$^{40}Ar/^{39}Ar$ AGE DETERMINATIONS FOR THE CARRIZO MOUNTAINS LACCOLITH, NAVAJO NATION, ARIZONA

STEVEN C. SEMKEN[1] and WILLIAM C. McINTOSH[2]

[1]Navajo Community College, Shiprock, Navajo Nation, NM 87420-0580; [2]New Mexico Bureau of Mines and Mineral Resources, Socorro, NM 87801

Abstract—We have obtained Late Cretaceous (73.8–70.65 Ma) ages for hornblende separates from three specimens of diorite porphyry from the Carrizo Mountains laccolith, located on the Navajo Nation in northeastern Arizona, using the $^{40}Ar/^{39}Ar$ step-heating method. The age spectra show no evidence of excess ^{40}Ar or contamination by older xenocrysts, both of which have called some published K-Ar ages from the Four Corners area into question. The Carrizo Mountains intrusive center is thus confirmed as an extension of the Laramide-age Colorado mineral belt into Arizona, first suggested by Armstrong (1969).

INTRODUCTION

Few Phanerozoic magmas have penetrated the thick sedimentary cover of the central Colorado Plateau. In the Four Corners region, within sight of massive volcanic outpourings that flank the Plateau, the only igneous bodies are the lamprophyric diatremes, dikes and sills of the Navajo volcanic field, and several prominent laccoliths formed of intermediate intrusives. The Carrizo Mountains, in the Navajo Nation in the extreme northeastern corner of Arizona, are the southernmost of these laccoliths. The mountains top the eastward-dipping Four Corners platform at the north end of the Defiance uplift and rise about 1000 m above surrounding steppes underlain by Mesozoic sedimentary rocks. They are approximately 21 km across and have an areal extent in excess of 250 km^2. The highest point is Pastora Peak (2869 m), which is known to the indigenous Diné (Navajo) as *Dzi Nahoozi ii* (DZILTH NA-hoe-zilth-lee), "the mountain that gropes around."

The geology of the Carrizo Mountains area (Fig. 1) has previously been discussed by Emery (1916), Gregory (1917), Strobell (1952a–d; 1956), O'Sullivan and Beikman (1963) and Akers et al. (1971). The intrusive complex consists of a central stock that feathers outward into several sills of variable thickness (maximum about 90 m) and dikes, which penetrate Upper Permian to Upper Cretaceous sedimentary strata. Contact metamorphism is generally limited to zones less than 1 m thick.

The intrusive rocks are diorite porphyry, light gray in color, consisting of abundant small phenocrysts of white plagioclase (andesine), and less abundant phenocrysts of hornblende in a groundmass that is mostly quartz, orthoclase and plagioclase (Emery, 1916; Strobell, 1956; O'Sullivan and Beikman, 1963). Accessory minerals include apatite, titanite, zircon and iron oxides. Small fine-grained, hornblende-rich (O'Sullivan and Beikman, 1963) inclusions occur locally. Xenoliths were not found in the areas that were sampled.

Mineralization in the Carrizo Mountains appears to be limited to a fault zone in the Salt Wash Member of the Jurassic Morrison Formation on the northeast flank of the dome near the Arizona-New Mexico state line (McLemore and Chenoweth, 1997, this volume). A copper mine operated here in 1921, and the old workings attracted interest during the uranium boom of the 1950s (Chenoweth, 1989). Minette dikes associated with the Navajo volcanic field intrude the laccolith at Teec Nos Pos on the north flank; these were dated at 23 Ma by Laughlin et al. (1986) by the K-Ar method on phlogopite separates. A minette dike also intrudes the central Carrizos at Zibetod Peak and is presumed to be of Oligocene age as well.

In the Carrizo Mountains, Cenozoic regional uplift of the Colorado Plateau has been superimposed on local intrusive uplift. The laccolith is dissected but not completely exposed. Intrusive rocks are covered in places by fractured and silicified sandstones, probably the Jurassic Wingate and Entrada Sandstones (Strobell, 1956; O'Sullivan and Beikman, 1963). Numerous stream drainages have cut deeply into the range and broad pediments extend away from it, particularly on the southeast and west sides.

Other laccolithic complexes in the Four Corners region of the Colorado Plateau include the Rico, La Plata, Ute, La Sal, Abajo, Henry and Navajo Mountains. All of these, as well as the Carrizo Mountains, lie along the Colorado lineament of Warner (1978), a northeast-trending system of Precambrian faults. This lineament also encompasses the Colorado mineral belt (CMB) of mineralized igneous centers associated with the Laramide orogeny in the Late Cretaceous to middle Tertiary (Tweto and Sims, 1963).

PREVIOUS GEOCHRONOLOGIC STUDIES OF FOUR CORNERS LACCOLITHS

Laccoliths in the Four Corners region have been of interest to geochronologists for more than three decades, because of their spatial and temporal association with the CMB and their implications for patterns of magmatism in the Colorado Plateau during and after the Laramide orogeny. The results of previous work (Armstrong, 1969; Nelson et al., 1992; Cunningham et al., 1994), suggest that the eight intrusive complexes form two distinct age groups separated by more than 30 Ma, in spite of geographic proximity, and geologic and petrologic similarities.

Armstrong (1969) obtained mostly Late Cretaceous to early Tertiary K-Ar ages (84–61 Ma) for the Rico, La Plata, Ute and Carrizo Mountains, which occur along a line subparallel to the trend of the Colorado lineament. Several anomalous older ages were disregarded because of suspicion of contamination by Precambrian xenoliths. The data strongly suggested that these four intrusive centers represented an extension of the Laramide CMB into the center of the Colorado Plateau.

For the Carrizo Mountains, Armstrong (1969) reported K-Ar ages of 67.9 Ma (recalculated as 69.60 ± 1.40 Ma using newer decay constants; Steiger and Jager, 1977; Reynolds et al., 1986) on whole rock (less heavy fraction) and hornblende separates from a diorite porphyry exposed at Teec Nos Pos Canyon (Fig. 1).

In contrast, the Abajo, La Sal and Henry Mountains, all in eastern Utah, appeared to be mid-Eocene to latest Oligocene in age (48–24 Ma), thus representing a completely different mid-Tertiary igneous episode (Armstrong, 1969). Stern et al. (1965) and Dubiel et al. (1990) also measured Eocene to Oligocene K-Ar ages in the La Sal and Henry Mountains, respectively.

The postulated time interval between intrusions in the CMB and eastern Utah corresponds approximately to the Laramide "magmatic gap" in western North America (Cross and Pilger, 1978; Armstrong and Ward, 1991). This "gap" has been alternatively attributed to shallowing of the subducted Farallon Plate (Dickinson and Snyder, 1978) or temporary cessation of subduction during the transpressional collision of a microplate with the western margin of North America (Maxson and Tikoff, 1996).

Fission-track and K-Ar ages reported in a subsequent, comprehensive study of CMB intrusives by Cunningham et al. (1994) more firmly established all or part of the Rico, La Plata and Ute Mountain centers as Laramide. They interpreted five fission-track ages (78–61 Ma) from Rico as representing a Late Cretaceous-early Tertiary intrusion reheated by a Pliocene thermal event that also caused extensive mineralization. A single K-Ar age of 110 Ma was disregarded.

In the La Plata Mountains, six fission-track and two K-Ar ages reported from monzonitic porphyries cluster around 67 Ma, and much of the associated mineralization appears to be Laramide as well (Cunningham et al., 1994). Four fission-track and one K-Ar age from Ute Mountain diorite, granodiorite and quartz monzonite porphyries range from 72 to 64 Ma, with 72 Ma considered to be the most geologically reliable (Cunningham et al., 1994). Like the Carrizo Mountains, Ute Mountain is poorly mineralized (Ekren and Houser, 1965; Condon, 1991); Cunningham et al. (1994) suggested that this is generally true of intrusives emplaced during the Laramide; most of the extensive mineral deposits associated with the CMB formed later, in the middle to late Tertiary.

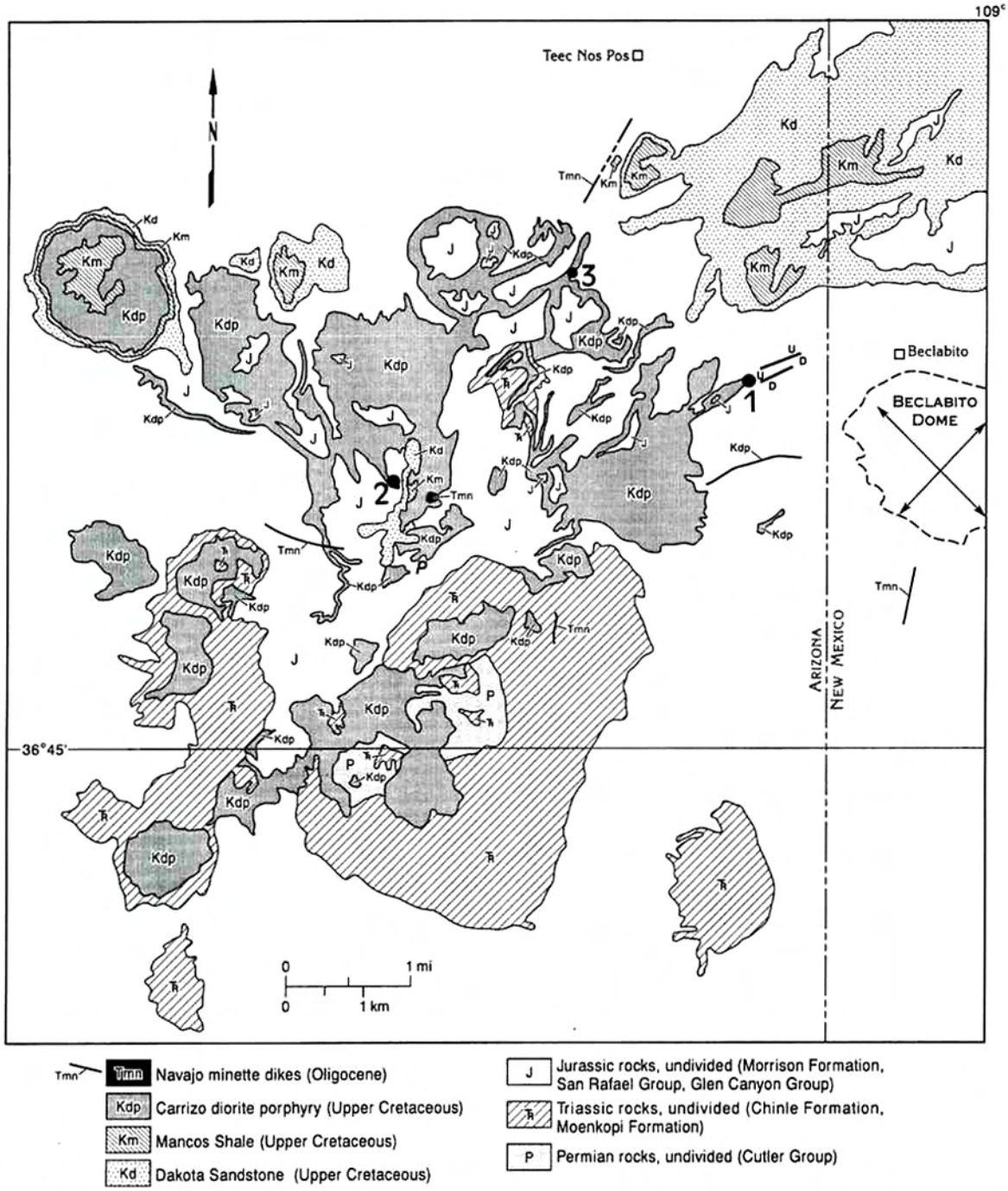

FIGURE 1. Generalized geologic map of the Carrizo Mountains area, from O'Sullivan and Beikman (1963) and Cooley et al. (1969). Sample localities 1, 2 and 3 are indicated; P is Pastora Peak.

A geochronologic study of the La Sal, Abajo and Henry Mountains published by Nelson et al. (1992) demonstrated that some K-Ar ages on Colorado Plateau intrusives might be questioned, because of the possibility that specimens have retained excess ^{40}Ar (i.e., trapped argon with $^{40}Ar/^{36}Ar$ ratios in excess of the atmospheric ratio, 295.5) or formed from magmas contaminated by Precambrian xenocrysts. In either case, reported ages would be too old. To resolve this issue, Nelson et al. (1992) dated a suite of diorite and syenite porphyries from the La Sal and Henry Mountains using $^{40}Ar/^{39}Ar$ step-heating and laser-fusion methods, which can identify geochemical disruption of K-Ar systematics. These they compared to fission-track ages from the same centers plus the Abajo Mountains. They concluded that published Eocene K-Ar ages for the eastern Utah laccoliths (Armstrong, 1969; Stern et al., 1965; Dubiel et al., 1990) indeed reflected excess ^{40}Ar and xenocryst-contamination effects in several specimens, and that the correct age range for these intrusions was middle Oligocene to early Miocene (31–20 Ma). The revised range corresponds to the post-Laramide ignimbrite flareup around the borders of the Colorado Plateau, and indicates that these laccoliths formed as part of a southwestward sweep of mid-Tertiary magmatism across the central Cordillera, possibly as a consequence of rollback of the shallowly-subducted Farallon plate (Nelson et al., 1992).

Another significant observation by Nelson et al. (1992) was that published fission-track ages for the eastern Utah laccoliths have proven more accurate than K-Ar ages, in spite of larger analytical uncertainties. This bolsters the Laramide ages of Cunningham et al. (1994) for the southwest Colorado laccoliths, which are mostly fission-track, and supports the idea of a "magmatic gap" in the Four Corners. But what of the Carrizo Mountains, which are situated at the geographic intersection of these two trends?

THIS STUDY

Because the only absolute ages for the Carrizo Mountains were the Cretaceous K-Ar ages published by Armstrong (1969) before $^{40}Ar/^{39}Ar$ methods were available to evaluate disruption of K-Ar systematics, the possibility existed that this intrusive complex was actually younger than previously thought. Following the approach of Nelson et al. (1992), we undertook to revise or confirm Armstrong's ages using $^{40}Ar/^{39}Ar$ dating, and compare our results with the fission-track and $^{40}Ar/^{39}Ar$ ages obtained more recently for other Four Corners laccoliths.

Methods

Three specimens of diorite porphyry were collected from the localities shown in Figure 1 and described in Table 1. A specimen of the minette from Zibetod Peak was also collected but proved to be too altered for use. Sampling was done with permission of the Navajo Nation Minerals Department.

Hornblende mineral separates were prepared from crushed samples using standard heavy liquid, magnetic and hand-picking techniques. The separates were then placed in machined Al discs together with interlaboratory standard Fish Canyon Tuff sanidine with an assigned age of 27.84 Ma (Deino and Potts, 1990), relative to Mmhb-1 at 520.4 Ma (Samson and Alexander, 1987), as the neutron flux monitor. After sealing stacked Al discs in an evacuated Pyrex tube, samples and monitors were irradiated for 7 hours in the D-3 position of the reactor at the Nuclear Science Center, College Station, TX.

Following irradiation, samples and monitors were placed within an automated ultra-high vacuum extraction system where they were heated using resistance-furnace or laser methods to extract argon. Individual crystals of monitor sandine were placed in a copper planchet and fused with a 10W Synrad CO_2 continuous laser. Multi-crystal samples of hornblende were step-heated in a double vacuum Mo resistance furnace. Evolved gases were purified of reactive species using SAES GP-50 getters operated at ~450° C. Argon isotopic compositions were analyzed by a MAP 215-50 mass spectrometer operated in static mode. Argon isotopes were detected by an electron multiplier with an overall sensitivity of 3.0×10^{-17} moles/pA. Extraction system and mass spectrometer blanks and backgrounds were measured numerous times throughout the course of the analyses. Typical furnace blanks were 300, 1, 0.6, 2 and 2×10^{-18} moles at masses 40, 39, 38, 37 and 36, respectively. J-factors were determined to a precision of ± 0.25% (1 ó) by analyzing 4 single crystal aliquots from each of 4 to 6 radial positions around the irradiation vessel. Correction for interfering nuclear reactions were determined using K- and Ca-rich glasses and salts. Errors are calculated by using the inverse variance as the weighting scheme (Samson and Alexander, 1987), and all errors are reported at the two sigma confidence level. The decay constant and isotopic abundances are those suggested by Steiger and Jager (1977).

TABLE 1: Sample localities, descriptions, and ages for Carrizo Mountains diorite porphyry samples.

Map (Fig. 1) Locality	Sample Number	North Latitude	West Longitude	Description of locality	$^{40}Ar/^{39}Ar$ age * (Ma)
1	CZO-CM	36°50′11″	109°04′05″	Immediately W of old copper mine area (see McLemore and Chenoweth, 1997)	70.92 ± 0.33
2	CZO-96-10-1	36°48′52″	109°11′07″	Top of sill in canyon, SE of Sidehill Spring	73.8 ± 1.0
3	CZO-96-10-2	36°51′26″	109°07′15′	Teec Nos Pos canyon (locality sampled by Armstrong, 1969)	70.65 ± 0.52

* "Plateau" ages; see text for discussion.

Results

The results of step-heating analyses are presented in Figures 2–4 and Table 2. With the exception of minor fluctuations in the ages of some low-

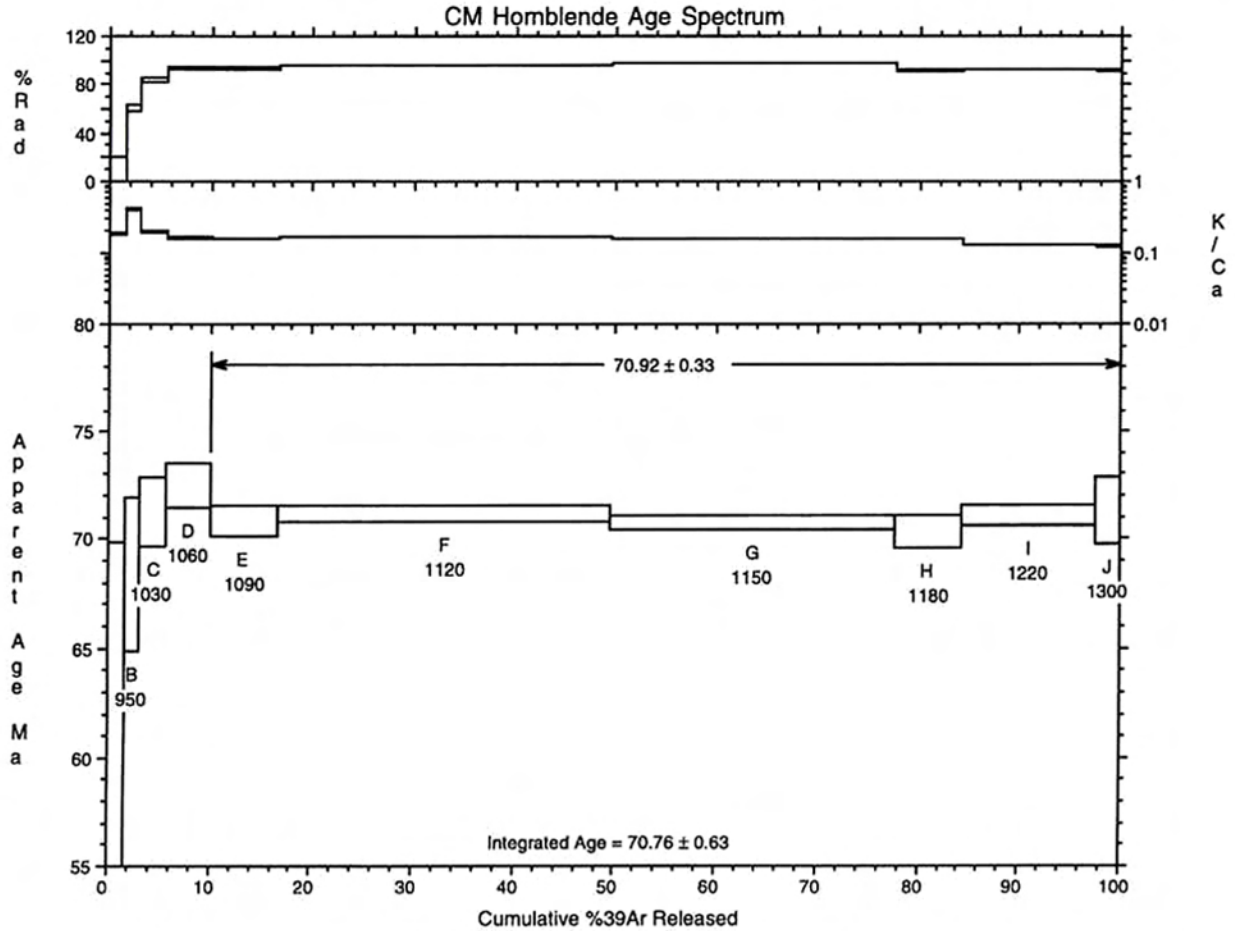

FIGURE 2. $^{40}Ar/^{39}Ar$ age spectrum for hornblende from Carrizo Mountains diorite porphyry CZO-CM.

TABLE 2. Analytical data from this study.

ID	Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-13} mol)	K/Ca	Cl/K (x 10^{-3})	$^{40}Ar^*$ (%)	^{39}Ar (%)	Age (Ma)	±2s (Ma)
CZO-96-10-1, H8:63, 6.80 mg Hornblende, J=0.000773325±0.10%, NM-63, Lab#=7616-01											
A	*800*	*268.3*	*2.034*	*749.4*	*0.162*	*0.25*	*-3.450*	*17.5*	*3.1*	*64.5*	*6.1*
B	*900*	*62.83*	*0.4865*	*55.44*	*0.097*	*1.0*	*-1.810*	*74.0*	*5.0*	*63.7*	*2.1*
C	*1000*	*60.58*	*1.363*	*37.88*	*0.136*	*0.37*	*2.4*	*81.7*	*7.7*	*67.8*	*1.4*
D	*1030*	*58.64*	*1.663*	*31.72*	*0.084*	*0.31*	*-1.790*	*84.2*	*9.3*	*67.7*	*1.9*
E	*1060*	*59.01*	*2.281*	*24.05*	*0.140*	*0.22*	*0.18*	*88.3*	*12.0*	*71.3*	*1.3*
F	1090	60.66	2.829	19.50	0.247	0.18	-0.180	90.9	16.8	75.44	0.88
G	1120	63.56	3.166	35.73	0.667	0.16	0.67	83.8	29.8	72.96	0.67
H	1150	57.86	3.415	12.45	1.42	0.15	0.93	94.1	57.3	74.57	0.41
I	1200	57.40	3.505	15.62	1.57	0.15	0.92	92.4	87.8	72.71	0.41
J	1300	59.31	3.742	17.57	0.624	0.14	0.26	91.7	99.9	74.54	0.56
K	*1650*	*275.1*	*0.1903*	*556.4*	*0.006*	*2.7*	*-13.694*	*40.2*	*100.0*	*148.2*	*61.3*
total gas age			n=11		5.15	0.18				73.02	0.84
plateau			n=5	steps F-J	4.52	0.15			87.9	73.8	1.0
CZO-96-10-2, K5:63, 6.83 mg Hornblende, J=0.000776127±0.10%, NM-63, Lab#=7640-01											
A	*800*	*182.8*	*1.765*	*458.9*	*0.110*	*0.29*	*-0.722*	*25.9*	*2.2*	*65.1*	*4.6*
B	*950*	*60.32*	*1.359*	*43.54*	*0.071*	*0.38*	*-1.344*	*78.8*	*3.6*	*65.5*	*2.3*
C	1030	56.90	2.685	22.79	0.180	0.19	-0.311	88.5	7.1	69.3	1.3
D	1060	54.96	2.924	14.46	0.328	0.17	0.80	92.6	13.6	70.05	0.72
E	1090	54.85	3.047	14.99	0.420	0.17	0.89	92.3	21.9	69.72	0.67
F	1120	53.45	3.016	6.589	1.58	0.17	1.3	96.8	53.0	71.17	0.33
G	1150	52.82	3.200	6.561	1.23	0.16	0.53	96.8	77.2	70.36	0.42
H	1180	56.62	3.046	21.41	0.194	0.17	2.1	89.2	81.0	69.5	1.2
I	1220	55.56	4.121	14.64	0.885	0.12	1.1	92.8	98.5	70.98	0.45
J	*1300*	*71.19*	*5.173*	*67.53*	*0.080*	*0.099*	*0.58*	*72.5*	*100.1*	*71.1*	*2.3*
K	*1650*	*-222.8508*	*4.948*	*-901.7887*	*-0.003*	*0.10*	*0.047*	*-19.7*	*100.0*	*60.8*	*145.4*
total gas age			n=11		5.07	0.16				70.41	0.57
plateau			n=7	steps C-I	4.82	0.16			94.9	70.65	0.52
CZO-CM, K3:63, 6.25 mg Hornblende, J=0.000777642±0.10%, NM-63, Lab#=7638-01											
A	*800*	*400.5*	*2.676*	*1221.2*	*0.081*	*0.19*	*-0.207*	*10.0*	*1.6*	*55.2*	*14.6*
B	*950*	*81.88*	*1.263*	*109.4*	*0.072*	*0.40*	*0.005*	*60.6*	*3.1*	*68.4*	*3.5*
C	*1030*	*61.66*	*2.565*	*34.29*	*0.122*	*0.20*	*1.8*	*83.9*	*5.6*	*71.3*	*1.6*
D	*1060*	*56.03*	*3.104*	*12.41*	*0.218*	*0.16*	*1.6*	*93.9*	*10.0*	*72.48*	*0.99*
E	1090	55.22	3.213	13.86	0.326	0.16	1.6	93.0	16.7	70.83	0.68
F	1120	54.09	3.060	9.112	1.61	0.17	1.2	95.5	49.5	71.17	0.34
G	1150	52.74	3.239	5.750	1.39	0.16	0.97	97.2	77.8	70.72	0.34
H	1180	55.89	3.185	17.34	0.320	0.16	1.4	91.3	84.3	70.34	0.78
I	1220	55.77	3.891	15.34	0.652	0.13	1.2	92.4	97.5	71.08	0.50
J	1300	56.51	4.022	17.33	0.123	0.13	0.54	91.5	100.0	71.3	1.5
K	*1650*	*-499.5544*	*3.349*	*-1418.4670*	*-0.001*	*0.15*	*79.8*	*16.0*	*100.0*	*-116.4*	*619.8*
total gas age			n=11		4.92	0.16				70.76	0.63
plateau			n=6	steps E-J	4.42	0.16			90.0	70.92	0.33

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

$(^{39}Ar/^{37}Ar)_{Ca}$ = 0.00070±0.00005
$(^{36}Ar/^{37}Ar)_{Ca}$ = 0.00026±0.00002
$(^{38}Ar/^{39}Ar)_K$ = 0.0119
$(^{40}Ar/^{39}Ar)_K$ = 0.0002±0.0003

temperature heating steps, the age spectra are nearly flat and radiogenic yields are high, generally 95–100%. Sample ages were determined using segments of the age spectra which met or closely approached the "plateau" criteria of Fleck et al. (1977), i.e., three or more contiguous incrementally heated gas fractions that agree within 2 ó error and together contain at least 50% of the ^{39}Ar released. Sample ages were calculated by weighting each step on the "plateau" by the inverse of its variance (Samson and Alexander, 1987). Neither the age spectra nor isochron analysis of the data show any evidence of significant excess ^{40}Ar or xenocrystic contamination observed in the eastern Utah intrusives by Nelson et al. (1992). Two of the three samples yielded precise ages of 70.92 ± 0.33 Ma and 70.65 ± 0.52 Ma. The slightly disturbed age spectrum of sample CZO-96-10-1 yielded a less precise age of 73.8 ± 1.0 Ma (Fig. 2; Tables 1, 2). Within experimental error, our age of 70.65 ± 0.52 Ma for the diorite porphyry in Teec Nos Pos Canyon is identical to the K-Ar age obtained by Armstrong (1969) for a specimen from the same locality. Our results confirm his original conclusion that the Carrizo Mountains are a Laramide intrusive complex and represent an extension of the CMB trend into northeastern Arizona.

It appears that emplacement of the Laramide laccoliths of the southwestern CMB, including the Carrizo Mountains at 74–70 Ma, followed the retreat of the Western Interior sea from the Four Corners area in a very short interval of geologic time (Tweto, 1975). Radiometric ages and paleontologic data (Fassett, 1987; Hunt and Lucas, 1992) indicate that the Upper Cretaceous Fruitland and Kirtland Formations were being deposited in a coastal-plain environment inboard of the retreating shoreline at this time, and afterward. The Carrizo Mountains and neighboring CMB laccoliths must have emerged beneath, or on the periphery of, the Late Cretaceous coastal plain. Volcanism may have occurred at some or all of these

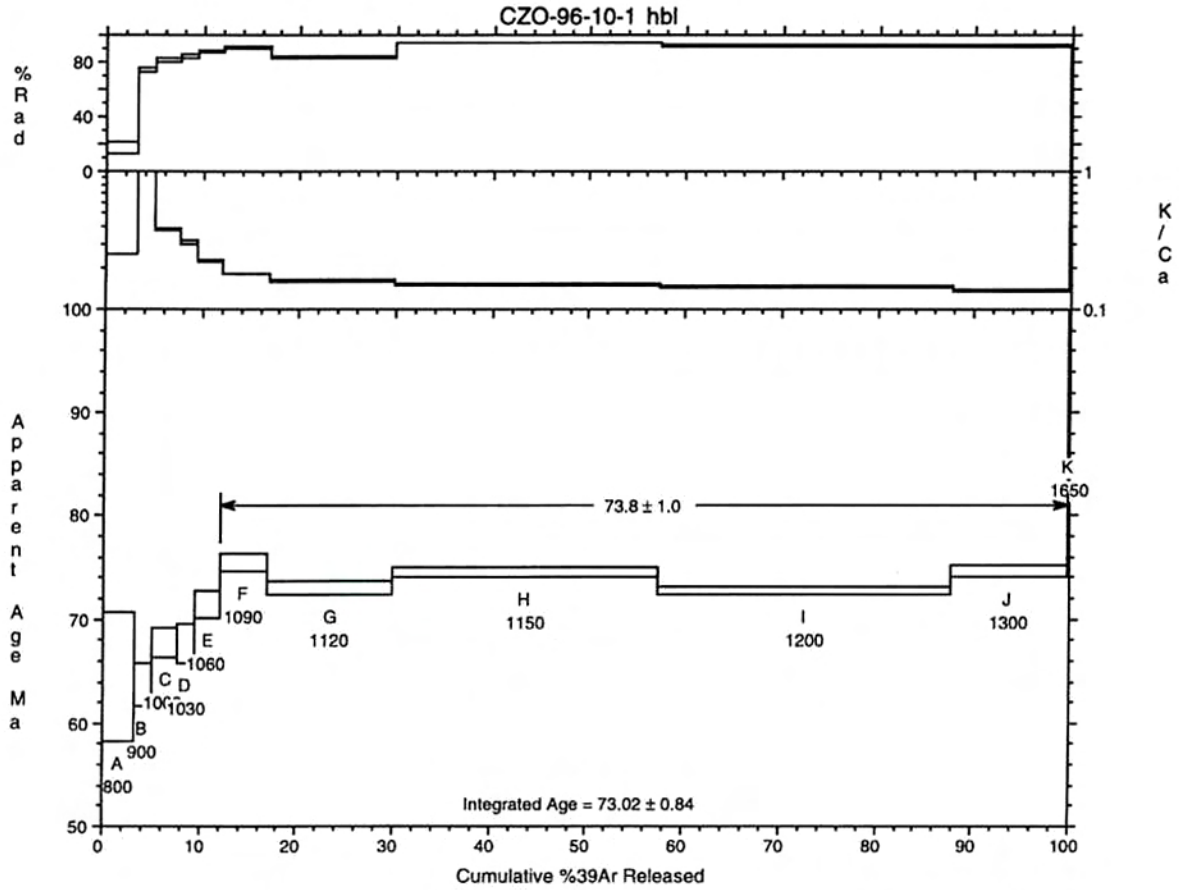

FIGURE 3. $^{40}Ar/^{39}Ar$ age spectrum for hornblende from Carrizo Mountains diorite porphyry CZO-96-10-1.

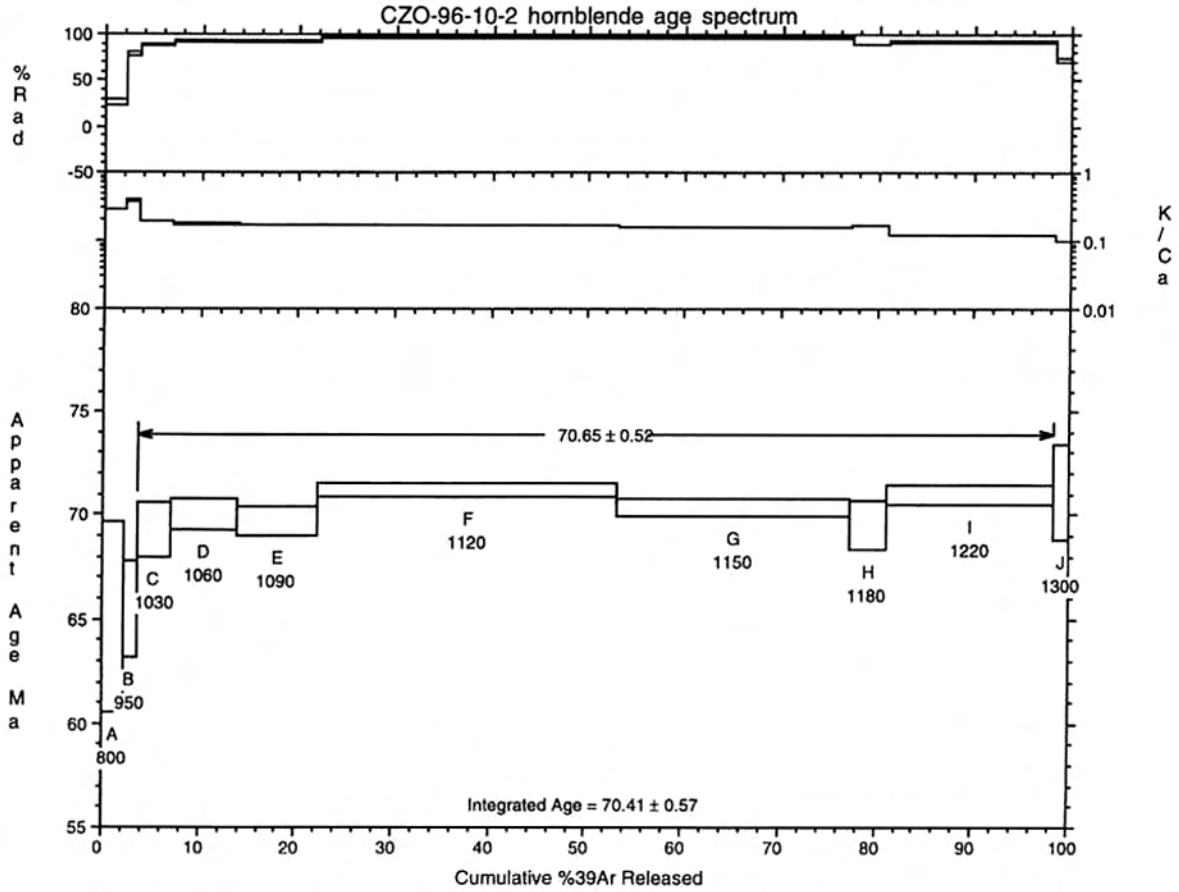

FIGURE 4. $^{40}Ar/^{39}Ar$ age spectrum for hornblende from Carrizo Mountains diorite porphyry CZO-96-10-2.

centers, accounting for all or part of the volcaniclastic material observed in some Upper Cretaceous–lower Tertiary sediments, such as the McDermott Member of the Animas Formation (Reeside, 1924). As first suggested by Tweto (1975), localized laccolithic uplift may also have influenced the retreat of the Western Interior sea and controlled the coastal paleotopography of the region.

ACKNOWLEDGMENTS

Mineral separation and $^{40}Ar/^{39}Ar$ laboratory operation were carried out at the New Mexico Geochronology Laboratory, New Mexico Tech, by Lisa Peters and Rich Esser. We thank the Navajo Nation Minerals Department for permission to conduct field research and collect samples. SCS thanks Michael Ross of the Utah Geological Survey for calling his attention to the portent of revised ages in the Four Corners, Bill Chenoweth and Virginia McLemore for sharing their knowledge of the Carrizos and Orin Anderson for several key references. The assistance of C. Goldtooth-Semken, M. Mitchell, L. Luna and Navajo Community College GLG 101 students in the field is much appreciated.

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