THE MESOZOIC-CENOZOIC TECTONOTHERMAL
EVOLUTION OF THE RUBY MOUNTAINS, EAST
HUMBOLDT RANGE, NEVADA:
A CORDILLERAN METAMORPHIC CORE COMPLEX

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Abstract. A combined K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological study of the Ruby Mountains-East Humboldt Range, Nevada, a Cordilleran metamorphic core complex, has revealed a complex tectonothermal history. The three structural subdivisions of the core complex (migmatitic core, mylonitic zone, and cover) share magmatic and deformational histories in part, but also display important contrasts in structural style, metamorphic paragenesis, and thermal history. During the Late Jurassic (ca 160 Ma), miogeoclinal rocks were polyphase-deformed, metamorphosed under amphibolite facies conditions, and pervasively intruded by peraluminous granitic magmas, thereby forming an igneous and metamorphic complex. Late Jurassic muscovite granite porphyry plugs also intruded unmetamorphosed cover rocks. Late Cretaceous cooling of the igneous and metamorphic complex is locally suggested by poorly resolved Cretaceous incremental-release $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende spectra and by U-Pb monazite ages from pelitic schist exposed in the northern Ruby Mountains. Between ca 45 Ma

and 20 Ma, the igneous and metamorphic rocks experienced an episode of complex extensional tectonism which involved the development of low-angle, normal-sense, simple shear zones. As a result, rocks metamorphosed at depth in the Mesozoic were translated to higher crustal levels which resulted in cooling through temperatures required for the intracrystalline retention of argon within minerals. Near concordance of hornblende and biotite plateau ages from the migmatitic core of the complex suggest relatively rapid exhumation. However, it is not certain if this cooling followed a prolonged maintenance at elevated temperatures after the ca 160 Ma metamorphism or if distinct, locally superposed late Mesozoic and/or middle Tertiary thermal overprints had affected the cooling history. A major extensional simple shear zone is marked by an approximately 1-kilometer-thick mylonite zone that experienced late kinematic, superposed brittle deformation. A geometric consequence of the development of low-angle extensional fault zones is the eventual translation of colder rocks over hotter rocks. Such a history is supported by the $^{40}\text{Ar}/^{39}\text{Ar}$ data. For example, mylonitic mafic orthogneisses from a major allochthon record $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende plateau ages between 44 and 48 Ma and biotite pla-

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teau ages between 32 and 33 Ma, and are structurally positioned above mylonitic rocks of the northern Ruby Mountains which record biotite cooling ages of ca 22–24 Ma. Such relations suggest either multiple episodes of Tertiary mylonitization or a protracted, multiphase history of mylonitization. However, after ca 20 Ma, all of the presently exposed mylonitic rocks were maintained below 100°C and have only experienced upper crustal brittle deformation.

INTRODUCTION

The discovery that metamorphic rocks exposed in many ranges of the Basin and Range province yielded Tertiary K–Ar mineral ages [Armstrong and Hansen, 1966; Mauger et al., 1968] initiated interest in the Tertiary tectonothermal history of the internal portion of the North American Cordillera. These reports were particularly interesting because the crystalline terranes were thought to represent uplifted exposures of the Mesozoic infrastructural core of the Cordillera [Armstrong and Hansen, 1966]. Tectonic features commonly associated with these igneous and metamorphic complexes, especially south of the Snake River Plain, are Tertiary low-angle normal faults that characteristically emplace upper crustal rocks on middle crustal rocks. The common association of a complexly deformed igneous and metamorphic terrane, a superposed mylonitic zone (commonly interpreted to record Tertiary ductile deformation), and an extensively faulted cover terrane has together been identified as a distinctive petrotectonic feature termed a "Cordilleran metamorphic core complex" [e.g., Coney, 1979; Crittenden et al., 1980]. Tertiary K–Ar ages are characteristic of the complexes [Damon et al., 1963; Armstrong and Hansen, 1966; Armstrong, 1982; McKee, 1983; Lee et al., 1986]. Several studies within these complexes reported that Tertiary K–Ar mineral ages were spatially related to detachment faults, thereby suggesting a possible Tertiary dynamothermal overprint [e.g., Lee et al., 1970, 1980; Martin et al., 1982; Davis et al., 1982]. On the other hand,

some workers [e.g., Kistler et al., 1981], have argued that the Tertiary K–Ar mineral ages merely record cooling through mineral argon closure temperatures of terranes previously maintained at deeper crustal levels.

Interpretation of K–Ar mineral ages from metamorphic rocks is typically difficult and requires consideration of other geochronological and structural data. In particular, incorporation of extraneous (excess) argon is common in both igneous and metamorphic rocks that have experienced superposed thermal events. In the initial stages of our geochronological investigation of the Ruby Mountains–East Humboldt Range, Nevada, several Mesozoic K–Ar hornblende ages were determined (ca 82, 110, 194, 224 Ma). Some of these ages seemed unreasonably old in light of the conventional view of a middle Mesozoic age for regional metamorphism within the eastern Great Basin [e.g., Misch, 1960]. To resolve radiogenic from potential extraneous argon components and to better define the tectonothermal history of the area, a systematic $^{40}\text{Ar}/^{39}\text{Ar}$ study was undertaken. These results together with the original, previously unpublished K–Ar dates are reported here. These data are integrated with the petrologic and structural history of the Ruby Mountains–East Humboldt Range [e.g., Snoke and Lush, 1984] in order to evaluate the thermal evolution of this Cordilleran metamorphic core complex.

GEOLOGIC FRAMEWORK

The Ruby Mountains–East Humboldt Range is a north-northeast trending horst system in the late Cenozoic Basin and Range province of northeast Nevada. Pre-Quaternary rocks exposed in the Ruby Mountains and East Humboldt Range may be grouped into three broad categories (Figure 1): (1) an igneous and metamorphic complex; (2) a sequence of low-grade to unmetamorphosed miogeoclinal rocks (Cambrian to Triassic); and (3) Tertiary sedimentary, volcanic, and plutonic rocks. The igneous and metamorphic complex can be divided into two distinct structural terranes (Figures 1

Fig. 1. Generalized regional geologic map of the Ruby Mountains-East Humboldt Range-Wood Hills, Nevada. Macroscopic folds (F_2) and distribution of mylonitic rocks shown. C.H. = Clover Hill and A.L. = Angel Lake. Outline of areas covered by Plates 1, 2, and 3 is indicated. Modified from Snoke and Lush [1984].

Fig. 2. Diagrammatic sketch of relations between the structural terranes in the Ruby Mountains-East Humboldt Range metamorphic core complex. Pzs, Paleozoic sedimentary rocks; Tsv, Tertiary sedimentary and volcanic rocks.

and 2): (1) a core region of upper amphibolite facies migmatitic rocks; and (2) an approximately 1-kilometer-thick zone of retrograde mylonitization superposed on the amphibolite facies rocks of the core. A major goal of our geochronological studies was to evaluate possible differences between the tectonothermal evolution of the migmatitic core and structurally overlying mylonitic zone.

Structurally above the igneous and metamorphic complex is a cover terrane consisting of a fault-bounded mosaic of low-grade to unmetamorphosed rocks. This terrane includes portions of the miogeoclinal rock sequence of the eastern Great Basin and thick sections of Oligocene and Miocene sedimentary and volcanic rocks. The faults are low- to high-angle and of Tertiary age. Pre-Tertiary cover rocks commonly display a more complex structural history and record earlier effects of both Mesozoic and Cenozoic deformations [Snoke and Lush, 1984; Taylor, 1984].

Some units within the cover terrane (e.g., Devonian Guilmette Formation) occur in the mylonitic zone and migmatitic core where they are metamorphosed and polydeformed [Snoke and Lush, 1984; Taylor, 1984]. Howard [1971] suggested that all of the metasedimentary rocks of the igneous and metamorphic complex in the northern Ruby Mountains were correlative with the miogeoclinal sequence of the eastern Great Basin.

Metasedimentary rocks within the core

of the northern Ruby Mountains-East Humboldt Range were pervasively intruded by a variety of igneous rocks that range from quartz gabbro to granite. The most abundant intrusive rock is leucocratic, commonly coarse-grained to pegmatitic, and consists largely of alkali-feldspar, sodic plagioclase, and quartz; modal variations span the range of granite to trondhjemite. Muscovite and biotite are commonly present in the leucocratic, pegmatitic granitoids; and garnet, sillimanite, zircon, and monazite are accessory minerals. The intrusive rocks vary in geometry from small dikes to large sheets that are complexly interlayered with the metamorphic rocks. Only a few of these intrusive masses are sufficiently extensive and homogeneous to qualify as mappable rock units, therefore, most have been grouped with the metasedimentary rocks and mapped as migmatitic lithostratigraphic units (e.g., migmatitic Prospect Mountain Quartzite).

Widespread sillimanite in metapelitic rocks and diopside in impure metacarbonate rocks indicate that the migmatitic core reached upper amphibolite facies metamorphic conditions [Snelson, 1957; Howard, 1966]. Metamorphic mineral assemblages are locally sufficiently diverse to more rigorously constrain temperature-pressure conditions. For example, at Clover Hill (Figure 1), the assemblage: kyanite + garnet + biotite + sillimanite + muscovite + quartz + plagioclase + ilmenite + rutile

TABLE 1. Summary of Structural Chronology of the Ruby Mountains-East Humboldt Range, Nevada

Age	Deformation	Metamorphism
Mid-Mesozoic(?)	pre-metamorphic thrust faulting, development of metamorphic layering, penetrative foliation (S_1), and small-scale isoclinal folds; microscopic to map-scale F_2 folds, with a locally penetrative foliation (S_2); late to postmetamorphic folds (F_3)	upper amphibolite facies (sillimanite grade)
Mid-Tertiary (ca 45 to 20 Ma)	mylonitic deformation in kilometer-scale zone of noncoaxial deformation, development of mylonitic foliation and lineation, local development of folds (F_4) that deform the mylonitic fabric; late ductile-brittle low-angle faults; synchronous low-angle and high-angle normal faults in the cover terrane	upper greenschist to lower amphibolite facies
Late Tertiary (ca 15 to 13 Ma)	detachment faulting (low-angle normal faulting) between unmetamorphosed cover rocks and the igneous and metamorphic complex; regional doming	sub-greenschist to greenschist(?) facies
Late Tertiary (<10 Ma)	Basin and Range normal faulting (planar to listric)	hydrothermal

is common in metapelitic rocks of the late Precambrian McCoy Creek Group [Snoke and Lush, 1984]. In the migmatitic core of the northern East Humboldt Range, Lush [1982] reported sillimanite-rich pelitic schist with sparse kyanite relict cores mantled by fibrolite. Staurolite is absent in these areas. Consequently, the sillimanite paragenesis probably reflects the kyanite = sillimanite inversion and/or the breakdown of muscovite in the presence of quartz. Regardless of its exact petrogenesis, the widespread occurrence of sillimanite + kyanite indicates that temperatures of at least 550°–600°C and pressures of 4.5 to 6 kbar [Greenwood, 1976] were attained during the culmination of regional metamorphism in the northern part of the East Humboldt Range. In the northern Ruby Mountains and southern East Humboldt Range, similar metamorphic conditions likely prevailed, but sillimanite is the

only aluminosilicate mineral identified in metapelitic schists. To the south, along the east flank of the Ruby Mountains (north of the Harrison Pass pluton, Figure 1), Willden and Kistler [1969] described metapelitic schists containing garnet, staurolite, and sillimanite. The maximum metamorphic temperature and pressure estimates for this area are ca 700°C and 6.5 kbar [Kistler et al., 1981]. Andalusite and very sparse kyanite were found in these same rocks by Johnson [1981] who proposed the following metamorphic history: (1) synkinematic growth of staurolite + kyanite; and (2) late- to postkinematic growth of sillimanite and andalusite. This transition was presumed to reflect an increase in temperature associated with a decrease in pressure [Johnson, 1981].

The deformational history of the Ruby Mountains-East Humboldt Range is summarized in Table 1. A complex pre-mylonitic

evolution characterizes the migmatitic core terrane and presumably rocks in the mylonitic zone. This history included: premetamorphic thrusting, polyphase folding, upper amphibolite facies metamorphism with associated migmatization, and mafic to silicic plutonism [Howard, 1966; Snoke and Lush, 1984]. A variably penetrative, mylonitic deformation is superposed on a large part of the igneous and metamorphic complex. This mylonitic zone is especially well-developed along the western flank of the Ruby Mountains-East Humboldt Range, but it extends across the range system in the north Ruby Valley area (Figure 1). A uniform sense-of-shear direction (top to the west-northwest) characterizes the mylonite shear zone along the western flank of the northern Ruby Mountains and East Humboldt Range [Snoke and Lush, 1984]. The physical conditions maintained during the mylonitic deformation have not been studied in detail. However, they must have at least been equivalent to those of the upper greenschist facies because biotite underwent ubiquitous syntectonic, dynamic recrystallization during this ductile deformation.

Numerous structures are superposed on the zone of mylonitic deformation. In part these represent a continuous progressive deformation under a variety of physical conditions during tectonic exhumation. A fundamental aspect of this structural chronology is the transition from dominantly ductile to dominantly brittle deformation processes. This is reflected by the development of ductile to brittle, low-angle faults. These faults localized strain and are characterized by the development of secondary mylonitic and cataclastic rocks along lithologic boundaries. As a result of this ductile-brittle deformation, large-scale folds were dismembered and transformed into fault-bound structural units. Similar relations exist between allochthonous cover rocks and structurally lower terranes. In all cases, faults above the core and mylonite zone emplace upper crustal rocks or higher structural levels onto structurally deeper rocks. This structural style reflects a crustal thinning in which structural elements with unlike tectonothermal histories

are juxtaposed along low-angle normal faults. Such structural relations are compatible with a low-angle, extensional shear zone model similar to that discussed by Wernicke [1981] and modified in part by Davis et al. [1986].

PREVIOUS GEOCHRONOLOGY

Rb-Sr whole-rock isochron ages of 160 ± 3 Ma and 83 ± 1.3 Ma were reported for two-mica granitic rocks from the igneous and metamorphic complex by Kistler et al. [1981]. Preliminary U-Pb zircon studies on the two-mica granitic rocks dated as Cretaceous by Rb-Sr whole-rock techniques indicate an older crystallization age, perhaps Late Jurassic (J. E. Wright, personal communication, 1985). The granitic rocks recording ca 160 Ma Rb-Sr whole-rock isochron age [Kistler et al., 1981] commonly interdigitate and share a metamorphic fabric with metasedimentary rocks of the igneous and metamorphic complex. The granitic rocks radiometrically dated as Cretaceous [Kistler et al., 1981] are commonly much less deformed and locally appear to be late to postkinematic. However, Johnson [1981] reported that granitic rocks that she mapped as a part of the "Cretaceous" suite were also locally strongly deformed. Given these conflicting geochronological and geological constraints, it is difficult to precisely constrain the time(s) of major Mesozoic ductile deformation and synkinematic metamorphism in the migmatitic core of the Ruby Mountains-East Humboldt Range. However, the late Jurassic (160 ± 5 Ma) was clearly a time of regionally significant two-mica, peraluminous granitic magmatism. It is likely that, at least locally, this magmatism was accompanied by regional metamorphism and penetrative ductile strain.

The Harrison Pass pluton (Figure 1) has yielded numerous Oligocene radiometric ages. K-Ar ages (ages recalculated according to IUGS constants; relative time referred to the DNAG geologic time scale [Palmer, 1983]) of 30, 32, 32, and 37 Ma (all listed with an analytical uncertainty of approximately ± 10 percent of the calculated age) were determined for four biotite concentrates prepared from samples

collected within the Harrison Pass pluton [Willden et al., 1967]. A poorly defined Rb-Sr whole-rock isochron age of 31.9 ± 1.2 Ma was reported by Kistler et al. [1981] for the Harrison Pass pluton. Recent mapping indicates that the pluton can be divided into a biotite + hornblende porphyritic phase and a muscovite + biotite phase [Snoke and Lush, 1984]. Preliminary results of U-Pb analyses of zircons from both phases of the pluton suggest an age of ca 36 Ma (J. E. Wright, personal communication, 1985). Snoke et al. [1982] described mylonitic ductile shear zones within the muscovite-biotite granite phase of the Harrison Pass pluton.

Tertiary radiometric ages (25 and 29 Ma) were reported for biotite from the igneous and metamorphic complex of the northern Ruby Mountains (samples of orthogneiss(?) collected in Lamoille Canyon; Armstrong and Hansen [1966]). Tertiary K-Ar biotite dates of 18.6 Ma and 29 Ma from the Ruby Mountains-East Humboldt Range were reported by Thorman ([1965]; details on locality and lithology of these samples were not given). A K-Ar (muscovite + quartz) age of 26.0 ± 0.8 Ma on "micaceous mylonitic quartzitic gneiss" from the Secret Creek gorge area was reported by Armstrong et al. [1976]. Kistler et al. [1981] chrontoured K-Ar biotite ages on their Figure 1, illustrating an east to west decrease in age (ca 36 Ma in the easternmost part of the Harrison Pass pluton to less than 20 Ma in the igneous and metamorphic complex along the western flank of the range; i.e., the mylonitic shear zone). Kistler et al. [1981] related this pattern to a northeast-trending arch that formed during the emplacement of the Harrison Pass pluton. According to their interpretation, the deepest crustal levels are presently exposed along the west flank of the range.

K-Ar dating of unmetamorphosed Tertiary volcanic rocks also provides constraints on the age of some deformational events. Basalt dikes locally intrude mylonitic rocks north of Secret Creek gorge, southwestern East Humboldt Range (Figure 1). A K-Ar whole-rock age of ca 17 Ma was reported for a representative of these dikes [Snoke, 1980]. Rhyolitic rocks from both

the Secret Creek gorge area and the northeast East Humboldt Range are cut by low-angle faults; their age range is ca 15 to 13.4 Ma [Snoke et al., 1983]. These data indicate that the mylonitic shear zone, exposed at the present level of erosion, developed before 17 Ma, although much brittle, low-angle faulting is younger.

ANALYTICAL PROCEDURES

K-Ar

K-Ar analyses were done in the laboratories of the U.S. Geological Survey, Menlo Park, California, using standard isotope-dilution procedures described by Dalrymple and Lanphere [1969]. The age determinations were performed on pure mineral concentrates (>99%) prepared by heavy liquid, magnetic, electrostatic, and hand-picking procedures. Potassium analyses were performed by lithium metaborate flux fusion-flame photometry techniques, the lithium serving as an internal standard [Ingamells, 1970]. Argon analyses were performed using a 60° sector, 15.2 cm radius, Nier-type mass spectrometer operated in the static mode for mass measurement. The precision of the data, shown as the + value, is the estimated analytical uncertainty at one standard deviation. It represents uncertainty in the measurement of radiogenic ^{40}Ar and K and is based on experience with replicated analyses in the Menlo Park laboratories. The decay constants and isotopic abundance ratios used for the K-Ar age calculations are those adopted by the International Union of Geological Sciences Subcommittee on Geochronology [Steiger and Jäger, 1977].

$^{40}\text{Ar}/^{39}\text{Ar}$

Analytical procedures followed during analysis of the Ruby Mountains-East Humboldt Range samples are similar to those described in detail in Dallmeyer and Rivers [1983]. Pure mineral concentrates (>99%) were prepared from crushed and sized rock powders using heavy liquid and magnetic separation techniques. These were wrapped in aluminum-foil packets, encapsulated in sealed quartz vials, and ir-

TABLE 2a. Potassium-Argon Ages on Minerals From the Northern Ruby Mountains, Nevada

Sample Number	Mineral	Percent K ₂ O	⁴⁰ Ar* mol/g	⁴⁰ Ar*%	Calculated Age (Ma) _{+σ}
A	hornblende	1.47	6.46554x10 ⁻¹¹	32.0	30.3 _{+1.0}
B	biotite	9.40	3.17957x10 ⁻¹⁰	74.5	23.4 _{+0.4}
C	hornblende	0.298	4.84244x10 ⁻¹¹	13.3	109.5 _{+10.0}
D	hornblende	0.603	7.23961x10 ⁻¹¹	51.4	81.6 _{+3.0}
E	hornblende	0.465	1.58859x10 ⁻¹⁰	64.7	223.5 _{+7.0}
		0.463			
F	hornblende	0.650	1.91893x10 ⁻¹⁰	63.5	194.4 _{+6.0}
G	biotite	8.07	1.54867x10 ⁻¹⁰	26.5	13.3 _{+1.0}
G	hornblende	1.360	7.51813x10 ⁻¹¹	39.3	38.1 _{+1.7}
H	biotite	7.70	1.71989x10 ⁻¹⁰	51.4	15.5 _{+0.4}
I	muscovite	10.06	2.3275x10 ⁻⁹	87.3	153.9 _{+0.9}

radiated in the central thimble position of the U.S. Geological Survey TRIGA reactor in Denver, Colorado. Variations in the flux of neutrons along the length of the irradiation assembly were monitored with several mineral standards, including MMhb-1 [Alexander et al., 1978]. The samples were heated incrementally until fusion with an RF induction generator. Each heating step was maintained for 45 min. Temperatures were controlled with an infrared sensing thermometer, and are accurate to $\pm 25^{\circ}\text{C}$ with an internal monitoring of $\pm 10^{\circ}\text{C}$. The evolved gas was purified with hot Cu/CuO and Ti-Zr getters. Each aliquot of gas was isotopically analyzed with a Nier-type, 15.2 cm radius, 60° sector mass spectrometer operated in a static mode. Measured isotopic ratios were corrected for the effects of mass discrimination and the interfering isotopes produced during irradiation (using factors reported by Dalrymple et al., 1981, for the reactor used in the present study). Apparent $^{40}\text{Ar}/^{39}\text{Ar}$ ages were calculated from the corrected isotopic ratios using the decay constants and isotopic abundance ratios listed by Steiger and Jäger [1977]. Total uncertainties in each apparent age (two sigma, interlaboratory) have been calculated following the methods outlined by Dalrymple and Lanphere [1971] which consider variations in inlet-time extrapolations, monitor ages, and various irradiation parameters. Analyses of the MMhb-1 monitor indicate that apparent K/Ca ratios

may be calculated through the relationship: $0.518 (+0.005) \times (^{37}\text{Ar}/^{39}\text{Ar})$ corrected.

RESULTS

K-Ar

Ten K-Ar ages have been determined for minerals separated from rocks of the northern Ruby Mountains. The analytical data are presented in Table 2a and sample locations are indicated on Plates 1 and 2 and in Table 2b.

Samples A and B were collected from nonmylonitic parts of the igneous and metamorphic complex. Sample A is from a hornblende granite, and a hornblende concentrate yielded a K-Ar date of 30.3 ± 1.0 Ma. Sample B is from a monazite-bearing biotite schist, and a biotite concentrate yielded a K-Ar date of 23.4 ± 0.4 Ma.

The remaining K-Ar samples, except sample I, were collected from the mylonitic shear zone exposed in the northernmost Ruby Mountains (Plate 2). These samples display considerable variation in K-Ar mineral dates: biotite dates (samples G and H) are 13.3 ± 1.0 and 15.5 ± 0.4 Ma; hornblende dates (samples C, D, E, F, and G) range from 38.1 ± 1.7 to 223.5 ± 7.0 Ma. Three of the hornblende concentrates (samples D, E, and G) were also analyzed with $^{40}\text{Ar}/^{39}\text{Ar}$ incremental-release techniques (samples 9, 11, and 12, respectively).

TABLE 2b. Field Sample Numbers and Locations

Sample Number	Field Number	Geographic Coordinates	
		West Longitude	North Latitude
A	170-44	115° 16' 37"	40° 46' 12"
B	108-3	115° 13' 57"	40° 47' 21"
C	175-54	115° 16' 17"	40° 49' 23"
D	AIRC-2	115° 15' 06"	40° 51' 53"
E	4-1	115° 14' 48"	40° 51' 49"
F	139-14A	115° 14' 25"	40° 50' 01"
G	36-2	115° 14' 23"	40° 51' 47"
H	931-10	115° 14' 35"	40° 52' 34"
I	197-8	115° 12' 42"	40° 52' 04"
1	NEV20-80	115° 21' 58"	40° 37' 41"
2	NEV21-80	115° 26' 10"	40° 39' 42"
3	NEV19-80	115° 28' 03"	40° 41' 34"
4	NEV 8B-80	115° 17' 38"	40° 46' 16"
5	NEV10-80	115° 16' 17"	40° 26' 20"
6	NEV9-80	115° 16' 33"	40° 46' 06"
7	175-29	115° 15' 56"	40° 49' 54"
8	NEV14-80	115° 16' 23"	40° 49' 32"
9	AIRC-2	115° 15' 06"	40° 51' 53"
10	NEV6B-80	115° 14' 54"	40° 51' 50"
11	4-1	115° 14' 48"	40° 51' 49"
12	N11-79	115° 14' 23"	40° 51' 47"
13	4119-9	115° 04' 47"	40° 50' 31"
14	4119-25	115° 04' 46"	40° 50' 21"
15	4169-60	115° 05' 50"	40° 49' 44"
16	NEV13-80	114° 59' 55"	41° 03' 21"
17	1-15-42	115° 00' 33"	41° 02' 42"
18	AS-1-79	115° 05' 52"	41° 01' 22"

Sample I is from a muscovite granite porphyry intruded into Ely Limestone, a unit of the unmetamorphosed, allochthonous cover sequence. Muscovite from the porphyry records a K-Ar age of 153.9 ± 0.9 Ma.

$^{40}\text{Ar}/^{39}\text{Ar}$: Rocks of the Migmatitic Metamorphic Core of the Northern Ruby Mountains

Lamoille Canyon. Hornblende and biotite concentrates were prepared from several metamorphic rocks collected within the migmatitic core exposed in Lamoille Canyon of the northern Ruby Mountains. These mineral separates were analyzed with

$^{40}\text{Ar}/^{39}\text{Ar}$ incremental-release techniques. The resultant analytical data are listed in Tables 3 and 4¹ and are displayed as age spectra in Plate 1. Biotite and hornblende from the nonmylonitic, migmatitic core (locations 1 and 2) display internally concordant age spectra that define similar plateau or total-gas ages of 25.3 ± 0.7 Ma (biotite) and 25.6 ± 0.8 Ma (hornblende). Biotite from the mylonitic

¹ Tables 3-8 are available with the entire article on microfiche. Order from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009. Document T86-003, \$2.50. Payment must accompany order.

western flank of the igneous and metamorphic complex yielded a well-defined plateau age of 20.8 ± 0.5 Ma (location 3, Plate 1).

Soldier Creek Canyon. Hornblende and biotite have been analyzed from two locations (4 and 6, Plate 1) within nonmylonitic parts of the migmatitic metamorphic core exposed in Soldier Creek Canyon, northern Ruby Mountains. Biotite from both samples displays nearly concordant release spectra yielding similar plateau dates of 21.5 ± 0.6 and 22.4 ± 0.7 Ma. The hornblende spectra for samples 4 and 6 are not well resolved; however, more than 90% of the gas evolved from each sample yields similar dates of 31.4 ± 1.4 and 31.6 ± 2.1 Ma which are markedly older than those recorded by coexisting biotite. Biotite from a pelitic horizon within mylonitic quartzite in the overlying Soldier Creek nappe (location 5, Plate 1) records a total-gas age of 21.7 ± 0.7 Ma (Table 4).

Mylonitic Rocks of the Northernmost Ruby Mountains and Southwestern East Humboldt Range

Below the Horse Creek allochthon. Variably mylonitic correlatives of the migmatitic core comprise a structurally complex terrane located structurally below the Horse Creek allochthon but above the migmatitic core (Plate 2). This terrane is a part of a kilometer-scale shear zone which separates allochthonous cover rocks from the migmatitic core. Biotite and hornblende concentrates prepared from several samples collected within this terrane were analyzed with $^{40}\text{Ar}/^{39}\text{Ar}$ incremental-release techniques. The resultant analytical data are presented in Plate 2 and Tables 5 and 6. Biotite from mylonitic quartz dioritic orthogneiss at locations 7 and 8 displays slightly discordant release spectra that yield similar total-gas dates of 23.5 ± 0.8 and 22.4 ± 0.8 Ma (Plate 2). Hornblende from location 12 (mylonitic quartz dioritic orthogneiss) records a distinctly older total-gas date of 35.2 ± 1.1 Ma, however, the slightly discordant release spectrum is poorly resolved (Plate 2). Hornblende from location 7 displays a

very discordant age spectrum with a markedly older total-gas date of 112 ± 2.1 Ma (Plate 2).

Within the Horse Creek allochthon. Rocks of the Horse Creek assemblage (including rocks correlative with the migmatitic core) constitute an allochthon of mylonitic rocks extensively exposed throughout the northernmost Ruby Mountains and southern East Humboldt Range (Plate 2). Mylonitization of these rocks is variable and the textural character (i.e., especially grain size reduction) of the samples analyzed reflects this variation. Biotite from protomylonitic quartz dioritic orthogneisses of the Horse Creek allochthon (locations 13 and 14) display internally discordant age spectra (Plate 2) which record plateau dates of 32.9 ± 0.8 and 31.9 ± 0.8 Ma (Table 6). Coexisting hornblende displays more discordant $^{40}\text{Ar}/^{39}\text{Ar}$ release spectra (Plate 2), but plateau dates of 44.5 ± 1.1 and 48.3 ± 1.1 Ma are defined by a significant fraction of the gas evolved from each sample (Table 5). Biotite from a less mafic but more mylonitic orthogneiss (location 15) displays a slightly discordant release spectrum that defines a total-gas date of 33.7 ± 1.1 Ma (Table 6). Hornblende concentrates from mafic rocks (hornblende-biotite quartz diorite orthogneiss and quartz amphibolite) collected in a very mylonitic part of the Horse Creek assemblages record discordant age spectra of variable character (Plate 2, Table 5). Samples from locations 10 and 11 display no systematic patterns of discordance and record very different total-gas ages of 149 ± 5 Ma and 218 ± 8 Ma (Plate 2). The pattern of discordance is more systematic for the hornblende from sample 9, with apparent ages regularly increasing to a poorly-resolved, high-temperature plateau of 88.3 ± 1.4 Ma (Plate 2).

Northeastern East Humboldt Range

Clover Hill. Coexisting biotite and hornblende were analyzed from two samples of mylonitic quartz dioritic orthogneiss exposed at Clover Hill (locations 16 and 17, Plate 3) in the northeastern part of the East Humboldt Range. Biotite displays

slightly discordant age spectra but records similar plateau dates of 25.0 ± 0.8 and 27.7 ± 0.8 Ma (Plate 3). Hornblende displays very discordant release patterns of quite different character (Plate 3; Table 7) which define total-gas dates of 117 ± 3 and 72.8 ± 3.4 Ma.

Angel Lake. Coexisting biotite and hornblende from a nonmylonitic amphibolite collected from the cirque wall at Angel Lake (northern part of the East Humboldt Range) were also analyzed (location 18, plate 3). The biotite records a well-defined plateau age of 25.3 ± 0.6 Ma (Plate 3; Table 8), whereas the hornblende spectrum is extremely discordant (Plate 3; Table 7) and yields a much older total-gas date of 154 ± 6 Ma.

INTERPRETATION

Rocks of the Migmatitic Metamorphic Core of the Northern Ruby Mountains

Soldier Creek Canyon. Two hornblende concentrates from the migmatitic metamorphic core exposed in Soldier Creek Canyon (locations 4 and 6) display slightly discordant, poorly-resolved $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra. However, more than 90% of the gas evolved from each sample yields dates that are similar within analytical uncertainties (31.4 ± 1.4 and 31.6 ± 2.1 Ma). These ages are similar to the conventional K-Ar date of 30.3 ± 1.0 Ma obtained on a hornblende concentrate from sample A. Anomalously older dates are recorded in the low-temperature $^{40}\text{Ar}/^{39}\text{Ar}$ gas fractions. Similar patterns of discordance in hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra have been interpreted by Dallmeyer [1975a], Harrison and McDougall [1981], and Dallmeyer and Rivers [1983] to reflect low temperature experimental liberation of gas with large components of extraneous (excess) ^{40}Ar relative to intracrystalline radiogenic ^{40}Ar . This interpretation likely applies to the Ruby Mountains results. The intermediate- and high-temperature $^{40}\text{Ar}/^{39}\text{Ar}$ dates (31.4 and 31.6 Ma) are, therefore, interpreted to closely date cooling through those temperatures required for intracrystalline retention of argon. Harrison [1981] has shown that hornblende

closure temperatures are generally insensitive to compositional variations, and suggested that a value of ca $500 \pm 25^\circ\text{C}$ is appropriate for the range of cooling rates likely to be encountered in most geological settings.

Biotite within the nonmylonitic metamorphic core (locations 4 and 6) record similar $^{40}\text{Ar}/^{39}\text{Ar}$ plateau dates of 21.5 ± 0.6 and 22.4 ± 0.7 Ma. Several workers have demonstrated that extraneous and radiogenic argon components are liberated simultaneously during incremental-release, $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of biotite [e.g., Roddick et al., 1980; Dallmeyer and Rivers, 1983]. As a result, well-defined but geologically meaningless or uninterpretable plateau dates are obtained. However, the concentration of extraneous argon components within metamorphic biotite has been shown to be extremely variable even on a local scale [Foland, 1979; Roddick et al., 1980; Dallmeyer and Rivers, 1983]. The consistency of the Ruby Mountains data, therefore, is interpreted to suggest that the 21.5 and 22.4 Ma biotite plateau ages are geologically meaningful and likely date postmetamorphic cooling through temperatures required for argon retention. Likewise, the conventional K-Ar date of 23.4 ± 0.4 Ma obtained on biotite from sample B, also collected from a nonmylonitic part of the igneous and metamorphic complex, probably reflects cooling through the closure temperature for ^{40}Ar biotite. Harrison et al. [1985] have demonstrated that biotite closure temperatures are strongly dependent upon composition, and increase markedly with decreasing Fe/Mg ratio. They suggest a value of ca $300 \pm 25^\circ\text{C}$ for the range of cooling rates likely to be encountered in most geological settings.

Hornblende and biotite from nonmylonitic parts of the igneous and metamorphic complex of the Ruby Mountains exposed in Soldier Creek Canyon record $^{40}\text{Ar}/^{39}\text{Ar}$ plateau or total-gas ages that corroborate the conventional K-Ar dates from this general area and appear to be related to postmetamorphic cooling through argon retention temperatures. Cooling between the ca 200°C difference between hornblende and biotite closure temperatures appears

to have been accomplished in ca 10 Ma during the middle Oligocene to early Miocene.

Biotite from mylonitic rocks exposed near the base of the Soldier Creek nappe (location 5) displays a slightly discordant $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum which defines a total-gas date of 21.7 ± 0.7 Ma. This is identical to the age recorded by biotite in structurally underlying, nonmylonitic parts of the migmatitic metamorphic core and is interpreted to date cooling through ca $300 \pm 25^\circ\text{C}$. This suggests that mylonitization and subsequent detachment along the base of the nappe occurred prior to ca 21–23 Ma and that rocks of the migmatitic core and overlying mylonitic shear zone subsequently experienced a similar thermal evolution.

Lamoille Canyon. Biotite from the migmatitic metamorphic core exposed within Lamoille Canyon displays internally concordant $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra that yield variable total-gas or plateau dates. Biotite from the central, nonmylonitic part of the migmatitic core (sample 1) yields a plateau date of 25.3 ± 0.7 Ma, whereas biotite from the mylonitic western margin of the metamorphic terrane (location 3) records a younger plateau date of 20.8 ± 0.5 Ma. This variation in biotite age is consistent with the regional variations outlined by Kistler et al. [1981]. It, therefore, suggests that the younger date recorded by sample 3 is not exclusively a result of mechanical deformation associated with the development of the mylonitic zone but, instead, likely reflects diachronous, postmetamorphic cooling.

Hornblende from location 2 in Lamoille Canyon displays a poorly resolved $^{40}\text{Ar}/^{39}\text{Ar}$ spectrum in which most of the gas was evolved in just two increments. However, within two sigma interlaboratory uncertainties the two increments record similar apparent ages corresponding to a plateau of 25.6 ± 0.8 Ma which is interpreted to date cooling through ca $500 \pm 25^\circ\text{C}$. This is distinctly younger than the 30.3–31.6 Ma cooling dates recorded by hornblende within the migmatitic core terrane exposed along Soldier Creek Canyon (samples 4 and 6), and suggesting more prolonged postmetamorphic cooling. The difference in cooling history is likely related to the

exposure of deeper structural levels within Lamoille Canyon.

Mylonitic Rocks of the Northernmost Ruby Mountains and Southwestern East Humboldt Range

Mylonitic rocks structurally below the Horse Creek allochthon. Hornblende from mylonitic quartz dioritic orthogneiss samples collected above the base of the Soldier Creek nappe but below the Horse Creek allochthon display variably discordant $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra that yield markedly different total-gas dates of 112 ± 2.1 Ma and 35.2 ± 1.1 Ma (locations 7 and 12). Although poorly resolved, both spectra are "saddle-shaped," with older apparent ages recorded in low- and high-temperature increments compared to those defined by intermediate-temperature gas fractions. Harrison and McDougall [1981] described similar $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende spectra with intermediate-temperature, low age saddles from a regional metamorphic terrane contaminated with extraneous argon. In that area, the older, high temperature ages were associated with marked variations in K/Ca ratios suggesting development of fine-scale, compositional (exsolution?) features within the hornblende grains. These workers interpreted the discordant spectra to reflect experimental evolution of extraneous components from markedly different lattice sites within the intergrown phases. The younger ages recorded by saddle portions of the spectra appeared in some cases to approach an age reasonable for postmetamorphic closure of hornblende in that area. Variations in apparent ages within hornblende concentrates prepared from samples collected at locations 7 and 12 in the Ruby Mountains-East Humboldt Range are not related to any systematic variations in K/Ca ratios. This relation, combined with a lack of petrographic evidence for exsolution, suggests that the hornblendes are chemically homogeneous. However, the samples are mylonitic, and the hornblende grains are locally characterized by intracrystalline strain manifested by undulatory extinction, twinning, and microcracking. These microstructures suggest that although

chemically homogeneous, the hornblende grains could be marked by two very different lattice domains: one represented by grain boundaries with high dislocation densities, and the other by relatively strain-free portions of the deformed crystals. It is likely that diffusion of extraneous argon components would be different in these contrasting lattice domains and could, therefore, explain the discordant $^{40}\text{Ar}/^{39}\text{Ar}$ spectra. Experimental evolution of those extraneous components held in a relatively low energy class of lattice sites could yield the older apparent ages recorded in low temperature gas fractions. Evolution of extraneous components from a higher energy class of sites could produce the older dates defined in high-temperature portions of the spectrum. At present, it is uncertain if the lower ages defined by intermediate-temperature gas fractions liberated from the Ruby Mountains-East Humboldt Range hornblende concentrates have geologic significance. However, the ca 33 Ma date defined by intermediate-temperature portions of the spectrum of sample 12 is similar to that recorded by hornblende within nonmylonitic portions of the migmatitic core as exposed in Soldier Creek Canyon. In view of these complications, the significance of conventional K-Ar biotite and hornblende dates (13.3 ± 1.0 and 38.1 ± 1.7 Ma) from sample G (collected from the same locality as sample 12) is uncertain. Also, the conventional K-Ar hornblende dates of 109.5 ± 10.0 (sample C) and 194.4 ± 6.0 Ma (sample F) are uninterpretable given the apparent common occurrence of extraneous Ar components in hornblende from rocks of the mylonitic shear zone.

Biotite from mylonitic rocks collected above the base of the Soldier Creek nappe display discordant $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra that are characterized by a slight increase in age within the higher-temperature increments (samples 7 and 8). The 23.5 and 22.4 Ma total-gas dates are similar to $^{40}\text{Ar}/^{39}\text{Ar}$ plateau dates recorded by biotite in both the nonmylonitic migmatitic core and the mylonitic zone exposed farther south in the Soldier Creek Canyon area. These data, therefore, further indicate a generally similar cooling history

for rocks both below and above the low-angle fault at the base of the Soldier Creek nappe. The geologic significance of discordant biotite spectra exhibited by samples 7 and 8 is uncertain.

Variably mylonitic rocks within the Horse Creek allochthon--Horse Creek Area. Hornblende from protomylonitic quartz dioritic orthogneiss of the Horse Creek assemblages (locations 13 and 14) displays internally discordant $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra. Hornblende from sample 13 displays a spectrum characterized by apparent ages which systematically increase through low temperature increments to a high-temperature plateau of 44.5 Ma. Similar discordance in $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende age spectra have been described by Turner [1970], Dallmeyer [1975b], and Harrison [1983], who have interpreted the discordance to result from partial volume diffusion loss of radiogenic ^{40}Ar . If a similar interpretation is applied to sample 13, the 44.5 Ma plateau date represents a minimum age for cooling through ca $500 \pm 25^\circ\text{C}$. Hornblende within sample 14 displays an age spectrum in which anomalously older dates are recorded in the low-temperature gas fractions compared to a 48.3 Ma plateau defined by the three intermediate- and high-temperature increments. As described earlier, this type of hornblende discordance is characteristic of samples that have been contaminated with extraneous argon following an initial cooling through argon retention temperatures. It is uncertain if the plateau portion of the saddle-shaped spectrum can reliably be interpreted to date cooling through argon retention temperatures.

Biotite from samples 13 and 14 display discordant $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra. In both, apparent ages systematically increase over low-temperature portions of the analyses to yield plateau dates of 32.9 and 31.9 Ma. This type of spectra discordancy is not typical of thermally overprinted biotite from nonmylonitic rocks [e.g., Dallmeyer, 1982], and its significance is not certain. Biotite from a more mylonitic biotite orthogneiss of the Horse Creek assemblage (location 15) displays an internally discordant age spectrum which defines a total-gas date of

33.7 Ma. Although more discordant, the total-gas age and overall character of the spectrum is similar to that displayed by biotite from less mylonitic samples collected at locations 13 and 14 within the Horse Creek allochthon.

The 44.5 Ma plateau age recorded by hornblende from protomylonitic quartz dioritic orthogneisses within the Horse Creek allochthon at location 13 is interpreted to date cooling through argon retention temperatures. The 32.9 and 31.9 Ma plateau dates determined for biotite at locations 13 and 14 suggest markedly younger cooling through the lower biotite closure temperature. Together the results suggest slightly earlier (late Eocene through early Oligocene) and slightly slower post-metamorphic cooling compared to those parts of the migmatitic core exposed farther south in the Ruby Mountains. Following cooling, there appears to have been a mild geologic disturbance of both biotite and hornblende systems which resulted in minor diffusional loss of radiogenic argon from hornblende in sample 13 and perhaps from biotite in samples 13 and 14. The ordinate intercept of the discordant spectrum of hornblende from sample 13 suggests that the geologic disturbance may have occurred at ca 20-24 Ma.

Variably mylonitic rocks within the Horse Creek allochthon--Secret Gorge area. Hornblende from protomylonitic quartz amphibolite collected at location 9 displays a discordant $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum in which apparent ages systematically increase to a poorly-resolved high-temperature plateau of 88.3 ± 1.4 Ma. As noted earlier this type of spectra discordance is characteristic of samples which have experienced diffusive redistribution of radiogenic argon as a result of postcrystallization geologic reheating. The discordant spectrum suggests a complex thermal record, including: 1) late Mesozoic (ca 90 Ma) cooling through argon retention temperatures; and 2) early Tertiary (ca 40-50 Ma) tectonothermal overprinting which effected diffusive redistribution of radiogenic argon.

Hornblende from a mylonitic quartz amphibolite collected at location 11 displays a discordant, saddle-type of age

spectrum which yields a total-gas age of 218 ± 8 Ma. There is no systematic relationship between variations in apparent age and apparent K/Ca ratios. Therefore, an interpretation similar to that evoked for the saddle-shaped hornblende spectra displayed by samples 7 and 12 is likely applicable (e.g., experimental evolution of extraneous argon components from both low- and high-energy intracrystalline sites). It is uncertain if the ca 160 Ma date defined by lower portions of the saddle has geologic significance. The conventional K-Ar hornblende dates of 81.6 ± 3.0 and 223.5 ± 7.0 Ma from samples D and E also reflect the complex tectonothermal history of these amphibolitic rocks in the mylonitic shear zone and, therefore, may not be confidently used to constrain the postmetamorphic cooling history.

Sample 10 was collected within a very mylonitic portions of the Horse Creek allochthon. Hornblende from this sample displays an extremely discordant age spectrum with no systematic low- to high-temperature variation in apparent age. The origin of the discordancy is uncertain and the spectrum does not provide any reliable geochronological information.

Variably Deformed Biotite Granodiorite Intrusion Structurally Above the Horse Creek Allochthon

Sample H is from a small, sheet-like granodiorite intrusion partially along a low-angle fault that separates mylonitic rocks of the Horse Creek assemblage from mylonitic marble of the Devonian Guilmette Formation (Plate 2). Biotite from the granodiorite yielded a K-Ar date of 15.5 ± 0.4 Ma. The granodiorite intrusion was apparently emplaced subsequent to mylonitization, for it locally recrystallized the mylonitic marble adjacent to its contact and is a nonmylonitic granitoid. Late stage movements along the low-angle fault are manifested by localized ductile-brittle deformation in the granodiorite. This faulting, accompanied by cataclasis and retrogression, may have resulted in resetting of the biotite K-Ar date to ca 16 Ma, and age similar to that inferred for movement along the youngest exposed

low-angle fault in the Secret Creek gorge area. This uppermost fault plate involves Tertiary rocks including a rhyolite dated ca 15 Ma [Snoke, 1980].

Muscovite Granite Porphyry Intruded Into Ely Limestone of the Allochthonous Cover Sequence

The late Jurassic K-Ar date of 153.9 ± 0.9 Ma on muscovite from the muscovite granite porphyry is in general agreement with a Rb-Sr whole rock-muscovite isochron date of 161 ± 2 Ma for the same intrusion (A.W. Snoke and P.D. Fullagar, unpublished manuscript, 1986). These Late Jurassic ages correspond closely to the 160 ± 3 Ma Rb-Sr whole-rock isochron reported by Kistler et al. [1981] for two-mica granitic rocks within the igneous and metamorphic complex of the Ruby Mountains and suggest that widespread granitic magmatism occurred during the Late Jurassic.

Northeastern East Humboldt Range

Clover Hill. Hornblende from mylonitic quartz dioritic orthogneiss collected at Clover Hill records variably complex, internally discordant $^{40}\text{Ar}/^{39}\text{Ar}$ release spectra. That displayed by sample 16 shows an increase in apparent age over the intermediate temperature portion (550° to 825°C) of the analysis. The gas evolved between 850° and 900°C records similar apparent dates of ca 110 Ma, whereas the fusion increment yields an older date of 128 Ma. The K/Ca ratio remains constant at ca 0.163 throughout intermediate- and high-temperature portions of the analysis, suggesting that the concentrate has a relatively uniform composition. This combined with the overall nature of the release spectra suggests that the sample has experienced significant loss of radiogenic argon during a post-ca 80 Ma episode of diffusive redistribution following an earlier cooling through argon retention temperatures in the Mesozoic.

The hornblende concentrate from sample 17 also records a consistent K/Ca ratio throughout the analysis (ca 0.161), however, it displays a discordant age spectrum which is of generally similar character to

that displayed by sample 10 from a very mylonitic part of the Horse Creek assemblage. As with sample 10, interpretation of this type of release pattern is uncertain.

Biotite coexisting with hornblende in the mylonitic quartz dioritic orthogneiss samples collected at locations 16 and 17 display internally concordant $^{40}\text{Ar}/^{39}\text{Ar}$ release spectra which record mutually similar plateau dates of 25.0 ± 0.8 and 27.7 ± 0.8 Ma. These are interpreted to date times of post-metamorphic cooling through ca $300 \pm 25^\circ\text{C}$.

$^{40}\text{Ar}/^{39}\text{Ar}$ incremental-release dating of coexisting biotite and hornblende from Clover Hill suggests a complex, polygenetic thermal evolution. The biotite results indicate that final cooling through argon retention temperatures likely occurred in the late Oligocene-early Miocene. This cooling had been preceded by syntectonic, dynamic recrystallization of biotite and quartz during development of mylonitic fabrics. An associated Tertiary thermal event appears to have effected partial, diffusive loss of radiogenic argon from hornblende which had previously recorded an older (Mesozoic?) postmetamorphic cooling.

Angel Lake. Biotite from high-grade metamorphic rocks exposed at Angel Lake displays an internally concordant $^{40}\text{Ar}/^{39}\text{Ar}$ release spectrum which defines a plateau of 25.3 ± 0.6 Ma. This is similar to plateau ages recorded by biotite at Clover Hill and suggests a similar late Tertiary cooling history. In marked contrast, coexisting hornblende at Angel Lake displays a very discordant, saddle-shaped spectrum yielding a total-gas date of 154 Ma. No systematic variations in K/Ca ratio are associated with the fluctuation in apparent ages. The spectrum is, therefore, provisionally interpreted to reflect experimental evolution of extraneous argon components from both low- and high-temperature intracrystalline sites.

TECTONIC IMPLICATIONS

A generalized time-temperature diagram depicting the late Mesozoic-Tertiary thermal evolution of the Ruby Mountains-East

Fig. 3. Time-temperature curve for the Ruby Mountains-East Humboldt Range metamorphic core complex. See text for discussion.

Humboldt Range metamorphic core complex is presented in Figure 3. It is based on the following isotopic closure temperatures: monazite (U-Pb) = $565 \pm 35^\circ\text{C}$ [Gebauer and Grünenfelder, 1979; Gale, 1982]; hornblende (^{40}Ar) = $500 \pm 25^\circ\text{C}$ [Harrison, 1981]; biotite (^{40}Ar) = $300 \pm 25^\circ\text{C}$ [Harrison et al., 1985]; apatite (fission-track) = $105 \pm 10^\circ\text{C}$ [Harrison and McDougall, 1981]. It is likely that a regional, high-grade metamorphism accompanied emplacement of migmatite granite at ca 160 Ma [Kistler et al., 1981]. However, it is uncertain if the $^{40}\text{Ar}/^{39}\text{Ar}$ mineral ages record Tertiary cooling following prolonged maintenance at elevated temperatures or if they date cooling following distinct, locally superposed late Cretaceous and/or middle Tertiary thermal overprints. In either case, there appears to have been relatively rapid cooling between hornblende and biotite argon closure temperatures. It appears that rapid cooling began at ca 45 Ma, and that the entire igneous and metamorphic complex had cooled below 300°C by ca 20 Ma. This is consistent with the amygdaloidal character of basaltic dikes which intruded the igneous and metamorphic comp-

lex at ca 17 Ma [Snoke, 1980]. Also, fission-track ages indicate that the igneous and metamorphic complex had cooled below 100°C by the earliest Miocene [Dokka et al., 1985].

As previously implied, it is likely that unroofing of the crystalline core of the Ruby Mountains-East Humboldt Range was accomplished by regional extension of the upper crust along low-angle normal faults which rooted into ductile shear zones at middle crustal levels. The widespread mylonitization of the igneous and metamorphic complex is, therefore, interpreted to represent intense extensional ductile strains localized at middle crust levels. Combined with the Rb-Sr whole-rock-mineral results of the Snoke and Fullagar (unpublished manuscript, 1986), the $^{40}\text{Ar}/^{39}\text{Ar}$ data indicate that the age of mylonitization is perhaps variable throughout the igneous and metamorphic complex. A protracted, polyphase history of Tertiary ductile-brittle deformation between ca 45 and 20 Ma is suggested. An example of possible variation in the age of mylonitization is suggested by the difference in biotite cooling ages (ca 32–33 Ma) in var-

iably mylonitic rocks from the Horse Creek allochthon and a Rb-Sr whole-rock muscovite age of 23 ± 1.0 Ma from the mylonitic two-mica granitic gneiss of Secret Peak (A.W. Snoke and P.D. Fullagar, unpublished manuscript, 1986). The 23 ± 1.0 Ma age records the last internal isotopic redistribution in the rocks and perhaps is near the age of mylonitization. A resetting of the Rb-Sr system in the mylonitic granitic gneiss of Secret Peak during the early Miocene is also suggested by a nine-point Rb-Sr whole-rock age of 19 ± 4 Ma with a very high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7402 ± 0.0006 (A.W. Snoke and P.D. Fullagar, unpublished manuscript, 1986). Furthermore, the Horse Creek allochthon was emplaced onto rocks that record biotite cooling ages of ca 22-24 Ma suggesting that tectonic juxtaposition must have occurred later. Basaltic dikes intrude across this tectonic boundary [Snoke, 1980], and their 17 Ma K-Ar whole-rock age provides a lower limit for the age of displacement of the allochthon. The tectonothermal record within the Horse Creek allochthon suggests structural emplacement of colder on hotter rocks and is, therefore consistent with crustal thinning along low-angle, extensional faults and shear zones. By contrast, a similar cooling history is indicated by biotite plateau ages on either side of the low-angle fault at the base of the Soldier Creek nappe. This low-angle fault apparently either did not juxtapose rocks of contrasting thermal histories or its displacement history was minor and/or predated the main episode of rapid late Oligocene-early Miocene cooling.

The $^{40}\text{Ar}/^{39}\text{Ar}$ data presented here indicate diachronous cooling across the migmatitic core. For example, migmatitic rocks exposed in Lamoille Canyon cooled below ca 500°C later than similar grade rocks exposed to the north in Soldier Creek Canyon. Therefore, deeper crustal levels are likely exposed in Lamoille Canyon compared to Soldier Creek Canyon. This conclusion is supported by geological mapping and structural studies [Howard, 1966; Howard et al., 1979].

Snoke et al. [1979] suggested that the 72-78 Ma U-Pb ages recorded by monazite

within pelitic schist in the northern Ruby Mountains (location B, Plate 1) provided evidence for Mesozoic thermal activity. Although locally within the Horse Creek allochthon and at Clover Hill there are suggestions of late Cretaceous cooling through hornblende closure temperatures, in most areas only Oligocene-Miocene cooling ages are recorded. Therefore, regional distribution, relative intensity, and overprinting relationships of potentially distinct Mesozoic vs. Tertiary tectonothermal events cannot be resolved by the present $^{40}\text{Ar}/^{39}\text{Ar}$ results.

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REFERENCES

- Alexander, E. C., Jr., G. M. Michelson, and M. A. Lanphere, MMhb-1: A new $^{40}\text{Ar}/^{39}\text{Ar}$ dating standard, Short Papers of the Fourth International Conference, Geochronology, Cosmochronology, Isotope Geology, edited by R.E. Zartman, U.S. Geol. Surv. Open File Rep., 78-701, 6-8, 1978.
- Armstrong, R. L., The geochronometry of Idaho, II, Isochron West, 15, 1-22, 1976.
- Armstrong, R. L., Cordilleran metamorphic core complexes--From Arizona to southern Canada, Annu. Rev. Earth Planet. Sci., 10, 129-154, 1982.
- Armstrong, R. L., and E. Hansen, Cordilleran infrastructure in the eastern

- Great Basin, Am. J. Sci., **264**, 112-127, 1966.
- Armstrong, R. L., R. C. Speed, W. C. Graustein, and A. Y. Young, K-Ar dates from Arizona, Montana, Nevada, Utah, and Wyoming, Isochron West, **16**, 1-6, 1976.
- Coney, P. J., Tertiary evolution of Cordilleran metamorphic core complexes, in, Cenozoic paleogeography of the Western United States, edited by J. M. Armstrong, M. R. Cole, and H. TerBest, Jr., Soc. Econ. Paleontol. Mineral. Pac. Sect. Symp., III, 15-28, 1979.
- Crittenden, M. D., Jr., P. J. Coney, and G. H. Davis, Cordilleran metamorphic core complex, Mem. Geol. Soc. Am., **153**, 490 pp., 1980.
- Dallmeyer, R. D., $^{40}\text{Ar}/^{39}\text{Ar}$ ages of biotite and hornblende from a progressively remetamorphosed basement terrain: Their bearing on interpretation of release spectra, Geochim. Cosmochim. Acta, **39**, 1655-1669, 1975a.
- Dallmeyer, R. D., $^{40}\text{Ar}/^{39}\text{Ar}$ release spectra of biotite and hornblende from the Cortlandt and Rosetown plutons, New York, and their regional implications, J. Geol. **83**, 629-643, 1975b.
- Dallmeyer, R. D., $^{40}\text{Ar}/^{39}\text{Ar}$ incremental-release ages of biotite from a progressively remetamorphosed Archean basement terrane, Labrador, Earth Planet. Sci. Lett., **61**, 85-96, 1982.
- Dallmeyer, R. D., and R. Rivers, Recognition of extraneous argon components through incremental-release $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of biotite and hornblende across the Grenvillian metamorphic gradient in southwestern Labrador, Geochim. Cosmochim. Acta, **47**, 413-428, 1983.
- Dalrymple, G. B., Critical tables for conversion of K-Ar ages from old to new constants, Geology, **7**, 558-560, 1979.
- Dalrymple, G. B., and M. A. Lanphere, Potassium-Argon Dating, 258 pp., W. H. Freeman, San Francisco, Calif., 1969.
- Dalrymple, G. B., and M. A. Lanphere, $^{40}\text{Ar}/^{39}\text{Ar}$ technique of K-Ar dating: A comparison with the conventional technique, Earth Planet. Sci. Lett., **17**, 300-308, 1971.
- Dalrymple, G. B., E. C. Alexander, Jr., M. A. Lanphere, and G. P. Kraker, Irradiation of samples for $^{40}\text{Ar}/^{39}\text{Ar}$ dating using the Geological Survey TRIGA reactor, U.S. Geol. Surv. Prof. Pap., **1176**, 55 pp., 1981.
- Damon, P. E., R. C. Erickson, and D. E. Livingston, K-Ar dating of basin and range uplift, Catalina Mountains, Arizona, Nuc. Geophys. Nucl. Sci. J., **38**, 113-121, 1963.
- Davis, G. A., J. L. Anderson, D. L. Martin, D. Krummenacher, E. G. Frost, and R. L. Armstrong, Geologic and geochronologic relations in the lower plate of the Whipple detachment fault, Whipple detachment fault, Whipple Mountains, southeastern California: A progress report, in Mesozoic-Cenozoic Tectonic Evolution of the Colorado River region, California, Arizona, and Nevada, Anderson-Hamilton Vol., edited by E. G. Frost and D. L. Martin, Cordilleran, San Diego, Calif. pp. 408-432, 1982.
- Davis, G. A., G. S. Lister, and S. J. Reynolds, Structural evolution of the Whipple and South Mountains shear zones, southwestern United States, Geology, **14**, 7-10, 1986.
- Dokka, R. K., M. J. Mahaffie, and A. W. Snoke, Fission track thermochronologic constraints on the timing and nature of major middle Tertiary extension, Ruby Mountains-East Humboldt Range, Nevada, Geol. Soc. Am. Abstr. Programs, **17**, 564, 1985.
- Foland, K. A., Limited mobility of argon in a metamorphic terrain, Geochim. Cosmochim. Acta, **43**, 793-801, 1979.
- Gale, N. H., The dating of plutonic events, in Numerical Dating in Stratigraphy, edited by G. S. Odin, pp. 441-450, John Wiley, New York, 1982.
- Gebauer, D., and M. Grünenfelder, U-Th-Pb dating of minerals in Lectures in Isotope Geology, edited by E. Jäger and J. C. Hunziker, pp. 105-131, Springer-Verlag, New York, 1979.
- Greenwood, H. J., Metamorphism at moderate temperatures and pressures, in The Evolution of the Crystalline Rocks, edited by D. K. Bailey and R. Macdonald, pp. 187-259, Academic, Orlando, Fla., 1976.
- Harrison, T. M., Diffusion of ^{40}Ar in hornblende, Contrib. Mineral. Petrol., **78**, 324-331, 1981.

- Harrison, T. M., Some observations on the interpretation of $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra, Isot. Geosci., 1, 319-338, 1983.
- Harrison, T. M., and I. McDougall, Investigations of an intrusive contact, northwest Nelson, New Zealand, I, Thermal, chronological and isotopic constraints, Geochim. Cosmochim. Acta, 44, 1985-2003, 1980.
- Harrison, T. M., and I. McDougall, Excess ^{40}Ar in biotite: Temperature, pressure and compositional effects, Geochim. Cosmochim. Acta, 49, 2461-2468, 1985.
- Howard, K. A., Structure of the metamorphic rocks of the northern Ruby Mountains, Nevada, Ph.D. thesis, 170 pp., Yale Univ., New Haven, Conn., 1966.
- Howard, K. A., Paleozoic metasediments in the northern Ruby Mountains, Nevada, Geol. Soc. Am. Bull., 82, 259-264, 1971.
- Howard, K. A., R. W. Kistler, A. W. Snoke, and R. Willden, Geological map of the Ruby Mountains, Nevada, = Mis. Invest. Ser. Map I-1136, scale 1:125,000, U.S. Geol. Surv., Reston, Va., 1979.
- Ingamells, C. O., Lithium metaborate flux in silicate analysis, Anal. Chim. Acta, 52, 323-334, 1970.
- Johnson, D. L., Two-mica granites and metamorphic rocks of the east-central Ruby Mountains, Elko County, Nevada, M.S. thesis, 145 pp., Stanford Univ., Stanford, Calif., 1981.
- Kistler, R. W., E. D. Ghent, and J. R. O'Neil, Petrogenesis of garnet two-mica granites in the Ruby Mountains, Nevada, J. Geophys. Res., 86, 10,591-10,606, 1981.
- Lee, D. E., R. F. Marvin, T. W. Stern, and Z. E. Peterman, Modification of potassium-argon ages by Tertiary thrusting in the Snake Range, White Pine County, Nevada, Geological Survey Research 1970, U.S. Geol. Surv. Prof. Pap., 700-D, D92-D102, 1970.
- Lee, D. E., R. F. Marvin, and H. H. Mehnert, A radiometric age study of Mesozoic-Cenozoic metamorphism in eastern White Pine County, Nevada, and nearby Utah, Geologic Studies in White Pine County, Nevada, U.S. Geol. Surv. Prof. Pap., 1158-A,B,C, 17-28, 1980.
- Lee, J., E. L. Miller, and J. F. Sutter, Ductile strain and metamorphism in an extensional tectonic setting: A case study from the northern Snake Range, Nevada, U.S.A., J. Geol. Soc. London Spec. Publ., in press, 1986.
- Lush, A. P., Geology of part of the northern East Humboldt Range, Elko County, Nevada, M.S. thesis, 138 pp., Univ. of S. C., Columbia, 1982.
- Martin, D. L., D. Krummenacher, and E. G. Frost, K-Ar geochronologic record of Mesozoic and Tertiary tectonics of the Big Maria-Little Maria-Riverside Mountains terrane, in Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada, Anderson, Hamilton Vol., pp. 519-549, edited by E. G. Frost and D. L. Martin, Cordilleran, San Diego, Calif., 1982.
- Mauger, R. L., P. E. Damon, and D. E. Livingston, Cenozoic argon ages on metamorphic rocks from the basin and range province, Am. J. Sci., 266, 579-589, 1968.
- McKee, E. H., Reset K-Ar ages: Evidence for three metamorphic core complexes, western Nevada, Isochron West, 38, 17-20, 1983.
- Misch, P., Regional structural reconnaissance in central-northeast Nevada and some adjacent areas: Observations and interpretations, Geology of east-central Nevada, Intermt. Assoc. Pet. Geol. Field Conf. Guide., 11, 17-42, 1960.
- Palmer, A. R., The decade of North American geology geologic time scale, Map Chart Ser. MC-50, Geol. Soc. of Am., Boulder, Colo., 1983.
- Roddick, J. C., R. A. Cliff, and D. C. Rex, The evolution of excess argon in alpine biotites-- $^{40}\text{Ar}/^{39}\text{Ar}$ analysis, Earth Planet. Sci. Lett., 48, 185-208, 1980.
- Snelson, S., The geology of the northern Ruby Mountains and the East Humboldt Range, Elko County, Nevada, Ph.D. thesis, 268 pp., Univ. of Wash., Seattle, 1957.
- Snoke, A. W., Transition from infrastructure to suprastructure in the northern Ruby Mountains, Nevada, in, Cordilleran Metamorphic Core Complexes, edited by M. D. Crittenden, Jr., et al., Mem. Geol. Soc. Am., 153, 287-333, 1980.
- Snoke, A. W., and A. P. Lush, Polyphase Mesozoic-Cenozoic deformational history

- of the northern Ruby Mountains-East Humboldt Range, Nevada, in Western Geological Excursions, Geological Society of America 1984 Annual Meeting, Reno, Nevada vol. 4, edited by J. Lintz, Jr., pp. 232-260, Mackay School of Mines, Department of Geological Sciences, Reno, Nev., 1984.
- Snoke, A. W., E. H. McKee, and T. W. Stern, Plutonic, metamorphic, and structural chronology in the northern Ruby Mountains, Nevada: A preliminary report, Geol. Soc. Am. Abstr. Programs, 11, 520-521, 1979.
- Snoke, A. W., S. L. Durgin, and A. P. Lush, Structural style variations in the northern Ruby Mountains-East Humboldt Range, Nevada, Geol. Soc. Am. Abstr. Programs, 14, 235, 1982.
- Snoke, A. W., R. G. McCall, and E. H. McKee, Tertiary stratigraphy and structure in the northern East Humboldt Range, Nevada--A clue to Cenozoic regional tectonic patterns, Geol. Soc. Am. Abstr. Programs, 15, 403, 1983.
- Steiger, R. H., and E. Jäger, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochemistry, Earth Planet. Sci. Lett., 36, 359-362, 1977.
- Taylor, G. K., Stratigraphy, metamorphism, and structure of the southeastern East Humboldt Range, Elko County, Nevada, M.S. thesis, 148 pp., Univ. of S. C., Columbia, 1984.
- Thorman, C. H., Mid-Tertiary K-Ar dates from late Mesozoic metamorphosed rocks, Wood Hills and Ruby-East Humboldt Range, Elko County, Nevada (abstract), Spec. Pap. Geol. Soc. Am., 87, 234-235, 1965.
- Turner, G., $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the lunar maria, Earth Planet. Sci. Lett., 12, 169-191, 1970.
- Wernicke, B., Low-angle normal faults in the Basin and Range province: Nappe tectonics in an extending orogen, Nature, 291, 645-648, 1981.
- Willden, R., and R. W. Kistler, Precambrian and Paleozoic stratigraphy in central Ruby Mountains Elko County, Nevada, in Basin and Range Symposium and Great Basin Field Conference, edited by G. W. Newman and H. D. Goode, pp. 221-243, Rocky Mountain Association of Geologists and Utah Geological Association, Denver, Colorado, 1979.
- Willden, R., H. H. Thomas, and T. W. Stern, Oligocene or younger thrust faulting in the Ruby Mountains, northeastern Nevada, Geol. Soc. Am. Bull., 78, 1345-1358, 1967.

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