhat variable and show a combination of slight ^{40}Ar loss and apparent excess ^{40}Ar and are characterized by low radiogenic yields. Together, these steps total only about 5 percent of the ^{39}Ar$_K$ released. Apparent ages derived from temperature steps between 950° to 1,350°C, however, have high (>90%) radiogenic yields, give a relatively flat age spectrum with similar apparent ages that range from 48.52 to 48.89 Ma, and constitute 93.7 percent of the ^{39}Ar$_K$ released (Fig. 2). The seven steps that define this interval are indistinguishable at the 95 percent confidence level and define a plateau using the criteria described above; a weighted mean for the these steps gives an apparent age of 48.62 ± 0.09 Ma (2σ).

^{40}Ar/^{39}Ar dating of the second phlogopite concentrate (sample YG91-2A) yielded essentially identical results. The sample gave a total gas date of 48.68 ± 0.24 Ma (Table 1), with minor ^{40}Ar loss and apparent excess ^{40}Ar in low-temperature steps, followed by concordant ages for higher temperature steps constituting 90 percent of the ^{39}Ar$_K$ released (Fig. 2). A plateau date calculated for the 1,250° to 1,600°C steps gave an apparent age of 48.69 ± 0.08 Ma. The two plateau dates are statistically indistinguishable at the 95 percent confidence level, demonstrating the excellent consistency and reproducibility of the ^{40}Ar/^{39}Ar dates despite having been irradiated at two separate times. Together, the two plateau dates yield a weighted mean age of 48.66 ± 0.06 Ma. Because the dike is relatively thin and was emplaced at shallow crustal levels, it must have cooled very rapidly. Hence, this date is considered to be a reasonable estimate for the emplacement age of the Yogo dike.

The new 48.66 Ma date from the Yogo dike is within the span of published K-Ar dates for intrusive rocks in the Little Belt Mountains, which range from 55.4 to 42.3 Ma (Marvin et al., 1973)[1]. Most intrusive rocks, however, were emplaced between 54 to 48 Ma, with only minor intrusive activity occurring at about 45 Ma (Marvin et al., 1973). The range of isotopic dates reported by Marvin et al. (1973) encompasses a wide variety of rock types ranging from granites and rhyolites to strongly alkaline mafic rocks, which undoubtedly have distinctly different origins and intrusive relationships. It is, therefore, more appropriate to compare the date from the Yogo dike with the dates of rocks with similar compositions, which are the shonkinite of the Yogo stock and related rocks (Witkind, 1973; Dahy, 1991). Biotite K-Ar dates from these rocks range from 49.8 to 52.6 Ma, with a weighted mean of 51.4 ± 0.9 Ma (2σ; n = 2 independent age determinations from three analyses of two samples from two intrusions). The Yogo dike is significantly younger than the range of reported K-Ar dates from the other shonkinites but is well within the 48 to 52 Ma range for K-Ar dates from strongly alkaline mafic rocks elsewhere in the central Montana alkalic province (Marvin et al., 1980; Harlan et al., 1988; Harlan, unpub. ^{40}Ar/^{39}Ar data). The isotopic dates from this study clearly indicate that emplacement of the sapphire-bearing Yogo dike did not occur during the youngest interval of igneous activity in the Little Belt Mountains at about 45 Ma (Marvin, 1973; Witkind, 1973), but high-precision ^{40}Ar/^{39}Ar dating of the other major igneous units is required in order to determine whether the

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[1] The K-Ar dates from the Little Belt Mountains reported here have been recalculated using the critical tables of Dalrymple (1992) to reflect the revised decay constants of Steiger and Jäger (1977).

TABLE 1. $^{40}Ar/^{39}Ar$ Incremental Heating Data for Samples from the Yogo Ouachitite Dike, Little Belt Mountains, Montana

Temperature (°C)	$^{40}Ar_R$	$^{39}Ar_K$	$^{40}Ar_R/^{39}Ar_K$	$^{39}Ar/^{37}Ar$	$\%^{40}Ar_R$	$\%^{39}Ar$	Apparent age (Ma at 1σ)
YG91-1: phlogopite; 50.9 mg; measured $^{40}Ar/^{36}Ar_a$ = 298.9; J value = 0.007675 ± 0.15% (1σ)							
700	0.08181	0.02577	3.175	0.39	18.2	1.0	43.43 ± 0.24
800	0.13157	0.03651	3.604	0.19	39.3	1.4	49.22 ± 0.29
900	0.36306	0.10038	3.617	0.27	72.0	3.9	49.40 ± 0.17
950	0.72562	0.20272	2.579		91.3	7.9	48.89 ± 0.26
1,000	1.2425	0.34946	3.555		96.3	13.6	48.57 ± 0.18
1,050	1.5262	0.42882	3.559	6.81	96.7	16.7	48.62 ± 0.09
1,100	1.4518	0.40864	3.553		97.1	15.9	48.53 ± 0.23
1,150	1.3167	0.36889	3.569		97.7	14.3	48.75 ± 0.09
1,200	0.91168	0.25667	3.552	4.45	94.4	10.0	48.52 ± 0.09
1,350	1.40296	0.39473	3.554	2.94	91.6	15.3	48.55 ± 0.13
Total gas			3.558				48.61 ± 0.15
YG91-2A: phlogopite; 61.8 mg; measured $^{40}Ar/^{36}Ar_a$ = 299.0; J value = 0.007080 ± 0.20% (1σ)							
1,000	0.05512	0.02084	2.645	0.60	20.7	0.3	33.47 ± 2.11
1,100	0.75350	0.19517	3.861	0.88	59.7	2.8	48.65 ± 0.13
1,200	1.8410	0.47178	3.902	21.25	85.6	6.7	49.16 ± 0.11
1,250	2.0338	0.52604	3.866	75.06	91.6	7.5	48.71 ± 0.14
1,300	2.1598	0.55944	3.861	138.9	95.8	8.0	48.65 ± 0.11
1,325	1.9666	0.50775	3.873	104.1	96.1	7.2	48.80 ± 0.12
1,350	2.4184	0.62623	3.862	97.01	95.7	8.9	48.66 ± 0.11
1,400	2.2537	0.58218	3.871	84.65	96.0	8.3	48.78 ± 0.11
1,425	2.2528	0.58437	3.855	70.08	97.0	8.3	48.58 ± 0.11
1,450	2.2113	0.57080	3.874	60.12	97.3	8.1	48.81 ± 0.11
1,500	3.0990	0.80400	3.854	41.20	97.5	11.5	48.56 ± 0.11
1,600	6.0344	1.5616	3.864	14.06	98.1	22.3	48.69 ± 0.11
Total gas			3.863				48.68 ± 0.12

$^{40}Ar/^{39}Ar_a$ is measured atmospheric argon used for mass discrimination at time of analysis; $^{40}Ar_R$ is radiogenic ^{40}Ar in volts signal; $^{39}Ar_K$ is potassium-derived ^{39}Ar in volts signal; $^{40}Ar_R/^{39}Ar_K$ is the ratio of $^{40}Ar_R$ to $^{39}Ar_K$ after correction for mass discrimination and interfering isotopes; $^{39}Ar/^{37}Ar$ = ratio of $^{39}Ar_K$ to $^{37}Ar_{Ca}$ (this value can be converted to the approximate K/Ca by multiplying by 0.52); $\%^{40}Ar_K$ and $\%^{39}Ar$ are the percent of radiogenic ^{40}Ar and percent of total ^{39}Ar released in each temperature step; temperature steps in bold face are those used in the calculation of the plateau age; conversion of volts signal to moles Ar can be made using a conversion factor of 1.252×10^{-13} moles argon per volt of signal

Yogo dike emplacement was precisely coeval with shonkinitic rocks in the Little Belt Mountains or was intruded during a slightly younger event.

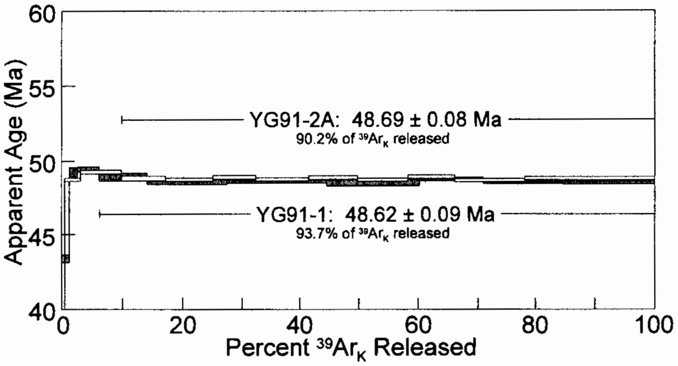

FIG. 2. Phlogopite $^{40}Ar/^{39}Ar$ age spectra from the Yogo dike, Little Belt Mountains, Montana. The height of the rectangle for each temperature step represents the error in the apparent age at ± 1σ. Shaded error rectangles are from sample YG91–1, open rectangles are from sample YG91–2A. The line above and below the age spectra shows the steps used in the calculation of the weighted mean plateau dates. The error in the plateau dates is reported at the 2σ level.

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