K-Ar Ages of Jurassic to Tertiary Plutonic and Metamorphic Rocks, Northwestern Utah and Northeastern Nevada

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By DAVID M. MILLER, JOHN K. NAKATA, and
LINDA L. GLICK

Isotopic data are used to interpret emplacement ages for plutons and ages for metamorphic episodes within a region encompassing the northwest corner of Utah and adjacent eastern Nevada and southern Idaho

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K-Ar Ages of Jurassic to Tertiary Plutonic and Metamorphic Rocks, Northwestern Utah and Northeastern Nevada

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Abstract

Conventional K-Ar ages for biotite, muscovite, sericite, and hornblende, in conjunction with ages obtained using other dating methods, are used to infer ages for pluton emplacement and metamorphism in northwestern Utah and adjacent Nevada and Idaho. Eleven K-Ar ages from four Jurassic plutons and related dikes are used together with data from previous studies to develop a model explaining the chronology of pluton emplacement. Most K-Ar biotite cooling ages for the igneous rocks are 155 to 150 Ma, whereas U-Pb zircon ages are 165 to 160 Ma. According to our model, all Jurassic plutons were emplaced during a short time interval, about 165 to 160 Ma; compositionally related dikes probably were emplaced shortly after, but K-Ar data constrain them to the interval 165 to 152 Ma. Some dikes in the Newfoundland and Silver Island Mountains were sericitically altered about 149 to 148 Ma. The approximately 10-m.y. difference between emplacement, given by U-Pb zircon ages, and the K-Ar biotite cooling ages we interpret as due to prolonged cooling in an upper crust widely heated by the plutonic rocks.

A conventionally determined K-Ar age and one done by the $^{40}Ar/^{39}Ar$ method support previous assertions that a biotite-muscovite granite in the Toano Range, the Toano Springs pluton, was emplaced during the Late Cretaceous. We estimate that emplacement occurred about 85 to 80 Ma. Micas in surrounding greenschist-facies metasedimentary rocks probably grew during Jurassic metamorphism, but their isotopic ages widely record this Cretaceous plutonic event. Our two K-Ar cooling ages for metamorphic muscovite combined with two that were previously reported range from 76 to 61 Ma. A metamorphic-biotite sample yielded a 94-Ma K-Ar cooling age, which is interpreted as representing incomplete resetting during the emplacement of the Toano Springs pluton.

A Tertiary pluton in the northern Toano Range yielded a K-Ar biotite age of 37 Ma, which is consistent with ages from other, compositionally similar, Tertiary plutons in the area. Single K-Ar age determinations for mica schist in the western Raft River Mountains (30 Ma) and hornblende gabbro in the southern Grouse Creek Mountains (49 Ma) require corroborating data for their full interpretation.

The K-Ar ages reported here, combined with previously reported ages, date all known plutons in Box Elder County, Utah, and eastern Elko County, Nevada. Emplacement ages inferred from the combined isotopic data document the history of plutonism in this part of the northeastern Great Basin as (1) scattered but widespread plutonism during restricted intervals of the Late Jurassic and late Eocene, and (2) rare plutonism during the Late Cretaceous and middle Oligocene.

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INTRODUCTION

The pioneering K-Ar studies of R.L. Armstrong (Armstrong and Hansen, 1966; Armstrong and Hills, 1967; Armstrong, 1970, 1976; Armstrong and Suppe, 1973) established Mesozoic and Cenozoic ages for both scattered plutons and regionally metamorphosed rocks throughout the eastern Great Basin. Several later studies in the northeastern Great Basin added to and refined the earlier data, documenting that many plutons were emplaced during restricted intervals of the Late Jurassic and late Eocene and that a few plutons are Late Cretaceous and middle Oligocene in age (Compton and others, 1977; Moore and McKee, 1983; Miller and others, 1987; Miller and others, 1988). These later studies and Snoke and Miller (1988) also confirmed that regional metamorphism in the northeastern Great Basin was late Mesozoic and middle Tertiary in age.

In the Great Basin, sparse Mesozoic plutons intruded Proterozoic to Mesozoic strata far to the east of the Mesozoic Sierra Nevada batholith but west of the Cretaceous to early Tertiary frontal fold-and-thrust belt. The Mesozoic plutons probably were emplaced during regional contraction. In contrast, Tertiary plutons in this same region were emplaced during widespread crustal extension, most recently manifested in the characteristic structure of the Basin and Range province (fig. 1). These Mesozoic and Tertiary plutonic pulses mark magmatic events in widely differing tectonic and probably divergent thermal regimes, and these plutons provide data for inferring crustal and mantle conditions during the different tectonic events.

As part of a regional tectonic study of northwestern Utah, northeastern Nevada, and southernmost Idaho, we have conducted a systematic K-Ar dating program for igneous and metamorphic rocks. In this paper we present data for several previously undated plutons and dike swarms, including a heretofore-unreported pluton in the Toano Range. We also compare previously reported geochronologic data with data reported here to interpret the intrusive ages for several other plutons. Our data further define the two main pulses of magmatism (Jurassic and Tertiary) in northwestern Utah; initially recognized by Armstrong and Suppe (1973), these magmatic episodes were later more narrowly dated, yielding intrusive ages of about 165 to 160 Ma and about 40 to 35 Ma (Moore and McKee, 1983; Miller and others, 1987). We also document a single pluton in the Toano Range that belongs to a group of less common Late Cretaceous plutons widely scattered to the south and west of our study area (see Miller and others, 1988).

Acknowledgments

Many individuals have contributed generously to our geochronologic studies, including Wendy Hillhouse and Victoria Todd, who contributed K-Ar dating; Larry Snee, who performed $^{40}Ar/^{39}Ar$ analysis; and P. Klock, Lauresno Espos, David Vivit, S. MacPherson, Marsha Dyslin, and Sarah Pribble, who provided potassium analyses. Rick Allmendinger and Terry Jordan continually stimulated our thinking on the geology of the region, and their geologic mapping and sample collection contributed directly to this study. Lydia K. Fox collaborated with studies at Crater Island and Sharon L. Gusa assisted with fieldwork there and in the Toano Range. Discussions with Elizabeth L. Miller, Phillip B. Gans, James E. Wright, and Arthur W. Snoke made us much more aware of geologic and geochronologic relations elsewhere in the Great Basin.

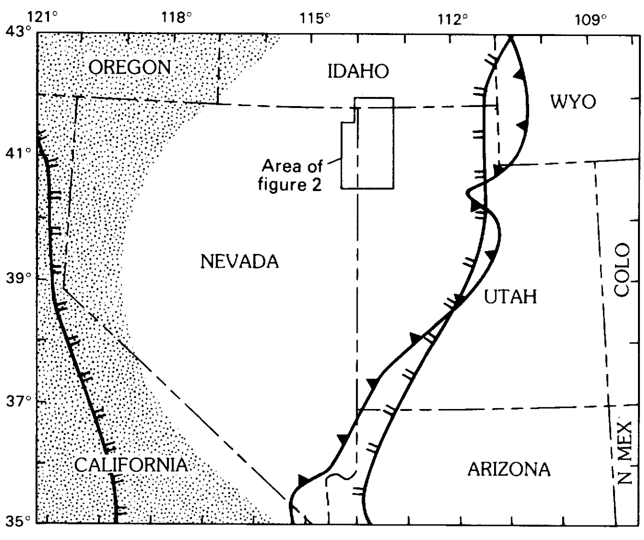

Figure 1. Location of study area and major Mesozoic and Cenozoic tectonic elements of the Great Basin. Most Mesozoic plutons lie within the Mesozoic magmatic arc (stippled), but in parts of the Great Basin, there are scattered plutons far east of this belt. Approximate east- and west-side limits of major Cenozoic extension in Great Basin indicated by line with hachures; line with sawteeth (on upper plate) is east front of Mesozoic and early Cenozoic frontal thrust belt.

METHODS

Most of the K-Ar age determinations were made in the Stable Isotope Laboratories of the U.S. Geological Survey at Menlo Park, Calif., using the methods described by Dalrymple and Lanphere (1969). Argon was extracted on an ultra-high-vacuum system by fusion. Reactive gases were scrubbed by an artificial molecular sieve, Cu-CuO, and Ti metals. The spectrometry was performed on a Nier-type, 15-cm radius, 60°-sector spectrometer and a multichannel, 23-cm radius, 60°-sector mass spectrometer, both operated in static mode. Argon isotopic composition was determined by standard isotopic-dilution procedures.

Potassium was analyzed by flame photometry at the U.S. Geological Survey analytical laboratory in Menlo Park using the procedure described in Cremer and others (1984). All analyses were duplicated to check precision.

For samples that were analyzed once, their reported errors (as ± range) generally are ±2.5 percent, which is a laboratory-determined conservative overall analytical precision, including errors resulting from sample preparation to spectrometry. A few older analyses were determined by different methods and have slightly higher errors (±3 percent). Some samples were analyzed twice. For these, we retained the conservative laboratory error, although several showed excellent replication and their precision is therefore underestimated.

In cases where we cite previously reported K-Ar data, those that used constants other than the constants of Steiger and Jäger's (1977), we have recalculated and annotated them as such. The table of Dalrymple's (1979) was used for recalculating the ages.

RESULTS

Ages reported here are primarily from samples collected from the Newfoundland Mountains westward to the Toano Range (fig. 2). Compton and others (1977) described two plutons in the northern part of this area, Caroon (1977) and Allmendinger and Jordan (1984) described the pluton in the Newfoundland Mountains, and Miller (1984) briefly described many others in the

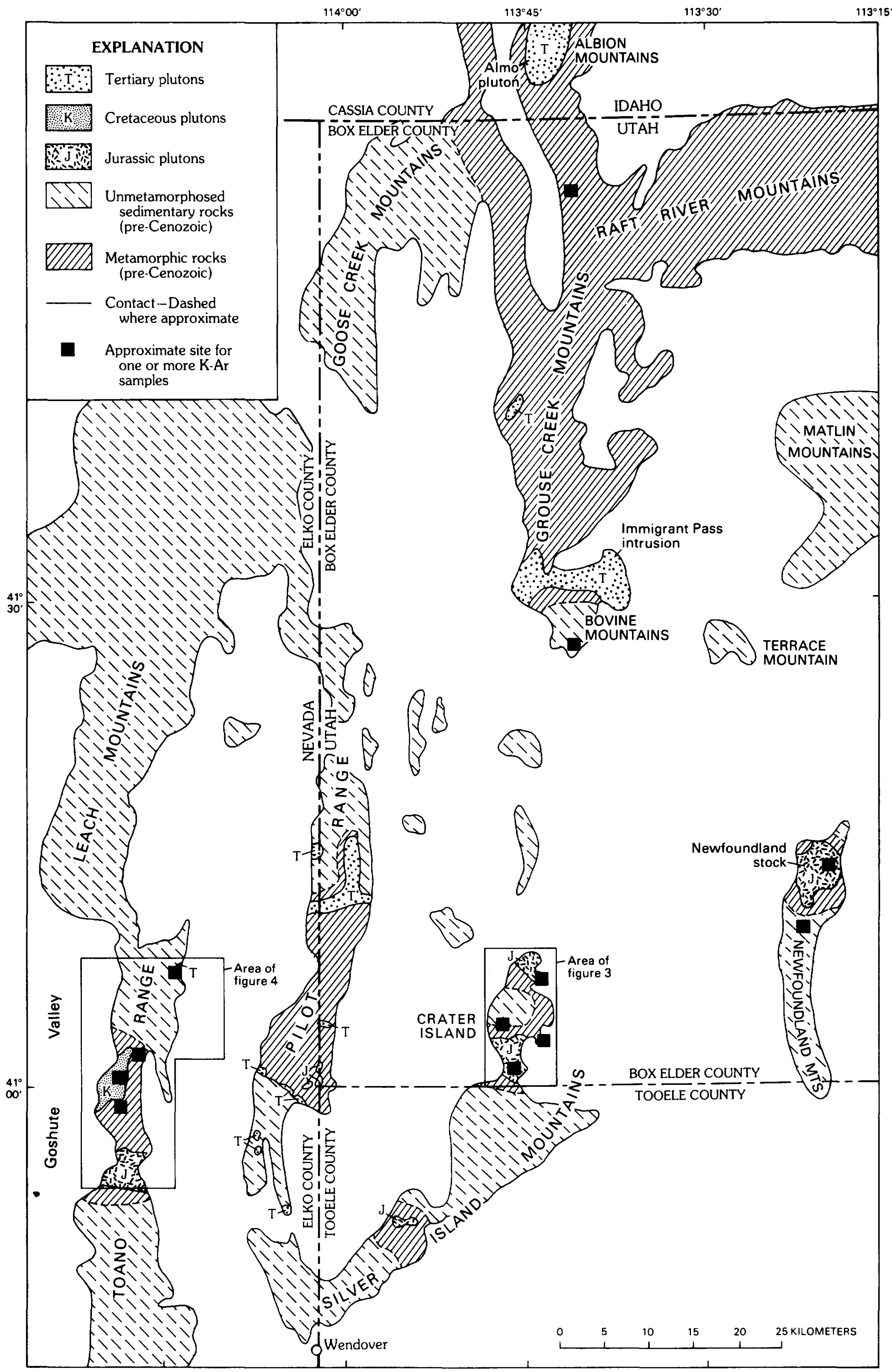

Figure 2. Simplified geology of study area, showing distribution of pre-Cenozoic strata and of Mesozoic and Cenozoic plutons and metamorphic rocks. Also shown are approximate K-Ar sample sites.

Pilot Range and Toano Range. The geochronology of plutons in the central Silver Island Mountains was detailed by Moore and McKee (1983) and in the Pilot Range by Hoggatt and Miller (1981) and Miller and others (1987). Most of our work reported herein focuses on the Toano Range and the Silver Island and Newfoundland Mountains. All of these mountain ranges contain one or more Jurassic plutons, the Toano Range contains a Cretaceous pluton, and Tertiary plutons are exposed in the Toano and Pilot Ranges and the Grouse Creek Mountains (fig. 2).

Metamorphic rocks are found as contact aureoles around the plutons and also in broader regions characterized by regional metamorphic assemblages and fabrics in the Silver Island Mountains and Pilot and Toano Ranges (Miller, 1984) and the Grouse Creek and Raft River Mountains (Compton and others, 1977). Supplementing similar work on Mesozoic metamorphism in the Pilot Range (Miller and others, 1987), we have studied the regionally metamorphosed rocks in the Toano Range.

We interpret most K-Ar ages as cooling ages because the minerals cool slowly following thermal events and do not cease diffusion instantaneously. The K-Ar ages therefore measure a period of temperature decline following such events as (1) peak metamorphism, (2) intrusion, (3) thermal disturbance, or (4) a combination of these. Unlike K-Ar methods, U-Pb systematics for plutonic zircon yields ages closely approximating emplacement ages because zircon is highly refractory and daughter products are not gaseous. Where possible, we have compared our K-Ar data to examples for which U-Pb zircon data and K-Ar cooling ages are both available.

In the absence of U-Pb zircon data, pluton-emplacement ages may be approximated from K-Ar ages on minerals with widely different blocking temperatures by calculating a cooling rate and then extrapolating this rate to emplacement temperatures. Unfortunately, blocking temperatures are not closely determined. Acknowledging this uncertainty, we use the following estimated blocking temperatures: hornblende, about 500 ± 50 °C (Spear and Harrison, 1989); coarse muscovite, about 350 ± 50 °C (Purdy and Jäger, 1976; Harrison and others, 1989); biotite, about 325 °C (Harrison and others, 1989), and sericite, a slightly lower temperature than muscovite. Ages for hornblende, with its high blocking temperature, are necessary to constrain the cooling rate of a pluton. Rather than strictly applying the poorly constrained blocking temperatures when interpreting K-Ar data, we use the data as qualitative measures of decreasing temperature, from hornblende, to muscovite and sericite, to biotite. Cooling rates also may be approximated using heat-flow calculations that employ parameters such as original pluton temperature, size, and depth, and initial wallrock temperature.

Calculating cooling rates has proved difficult in northern Utah. Miller and others (1987) demonstrated that in the Pilot Range excess argon was in most or all cases retained in hornblende. For this reason, we did not systematically study hornblende from granites. The sizes and shapes of the plutons are inadequately constrained by geologic and geophysical data. Although the maximum temperatures of the host rocks are known from conodont-alteration indexes, the times that the rocks attained those temperatures are not known. Because of these limitations, we were unable to establish precise cooling rates for the plutons.

Jurassic Plutons

The ages of Jurassic plutons in the Toano and Pilot Ranges are well-constrained by U-Pb zircon ages—162 Ma for the Toano Range (J.E. Wright, oral commun., 1986) and 165 to 155 Ma for the Pilot Range (Miller and others, 1987). Jurassic ages for diorite and granodiorite (K-Ar ages of 174 Ma on hornblende and 160 Ma on biotite) in the Silver Island Mountains just to the east were established by Moore and McKee (1983).

In the Pilot Range, leucocratic muscovite-biotite granite occurs as networks of dikes within metamorphosed lower Paleozoic rocks. These dikes, in addition to common aplite and pegmatite dikes, and a broad metamorphic halo surrounding the area in which they lie (Miller and others, 1987) suggest that one or more large plutons lie below the area. Discordant U-Pb data were interpreted by Miller and others (1987) as indicating an emplacement age between 165 and 155 Ma.

In the Toano Range (fig. 2), the Silver Zone Pass pluton (named by Pilger, 1972) intruded greenschist-facies Proterozoic and Cambrian strata at Silver Zone Pass. The pluton is composed of subequigranular, hornblende-biotite granodiorite (rock-classification scheme of Streckeisen, 1976) containing light-brown-weathering feldspar, light-gray quartz, and about 15 percent mafic minerals, which are evenly distributed through the rock. Biotite in places forms distinctive oikocrysts. Accessory minerals include epidote, calcite, chlorite, and opaque minerals, with lesser amounts of sphene, apatite, and zircon. Small mafic xenoliths occur throughout the pluton, and hornblende gabbro bodies (as much as 9 m^2 in surface exposure) of uncertain origin occur in a few places.

Broad metamorphic aureoles and tight anticlines and foliated strata lie adjacent to the pluton, but the intrusive contact is generally sharp. These characteristics we interpret as representing a lower-epizonal intrusive setting. A region about 8 km by 17 km surrounding the exposed pluton has a strong geophysical expression that Grauch and others (1988) interpreted as probably related to the subsurface part of the pluton. These inferred subsurface dimensions exceed surface exposures by about 2 km on the east and north and by at least 10 km on the southwest. A few northeast- to northwest-trending dikes consisting of fine-grained hornblende- and biotite-bearing granite to granodiorite intruded the adjacent rocks. Aphanitic felsic dikes, mafic dikes, and quartz veins also cut the Silver Zone Pass pluton. Isotopic study of the Silver Zone Pass pluton shows that it lacks a significant crustal component (Farmer and DePaolo, 1983), suggesting rapid ascent through continental crust.

K-Ar dating of biotite sampled near the center of the pluton has yielded a range of ages (all recalculated using new constants): 152±8 Ma (Coats and others, 1965), 133±3 Ma (Armstrong and Suppe, 1973), and 127 Ma (McDowell, 1971). Of these K-Ar data, the two younger ages were obtained from impure samples. McDowell (1971) reported 24 percent chlorite and 10 percent hornblende in the sample that yielded an age of 127 Ma. Armstrong and Suppe (1973) reported somewhat-low K_2O for biotite (average 6.96 percent) in the sample that yielded an age of 133 Ma. Of the three K-Ar ages, we consider the 152-Ma age to most accurately represent the K-Ar cooling age for the pluton. U-Pb analysis of two size fractions of zircon yielded discordant results, but the smaller size was essentially concordant at 162 Ma (J.E. Wright, oral commun., 1986), which we interpret as the emplacement age. The 10-m.y. difference between emplacement and K-Ar cooling ages we interpret as representing protracted cooling of a pluton emplaced into greenschist-facies rock.

Newfoundland Mountains

The Newfoundland stock of Caroon (1977) crops out in the northern Newfoundland Mountains (fig. 2). It is about 5.5 km in diameter, although a prominent positive aeromagnetic anomaly (Zietz and others, 1976) centered on it and extending eastward some 10 km may indicate a large subsurface extent for the stock and related intrusive bodies. The stock intruded an unmetamorphosed Cambrian and Ordovician miogeoclinal sequence consisting mainly of carbonate rocks, with subordinate shale and quartzite. Along the margin of the pluton, strata are highly metamorphosed in a zone about 150 m wide (Caroon, 1977). The pluton is zoned from central equigranular and porphyritic monzogranite, to equigranular granodiorite, to peripheral porphyritic monzogranite (Caroon, 1977). All of the rocks generally contain subequal amounts of biotite and hornblende, totaling 5 to 13 percent, and minor sphene and magnetite. Several sets of dikes are spatially associated with the pluton. One set, composed of monzogranite porphyry that appears to be chemically related to the pluton (Caroon, 1977), cuts the pluton and emanates widely into country rocks.

Two of the K-Ar analyses reported here were used by Caroon (1977) to establish a Jurassic age for pluton intrusion and three other ages that we report were used by Allmendinger and Jordan (1984) to establish a Jurassic or older age for thrust and normal faulting. Two samples of the peripheral porphyritic monzogranite were analyzed by W.C. Hillhouse and V.R. Todd: biotite from the first sample (NFL–1) yielded an age of 153.2±4.6 Ma, and hornblende from the second (NFL–2) yielded an age of 147.7±4.4 Ma (table 1). The hornblende sample contains about 2 percent chlorite and biotite, perhaps causing the slightly (but not significantly) younger age than that given by biotite (Caroon, 1977). Alternatively, hornblende may have been too refractory to completely release argon during fusion. This peripheral porphyritic-monzogranite phase of the pluton grades into the other two main phases of the Newfoundland stock, and the ages therefore suggest a minimum crystallization age of about 150 Ma for the pluton.

Three samples (collected by R.W. Allmendinger and T.E. Jordan) from monzogranite porphyry dikes related to the pluton yielded ages roughly in accord with those for the pluton (table 1). Biotite from two dikes yielded ages of 150.8±4.5 Ma (sample 81B69, table 1) and 143.7±4.4 Ma (sample T82–47, table 1). Both dikes show chloritic alteration, and chlorite may have been present in the samples analyzed. A sericitized monzogranite porphyry dike (sample RA82–2, table 1) yielded a K-Ar age of 149.1±3.7 Ma on sericite. These mica ages were interpreted by Allmendinger and Jordan (1984) as minimum ages for emplacement of the dikes. They used these ages, in conjunction with field relations, to constrain the age of two thrust faults, several high- and low-angle normal faults, and folds spatially associated with the pluton as being Jurassic or older.

The K-Ar cooling ages do not allow us to precisely establish the time of emplacement for the Newfoundland stock and related dikes, but it probably is at least as old as the oldest (153-Ma) cooling age. Caroon (1977) estimated depth of emplacement at 6 km based on stratigraphic thickness. The depth actually may have been less than this, because he did not attempt to adjust for a major Late Pennsylvanian unconformity in the Newfoundland Mountains (Allmendinger and Jordan, 1984) or for pre-Late Jurassic structure and erosion. Metamorphic zones 150 m wide and a wider zone of ductile deformation around the pluton are consistent with a lower-epizonal emplacement. At 6-km depth, preemplacement temperatures may have been about 200 °C, assuming a thermal gradient of about 30 °C/km. Rapid cooling of granite to biotite closure temperature would not be expected, since the pluton is at least 5.5 km in diameter. We estimate that the pluton probably required several million years to cool to biotite Ar-retention temperatures. A K-Ar age of 153 Ma for the Newfoundland stock is similar to the 152-Ma K-Ar

Table 1. K-Ar data for Jurassic igneous rocks

[rad, radiogenic; *, analyses done by W.C. Hillhouse and V.R. Todd; ---, not applicable. Replicate-analysis results shown in parentheses. Decay constants from Steiger and Jäger (1977)]

Sample	Sample site		Rock type sampled	Mineral dated	Mean K_2O (wt pct)	$^{40}Ar_{rad}$ (pct)	$^{40}Ar_{rad}$ (10^{-10} mol/g)	Replicate calculations (Ma)	Age (Ma)
	Lat (N)	Long (W)							
NFL-1	~41°14'	~113°22'	Granite	Biotite*	8.55	95.39	19.7	---	153.2±4.6
NFL-2	~41°14'	~113°22'	Granite	Hornblende*	.66	73.55	1.45	---	147.7±4.4
81B69	41°10'43"	113°23'07"	Granodiorite dike	Biotite	7.05	87.03 (81.00)	15.96 (15.97)	150.7 (150.8)	150.8±4.5
T82-47	41°07'53"	113°23'33"	Granodiorite dike	Biotite	7.79	85.77 (86.39)	16.54 (17.00)	141.8 (145.6)	143.7±4.5
RA82-2	41°11'16"	113°22'15"	Sericitized dike	Sericite	10.42	92.20	23.31	---	149.1±3.7
M84CI-65	41°06'55"	113°45'15"	Granodiorite	Biotite	8.87	85.82 (34.74)	20.06 (19.98)	150.6 (150.0)	150.3±3.8
SI-1	41°02'17"	113°46'13"	Quartz monzonite	Biotite*	7.13	95.86	16.3	---	152.2±4.6
M85CI-14	41°03'07"	113°44'13"	Granite	Biotite	7.74	88.04	17.96	---	154.2±3.8
F84SI-58	41°01'13"	113°46'43"	Granodiorite dike	Biotite	8.45	75.65 (84.08)	19.70 (18.96)	155.0 (149.4)	152.2±3.8
M85CI-27	41°03'50"	113°47'15"'	Granodiorite dike	Biotite	7.22	89.64	16.78	---	154.6±3.9
M84CI-48	41°04'33"	113°44'48"	Sericitized dike	Sericite	5.29	92.70	11.77	---	148.1±3.7

biotite age (Coats and others, 1965) for the lithologically similar Silver Zone Pass pluton, although the latter pluton was emplaced within a wider metamorphic zone. The U-Pb zircon age of 162 Ma for the Silver Zone Pass pluton leads us to infer a 165- to 160-Ma time of emplacement for the Newfoundland stock. Because the dikes probably intruded metamorphic rocks still at high temperatures, their K-Ar cooling ages may not closely correspond to time of emplacement. In addition, the K-Ar results from dikes probably record effects of subsequent alteration. Sericitic alteration at or shortly before about 149 Ma apparently followed pluton emplacement by 10 to 15 m.y.

Crater Island

Dioritic to granitic plutons crop out in the central and northern Silver Island Mountains (fig. 2) and were first mapped and described by W.L. Anderson and F.E. Schaeffer (see Schaeffer, 1960). Although Schaeffer and Anderson tentatively assigned the plutons a Tertiary age, two of them in the central Silver Island Mountains and one in the northern Silver Island Mountains gave Jurassic K-Ar ages (Armstrong and Suppe, 1973; Moore and McKee, 1983). We did detailed field studies of the plutons at Crater Island in the northern Silver Island Mountains (fig. 3) and did additional analyses on selected samples from them.

The geologic framework of Crater Island is similar to that of the Newfoundland Mountains 25 km to the east. Cambrian to Permian miogeoclinal strata dip moderately westward and are cut by several classes of faults: (1) small-displacement low-angle faults (not shown on fig. 3), (2) east-striking high-angle dip-slip faults, and (3) north-northeast- to north-northwest-striking high-angle dip-slip faults. Several faults of the second and third classes are cut by the plutons and dikes; the faults have been described in detail by Miller (1990) and Miller and others (1990). These intrusive rocks share many modal, chemical, and textural characteristics and are considered to represent a magmatically related suite. Unifying features include overlapping modal and chemical compositions, broadly colinear variations of oxides with respect to SiO_2, similar xenolith suites, ubiquitous dikes, and features such as broad metamorphic aureoles indicating a lower-epizonal level of emplacement.

The igneous suite at Crater Island forms two composite plutonic centers, one at the north end of Crater Island and the other at Donner-Reed Pass (fig. 3); part of another small pluton of this suite forms a promontory 1.6 km northeast of Donner-Reed Pass. Several dike swarms and individual dikes related to the igneous suite are scattered throughout Crater Island. The dikes range widely in composition and texture but seem to mirror the compositional variations seen in the plutonic rocks.

The plutonic center underlying about 15 km^2 of the northern part of Crater Island was referred to as the "North stock" and the "Sheepwagon stock" by Schaeffer (1960). The bulk of the pluton consists of light-gray, porphyritic biotite granodiorite to monzogranite with a modal mafic-minerals content of 10 to 18 percent, but it is intruded by and grades over a short distance into porphyritic, fine-grained granodiorite to monzogranite (Miller and Glick, 1986). Sparse pegmatite and aplite dikes cut the pluton. The pluton carries common mafic inclusions. A metamorphic aureole about 1 km wide surrounds the southwestern part of the pluton. Within this contact aureole are Ordovician strata that were foliated and folded into a tight anticline by pluton emplacement (Allmendinger and others, 1984; Miller and others, 1990). A K-Ar cooling age of 150.3±3.8 Ma on biotite (sample M84CI–65, table 1) from the porphyritic granodiorite establishes the northern plutonic center as probably Jurassic in age.

The composite pluton underlying much of southern Crater Island near Donner-Reed Pass (fig. 3) is composed of two phases—quartz monzonite and subordinate dark monzodiorite—of the Crater Island Quartz Monzonite. Anderson (see Schaeffer, 1960) named the pluton as two geographically separate stocks—"Crater Island stock" and "South stock"—but recognized that they represent a single igneous body. Zietz and others (1976) depicted a prominent aeromagnetic high centered just west of, and encompassing, outcrops of the Crater Island Quartz Monzonite. The pattern suggests that the magnetite-bearing pluton occupies at least 80 km^2 of the shallow subsurface, extending at least 10 km west of Donner-Reed Pass.

The quartz monzonite phase of the Crater Island Quartz Monzonite is homogeneous and consists of biotite-hornblende quartz monzonite to monzogranite. Mafic minerals range from 12 to 24 modal percent. Metamorphosed Permian strata form an anticline parallel to the north margin of the pluton. Armstrong and Suppe (1973) dated a biotite and hornblende mixture, containing 10 percent chlorite, from the Crater Island Quartz Monzonite (their sample YAG–88), yielding an age of 143±3 Ma (recalculated using new decay constants). The mixture's average K_2O concentration was 2.75 percent, so it must have contained only a small proportion of biotite. Owing to the impurity of this sample from a region for which many coexisting mineral pairs yield discordant ages, the significance of this K-Ar age is highly uncertain. We consider that our K-Ar age of 152.2±4.6 Ma on biotite (sample SI–1, table 1) from the Crater Island Quartz Monzonite better represents the cooling age of the pluton and thus suggests a Jurassic age of emplacement.

The dark monzodiorite phase forms the northwestern and southeastern parts of the Crater Island pluton. This phase is biotite-augite monzodiorite to monzonite

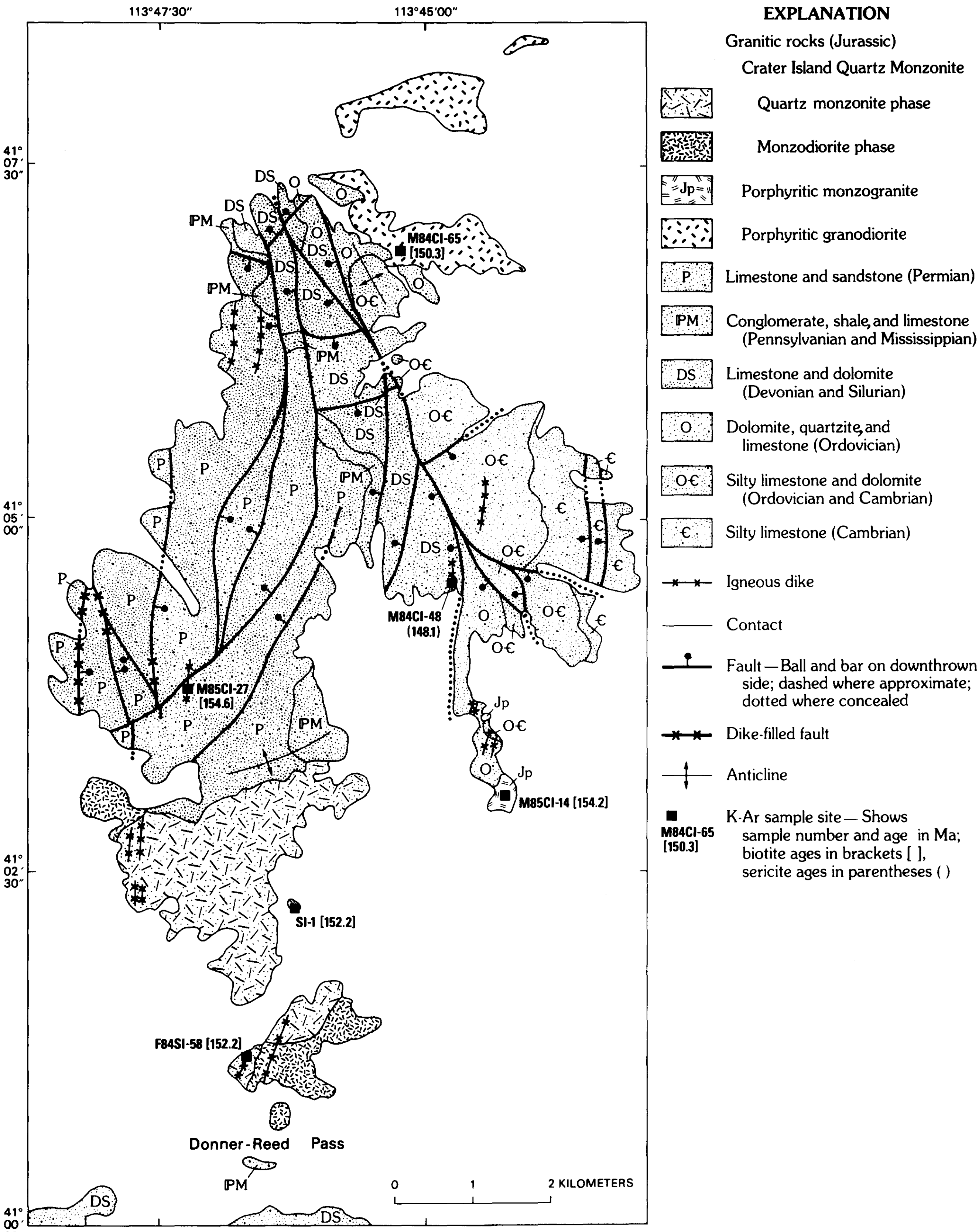

Figure 3. Generalized geology of pre-Cenozoic rocks at Crater Island (northern Silver Island Mountains) and K-Ar sample locations. Location of map area is shown in figure 2. Geology simplified from Glick and Miller (1986), Miller and Glick (1986), Miller (1990), and Miller and others (1990).

containing rare olivine. The rock in many places exhibits sharp contacts with the quartz monzonite phase, but in some places a compositionally transitional quartz monzodiorite intervenes. The transitional phase appears to grade into monzodiorite, but locally it and the monzodiorite form inclusions within the quartz monzonite. These relations indicate that the monzodiorite phase is older than the quartz monzonite phase, but gradational rock types and petrographic and petrologic affinities indicate a close relationship between the two, so the monzodiorite phase is inferred to be Jurassic in age.

Porphyritic biotite monzogranite bearing about 10 percent mafic minerals crops out over less than 1 km^2 at the south end of a promontory 1.6 km east of the Crater Island Quartz Monzonite (fig. 3). Although no Paleozoic strata are exposed between this small body and the Crater Island pluton, the different rock types indicate that the bodies may represent different intrusions. Biotite from the porphyritic monzogranite (sample M85CI–14, table 1) yielded a K-Ar cooling age of 154.2±3.8 Ma, suggesting that the body is approximately coeval with other plutons at Crater Island.

Other than the few aplite and pegmatite dikes that are closely associated with plutons, igneous dikes at Crater Island may be divided into three general groups: (1) common granodioritic dikes occurring as swarms cutting the Crater Island pluton and most sedimentary rocks, (2) mafic dikes occurring sparsely in sedimentary rocks, and (3) rare felsite dikes cutting sedimentary rocks and granodiorite dikes. These dikes mirror compositional types seen in the plutons, and our dating shows that they were emplaced at approximately the same time as the plutons.

We have dated the granodioritic dikes from three locations. Near Donner-Reed Pass, a swarm of hornblende-biotite granodiorite dikes cutting the Crater Island pluton yielded a K-Ar cooling age of 152.2±3.8 Ma on biotite (sample F84SI–58, table 1), indicating that the dikes were emplaced shortly after the pluton and that the pluton and dikes shared a similar cooling history (compare biotite sample SI–1 (table 1) from the same pluton: 152.2±4.6 Ma). Virtually identical granodioritic dikes cut sedimentary rocks north of the Crater Island Quartz Monzonite. Biotite from a fine-grained, hornblende-biotite granodiorite dike intruding a normal fault (sample M85CI–27, table 1) yielded a K-Ar cooling age of 154.6±3.9 Ma, which is consistent with the interpretation that these dikes are coextensive with dikes in the Crater Island pluton. In a few locations, these dikes are highly sericitized. One such dike in central Crater Island yielded a K-Ar cooling age of 148.1±3.7 Ma on sericite (sample M84CI–48, table 1). Since the blocking temperature for sericite is higher than for biotite, these data indicate that the dike may have cooled less quickly than others we dated or, more likely, that it was altered after emplacement.

As with the Newfoundland stock, we interpret the K-Ar ages for Crater Island plutonic rocks as cooling ages and therefore minimum ages for emplacement. By analogy with the Silver Zone Pass pluton, we infer that the K-Ar ages represent protracted cooling, suggesting crystallization perhaps 165 to 160 Ma. The narrow range of cooling ages for several plutons and dikes suggests that they were all emplaced during a short timespan and cooled synchronously. Ages for unaltered dikes should closely approximate their emplacement ages if the dikes intruded cool rock, for the dike minerals should quickly cool to Ar-retention temperatures. The 155-Ma age for a dike cutting sedimentary rocks probably most closely approximates the crystallization age. However, conodont-alteration indexes of 5 (Miller and others, 1990) for Ordovician strata several kilometers to the northeast and far from any mapped pluton indicate maximum temperatures of 300 to 400 °C (Epstein and others, 1977). Even if somewhat-lower temperatures obtained in Permian rocks near the dated dike at the time of intrusion, thermal decay to biotite Ar-retention temperatures may have been delayed. If cooling was prolonged by 2 to 3 m.y., then the measured age of 154.6±3.9 Ma (sample M85CI–27, table 1) would imply that the dikes were emplaced within the interval 161 to 153 Ma. At the other extreme, cooling of the dikes may have been controlled by the cooling of voluminous nearby plutons and, like the plutons, may have been as long as 10 m.y. Sericitic alteration of dikes about 148 Ma apparently took place about 5 to 15 m.y. after their emplacement.

Cretaceous Plutons

Cretaceous plutons are absent in northwestern Utah (Moore and McKee, 1983; Miller and others, 1987) and sparse in northeastern Nevada. A single pluton of presumed Cretaceous age, the Toano Springs pluton (Pilger, 1972) is present in the Toano Range (fig. 4). This pluton is composed of homogeneous muscovite-phenocrystic biotite-muscovite monzogranite. On fresh exposures, large books of weakly aligned muscovite are prominent. Minor accessory minerals include garnet, apatite, sericite, and very minor opaques. Common garnet-muscovite pegmatite and aplite dikes and randomly oriented quartz veins cut the pluton. The common pegmatite and aplite dikes suggest a water-rich vapor phase, at least in the late stages of crystallization, in strong contrast with the Jurassic granitoids, which contain few aplite dikes and rare pegmatites. Aligned mica defines an indistinct foliation in the monzogranite and at one locality subparallels the southeast margin of the pluton. Surface exposures of the pluton indicate a minimum size of 7 by 3 km, but it could extend more widely in the subsurface; studies by Grauch and others (1988) identified no geophysical expression associated with the pluton.

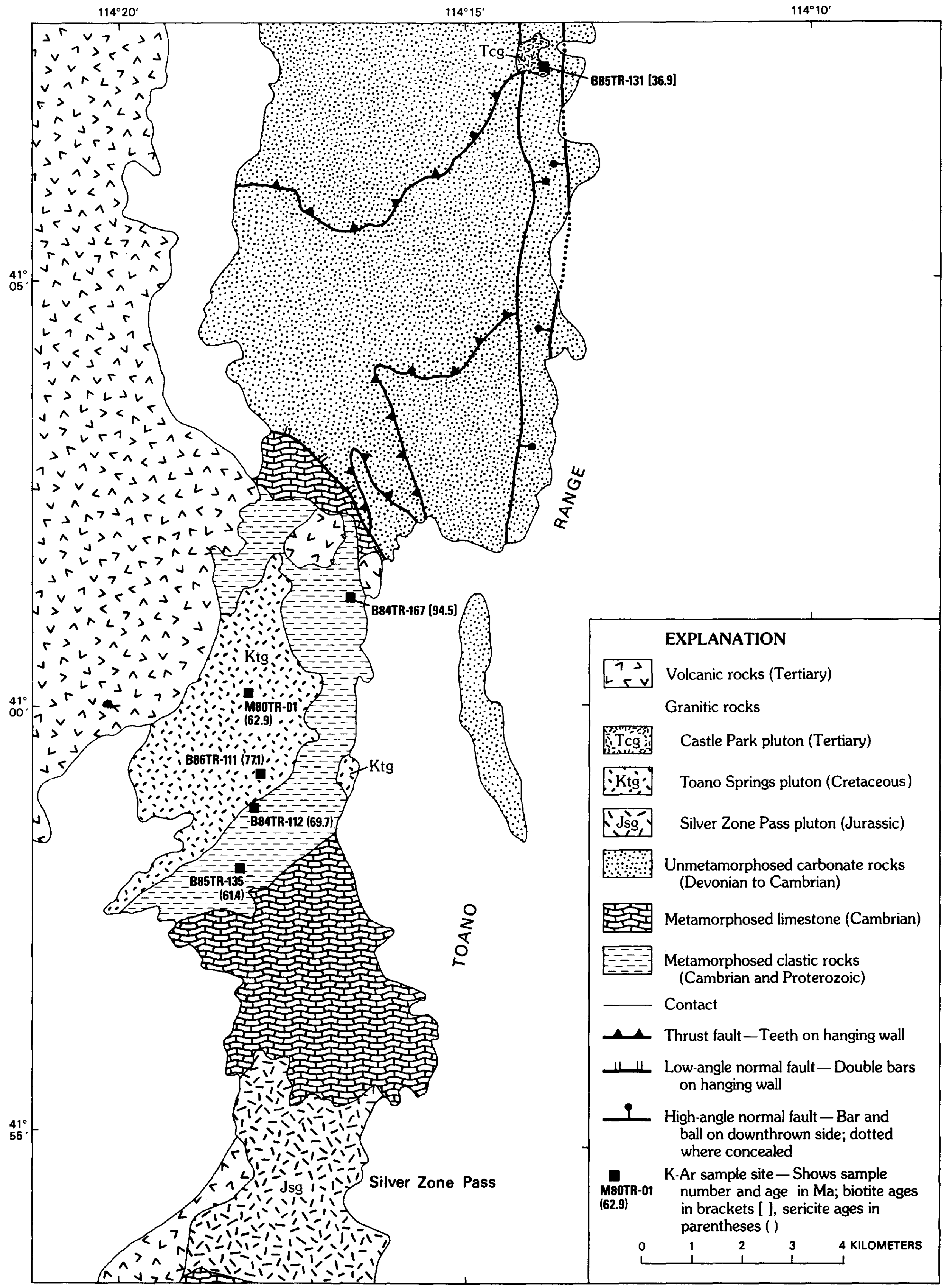

Figure 4. Generalized geology of Miocene and older rocks, northern Toano Range, and K-Ar sample sites. Location of map area shown in figure 2. Map after Glick (1987) and D.M. Miller and L.L. Glick (unpub. mapping, 1987).

Table 2. K-Ar data for Cretaceous and Tertiary igneous and metamorphic rocks

[rad, radiogenic; *, analyses done by W.C. Hillhouse. Decay constants from Steiger and Jäger (1977)]

Sample	Sample site		Rock type sampled	Mineral dated	Mean K_2O (wt pct)	$^{40}Ar_{rad}$ (pct)	$^{40}Ar_{rad}$ (10^{-10} mol/g)	Age (Ma)
	Lat (N)	Long (W)						
M80TR-01	41°00'10"	114°18'11"	Aplite	Muscovite*	10.76	76.24	9.93	62.9±1.9
B84TR-112	40°58'56"	114°18'05"	Quartzite	Muscovite	9.9	93.88	10.13	69.7±1.7
B85TR-135	40°58'12"	114°18'18"	Schist	Muscovite	9.95	93.42	8.95	61.4±1.5
B84TR-167	41°01'13"	114°16'39"	Schist	Biotite	9.54	86.73	13.33	94.5±2.4
M84RR-99	41°54'00"	113°42'36"	Schist	Muscovite	10.44	74.81	4.54	29.9±0.7
B85TR-131	41°07'02"	114°13'47"	Granite	Biotite	7.15	80.50	3.84	36.9±0.9
81B1	41°27'08"	113°41'20"	Gabbro	Hornblende*	1.24	61.84	.90	49.2±1.2

The pluton intruded upper Proterozoic metamorphic rocks but shows little evidence for ductile deformation of wallrocks. We infer an epizonal setting for emplacement.

Aphanitic dikes appear to emanate extensively from the Toano Springs pluton into the adjacent Paleozoic rocks. These felsic dikes are finer grained than the rocks of the pluton but characteristically contain muscovite. Similar aphanitic dikes cut the Silver Zone Pass pluton to the south. In both areas, these dikes may represent a late phase of the emplacement cycle that produced the Toano Springs pluton.

Conventional K-Ar methods have yielded Cretaceous and Tertiary ages for the Toano Springs pluton. Lee and Marvin (1981) reported K-Ar ages (their sample 451) of 71.7±2.0 Ma for primary muscovite and 15.4±0.5 Ma for biotite with a K_2O content of 6.10 percent. (According to D.E. Lee (written commun., 1985), Lee and others (1981) had reported an erroneous K-Ar biotite age of 128 Ma for this pluton.) Lee and others (1984) attributed the young biotite age to alteration to hydrobiotite and considered the muscovite age to approximate the time of emplacement. Lee and others (1986) supported the presumed Late Cretaceous age by comparing the Toano Springs body with better dated and chemically and isotopically similar granite bodies in east-central Nevada. We obtained a younger K-Ar muscovite age of 62.9±1.9 Ma (sample M80TR–01, table 2) from an aplite dike within the pluton. This muscovite age and that reported for the main body of the pluton by Lee and others (1984) indicate cooling during Cretaceous and early Tertiary (Paleocene) time. However, Miller (1984) inferred a Jurassic age for this pluton based on compositional similarity with the two-mica Miners Spring Granite in the Pilot Range.

We have been unable to extract enough zircon from the pluton for U-Pb age determinations because the grains are both sparse and small (Lee and others, 1986), but $^{40}Ar/^{39}Ar$ analysis of muscovite sample B86TR–111 (table 3) yielded a simple spectrum with a plateau age of 77.1±0.3 Ma (fig. 5). Because the degassing spectrum shows no evidence of thermal disturbance, we consider this age to be a cooling age following crystallization. The probable deep (8–10 km) stratigraphic level of intrusion indicates a preintrusion temperature of wallrocks of at least 250 to 300 °C, suggesting a prolonged cooling of the pluton. We guess that the emplacement age is roughly 85 to 80 Ma. The K-Ar muscovite age of 71.7 Ma (Lee and Marvin, 1981) is crudely compatible with our $^{40}Ar/^{39}Ar$ age, but our younger age (62.9 Ma) on muscovite from the aplite dike is not. The disparity in ages may have resulted from (1) analytical errors, (2) dike emplacement about 15 m.y. after pluton emplacement, or (3) postemplacement thermal disturbance. In view of current data, we favor the first alternative. Compositional similarity between pluton and dike rocks disfavors the second alternative, and the simple Ar-release spectrum for the pluton disfavors the third alternative. The new data indicate that the Toano Springs pluton is Late Cretaceous in age and that it is unrelated to Jurassic muscovite-bearing granite in the Pilot Range.

Metamorphic Rocks

Metamorphic rocks of Mesozoic age are widespread in the Toano and Pilot Ranges (Glick, 1987; Miller and others, 1987) and metamorphic rocks of Tertiary age and probable Mesozoic age are widespread in the Grouse Creek and Raft River Mountains (Compton and others, 1977; Snoke and Miller, 1988). In the Pilot Range, metamorphic rocks achieved peak temperatures at about 155 Ma and last cooled through K-Ar blocking temperatures for biotite and muscovite during Late Cretaceous time (Miller and others, 1987).

We have studied metamorphic rocks in the Toano Range similar to those in the Pilot Range. Similar but lower grade metamorphic rocks occur in the central Silver Island Mountains, although they have not yet been studied. The local contact-metamorphic zones around Jurassic plutons at Crater Island and in the Newfoundland Mountains were caused by pluton emplacement and presumably are of the same age as the plutons. We obtained a single K-Ar age for schist in the Raft River Mountains as well.

Table 3. $^{40}Ar/^{39}Ar$ analytical data for muscovite sample B86TR-111 from the Toano Springs pluton

[Analyses done by L.W. Snee; machine sensitivity at analysis, 9.7×10^{-13} mol/V. Sample weight, 30 mg. Decay constants from Steiger and Jäger (1977). Age of monitor mineral (Minnesota hornblende), 520.4 Ma. Sample site: lat. 40°59'05" N., long. 114°18'17" W. Irradiation parameter, J=0.007208±0.25 percent. at, atmospheric; Ca, calcium derived; Cl, chlorine derived; K, potassium derived; rad, radiogenic. Total-fusion age, 77.4±0.3 Ma]

Temperature (°C)	$^{36}Ar_{at}$ (volts)	$^{37}Ar_{Ca}$ (volts)	$^{38}Ar_{Cl}$ (volts)	$^{39}Ar_{K}$ (volts)	$^{40}Ar_{rad}$ (volts)	Age (Ma)
500	0.00177	0.00135	0.00078	0.01997	0.12226	77.91±0.81
600	.00111	.00130	.00003	.04342	.24376	71.57±0.30
700	.00412	.00104	.00017	.14175	.83835	75.31±0.32
750	.00431	.00083	.00005	.18649	1.13308	77.32±0.32
800	.00802	.00079	.00011	.36211	2.24166	78.75±0.33
850	.02595	.00000	.00024	1.18863	7.32528	78.41±0.33
900	.01227	.00092	.00019	1.16762	7.05584	76.91±0.32
950	.01416	.00207	.00021	.98690	5.96381	76.92±0.32
1000	.00920	.00095	.00016	.63485	3.84904	77.16±0.32
1050	.00778	.00096	.00008	.69538	4.24311	77.65±0.32
1100	.00265	.00145	.00000	.57287	3.46577	77.00±0.32
1150	.00037	.00121	.00000	.01677	.09403	71.47±1.00
1200	.00031	.00113	.00002	.00592	.03290	70.80±2.39

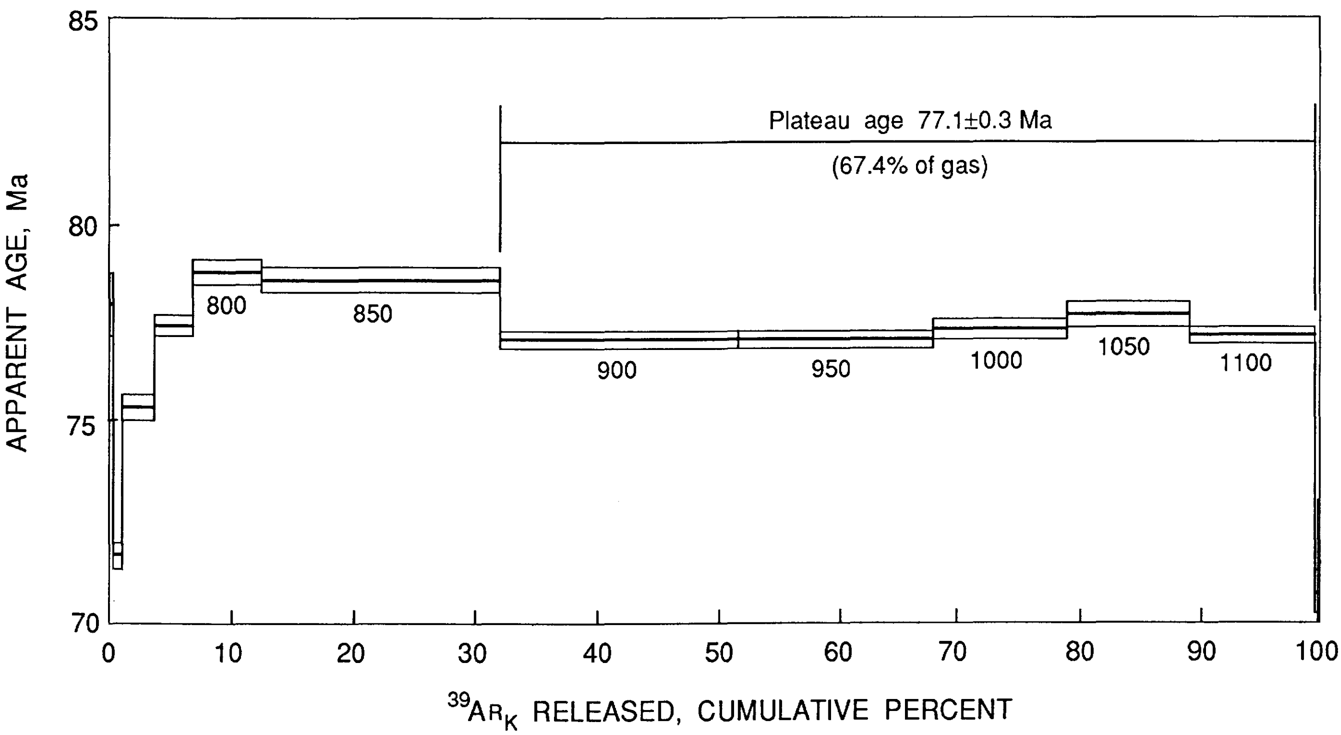

Figure 5. Age spectra diagram for muscovite sample B86TR-111 from the Toano Springs pluton. Temperatures corresponding to major steps in Ar-release spectrum are shown in degrees Celsius. Vertical width of steps indicates analytical error for apparent-age data.

Toano Range

Upper Proterozoic and Cambrian rocks in the lower plate of a detachment fault (fig. 4) underwent greenschist-facies metamorphism and local penetrative deformation. The upper Proterozoic rocks form a thick sequence of metamorphosed orthoquartzite, quartz wacke, feldspathic wacke, siltstone, and rare calc-silicate rock. Although all of these were similarly metamorphosed, the metasiltstone contains the best mineralogic indicators of metamorphic grade. Unlike the Proterozoic rocks, evidence of metamorphism is not apparent in all of the Cambrian rocks. The Cambrian graphitic phyllite, limestone, and siltstone may not have bulk compositions favorable for growth of facies-indicative minerals.

Greenschist metamorphism of the upper Proterozoic and Cambrian rocks is defined by widespread muscovite, biotite, chlorite, and minor tremolite. Amphibolite-facies mineral assemblages are recognized at only one locality, 1.3 km northeast of the Toano Springs pluton. There, coexisting muscovite, biotite, staurolite, and garnet indicate almandine-amphibolite facies.

K-Ar analysis of metamorphic biotite and muscovite from greenschist-facies rocks east of the main mass of Toano Springs pluton have yielded Cretaceous and Tertiary ages of 94.5±2.4 Ma (biotite sample B84TR–167), 69.7±1.7 Ma (muscovite sample B84TR–112), and 61.4±1.5 Ma (muscovite sample B85TR–135) (table 2). These ages bracket the results of Lee and others (1980), who reported K-Ar muscovite ages of 75.6±2.1 and 72.5±2.0 (their samples 512 and 511) from Proterozoic metaquartzite near the Toano Springs pluton.

Although metamorphic minerals from these rocks primarily yield Cretaceous apparent ages, field evidence suggests Jurassic metamorphism. Penetrative fabrics in the Cambrian rocks are truncated by the Late Jurassic Silver Zone Pass pluton (Glick, 1987) and its dikes, neither of which shows a penetrative fabric or any other sign of deformation. These relations indicate that metamorphic fabrics in the vicinity of this Late Jurassic pluton formed during, or more likely prior to, its emplacement.

Since the metamorphic fabrics in wallrocks around the Toano Springs pluton appear to be continuous with those cut by the Silver Zone Pass pluton and therefore Jurassic in age, one or more processes could have produced the Cretaceous apparent ages: (1) a protracted period of cooling, (2) long-term burial at elevated temperature followed by rapid tectonic denudation, and (3) resetting caused by emplacement of the Toano Springs pluton. According to the first hypothesis, the ages represent cooling over a protracted interval subsequent to the Jurassic metamorphic event. If so, cooling took place over more than 90 m.y., during which time the rocks remained deep or temperature decline was otherwise retarded. However, studies pertaining to the Pilot Range and other parts of the northeastern Nevada and northwestern Utah region (Miller and others, 1987) indicate surprisingly consistent mica cooling ages of about 80 to 65 Ma. This regionwide concurrence favors the hypothesis of tectonic denudation to rapidly curtail Ar diffusion in micas. However, for the Toano Range, two of our K-Ar ages yielded by metamorphic minerals and those reported by Lee and others (1980) also approximate cooling ages for the Toano Springs pluton. These relations indicate that local heating (by intrusion of the pluton) and subsequent cooling (perhaps during regional denudation) were most likely responsible for the Cretaceous ages. That the resetting by the pluton was only local is indicated by the biotite cooling age of 94.5±2.4 Ma (sample B84TR–167, table 2). It may be that the pluton extends shallowly under metamorphic rocks to the south, causing widespread resetting of Jurassic micas, but has a steep north border along which the resetting was restricted to a much narrower zone.

Raft River Mountains

The Grouse Creek and Raft River Mountains were metamorphosed during the Tertiary (Compton and others, 1977). However, to the north, in the Albion Mountains, rocks that are strikingly similar to those in the Grouse Creek and Raft River Mountains show evidence of both Mesozoic and Cenozoic metamorphism (Armstrong, 1976). The continuity of these three mountain ranges (fig. 2) suggests that Mesozoic metamorphism in the Raft River and Grouse Creek Mountains may have been overprinted pervasively by Tertiary metamorphism (Miller and others, 1983; Snoke and Miller, 1988).

The metavolcanic(?) muscovite schist member of the schist of the Upper Narrows (Compton, 1972) was sampled in the western Raft River Mountains (fig. 2) at a location about 12 km south of the Almo pluton of Armstrong and Hills' (1967). They dated this pluton at 30 Ma by the Rb-Sr method. Our K-Ar age on muscovite from the schist member (sample M84RR–99, table 2) is 29.9±0.7 Ma. The similarity of our result to the 30-Ma Rb-Sr age for the Almo pluton may reflect complete resetting caused by heat from the pluton. Alternatively, the similarity may be coincidental and our data may reflect cooling from any one of several possible metamorphic events. The age roughly fits biotite-age contours extrapolated southward from the Albion Mountains (see fig. 8 of Armstrong, 1976), reinforcing the assumption that there were coeval thermal events in the Albion and Raft River Mountains.

Tertiary Plutons

Late Eocene granitoids have been dated in several parts of northern Utah. A late Eocene granodiorite pluton in the southern Grouse Creek Mountains (fig. 2) yielded a Rb-Sr age of 38.2±2.0 Ma (Compton and others, 1977). A K-Ar age of 23.9 Ma—recalculated from Armstrong's (1970) data using new decay constants—for this pluton suggests either different ages of intrusion for different lobes or a complex cooling history (Compton and others, 1977). Granodiorite from the Pilot Range yielded a U-Pb zircon age of 38.9±0.9 Ma (Miller and others, 1987). Similar plutons (granodiorite to monzogranite), small bodies, and dikes in the Pilot Range yielded 37- to 30-Ma K-Ar biotite ages, which Miller and others (1987) interpreted as cooling following emplacement at about 39 Ma.

Toano Range

The Castle Park pluton, first reported by Glick (1987), is located in the northeasternmost Toano Range (fig. 4). The pluton is composed of subequigranular monzogranite that contains about 10 percent of small (0.5-mm) and large (5-mm) books of rectangular and hexagonal biotite. The 0.8-km^2 pluton is poorly exposed and intrudes Ordovician and Silurian rocks predominantly consisting of dolomite and quartzite. Spatially associated dikes considered to be genetically related to the pluton intrude Silurian and Devonian dolomite and cut north-striking faults (Glick, 1987). The pluton may be a small part of a much more extensive intrusive body or group of bodies in the subsurface, judging from geophysical data. Grauch and others (1988) depicted a magnetic anomaly that could be the expression of a pluton in the area where Glick (1987) identified the Castle Park pluton. Because no igneous rocks were identified on the geologic map used by Grauch and others, they only inferred the presence of a buried pluton. The anomaly identified by Grauch and others (1988) encloses about 25 km^2 centered on the outcrops Glick (1987) identified, and it extends from there about 10 km to the west and thereon in a south-southwest direction for several tens of kilometers. Even if the part of this anomaly that coincides with Goshute Valley (fig. 2) west of the Toano Range is caused by other rocks such as Tertiary basalt, the part of the anomaly coinciding with the northern Toano Range is much larger than the exposed pluton and suggests a large body in the subsurface. The pluton has a narrow metamorphic aureole, suggesting that it was emplaced at a much-shallower depth than the Mesozoic plutons farther south in the Toano Range.

Biotite (table 2, B85TR–131) from this pluton yielded an apparent K-Ar age of 36.9±0.9 Ma. This K-Ar age resembles those for the lithologically similar late Eocene plutonic rocks in the neighboring Pilot Range, so we infer an emplacement age for the Castle Park pluton similar to the 39-Ma U-Pb zircon age for the Bettridge Canyon Granodiorite in the Pilot Range. This inference yields a 1- to 3-m.y. interval for cooling the pluton to biotite blocking temperatures following emplacement, which is consistent with a shallower emplacement than is characteristic of the Jurassic plutons.

Bovine Mountains

Along the south flank of the Bovine Mountains (fig. 2), which lie south of the 38-Ma (Rb-Sr) Immigrant Pass intrusion of Compton and others' (1977), abundant hornblende gabbro boulders locally lie on a beach terrace of Lake Bonneville. The gabbro somewhat resembles local mafic phases of the Immigrant Pass intrusion, but definite outcrop was not found. Hornblende from this gabbro gave a K-Ar age of 49.2±1.2 Ma (sample 81B1, table 2). In view of the uncertainty that all of the Immigrant Pass pluton is 38 Ma (Compton and others, 1977, p. 1248) and because of the uncertain relationship of the dated gabbro to that pluton, it is difficult to evaluate the age. The age may indicate an intrusion older than the Immigrant Pass, or may result from retention of excess Ar by hornblende such as was documented by Miller and others (1987) for a late Eocene pluton in the Pilot Range.

SUMMARY AND CONCLUSIONS

K-Ar biotite ages for Jurassic plutons and dikes in northwestern Utah and northeastern Nevada cluster at 155 to 150 Ma (fig. 6), corroborating the peak of K-Ar ages at about 155 Ma reported by Armstrong and Suppe (see fig. 4 of Armstrong and Suppe, 1973) for a much wider area. We suggest that our K-Ar ages represent slow cooling following widespread emplacement of plutons about 165 to 160 Ma, based primarily upon the 162-Ma U-Pb zircon emplacement age for one pluton, the Silver Zone Pass pluton (J.E. Wright, oral commun., 1986). This restricted emplacement age is also strongly supported by the 165- to 155-Ma U-Pb zircon age of the Miners Spring Granite in the Pilot Range (Miller and others, 1987) and by similar U-Pb zircon ages of about 160 Ma for three plutons in the southern Snake Range in east-central Nevada (Miller and others, 1988). Most Jurassic plutons we have studied were emplaced in lower-epizonal settings and are compositionally similar, suggesting that they all had similar cooling histories. K-Ar apparent ages younger than the 155- to 150-Ma group (fig. 6) include those reported for the Silver Zone Pass pluton (133 and 127 Ma) and the Crater Island Quartz Monzonite (143 Ma). These anomalously young ages probably result from impure samples, since other K-Ar ages on these same plutons are within the 155- to 150-Ma peak.

Dikes cutting the Jurassic plutons and wallrocks also yield 155- to 150-Ma K-Ar biotite ages, with the exception of an altered dike (sample T82–47, table 1) near the Newfoundland stock (144 Ma). The dikes intruded rocks that at some point were fairly hot, as indicated by elevated conodont-alteration indexes (Harris and others, 1980) and their proximity to the previously emplaced plutons. If the rocks were hot at the time of dike emplacement, cooling to the Ar-retention temperature may have been prolonged compared to the rapid cooling of a narrow dike injected into cold rock. We cannot accurately date the time of emplacement of the dikes, but the similarity of both their compositions and K-Ar ages to those of the plutons suggest emplacement soon after the plutons solidified and almost certainly before 153 Ma. Sericite in some highly altered dikes yielded younger ages than biotite in unaltered dikes. Since sericite has a higher blocking temperature than biotite, alteration of these dikes apparently took place about 150 to 148 Ma, well after emplacement.

If all Jurassic plutons in the Newfoundland and Silver Island Mountains and Toano Range were intruded within a short timespan, the cooling ages of plutonic and dike rocks indicate that roughly 10 m.y. was required to cool plutons and nearby wallrocks to Ar-retention temperatures for biotite. No data indicate that the plutons were emplaced deeper than the 6- to 8-km depths indicated by stratigraphic thicknesses. We suggest that voluminous plutons heated a broad region of the shallow crust from about 165 and 160 Ma and that the thermal decay in this region was protracted because of the enormous volume of plutonic rocks.

Our K-Ar ages for the Toano Springs pluton strengthen its previous Late Cretaceous age assignment by Lee and Marvin (1981). A simple $^{40}Ar/^{39}Ar$ plateau age on muscovite from this pluton, giving a cooling age of about 77 Ma, indicates an emplacement age somewhat before 77 Ma. Although the depth of emplacement and size of the pluton and the temperature history of the wallrocks are all poorly constrained, we speculate that the pluton was emplaced in lower-greenschist facies rocks and therefore probably cooled slowly. Our best

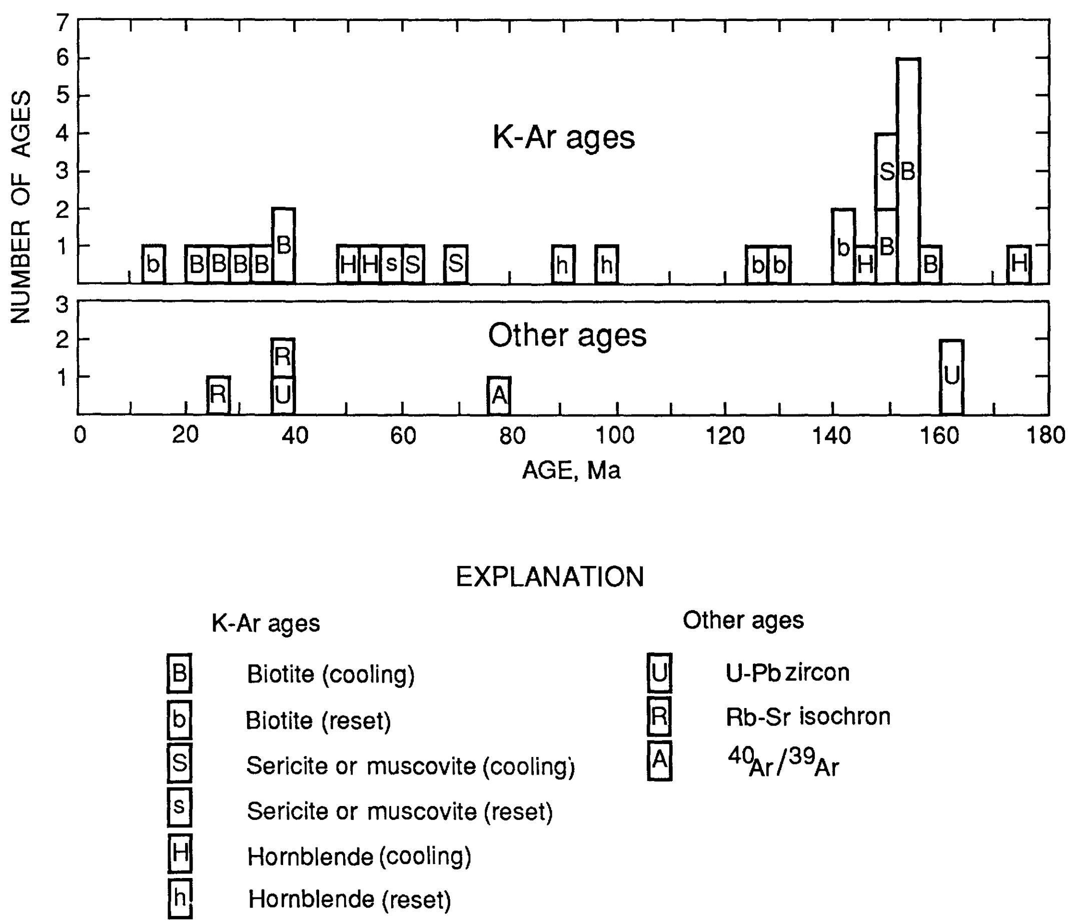

Figure 6. Histogram of isotopic ages for intrusive igneous rocks in five mountain ranges: Newfoundland, Silver Island, Pilot, Toano, and Grouse Creek. Conventional K-Ar data are compiled from this report and reports cited herein; other types of isotopic ages (U-Pb, Rb-Sr, and $^{40}Ar/^{39}Ar$) are included for comparison. These latter ages generally more closely approximate the time of intrusion, whereas conventional K-Ar ages in this region generally record cooling or resetting by later thermal events. U-Pb zircon data for the Miners Spring Granite, interpreted by Miller and others (1987) to indicate an intrusion age between 165 and 155 Ma, are represented at 160 Ma.

estimate for the emplacement age of the Toano Springs pluton is about 85 to 80 Ma.

Greenschist-facies metamorphic rocks surrounding the Toano Springs pluton were first metamorphosed during the Jurassic, as recorded by fabrics truncated by the 162-Ma Silver Zone Pass pluton. However, these metamorphic rocks typically yield Cretaceous to Paleocene K-Ar mica ages, most probably due to a combination of heating by the Toano Springs pluton and possible regional cooling, as proposed by Miller and others (1987). One K-Ar biotite cooling age of 94 Ma suggests that resetting of Jurassic K-Ar ages for metamorphic minerals was not complete in part of the northern Toano Range. Miller and Gans (1989) suggested that muscovite-bearing Late Cretaceous granitoids in east-central Nevada typically created wide metamorphic halos, regional in character, because the plutons and associated fluids efficiently transferred heat from the lower crust. Their model agrees with the evidence for widespread metamorphism around the Toano Springs pluton. Although Miller and Gans (1989) established that Late Cretaceous metamorphism was the major Mesozoic thermal event in east-central Nevada, geologic and geochronologic data presented by Miller and others (1987) for the Pilot Range indicate a more prominent Jurassic than Cretaceous metamorphism at lat. 41° N. The model for thermal transfer by wet granites (Miller and Gans, 1989) can account for this apparent geographic distinction in age of major metamorphism in the eastern Great Basin. The most extensive and highest grade metamorphic rocks in the northeastern Great Basin are in the southern Pilot Range, where they are spatially associated with muscovite-bearing Jurassic granite and pegmatite (Miller and others, 1987). According to this model, muscovite-bearing granites—whatever their age—produce regional-metamorphic zones; the preponderant age of metamorphism in any region of the eastern Great Basin is simply a function of the age of the wet granites. This model can be compared with other models for the origin of regional metamorphism by determining in detail the pressure-temperature-time histories for rocks in the Pilot and Toano Ranges.

A small exposure of a large subsurface pluton in the northern Toano Range yielded a 37-Ma K-Ar biotite age, on which basis we combine it with other plutons in the area that indicate an approximately 39-Ma intrusive event (Miller and others, 1987). Plutons representing this intrusive event evidently were emplaced at shallow depths. They have narrow metamorphic auroeles, and their K-Ar ages are about 2 to 5 m.y. younger than U-Pb and Rb-Sr ages, indicating rapid cooling to Ar-retention temperatures for biotite. Hornblende from a gabbro possibly representing a phase of the 38-Ma Immigrant Pass intrusion in the Grouse Creek Mountains yielded a K-Ar age of 49 Ma, but this age may reflect excess Ar retention.

Our data support the conclusion of Armstrong and Suppe's (1973) and Moore and McKee's (1983) that most of the scattered plutons in northwestern Utah and northeastern Nevada are Jurassic and Tertiary in age. As suggested by Miller and others (1987), the Jurassic intrusive event may have been brief but widespread in the area. Moreover, Jurassic plutons of a similarly restricted age range are numerous over a much larger area, including east-central Nevada (Miller and others, 1988), central Nevada (Roberts and others, 1971), and western Nevada (Dilles and Wright, 1988).

The Cretaceous Toano Springs pluton in the Toano Range (fig. 4) apparently marks the northeastward extent of plutons of Late Cretaceous age in the Great Basin; the plutons are scattered to the southwest in east-central Nevada (Miller and others, 1988) and central Nevada (Roberts and others, 1971; Snoke and Miller, 1988). An earliest Cretaceous K-Ar biotite age of 138.4 Ma (revised with new constants) reported from a small pluton 50 km north of the Toano Range (Slack, 1974) also may represent Cretaceous magmatism, but its apparent age falls between more firmly dated plutonic events and needs to be verified. The 138.4-Ma age is similar to some analytically dubious ages for the Jurassic Silver Zone Pass pluton.

All Tertiary plutons we have studied in northwestern Utah and many to the south and east in Utah (Moore and McKee, 1983) are latest Eocene in age: Most K-Ar biotite cooling ages range from 37 to 35 Ma, and one U-Pb zircon age is 39 Ma. However, somewhat-younger (Oligocene) plutons occur in a metamorphic core complex setting in the Albion (Armstrong and Hills, 1967) and Grouse Creek (Compton and others, 1977) Mountains. Volcanic rocks in this part of northwestern Utah yield 44- to 33-Ma K-Ar ages (Compton, 1983; Moore and McKee, 1983; Miller, 1984; Miller and Glick, 1986), probably corresponding to the latest Eocene plutonic event. These data add to those of Armstrong and Suppe's (1973, fig. 4) and of many other workers' (see Roberts and others, 1971; Compton and others, 1977; Miller and others, 1988) that suggest a widespread intrusive and extrusive event in late Eocene time. Dating these plutons by the U-Pb zircon method is required to more closely restrict their emplacement ages and to determine cooling rates and the effects of possible younger thermal events.

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