

New $^{40}\text{Ar}/^{39}\text{Ar}$ isotopic dates from Miocene volcanic rocks in the Lake Mead area and southern Las Vegas Range, Nevada

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Abstract: New $^{40}\text{Ar}/^{39}\text{Ar}$ dates on volcanic rocks interlayered with synextensional Miocene sedimentary rocks in the western Lake Mead area and southern end of the Las Vegas Range provide tight constraints on magmatism, basin formation, and extensional deformation in the Basin and Range province of southern Nevada. Vertical axis rotations associated with movement along the Las Vegas Valley shear zone occurred after 15.67 ± 0.10 Ma (2σ), based on a $^{40}\text{Ar}/^{39}\text{Ar}$ date from a tuff in the Gass Peak formation in the southern Las Vegas Range. Basaltic magmatism in the western Lake Mead area began as early as 13.28 ± 0.09 Ma, based on a date from a basalt flow in the Lovell Wash Member of the Horse Spring Formation. Isotopic dating of a basalt from the volcanic rocks of Callville Mesa indicates that these rocks are as old as 11.41 ± 0.14 Ma, suggesting that volcanic activity began shortly after formation of the Boulder basin, the extensional basin in which the informally named red sandstone unit was deposited. The red sandstone unit is at least as old as 11.70 ± 0.08 Ma and contains megabreccia deposits younger than 12.93 ± 0.10 Ma. This result shows that formation of the Boulder basin was associated with development of topographic relief that was probably generated by movement along the Saddle Island low-angle normal fault. Stratal tilting associated with extension occurred both prior to and after 11.5 Ma.

Résumé : Les âges $^{40}\text{Ar}/^{39}\text{Ar}$ nouvellement obtenus sur les roches volcaniques, interstratifiées dans les lithologies sédimentaires miocènes d'extension syntectonique, de la région du lac Mead et de l'extrémité sud du chaînon de Las Vegas, imposent des contraintes serrées pour ce qui est de l'interprétation du magmatisme, de la formation de bassin, et de la tectonique d'extension dans la province de Bassin et Chaîne des Rocheuses du Nevada méridional. L'âge $^{40}\text{Ar}/^{39}\text{Ar}$ de $15,67 \pm 0,10$ Ma (2σ) d'un tuf de la Formation de Gass Peak, dans la région sud du chaînon de Las Vegas, indique que les axes de rotation verticale associés au mouvement le long de la zone de cisaillement de la vallée de Las Vegas ne sont apparus qu'après cette date. Un âge fourni par une coulée de basalte du Membre de Lovell Wash, de la Formation de Horse Spring, révèle que le magmatisme basaltique dans la partie occidentale de la région du lac Mead a débuté aussi hâtivement que $13,28 \pm 0,09$ Ma. Un âge isotopique déterminé sur un basalte appartenant aux roches volcaniques de Callville Mesa indique que ces roches sont aussi anciennes que $11,41 \pm 0,14$ Ma, et suggère que l'activité volcanique a débuté peu de temps après la formation du bassin de Boulder, un bassin d'extension tectonique dans lequel fut déposée l'unité, désignée informellement, comme le grès rouge. L'unité de grès rouge est au moins aussi vieille que $11,70 \pm 0,08$ Ma, et elle contient des dépôts de mégabèche plus jeunes que $12,93 \pm 0,10$ Ma. Ces données montrent que la formation du bassin de Boulder fut associée au développement du relief topographique, qui résulte probablement de mouvements le long de la faille normale subhorizontale de Saddle Island. Le basculement des strates associé au régime d'extension a eu lieu avant et aussi après 11,5 Ma.

[Traduit par la rédaction]

Introduction

Basalt and felsic tuffs are interlayered with synextensional Miocene sedimentary rocks in the western Lake Mead area (Fig. 1) and at the southern margin of the Las Vegas Range in southern Nevada (Fig. 2). We report new high-precision $^{40}\text{Ar}/^{39}\text{Ar}$ isotopic dates that provide more precise constraints on the timing of basin formation and extensional deformation

in southern Nevada than previously possible using published conventional K–Ar and fission-track age determinations.

The Lake Mead area is located at the northern edge of the northern Colorado River extensional corridor (Fig. 1) (Faulds et al. 1990, 1992) and contains both core-complex-type detachment faults and two of the largest strike-slip faults in the Basin and Range province. Large-magnitude extension in this area occurred between 17 and 10 Ma (Fleck 1970; Anderson 1973; Bohannon 1984) and was accompanied by development and subsequent dismemberment of sedimentary basins. Miocene rocks of the Lake Mead region are divided into three unconformity-bounded sequences (Bohannon 1984): (i) the Horse Spring Formation, (ii) the informally named red sandstone unit and associated volcanic rocks of Callville Mesa, and (iii) the Muddy Creek Formation. Published age determinations from the western Lake Mead area include fission-track dates on zircon extracted from tuffs and K–Ar whole-rock and plagioclase dates on basalt and basaltic–andesite flows or

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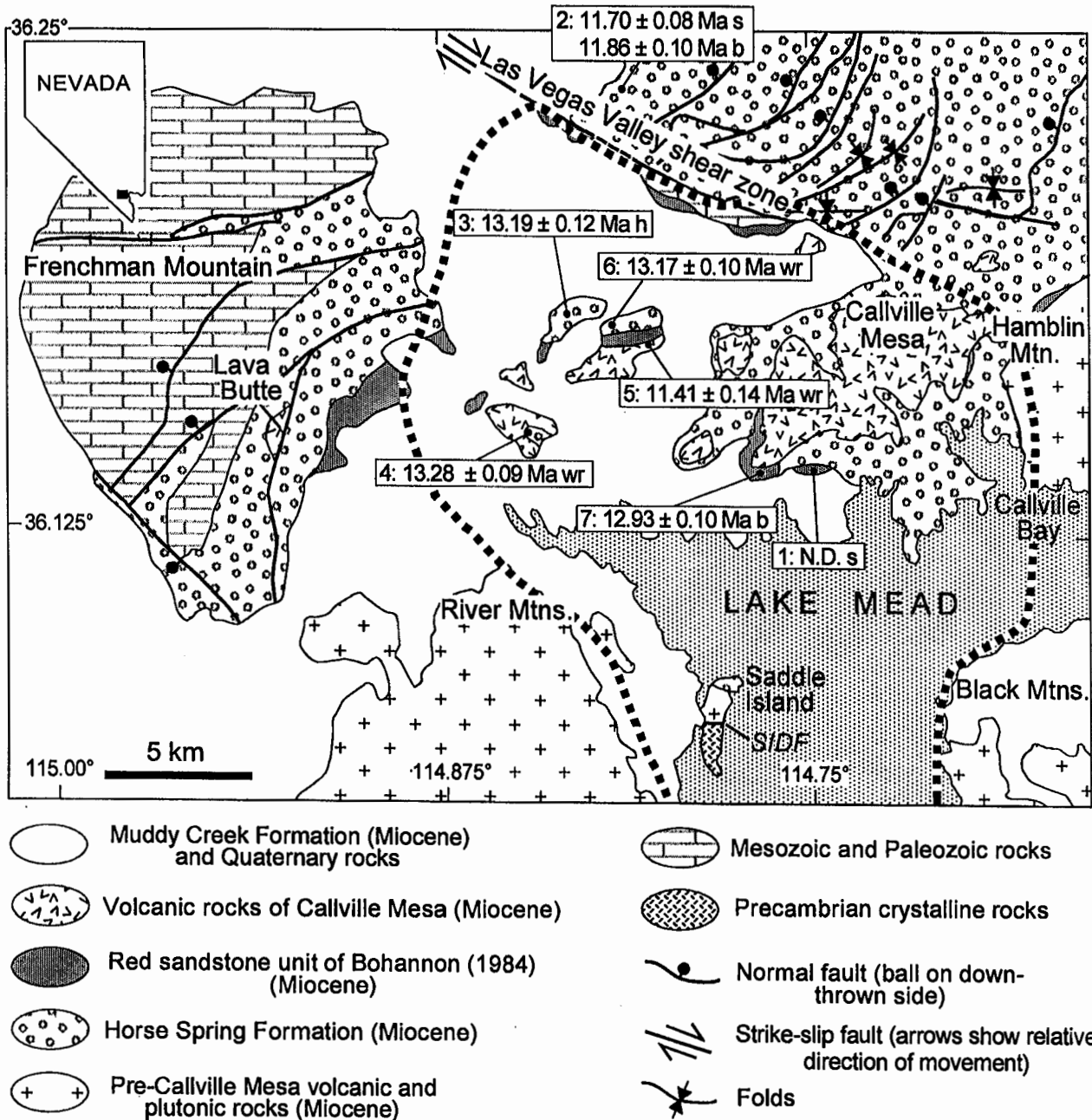
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Fig. 1. Generalized geologic map of the western Lake Mead area showing the locations and $^{40}\text{Ar}/^{39}\text{Ar}$ ages and their 2σ errors of samples dated in this report (map modified from Duebendorfer and Wallin 1991). The heavy broken line shows the approximate limits of the Boulder basin. Sample localities 1–7, minerals dated, and apparent ages are keyed to Table 1 and the text. N.D., the apparent age of the sample was not determined, as discussed in the text; SIDD, Saddle Island detachment fault; b, biotite; s, sanidine; h, hornblende; wr, whole rock.

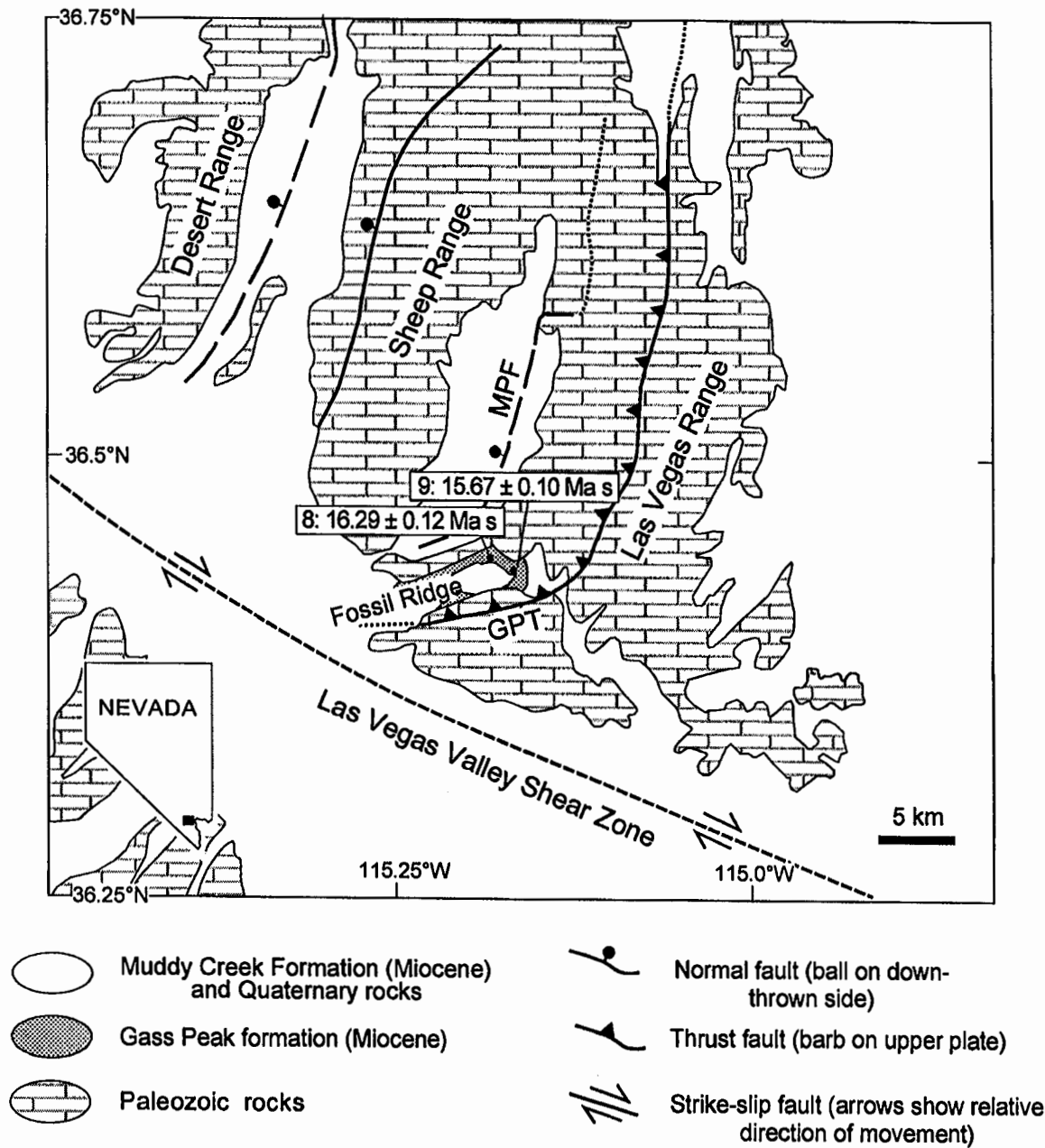


intrusive rocks that cut the sedimentary sequence (Anderson et al. 1972; Bohannon 1984; Feuerbach et al. 1991). A composite stratigraphic column showing the range of previously published isotopic dates is shown in Fig. 3.

The southern Las Vegas Range (Fig. 2) lies just north of the Las Vegas Valley shear zone and comprises the extreme southeastern portion of the Sheep Range detachment system (Wernicke et al. 1984). The Miocene rocks of this area were initially correlated with the Horse Spring Formation (Ebanks 1965; Longwell et al. 1965), but more recent studies have concluded that these strata do not correlate lithostratigraphically

with the Horse Spring Formation. This unit has been informally termed the Gass Peak formation (Guth et al. 1988; Deibert 1989). Sedimentary rocks of the Gass Peak formation were deposited in a basin separate from the one represented by the Horse Spring Formation in the Lake Mead area. The Gass Peak formation is divided into lower (Fossil Ridge) and upper (Castle Rock) members which have K–Ar dates of about 16 and 12 Ma, respectively (Deibert 1989). East-trending high-angle normal faults of the Sheep Range detachment system postdate the deposition of sediments of the Gass Peak formation. The high-angle normal faults and the Gass Peak

Fig. 2. Geologic map of the Las Vegas Range and vicinity, showing the location and apparent ages of $^{40}\text{Ar}/^{39}\text{Ar}$ samples from the Gass Peak formation dated in this report (map modified from Deibert 1989 and Nelson and Jones 1987). Sample localities 8 and 9, minerals dated, and the apparent ages are keyed to Table 1 and the text. GPT, Gass peak thrust; MPT, Mormon Pass fault.



formation are believed to have been rotated almost 90° clockwise about a vertical axis due to deformation associated with right-slip movement along the Las Vegas Valley shear zone (Deibert 1989).

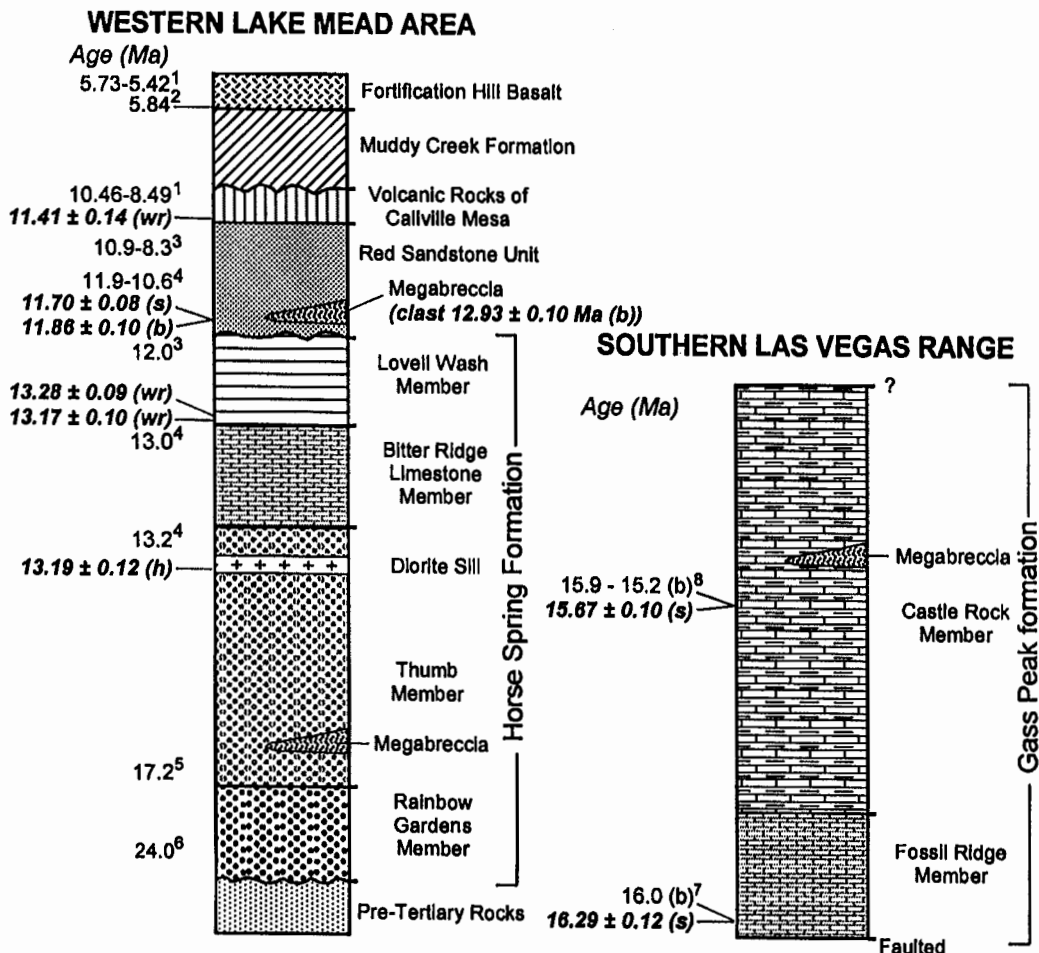
Analytical methods

Eight mineral separates or whole-rock samples from volcanic and intrusive rocks from seven localities in the Lake Mead area and two samples of tuff from the southern Sheep Range were dated by the $^{40}\text{Ar}/^{39}\text{Ar}$ technique. Whole-rock and mineral separates were prepared by standard crushing and sieving tech-

niques. Mineral concentrates were prepared using standard gravimetric (heavy liquid) and magnetic separation techniques, followed by hand-picking to prepare pure (estimated visual purity for most samples was >99.9%) mineral separates. Whole-rock samples were washed in 10% HCl to remove carbonate alteration; sanidine concentrates were washed in 5% HF to remove any glass adhering to the crystals.

The whole-rock and mineral separates were loaded in aluminum foil capsules, sealed in silica vials, and irradiated for 30 h in the central thimble of the U.S. Geological Survey TRIGA reactor. Vertical and horizontal gradients in neutron flux in the irradiated package were monitored by 8–10 standards distributed along

Fig. 3. Generalized stratigraphic column of Tertiary rocks in the Lake Mead area (after Bohannon 1984; Duebendorfer and Wallin 1991). Superscripts 1–8 as follows: 1, K–Ar, plagioclase (Feuerbach et al. 1991); 2, K–Ar, plagioclase (Shafiqullah et al. 1980); 3, K–Ar, plagioclase (Duebendorfer et al. 1991); 4, fission track on ash-fall tuffs (Bohannon 1984); 5, K–Ar, whole rock (Anderson et al. 1972, cited in Bohannon 1984); 6, ⁴⁰Ar/³⁹Ar, sanidine (Beard 1996); 7, K–Ar, biotite (R.J. Fleck 1988, cited by Deibert 1989, no error reported); 8, K–Ar, biotite (J.F. Sutter, personal communication, 1968, to W.J. Ebanks, Jr. cited by Deibert 1989, no error reported). Ages reported in bold italics are the new ⁴⁰Ar/³⁹Ar dates and their 2σ errors from this report. b, biotite; s, sanidine; h, hornblende; wr, whole rock.



the length of each vial; the geometry of the irradiated package was such that each unknown sample was adjacent to at least one standard. Neutron flux during irradiation was monitored using hornblende standard MMhb-1, which has a K–Ar age of 520.4 ± 1.7 Ma (Samson and Alexander 1987). Corrections for reactor-produced interfering reactions were made using argon isotopes of K_2SO_4 and CaF_2 irradiated in each package.

After irradiation, the samples were progressively degassed in a double-vacuum resistance furnace in a series of eight to ten 20 min long steps to a maximum temperature of 1450°C. After each heating step, the gas was collected and purified using Zr–Al–Ti getters, and all five argon isotopes were measured using a mass spectrometer operated in the static mode. Apparent ages were calculated using decay constants recommended by Steiger and Jäger (1977). The argon data were evaluated using age spectra, apparent ³⁹Ar/³⁷Ar ratios (for hornblende and whole-rock samples), and ³⁹Ar/⁴⁰Ar versus ³⁶Ar/⁴⁰Ar “inverse isochron” diagrams. The determination of whether the individual apparent ages in an age spectrum

yielded a “plateau” was made using the criteria of Fleck et al. (1977). Following this criteria, a plateau is defined as comprising two or more contiguous gas fractions which yield apparent ages that are statistically indistinguishable at the 95% confidence level (using the critical value test of Dalrymple and Lanphere 1969) and which together constitute greater than 50% of the total potassium-derived ³⁹Ar (³⁹Ar_K) released in the incremental heating experiment. A detailed description of analytical procedures similar to those used in this study is given in Tysdal et al. (1990, their Appendix 1). A summary of the isotopic dating results is given in Table 1.²

⁴⁰Ar/³⁹Ar dates and interpretation

Sample TV91-32 (locality 1, Fig. 1) is from a crystal vitric tuff

² Complete analytical data for the dated samples (Table D1) may be purchased from the Depository of Unpublished Data, Document Delivery, CISTI, National Research Council Canada, Ottawa, ON K1A 0S2, Canada.

Table 1. Rock units dated, sample locations, and summary of isotopic dating results.

Sample No.	Location (Figs. 1, 2)	Rock type	Lat. N	Long. W	Material dated	Plateau date (Ma)	Isochron date (Ma)	$^{40}\text{Ar}/^{36}\text{Ar}_i$	MSWD	Total gas date (Ma)
TV91-32	1	Crystal vitric tuff	36°08'28"	114°44'30"	Sanidine	No plateau	—	—	—	12.1±0.1
TV92-2	2	Crystal vitric tuff	36°14'01"	114°48'20"	Sanidine	11.70±0.08	11.65±0.09	329±54	2.441	11.73±0.10
do	2	Crystal vitric tuff	36°14'01"	114°48'20"	Biotite	11.86±0.10	11.82±0.08	300±12	1.090	11.75±0.12
TV92-3	3	Diorite sill	36°10'46"	114°50'14"	Hornblende	13.19±0.12	13.25±0.05	293±22	0.961	13.09±0.22
TV92-4	4	Basalt flow	36°09'10"	114°51'31"	Whole rock	13.47±0.08	13.28±0.09	313±5	1.971	13.65±0.10
TV92-5	5	Basalt flow	36°10'28"	114°48'45"	Whole rock	11.41±0.14	11.45±0.18	300±13	0.993	11.65±0.16
TV92-7	6	Basalt flow	36°10'39"	114°48'52"	Whole rock	13.17±0.10	13.27±0.16	294±4	4.903	13.29±0.10
TV92-8	7	Dacite clast	36°08'28"	114°45'52"	Biotite	12.93±0.10	12.96±0.09	289±10	1.891	12.91±0.10
JDT7	8	Crystal vitric tuff	36°26'19"	115°12'27"	Sanidine	16.29±0.12	16.29±0.09	291±17	0.472	16.26±0.14
JDT13	9	Crystal vitric tuff	36°26'16"	115°11'07"	Sanidine	15.67±0.10	15.67±0.08	288±11	0.484	15.6±1.1

Notes: Apparent ages are reported at the 2 σ confidence level. Ages in bold represent our best estimate for the age of the sample. $^{40}\text{Ar}/^{36}\text{Ar}_i$, initial $^{40}\text{Ar}/^{36}\text{Ar}$ ratio for the sample determined by the inverse correlation diagram; MSWD, mean square of weighted deviates for the inverse isochron regression.

from a 1 m thick (variable) bed near the base of the informally named red sandstone unit of Bohannon (1984). The tuff contains intact, delicate, and angular glass shards near its base, suggesting that is an air-fall tuff. It is laminated in the middle and upper parts of the section, however, indicating that these parts were reworked by fluvial processes following deposition of the tuff. A sanidine concentrate, containing minor quartz and glass, yielded a total gas date of 12.1 Ma (Table 1), but its age spectrum is highly discordant (Fig. 4a). The initial 700°C step gave an apparent age of 9.4 Ma, followed by an overall step-like increase in apparent ages at greater temperatures up to a maximum age of 22.4 Ma.² The irregularity of the age spectrum suggests the concentrate may contain a combination of feldspars of significantly different age, perhaps due to contamination by lithic K-feldspar during sedimentary reworking as noted above. Similar climbing age spectra have been obtained from some samples from the Mogollon–Datil volcanic field by McIntosh et al. (1990) and were interpreted to have been contaminated by either xenocrystic feldspars or lithic feldspars of significantly different age. Given the highly discordant nature of the age spectrum, neither the total gas date nor the apparent ages from individual temperature steps give meaningful information regarding the age of this tuff.

The second sample (TV92-2, locality 2, Fig. 1) was collected from a 1.5 m thick crystal vitric tuff located about 50 m above the base of the red sandstone unit. The red sandstone unit is 290 m thick at Frenchman Mountain (Duebendorfer and Wallin 1991). The tuff is interbedded with gypsiferous siltstone and very fine grained siltstone. It may correlate with a tuff near Frenchman Mountain dated by Bohannon (1984) as 11.2 ± 1.2 Ma (zircon, fission track). The tuff contains visible intact glass shards and randomly oriented biotite crystals, indicating that this is an air-fall tuff that has probably not been reworked by subsequent sedimentary processes. Both sanidine and biotite concentrates from this sample have similar total gas dates of 11.73 ± 0.10 and 11.75 ± 0.12 Ma (2 σ), respectively (Table 1). Overall, the sanidine age spectrum is slightly U-shaped, perhaps indicating the presence of minor excess ^{40}Ar , but is essentially flat over greater than 90% of the $^{39}\text{Ar}_K$ released (Fig. 4b). The possibility of minor excess ^{40}Ar suggested by the slightly U-shaped spectrum cannot be evaluated because of the limited spread in $^{39}\text{Ar}/^{40}\text{Ar}$ versus $^{36}\text{Ar}/^{40}\text{Ar}$

values for individual temperature steps, which results in an initial $^{40}\text{Ar}/^{36}\text{Ar}$ intercept that is poorly defined (i.e., 329 ± 54; Table 1) and which overlaps the atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ value of 295.5. However, apparent ages from five steps (925–1150°C) yield an acceptable plateau date of 11.70 ± 0.08 Ma (2 σ),² which we consider to be a reasonable estimate for the age of this mineral separate. The biotite from this sample also yielded a simple age spectrum. The initial temperature step at 700°C has an apparent age of about 10.3 Ma, but the rest of the spectrum gives concordant dates of about 11.8 Ma (Fig. 4c).² A plateau date calculated from the 800 to 1150°C steps is 11.86 ± 0.10 Ma and represents 91.6% of the $^{39}\text{Ar}_K$ released during the heating experiment.² This age is similar, although slightly older than the plateau date from the coexisting sanidine. Averaging the two ages gives a weighted mean of 11.76 ± 0.12 Ma (2 σ). However, given problems with disparate ages determined from coexisting sanidine and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ dates from some tuffs, with biotites generally giving somewhat older to significantly older apparent ages (Kellogg et al. 1994; W.C. McIntosh, written communication, 1997), the best estimate for the age of this tuff is probably represented by the sanidine plateau age of 11.70 ± 0.08 Ma.

Sample TV92-3 (locality 3, Fig. 1) was collected from a diorite(?) sill that intrudes the Thumb Member of the Horse Spring Formation. The sill is composed primarily of brown hornblende and plagioclase, with subordinate clinopyroxene and olivine. Spene is an abundant accessory mineral. K–Ar and fission-track dates from the Thumb Member range from 17.2 to 13.2 Ma (Bohannon 1984). The hornblende gives a total gas date of 13.09 ± 0.22 Ma, and a somewhat discordant age spectrum. Apparent ages from low-temperature (650–950°C) and high-temperature (1200–1400°C) steps are variable (Fig. 4d),² but three steps which together constitute about 75% of the $^{39}\text{Ar}_K$ are concordant at 13.19 ± 0.12 Ma (Table 1). We interpret the plateau date to record the approximate age of emplacement of this hypabyssal sill. This date establishes an upper age limit for the Thumb Member of the Horse Spring Formation in the western Lake Mead area.

Sample TV92-4 (locality 4, Fig. 1) is from an aphanitic basalt flow, which gives a total gas date of 13.65 ± 0.10 Ma (Table 1). Initial low-temperature and the final high-temperature steps give young and anomalously old apparent ages, but

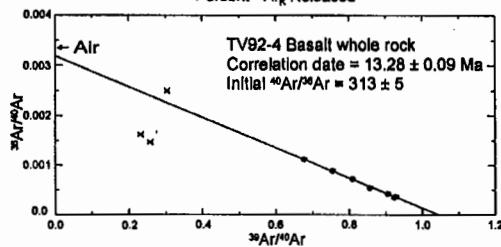
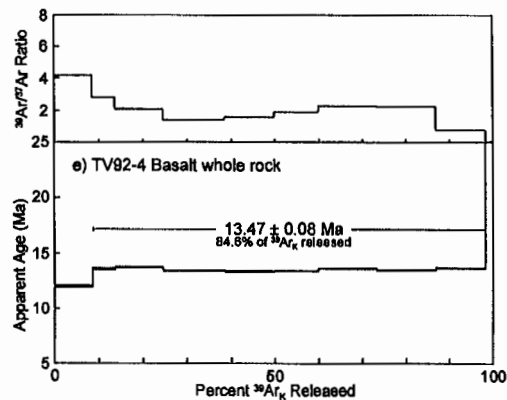
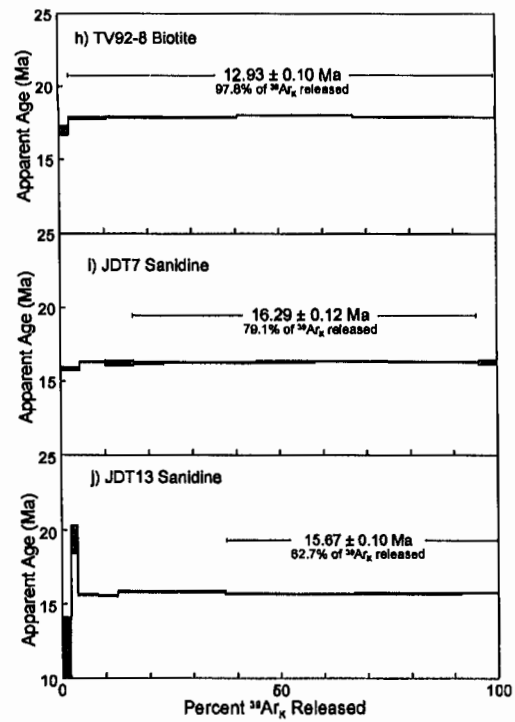
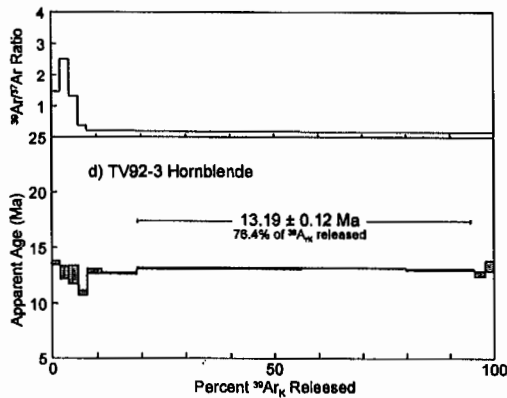
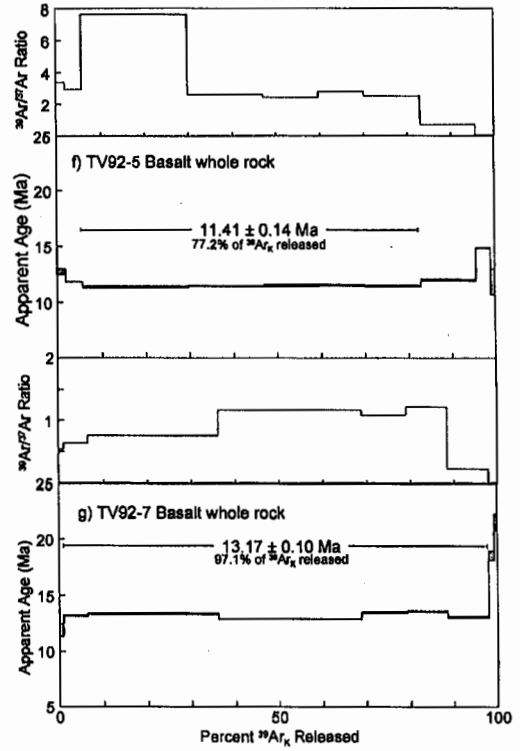
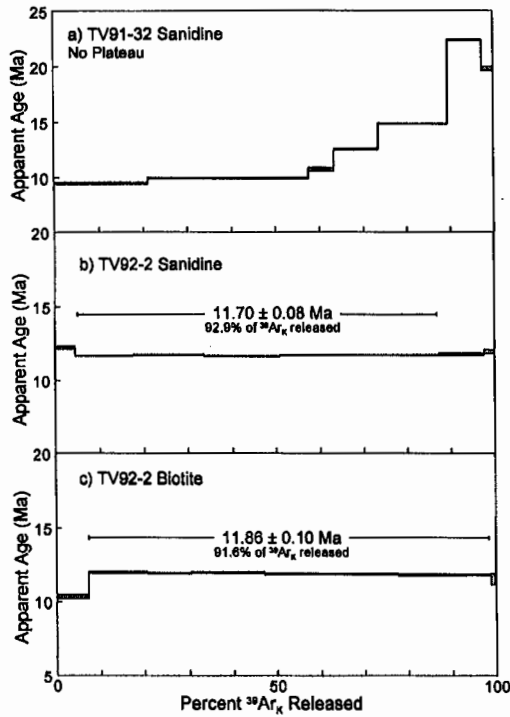


Fig. 4. $^{40}\text{Ar}/^{39}\text{Ar}$ apparent age spectra for samples dated in this report. Also shown for hornblende and whole-rock samples are the $^{39}\text{Ar}/^{37}\text{Ar}$ ratios. A $^{36}\text{Ar}/^{40}\text{Ar}$ vs. $^{39}\text{Ar}/^{40}\text{Ar}$ "inverse isochron" diagram is shown for sample TV92-4 in Fig. 4e. ●, heating steps in the inverse isochron diagram which statistically define an isochron; ×, heating steps rejected from the regression. Apparent ages listed in the diagrams are reported at the 2 σ confidence level.

most of the steps are characterized by relatively constant ages that range from about 13.2 to 13.6 Ma (Fig. 4e).² The apparent ages that define this relatively flat interval do not define a plateau using the strict criteria of Fleck et al. (1977), but a weighted mean of apparent ages from the 700 to 1100°C temperature steps gives 13.47 ± 0.08 Ma (84.6% of the $^{39}\text{Ar}_K$ released) (Table 1). A $^{39}\text{Ar}/^{40}\text{Ar}$ versus $^{36}\text{Ar}/^{40}\text{Ar}$ inverse isochron diagram gives a somewhat younger apparent age of 13.28 ± 0.09 Ma and an initial $^{40}\text{Ar}/^{36}\text{Ar}$ value of 313 ± 5 (2 σ), which is significantly greater than the atmospheric value of 295.5. Because the inverse correlation diagram makes no assumptions regarding the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of the trapped argon component in the sample, we regard the isochron date to best represent the age of eruption and cooling of the basalt flow. The 13.3 Ma age indicates that this basalt is probably part of the Lovell Wash Member of the Horse Spring Formation.

Sample TV92-5 (locality 5, Fig. 1) is from a clinopyroxene-plagioclase basalt (49% SiO_2) flow. The basalt gives a total gas date of 11.65 ± 0.16 Ma (Table 1) and a slightly U-shaped age spectrum (Fig. 4f). The 700–1000°C steps give essentially uniform apparent ages that yielded a weighted mean of 11.41 ± 0.14 Ma over 77% of the $^{39}\text{Ar}_K$ released. Strictly speaking, these steps do not define a plateau according to the criteria of Fleck et al. (1977), but this date is probably a reasonable estimate for the geologic age of this sample. The inverse isochron from this sample yields a similar age of 11.45 ± 0.18 Ma and an initial $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 300 ± 13 that is indistinguishable from the atmospheric value (Table 1). The basalt is considered to be part of the volcanic rocks of Callville Mesa (E.M. Duebendorfer, unpublished mapping). The flow unconformably overlies the red sandstone unit with variable angular discordance that ranges from 20 to 40°. At one locality, the base of the flow dips 38° south, whereas the underlying red sandstone dips 61° southeast. This relationship suggests that tilting in this part of the Lake Mead area occurred both before and after deposition of the basalt flow at 11.4 Ma.

Sample TV92-7 (locality 6, Fig. 1) is from an olivine phyrlic basalt flow interbedded with tuffaceous and calcareous sandstone and siltstone of the Lovell Wash Member of the Horse Spring Formation. The basalt has a discordant age spectrum and gives a total gas date of 13.29 ± 0.10 Ma (Table 1). Most of the spectrum (about 95%) is relatively flat (Fig. 4g), with apparent ages that range from 13.02 to 13.54 Ma and a weighted mean age of 13.17 ± 0.10 Ma. An inverse isochron diagram analysis for these same steps gives an initial $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 296 ± 6 and an apparent age of 13.27 ± 0.16 Ma. Because the initial $^{40}\text{Ar}/^{36}\text{Ar}$ value is identical to the atmospheric value, we consider the plateau date to represent the best estimate for the age of this sample. This date is consistent with fission-track age determinations on tuffs exposed elsewhere in the Lovell Wash Member (Bohannon 1984).

Sample TV92-8 (locality 7, Fig. 1) is a hornblende-bearing biotite dacite collected from a clast within a megabreccia. Dacite clasts up to 1 m in diameter are common in this deposit. The megabreccia is bounded above and below by fine-grained

sandstone and gypsiferous siltstone of the informally named red sandstone unit (Fig. 3). A biotite separate from the dacite gives a total gas date of 12.91 ± 0.10 Ma (Table 1) and a relatively simple age spectrum that is flat over greater than about 98% of the $^{39}\text{Ar}_K$ released (Fig. 4h). A plateau date calculated for the 800–1150°C steps gives an apparent age of 12.93 ± 0.10 Ma. This date indicates that the megabreccia deposit is younger than the Thumb Member of the Horse Spring Formation, which also contains megabreccia deposits. The $^{40}\text{Ar}/^{39}\text{Ar}$ date from the dacite clast indicates that there are two distinct episodes of megabreccia deposition in the Lake Mead area.

Samples JDT7 and JDT13 are from the southern Las Vegas range (localities 8 and 9, respectively; Fig. 2). Sample JDT7 is from a crystal vitric tuff in a 0.25 m thick bed (ash bed T7 of Deibert 1989), approximately 9 m above the base of the Fossil Ridge member of the Gass Peak formation. The ash is interbedded with bioclastic lime mudstone, and we interpret this ash to be an air-fall tuff that was deposited in a freshwater lake. The tuff and the enclosing beds do not contain evidence of clastic sediments, which suggests that the tuff has not been reworked. A biotite from this same tuff was dated by the K–Ar method as 16.0 Ma (R.J. Fleck, written communication, 1988, cited by Deibert 1989). The sanidine gives a total gas date of 16.26 ± 0.14 Ma (Table 1) and an easily interpreted age spectrum with essentially concordant apparent ages over greater than 95% of the $^{39}\text{Ar}_K$ released (Fig. 4i). A plateau date from the 975–1200°C steps gives an apparent age of 16.29 ± 0.12 Ma (Table 1). This age is in good agreement with the age reported by Fleck in Deibert (1989), although no analytical details are available regarding that age determination.

Sample JDT13 is from a crystal vitric tuff that was collected from a 0.5 m thick ash bed (ash bed T13 of Deibert 1989) located 160 m above the base of the Castle Rock member of the Gass Peak formation. The ash is interbedded with silty limestone and we suggest that it is an air-fall tuff that was deposited in a saline lake. The upper parts of the tuff are laminated, suggesting that they have been reworked to some extent. K–Ar dates for biotite from this ash range from 15.9 and 15.2 Ma (J.F. Sutter, personal communication, 1968, to W.J. Ebanks, Jr., cited by Deibert 1989) and 13.6 and 12.1 Ma (R.J. Fleck, written communication, 1988, cited by Deibert 1989). A sanidine from the ash gives a total gas of 15.6 ± 1.1 Ma (Table 1). The apparent ages of low-temperature steps are somewhat variable (Fig. 4j),² but overall the age spectrum is relatively simple and easily interpreted with apparent ages from the 900 to 1475°C temperature steps ranging from 15.60 to 15.82 Ma, with a weighted mean of 15.71 ± 0.10 Ma (97.2% of the $^{39}\text{Ar}_K$ released). These steps, however, do not yield a plateau using the strict criteria of Fleck et al. (1977). The preferred age for this sample is 15.67 ± 0.10 Ma (63% of the $^{39}\text{Ar}_K$ released) calculated from the 1100–1450°C temperature steps, which is statistically identical to the age described above. This age is within the range of K–Ar dates previously determined by J.F. Sutter, but significantly older than the dates determined

by R.J. Fleck (cited in Deibert 1989). The reason for the discrepancy between the younger K–Ar dates and our $^{40}\text{Ar}/^{39}\text{Ar}$ date is not clear, but may have resulted from alteration of the biotite in the saline lake environment. In the absence of the analytical data for the K–Ar dates, however, this or other possible explanations cannot be evaluated. We suggest that the $^{40}\text{Ar}/^{39}\text{Ar}$ date reported here is the best estimate for the age of this ash bed.

Implications of the $^{40}\text{Ar}/^{39}\text{Ar}$ Ar dates

Our $^{40}\text{Ar}/^{39}\text{Ar}$ Ar dates lead to the following conclusions regarding the age of sedimentary and volcanic successions and periods of extensional deformation in the western Lake Mead area.

The basal red sandstone unit in the Boulder basin must be older than 11.70 ± 0.08 Ma, the age of the sanidine collected approximately 50 m above the base of the sandstone. This date agrees within error with Bohannon's (1984) zircon fission-track dates of 11.9 ± 0.9 and 11.7 ± 1.3 Ma from White Basin, but is somewhat older than his dates from Frenchman Mountain (10.6 ± 0.9 and 11.2 ± 1.2 Ma). The analytical precision of the $^{40}\text{Ar}/^{39}\text{Ar}$ Ar dates reported here provides a tighter limit on the age of the lower part of the red sandstone unit than the previously reported fission-track dates. In addition, the 12.93 ± 0.10 Ma date on biotite from the dacite clast within a megabreccia deposit provides an absolute lower limit for the age of the red sandstone unit; however, the date reported above is probably closer to the real age of the basal red sandstone unit.

Identification of clasts within a megabreccia with an apparent age of 12.93 Ma suggests that there were at least two episodes of megabreccia deposition in the Lake Mead area. The first occurred between 17.2 and 13.2 Ma during deposition of the Thumb Member. The second probably occurred during deposition of the red sandstone unit, or between about 11.77 and 8.6 Ma. This second episode of megabreccia deposition may reflect topographic relief generated by movement along the Saddle Island low-angle normal fault.

The volcanic rocks of Callville Mesa which are interstratified with and locally overlie the red sandstone unit are as old as 11.41 ± 0.14 Ma. Previously, the oldest isotopic date from the volcanic rocks of Callville Mesa is a K–Ar date of 10.46 ± 0.23 Ma on plagioclase from a basalt reported by Feuerbach et al. (1991). Thus, localized volcanic activity associated with the Callville Mesa volcanic field began shortly after the beginning of deposition of the red sandstone unit. The $^{40}\text{Ar}/^{39}\text{Ar}$ Ar date reported here is from a flow that overlies the red sandstone unit with variable angular discordance of 20–40°. At one locality, the flow dips 38° south, whereas the underlying red sandstone dips 61° southeast. This relationship suggests that tilting associated with extension in this part of the Lake Mead area occurred both before and after 11.4 Ma.

Essentially high-precision $^{40}\text{Ar}/^{39}\text{Ar}$ Ar dates of 13.28 ± 0.09 and 13.17 ± 0.10 Ma from basalts interbedded with the Lovell Wash Member of the Horse Spring Formation in the Boulder basin indicate that the age of this unit may be somewhat older (although statistically indistinguishable) than previously thought based on a fission-track date of 13.0 ± 0.8 Ma (Bohannon 1984). This new isotopic date suggests that the Lovell Wash Member may in part be time correlative with the Bitter Ridge Limestone Member which generally underlies it. This

inference is supported by the observation that, east of Frenchman Mountain, tuffaceous rocks similar in appearance to the Lovell Wash Member interfinger with lacustrine carbonate rocks of the Bitter Spring Member.

New isotopic dates from sedimentary rocks of the Gass Peak formation in the southern part of the Las Vegas Range indicate that the majority of the sediments were deposited between 16.29 ± 0.12 and 15.67 ± 0.10 Ma. These dates also indicate that the Castle Rock Member of the Gass Peak formation is significantly older than 12 Ma, an age based on a previously reported conventional K–Ar date (R.J. Fleck, written communication, 1988, cited by Deibert 1989). The younger date from the Gass Peak formation suggests that vertical axis rotation of crustal blocks at the southern end of the Las Vegas Range occurred after 15.67 ± 0.10 Ma.

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