AGE AND POSSIBLE SOURCE OF AIR-FALL TUFFS OF THE MIOCENE CARLIN FORMATION, NORTHERN NEVADA

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ABSTRACT

$^{40}Ar/^{39}Ar$ laser-fusion ages have been obtained from alkali-feldspar-bearing air-fall tuffs of the Carlin Formation, a Miocene clastic and volcaniclastic sedimentary unit of north-central Nevada. Ages of these tuffs are grouped tightly, ranging from 14.4 to 15.1 Ma, but even this limited range may be exaggerated by contamination during deposition with feldspar from underlying rhyolitic volcanic rocks. These tuffs and much of the Carlin Formation post-date at least some of the gold mineralization in the Midas and Ivanhoe mining districts, where ages of 15.3 and 15.1 Ma, respectively, are reported for vein adularia. Younger quartz-adularia veins in the Santa Renia Fields quadrangle cut detrital units of the Carlin Formation that overlie the air-fall tuff horizons northwest of the dated locations, suggesting that circulation of hydrothermal fluids probably continued during deposition of the formation.

The age, location, and major-element chemistry of the glass shards in the tuffs of the Carlin Formation are consistent with derivation from silicic volcanic centers associated with the Yellowstone hotspot and/or the northern Nevada rift. These parameters are most consistent with a subalkaline source in the Owyhee Plateau of Idaho, such as the Juniper Mountain volcanic center, but tuffs also could have been derived from local sources in the Snowstorm or Sheep Creek Mountains or from more distant calderas of the McDermitt or Lake Owyhee volcanic fields 50-60 km to the west or northwest. Additional studies of minor- and trace-element compositions of the tuffs and better age and chemical characterization of middle Miocene volcanic centers of the region are necessary for more precise tephrochronology of 14- to 16-Ma volcanism in northern Nevada and adjacent areas of Oregon and Idaho.

GEOLOGIC SETTING

The Carlin Formation was defined by Regnier (1960) for a sequence of largely unconsolidated silts, sands, fanglomerate, and pyroclastic rocks that overlie Ordovician to Miocene(?) strata in the vicinity of Carlin, Nev., approximately 50 km south-southeast of the Santa Renia Fields quadrangle (fig. 1). In that area the Carlin Formation is approximately 130-200 m thick (Regnier, 1960). Originally thought to be entirely Pliocene in age (Regnier, 1960), based on the presence of vertebrate fossils approximately 5 km northeast of Carlin, the strata were assigned a Miocene and Pliocene age by Evans and Cress (1972) and Evans (1972, 1974). As mapped in the western part of the Santa Renia Fields quadrangle by T.G. Theodore, J. Kelly Cluer, and Stanley C. Finney (unpub. data, 1997), four units are identified, but these were not found to be mappable throughout the area (fig. 2). In the quadrangle, the 30 m-to-50 m-thick basal tuff unit includes thin beds of partly welded tuff and lesser amounts of siltstone, mudstone, and gravel. This unit rests on Miocene rhyolite porphyry informally named the Craig Rhyolite of Bartlett and others (1991). W.E. Brooks (written communication, 1997) reports an $^{40}Ar/^{39}Ar$ incremental-heating plateau age of 15.03±0.05 Ma for similar rhyolite porphyry approximately 5 km southwest of location 4 (fig. 2) in the adjacent Willow Creek Reservoir SE quadrangle. The basal tuff unit is overlain by a unit, as much as 400 m thick, including mostly unconsolidated silts, sands, and sedimentary breccia, as well as abundant volcanic ash and air-fall tuff. Because the volcanic debris is present variously as unconsolidated and consolidated deposits, the terms, ash, tuff, and tephra are all correct and are used here depending upon the context. Bedded air-fall tuff crops out prominently throughout the quadrangle as nearly white bands across slopes (fig. 3). Beds in the various units of the Carlin Formation are either horizontal or gently dipping; most exposed sequences are horizontal and ample evidence is present in the form of pisolites and abundant worm burrows to indicate subaqueous deposition, probably lacustrine. The organisms commonly used brown mud or silt to fill their burrows through the air-fall tuff. Roadcuts through the formation reveal that many well-layered sequences of air-fall tuff are broken by high-angle normal faults that have separations of as much as 1 to 1.5 m. Where the air-fall-tuff-rich unit laps unconformably onto lower Paleozoic rocks, an underlying, thin, yellow-brown, sandy silt or massive olive-brown mudstone is present. In places the underlying units form mud lumps in beds of gray-white, air-fall tuff. Thin beds of granitic debris, possibly derived from the Jurassic Goldstrike

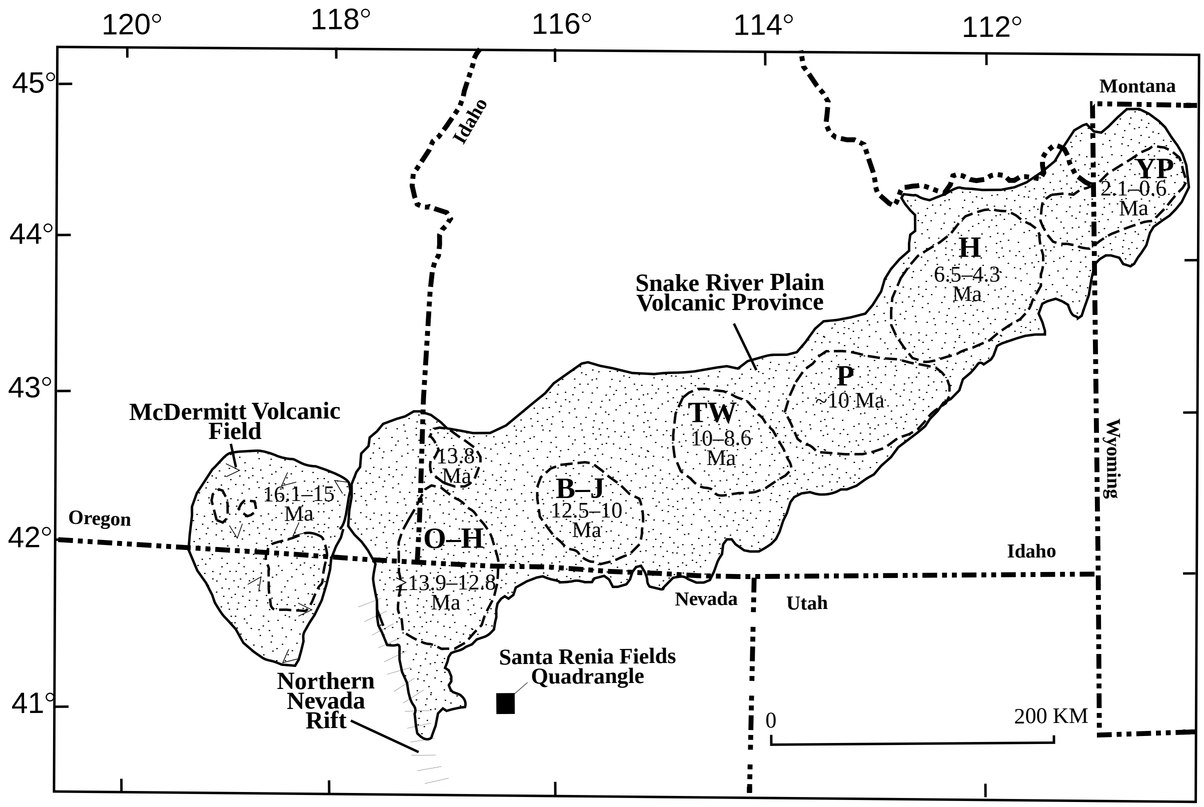


Figure 1. Index map showing location of the Santa Renia Fields quadrangle, Nev., the Snake River volcanic province (modified from Perkins and others, 1995), the McDermitt volcanic field (modified from Rytuba and McKee, 1984), and the northern Nevada rift (Zoback and Thompson, 1978; Zoback and others, 1994). Dashed lines within Snake River volcanic province approximate the major volcanic fields proposed by Perkins and others (1995): **O–H**, Owyhee-Humboldt volcanic field; **B–J**, Bruneau-Jarbidge volcanic field; **TW**, Twin Falls volcanic field; **P**, Picabo volcanic field; **H**, Heise volcanic field; **YP**, Yellowstone Plateau volcanic field. Age range of major explosive volcanic activity in Snake River volcanic province modified from Pierce and Morgan (1992) and Perkins and others (1995). Dashed lines within McDermitt volcanic field are locations of major calderas with age range modified from Rytuba and McKee (1984).

pluton approximately 10 km to the southeast, also are present locally in the air-fall-rich sequence. The tuff-bearing unit is overlain, in turn, by poorly exposed silts and sands, mostly unconsolidated, that are conspicuously free of air-fall tuff. All of these units are overlain by unconsolidated fanglomerate deposits — typically as much as 130 m thick and locally as much as 600 m thick — that appear to have been derived principally from Paleozoic rocks in the area of Beaver Peak, approximately 10 km to the east.

The spatial and temporal relationship of epithermal and hot-springs-generated ore deposits in the northern Great Basin to magmatic and hydrothermal activity has been documented by field and geochronologic studies of these deposits (McKee and others, 1974; Silberman and others, 1976; Noble and others, 1988; Wallace and others, 1990). Noble and others (1988) summarize evidence for mineralization throughout the 17- to 14-Ma period in this region. West of the Santa Renia Fields quadrangle, sedimentary strata correlated with the Carlin Formation overlie volcanic rocks thought to post-date mineralization in the Hollister mine in the Ivanhoe mining district (McKee and others, 1974; Alan R. Wallace, written commun., 1997). Locally within the quadrangle, however, some sequences of the Carlin Formation are cut by low-temperature quartz-adularia veins. Roughly 4.8 km west of the Dee gold mine, near the west edge of the quadrangle, these veins are present as fracture and fragment coatings within fanglomerate of the formation (fig. 4). Rhyolite flows and hypabyssal domes that appear to postdate some of the Carlin sedimentary rocks show evidence of weak alteration (Alan R. Wallace, written commun., 1997), and support the continuation of mineralization during Carlin sedimentation.

SAMPLING AND ANALYTICAL TECHNIQUES

Sample Collection of Air-Fall Tuffs

Samples of bedded air-fall tuff were obtained from the Carlin Formation in the central part of the Santa Renia Fields

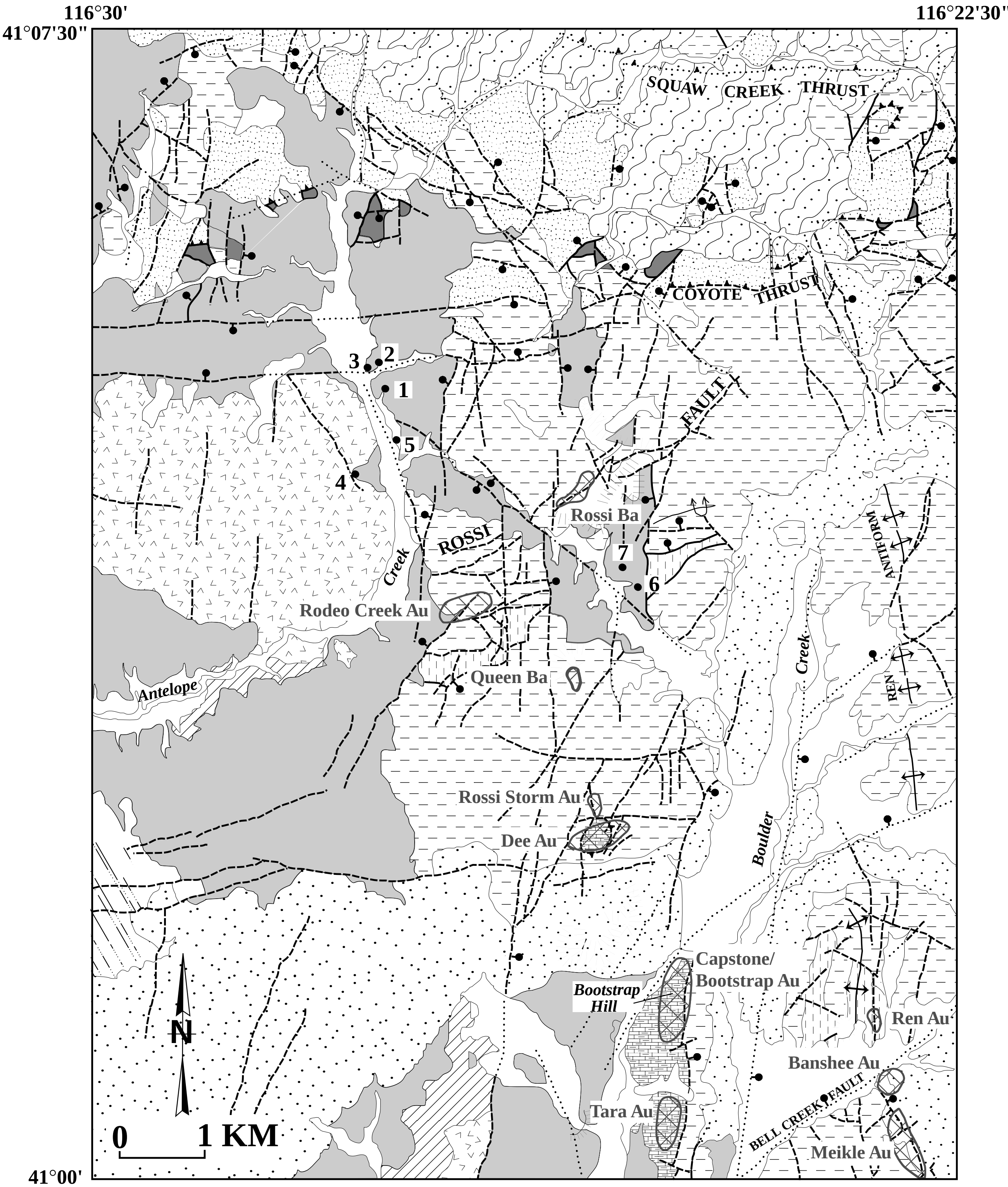
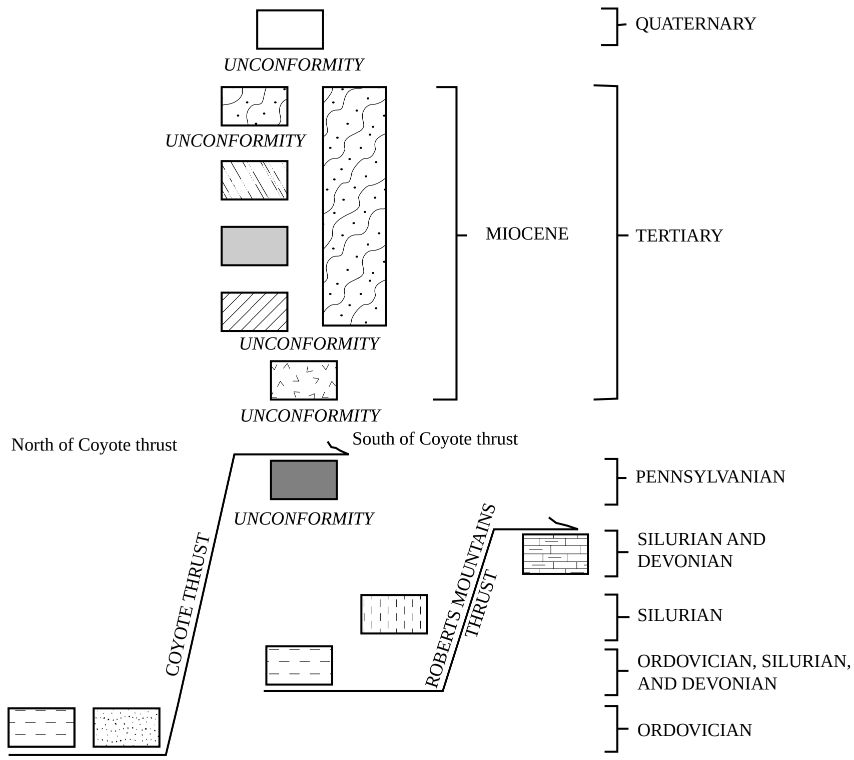


Figure 2. Geologic sketch map of the Santa Renia Fields quadrangle, Nev., showing locations of samples dated from Miocene Carlin Formation. Modified from T.G. Theodore, J.K. Cluer, and S.C. Finney (unpub. data, 1997). Location numbers same as in tables 1–3.

Figure 2—Explanation

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

Alluvium and other unconsolidated deposits (Quaternary)

Carlin Formation—Fanglomerate deposits, unconsolidated (Miocene)

Carlin Formation—Silts and sands, mostly unconsolidated (Miocene)

Carlin Formation—Silts and sands, mostly unconsolidated, sedimentary breccias, and abundant air-fall tuff (15.1 to 14.4 Ma, Miocene)

Carlin Formation—Tuff, partly welded, and minor silts and sands, mostly unconsolidated (Miocene)

Carlin Formation—Undivided (Miocene)

Porphyritic rhyolite vitrophyre (north of Antelope Creek) and peralkaline rhyolite (west of Boulder Creek). Same as informally named Craig rhyolite of Bartlett and others (1991) (Miocene)

Strathearn Formation—Chert-pebble conglomerate (Pennsylvanian and Permian)

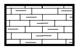
(See page 180 for remainder of map units and symbols)

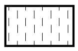
quadrangle after repeated visual examination to assure collection of the freshest and least contaminated material. Twelve of these samples from seven different localities (fig. 2) were selected for initial $^{40}Ar/^{39}Ar$ dating and several additional samples were used for tephrochronology. Many additional localities were examined but rejected because of inadequate exposures or alteration of the tuffs. Most samples represent material obtained from approximately 10-cm-thick, well-bedded stratigraphic intervals with minimal evidence of reworking. Some outcrops of the tuff, however, are severely bioturbated such that only traces of bedding surfaces remain.

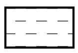
$^{40}Ar/^{39}Ar$ Laser-Fusion Dating

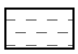
The $^{40}Ar/^{39}Ar$ dating technique was first utilized in its common form by Merrihue and Turner (1966) and has since become utilized more commonly than conventional K-Ar

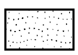
Figure 2—Explanation cont'd.


Undivided autochthonous carbonate rocks below Roberts Mountains thrust—Includes laminated and shaly limestone of Silurian and Devonian Roberts Mountains Formation, ooid packstone of the informally named Devonian Bootstrap limestone, and laminated limey mudstone of the Devonian Popovich Formation


Elder Sandstone in upper plate Roberts Mountains thrust—Mostly siltstone and minor chert (Silurian)


Undivided siliceous sedimentary rocks in upper plate of Roberts Mountains thrust south of Coyote thrust—Mostly chert and argillite of Ordovician Vinini Formation, chert and argillite of probable Devonian Slaven Chert, and minor siltstone of Silurian Elder Sandstone. May include small areas of outcrop of cherty rocks belonging to Devonian Rodeo Creek unit (see text) (Ordovician, Silurian, and Devonian)


Undivided siliceous sedimentary rocks in upper plate of Coyote thrust—Siltstone, mostly, and some chert, probably belonging to Ordovician Vinini Formation (Ordovician)


Vinini Formation—Quartzarenite, mostly (Ordovician)


Contact


Fault—Dashed where approximately located; dotted where concealed; bar and ball on down-dropped side


Thrust fault—Sawteeth on upper plate. Dashed where approximately located; dotted where concealed

Mine dump

dating because of its increased precision and utility (Dalrymple, 1989). Although the early advances with ^{40}Ar/^{39}Ar involved step-wise heating of samples and evolving the argon gas in multiple increments, total fusion of extremely small amounts of material through the use of a continuous laser (laser-fusion ^{40}Ar/^{39}Ar) has become the technique of choice for mineral separates from thermally undisturbed samples (York and others, 1981; Dalrymple and Duffield, 1988). Laser-fusion ^{40}Ar/^{39}Ar dating has evolved to dating of single or small numbers of mineral grains and is especially useful to detect and overcome the effects of xenocrystic contamination (LoBello and others, 1987; Fleck and Carr, 1990) and incomplete extraction of radiogenic Ar from alkali feldspar (McDowell, 1983).

The laser-fusion technique used in this study follows procedures described by Dalrymple and Duffield (1988), Dalrymple (1989), and Fleck and Carr (1990). These analyses were performed on the same mass spectrometer and using the same argon extraction-system described by Dalrymple (1989). Samples used in ^{40}Ar/^{39}Ar dating were irradiated for 16 hours in the U.S. Geological Survey TRIGA Reactor Facility in Denver, Colorado. An intralaboratory standard sanidine, 85G003, (Taylor Creek Rhyolite, 27.92 Ma) was used for calculation of the neutron flux in all irradiations. The age of this monitor mineral is as reported by Duffield and Dalrymple (1990), standardized to an age of 513.9 Ma for interlaboratory

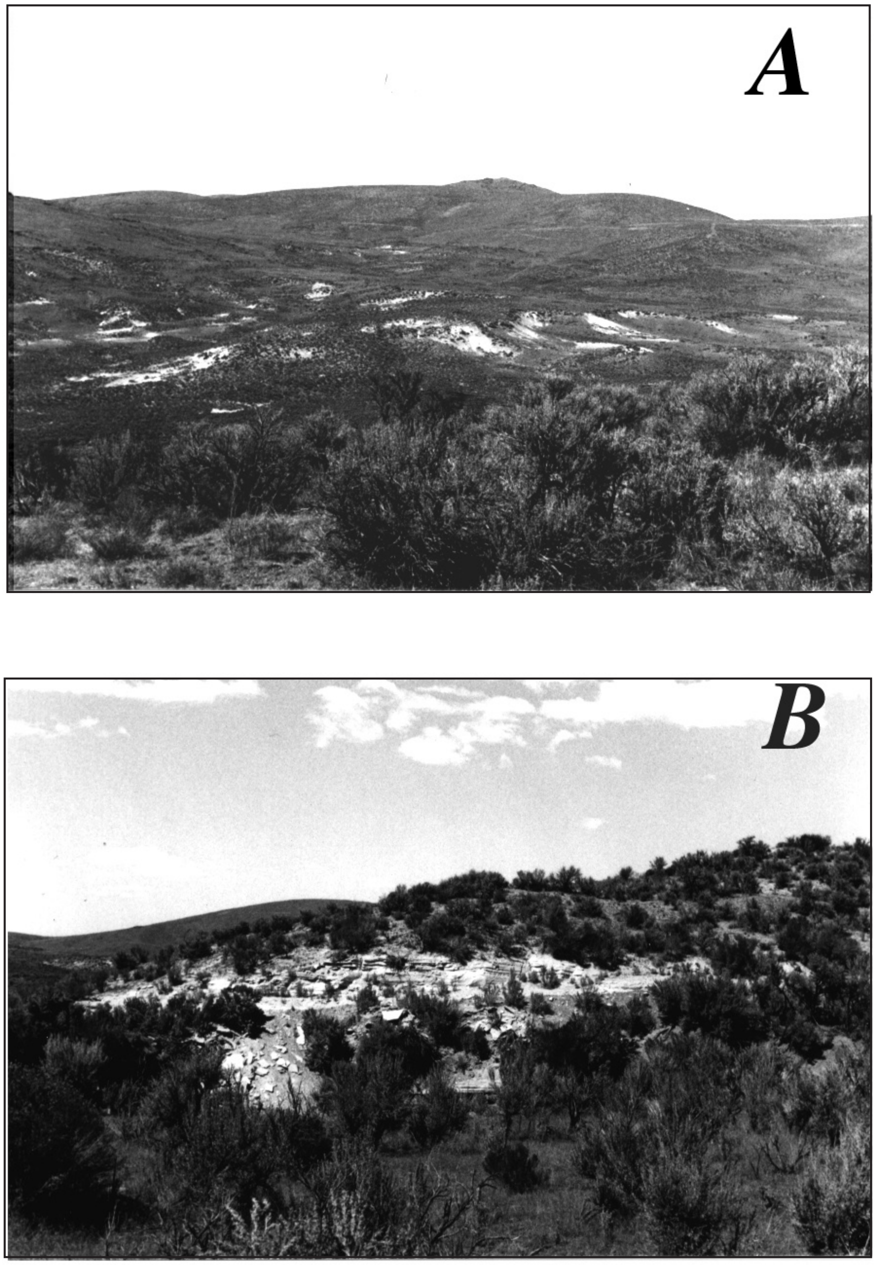


Figure 3. Photographs showing field relations of air-fall tuff-rich unit of Miocene Carlin Formation, Santa Renia Fields quadrangle, Nev. ***A***, Distribution of air-fall tuff west of Santa Renia Springs near upper reaches of Antelope Creek, Santa Renia Fields quadrangle, Nevada; ***B***, character of well exposed air fall tuff at map location 3 (fig. 2).

standard hornblende, MMhb-1 (Samson and Alexander, 1987) as measured in the Menlo Park laboratory and the intralaboratory standard biotite, SB-3 (Lanphere and others, 1990). Decay and abundance constants for all ages reported are those recommended by Steiger and Jager (1977).

Best-estimate ages for each sample are represented by the weighted means of replicate laser-fusion analyses, with the inverse variance of propagated, within-run (*i.e.*, “internal”) errors used as the weighting factors (Taylor, 1982). The goodness of fit parameter, MSWD or Mean-Square-of-Weighted-Deviates (McIntyre and others, 1966), is calculated for these means and is used to determine the presence of any error component in excess of estimated analytical error (an “external” error). Where the MSWD of a mean is greater than

Figure 3. (cont'd) Photographs showing field relations of air-fall tuff-rich unit of Miocene Carlin Formation, Santa Renia Fields quadrangle, Nev. ***C***, gently dipping beds of air-fall tuff near upper contact of unit in west-central part of quadrangle, Nev. ***D***, close-up of thin layers of air-fall tuff and pisolites approximately 2-5 cm above sample 96TT134 (loc. 3, fig. 2)

1.0, analytical errors are multiplied by the square root of MSWD, as discussed by Ludwig (1988) and Fleck and others (1996), to incorporate this error.

Tephrochronologic Methods

Volcanic glass shards from samples of air-fall tuff (tephra layers) of the Carlin Formation were separated and analyzed by electron microprobe using methods described by Sarna-Wojcicki and others (1984). Briefly, samples were wet-sieved with water in plastic sieves fitted with nylon screens, retaining the 200 to 100 mesh size fraction (about 80 to 150 microns, respectively) for separation of glass shards. This fraction was placed in water in an ultrasonic vibrator, treated with a 10 percent solution of HCl for a few minutes to remove authigenic

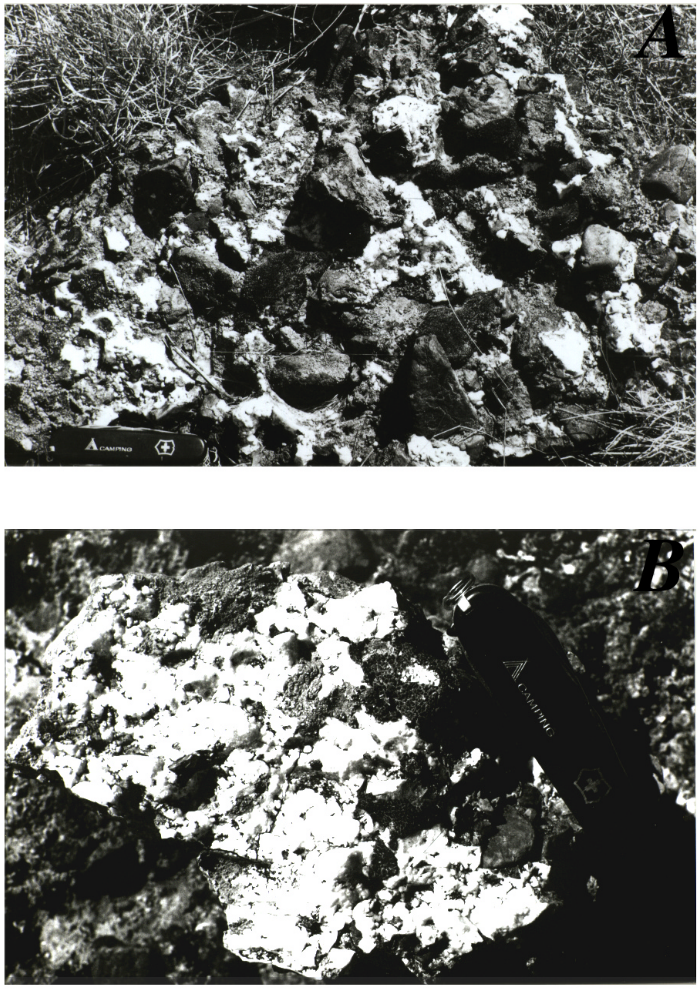


Figure 4. Photographs of quartz-adularia veins (white) in air-fall tuff-rich unit of Miocene Carlin Formation approximately 4.8 km west of Dee gold mine. ***A***, Veins cementing largely unconsolidated fanglomerate deposits; ***B***, veins along fracture surface in fanglomerate.

carbonate adhering to the glass particles, and leached with an 8 percent solution of HF acid for about 30 seconds to one minute to remove other coatings or altered rinds that may have been present on the glass shards. The glass shards were then separated from other components of each tephra sample using (**1**) a magnetic separator and (**2**) heavy liquids of variable density made from mixtures of methylene iodide and neothene or acetone. Most glass samples analyzed in the present study were already partly processed during separation of alkali feldspar (sized and most crystalline material was separated), and the volcanic glass was suitable for analysis.

Each glass separate was mounted in epoxy resin in shallow holes drilled into Plexiglas slides, and the slides were ground-down and polished with diamond paste to expose the shards and prepare a smooth, uniform surface for analysis. The polished sample was coated with carbon, and 15 to 25 individual glass shards were analyzed for Si, Al, Fe, Mg, Mn, Ca, Ti, Na, and K using a JEOL 8900 electron-microprobe. Details of the analytical techniques are reported by Sarna-Wojcicki and others (1984).

ANALYTICAL RESULTS

Results of individual laser-fusion $^{40}Ar/^{39}Ar$ experiments on samples from air-fall tuff or ash layers collected within the Santa Renia Fields quadrangle are shown in table 1 and summarized in table 2. Apparent ages range from 15.1 Ma to 14.4 Ma, but internal precision varies as shown by the MSWD. Values of MSWD greater than about 2.5 are commonly considered to reflect scatter beyond reasonable expectations of analytical error and are interpreted as indicating geologic

Table 1 $^{40}Ar/^{39}Ar$ Laser-Fusion Analyses of Alkali Feldspars from the Miocene Carlin Formation, Nevada

Sample #/Irrad #	Run #	J	$^{40}Ar^*$ (mol)	K/Ca	$^{40}Ar^*$ (%)	Age (Ma)
96TT129	252A	0.0037795	1.153E-15	9.88	93.4	14.87 ± 0.19
CXLIII-1	252B	"	9.202E-15	13.27	94.7	14.32 ± 0.12
Map location 1	252C	"	7.094E-15	6.37	92.7	14.28 ± 0.13
	252E	"	6.270E-15	2.56	90.5	14.43 ± 0.15
	252F	"	1.335E-14	7.29	95.3	14.49 ± 0.10
	Means		7.414E-15	7.88	93.35	
					Wtd. Mean	14.43 ± 0.08
					MSWD	1.92
96TT130	253A	0.0037761	5.317E-15	3.78	92.7	14.22 ± 0.16
CXLIII-2	253B	"	5.855E-15	6.78	93.8	14.71 ± 0.16
Map location 1	253C	"	7.036E-15	8.30	98.0	15.13 ± 0.14
	253D	"	4.207E-15	10.73	63.7	13.96 ± 0.20
	253E	"	4.511E-15	7.19	91.1	14.92 ± 0.19
	253F	"	5.217E-15	7.08	88.9	14.07 ± 0.16
	Means		5.365E-15	8.02	87.10	
					Wtd. Mean	14.55 ± 0.20
					MSWD	8.62
96TT131	254A	0.0037728	1.220E-14	10.35	91.5	14.47 ± 0.10
CXLIII-3	254B	"	1.569E-14	10.66	96.3	14.36 ± 0.09
Map location 1	254C	"	1.428E-14	13.41	96.3	14.39 ± 0.09
	254D	"	1.145E-14	7.93	60.7	14.43 ± 0.11
	254E	"	1.044E-14	8.33	95.6	14.42 ± 0.10
	Means		1.281E-14	10.14	88.08	
					Wtd. Mean	14.41 ± 0.04
					MSWD	0.19
96TT132	255A	0.0037695	8.288E-15	6.63	96.9	14.51 ± 0.11
CXLIII-4	255B	"	8.815E-15	6.08	95.1	14.43 ± 0.11
Map location 2	255C	"	4.188E-15	4.92	89.4	14.30 ± 0.17
	255D	"	1.088E-14	7.86	96.6	14.54 ± 0.10
	255E	"	5.036E-15	5.00	90.0	14.53 ± 0.15
	255F	"	9.042E-15	6.39	97.2	14.45 ± 0.11
	Means		7.592E-15	6.05	93.67	
					Wtd. Mean	14.48 ± 0.05
					MSWD	0.37

Table 1 $^{40}Ar/^{39}Ar$ Laser-Fusion Analyses of Alkali Feldspars from the Miocene Carlin Formation, Nevada — *Continued*

Sample #/Irrad #	Run #	J	$^{40}Ar^*$ (mol)	K/Ca	$^{40}Ar^*$ (%)	Age (Ma)
96TT133	97Z0256A	0.0037624	8.010E-15	5.59	97.8	14.68 ± 0.12
CXLIII-5	97Z0256B	"	1.025E-14	6.15	98.0	14.68 ± 0.10
Map location 3	97Z0256C	"	1.038E-14	6.37	99.6	14.80 ± 0.11
	97Z0256E	"	7.492E-15	4.75	98.4	14.71 ± 0.12
	97Z0256F	"	1.200E-14	8.25	98.6	14.70 ± 0.10
	Means		9.627E-15	6.22	98.49	
					Wtd. Mean	14.72 ± 0.05
					MSWD	0.24
96TT134	97Z0257A	0.0037587	1.283E-14	9.23	99.4	14.86 ± 0.10
CXLIII-6	97Z0257B	"	1.095E-14	7.73	97.2	14.88 ± 0.10
Map location 3	97Z0257C	"	1.312E-14	9.65	98.6	14.62 ± 0.10
	97Z0257D	"	6.944E-15	8.74	95.1	14.47 ± 0.12
	97Z0257E	"	7.628E-15	12.88	96.2	14.29 ± 0.12
	97Z0257F	"	6.766E-15	6.91	95.1	14.30 ± 0.12
	Means		9.080E-15	9.18	96.46	
					Wtd. Mean	14.61 ± 0.10
					MSWD	5.58
96TT136	97Z0258A	0.0037550	7.386E-15	1.43	96.8	14.87 ± 0.12
CXLIII-7	97Z0258B	"	5.837E-15	1.16	96.5	14.78 ± 0.14
Map location 4	97Z0258C	"	5.563E-15	1.63	95.2	14.58 ± 0.14
	97Z0258D	"	6.084E-15	1.92	99.8	15.31 ± 0.14
	97Z0258E	"	7.100E-15	1.67	99.1	15.19 ± 0.13
	97Z0258F	"	7.793E-15	2.52	97.6	14.83 ± 0.12
	Means		6.476E-15	1.78	97.65	
					Wtd. Mean	14.93 ± 0.10
					MSWD	3.88
96TT137	97Z0263A	0.0037513	8.321E-15	1.62	95.0	14.76 ± 0.12
CXLIII-8	97Z0263B	"	1.086E-14	2.28	98.3	15.00 ± 0.10
Map location 4	97Z0263C	"	4.796E-15	2.46	86.0	14.65 ± 0.16
	97Z0263D	"	1.092E-14	1.75	98.6	15.20 ± 0.11
	97Z0263E	"	7.260E-15	2.02	97.8	15.07 ± 0.13
	97Z0263F	"	8.084E-15	1.20	86.7	14.97 ± 0.12
	Means		8.384E-15	1.94	93.46	
					Wtd. Mean	14.97 ± 0.08
					MSWD	2.59

Table 1 $^{40}Ar/^{39}Ar$ Laser-Fusion Analyses of Alkali Feldspars from the Miocene Carlin Formation, Nevada — *Continued*

Sample #/Irrad #	Run #	J	$^{40}Ar^*$ (mol)	K/Ca	$^{40}Ar^*$ (%)	Age (Ma)
96TT138	97Z0267A	0.0037310	4.428E-14	4.40	97.7	14.73 ± 0.09
CXLIII-12	97Z0267B	"	2.873E-14	9.73	97.8	14.77 ± 0.09
Map location 4	97Z0267D	"	4.232E-14	1.58	97.9	14.95 ± 0.09
	97Z0267E	"	6.322E-14	7.81	98.4	14.87 ± 0.09
	97Z0267F	"	3.905E-14	4.20	96.8	14.91 ± 0.09
	Means		4.333E-14	5.83	97.75	
					Wtd. Mean	14.84 ± 0.04
					MSWD	1.12
96TT139	97Z0264A	0.0037434	1.856E-14	3.10	95.7	15.20 ± 0.09
CXLIII-9	97Z0264B	"	2.052E-14	10.45	98.1	15.07 ± 0.09
Map location 5	97Z0264C	"	2.942E-14	3.86	97.8	15.08 ± 0.09
	97Z0264D	"	2.687E-14	4.80	98.1	14.81 ± 0.09
	97Z0264E	"	1.473E-14	5.08	98.5	14.92 ± 0.10
	97Z0264F	"	2.262E-14	5.33	97.3	15.48 ± 0.09
	Means		2.283E-14	5.90	97.96	
					Wtd. Mean	15.09 ± 0.09
					MSWD	6.26
96TT151	97Z0265A	0.0037393	1.441E-14	1.63	90.3	15.15 ± 0.10
CXLIII-10	97Z0265B	"	7.263E-15	0.89	86.2	15.47 ± 0.13
Map location 6	97Z0265C	"	1.117E-14	1.21	90.5	14.95 ± 0.11
	97Z0265E	"	8.729E-15	1.41	91.1	14.99 ± 0.12
	97Z0265F	"	1.355E-14	1.23	97.0	15.07 ± 0.10
	Means		1.018E-14	1.19	91.19	
					Wtd. Mean	15.10 ± 0.08
					MSWD	2.80
96TT153	97Z0266A	0.0037352	1.288E-14	1.22	98.4	15.37 ± 0.10
CXLIII-11	97Z0266B	"	1.628E-14	0.90	98.6	15.33 ± 0.10
Map location 7	97Z0266C	"	1.802E-14	1.46	95.1	15.17 ± 0.10
	97Z0266D	"	2.007E-14	1.44	96.7	15.19 ± 0.09
	97Z0266E	"	1.214E-14	3.29	95.2	14.64 ± 0.10
	97Z0266F	"	3.294E-14	11.34	97.4	14.87 ± 0.09
	Means		1.989E-14	3.68	96.61	
					Wtd. Mean	15.09 ± 0.11
					MSWD	8.32

Table 2. Compilation of $^{40}Ar/^{39}Ar$ laser-fusion analyses of air-fall tuff units within the Carlin Formation, northern Nevada.

Location # (figure 1)	N Latitude	W Longitude	Sample #	Number of Analyses	J	Averages for Analyses $^{40}Ar^*$ (mol)	K/Ca	$^{40}Ar^*$ (%)	Wtd Mean Age (Ma)	MSWD
1	41° 05.182'	116° 27.545'	96TT129	5	0.0037795	7.414E-15	7.88	93.35	14.43 ± 0.08	1.925
	"	"	96TT130	6	0.0037761	5.365E-15	8.02	87.10	14.55 ± 0.20	8.625
	"	"	96TT131	5	0.0037728	1.281E-14	10.1 4	88.08	14.41 ± 0.04	0.185
2	41° 05.24'	116° 27.462'	96TT132	6	0.0037695	7.592E-15	6.05	93.67	14.48 ± 0.05	0.374
3	41° 05.28'	116° 27.652'	96TT133	5	0.0037624	9.627E-15	6.22	98.49	14.72 ± 0.05	0.241
	"	"	96TT134	6	0.0037587	9.080E-15	9.18	96.46	14.61 ± 0.10	5.582
4	41° 04.589'	116° 27.724'	96TT136	6	0.0037550	6.476E-15	1.78	97.65	14.93 ± 0.10	3.876
	"	"	96TT137	6	0.0037513	8.384E-15	1.94	93.46	14.97 ± 0.08	2.588
	"	"	96TT138	5	0.0037310	4.333E-14	5.83	97.75	14.84 ± 0.04	1.123
5	41° 04.957'	116° 27.426'	96TT139	5	0.0037434	2.283E-14	5.90	97.96	15.01 ± 0.07	2.656
6	41° 03.84'	116° 25.285'	96TT151	5	0.0037393	1.018E-14	1.18	91.19	15.10 ± 0.08	2.804
7	41° 03.923'	116° 25.385'	96TT153	6	0.0037352	1.989E-14	3.68	96.61	15.09 ± 0.11	8.321

error. The most probable form of geologic error in age determinations of air-fall tuff is contamination of the ash by accidental material incorporated during eruption or by detrital grains mixed into the ash during post-depositional reworking. The ages of these samples fall into 3 general groupings. Those from locations 1 and 2 (fig. 2) indicate an age of about 14.45 Ma. Samples from locations 4-7 with an age of about 15.0 Ma are statistically different from the first group, but in moderate agreement with each other. Samples from location 3 yield ages between the other two groupings, but sample 96TT134 has a high MSWD and 3 of the 6 analyses agree well with the 14.45 Ma group (tables 1 and 2). Consideration of the depositional environment of these types of deposits may explain some of the age variation.

As discussed briefly above, air-fall tuffs and ash may incorporate xenocrysts or xenoliths from older units as accidental materials from the volcanic edifice during eruption or as detrital material incorporated during reworking of the ash by wind or water. Contamination is common in pyroclastic materials (*see also:* Dalrymple and others, 1965; LoBello and others, 1987; Fleck and Carr, 1990) and represents the most probable cause of geologic error in their $^{40}Ar/^{39}Ar$ ages. Where the contaminating grains are from much older rocks, the contamination is easily recognized in laser-fusion $^{40}Ar/^{39}Ar$ ages because large age variations will be found between replicate measurements. Where contaminants are only slightly older than the ash, however, contamination may be difficult to identify unless single mineral grains can be analyzed. Because the Carlin Formation in the area of study is immediately underlain by the Craig Rhyolite containing alkali feldspar that has yielded an age of 15.03±0.05 Ma (W.E. Brooks, written commun., 1997), the potential for contamination of the water-laid ashes is considerable and the small age difference further complicates interpretation. This may be especially true in distal ashes, where small grain-size requires fusion of many grains to produce reliably measurable signals. Grain sizes of the alkali feldspar utilized in this study required between 8 and 12 grains for high-precision analyses.

As mentioned earlier, statistical parameters such as MSWD, must be utilized to measure the dispersion of age data compared to estimates of analytical error, as a means to identify contamination. Sample 96TT153 (loc. 7, table 1; fig. 2) is an example of potential contamination because the age range of 14.6 to 15.4 Ma is well outside analytical error, as reflected by the MSWD of 8.32 (table 1). Age results for samples 96TT130 and 134 (table 1) also exhibit scatter outside analytical error, but the external agreement between the mean ages lends some confidence to those results. Although these ages may be accurate, their lower than expected precision leaves them suspect.

To provide additional information on the possible presence of contamination, independent chemical parameters were evaluated using tephrochronologic techniques. Average major element compositions were obtained for 15 to 20 individual glass shards from each tuff sample using the electron microprobe (table 3). Results indicate a high degree of similarity between all samples except 96TT154, for which no age results are available. Samples from locations 1-3 are nearly identical, whereas the remaining ashes have somewhat greater dispersion. Comparison of Al_2O_3 and SiO_2 contents in the glass shards (approximately 12 and 76 weight percent, respectively) suggests that the eruptive center from which these tuffs were derived has a distinctly peralkaline character (table 3). Returning to table 2, K/Ca ratios for the alkali feldspars are calculated from amounts of Ca-derived ^{37}Ar and K-derived ^{39}Ar produced during irradiation and measured during $^{40}Ar/^{39}Ar$ analyses. The most important information from the K/Ca values is that the alkali feldspars are not high-K sanidines, which yield K/Ca ratios of 30 to 60, but are either Na-rich sanidine or anorthoclase with K/Ca of 1 to 10, typical of alkaline magmas. The K/Ca values also indicate strong similarity between samples from locations 1-3, which may be chemically distinct from locations 4-7. Because the ages of location 3 samples and their MSWD are elevated at the 95-percent level of confidence relative to chemically indistinguishable tuffs from locations 1 and 2, location 3 samples are probably contaminated by xenocrystic alkali feldspar, possibly from the Craig Rhyolite. The minimal scatter and low MSWD of measurements on 96TT133 question this interpretation, but results for 96TT134 and the chemical similarity to younger samples support it (table 2).

Differences in glass chemistry between locations 1-3 and 4-7 support an interpretation of a true difference in age. Location 4 is immediately above the base of the Carlin Formation where it rests directly on the Craig Rhyolite (fig. 2). Locations 2 and 3, however, are located north of the east-west-trending fault bounding a graben containing as much as 400 m of Carlin sedimentary fill. This large variation in thickness of the Carlin Formation is documented by drilling northwest of location 3, demonstrating that the older apparent ages at location 4 are consistent with the observed stratigraphy. If the age of the Craig Rhyolite is 15.03±0.05 Ma as reported (W.E. Brooks, written commun., 1997), the ages measured at locations 4-7 may be slightly contaminated, but this cannot be proven with available data. With the available age control, the best age estimates for the ash layers are about 14.4 and 15 Ma. Additional studies are underway to refine this chronology.

SOURCE OF AIR-FALL TUFFS OF THE CARLIN FORMATION

Age estimates of about 14.4 Ma to 15.1 Ma for air-fall tuffs of the Carlin Formation reported here permit a wide variety of potential source areas of silicic tuffs in northern Nevada, southeasternmost Oregon, and southwesternmost Idaho (Luedke and Smith, 1981; 1982; 1983; 1984). Volcanic rocks of the approximate age are abundant in the immediate area of study, such as the Snowstorm or Sheep Creek Mountains (fig. 2; Luedke and Smith, 1984), but major calderas have yet to be identified there. Volcanic centers that represent known sources of pyroclastic materials and for that reason are targets for additional, more detailed study include the McDermitt, Lake Owyhee, and the Owyhee Plateau volcanic fields. Ages of 16.1 to 15.0 Ma are reported by Rytuba and McKee (1984) for the major ash-flow tuffs of the McDermitt center. The tuff of Whitehorse Creek, from the Whitehorse caldera, the youngest of the McDermitt calderas, yielded an age of 15.0±0.3 Ma (Rytuba and McKee, 1984), similar to ages of the older group of Carlin tuffs. Rytuba and VanderMeulen (1991), however, report similar ages of 15.5 to 15.0 Ma for ash-flow tuffs of the Lake Owyhee volcanic field and ages from about 16 to 13.8 Ma are reported by Ekren and others (1984) for the older volcanic rocks of the Juniper Mountain volcanic center on the Owyhee Plateau, but younger ages are dominant to the east (fig. 1; Perkins and others, 1995).

Despite the limited chemical variation in volcanic glass of the tuffs of the Carlin Formation, correlation with other ashes and identification of their source requires study of the chemistry and age of more proximal ashes whose sources can be ascertained. Minor- and trace-element studies of the Carlin Formation air-fall tuffs are planned to extend coverage beyond the major element suite currently available. Current results permit some observations and interpretations, however. The low Mg and Ca contents of the glass and a paucity of mafic minerals in the tuffs are compatible with either peralkaline or subalkaline magmas. The low-K content of the alkali feldspars from the Carlin Formation tuffs is consistent with more alkalic sources rather than metaluminous sources. Total alkalies (Na_2O plus K_2O) and aluminum of glass shards of Carlin Formation tuffs indicate a generally subalkaline magmatic character (table 3), although the alkali contents in bedded ash layers may be subject to substantial diagenetic modification. The molecular $(Na_2O+K_2O)/Al_2O_3$ of the tuffs is quite constant at about 0.90, however, suggesting that alteration has not produced significant effects. Figure 5 shows the distribution of alkalies versus alumina for the glass of the Carlin tuffs compared to rhyolites of the McDermitt (Rytuba and McKee, 1984) and Juniper Mountain (Owyhee Plateau, Ekren and others, 1984) volcanic fields. Compositions of glass from both groups of Carlin Formation tuffs (locations 1-3 and 4-7) plot entirely within the subalkaline field, although not far inside the alkaline/subalkaline boundary (fig. 5). The peralkaline character of the McDermitt and Lake Owyhee volcanic fields, however, makes those areas less attractive as possible sources of the Carlin Formation tuffs, although a substantial number of the analyses from the McDermitt field are subalkaline (fig. 5). The Lake Owyhee field contains both peralkaline and metaluminous tuffs, according to Rytuba and VanderMeulen (1991). Analyses of rhyolites of the Juniper Mountain volcanic center (Ekren and others, 1984) group tightly with those of the Carlin tuffs (fig. 5), providing the best fit with available

Table 3. Electron-microprobe analyses of volcanic glass shards from tuffs of the Miocene Carlin Formation, northern Nevada.

Sample #	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	TiO_2	Na_2O	K_2O	Total(O)	Total(R)
96TT129	76.14	12.1	1.88	0.03	0.03	0.56	0.17	2.32	6.78	93.46	100.01
±s; n=20	0.51	0.13	0.09	0.01	0.03	0.03	0.04	0.14	0.17	0.52	
96TT130	76.17	12.06	1.91	0.04	0.03	0.58	0.14	2.29	6.78	93.69	100.00
±s: n=19	0.53	0.17	0.06	0.01	0.02	0.02	0.05	0.17	0.26	0.52	
96TT131	76.26	12.1	1.79	0.03	0.03	0.54	0.14	2.33	6.76	93.64	99.98
±s; n=18	0.4	0.17	0.08	0.01	0.03	0.03	0.04	0.12	0.17	0.49	
96TT132	76.06	12.08	1.88	0.04	0.03	0.57	0.17	2.27	6.91	93.53	100.01
±s; n=20	0.49	0.14	0.13	0.02	0.03	0.1	0.05	0.1	0.21	0.59	
96TT133	76	12.09	1.93	0.04	0.04	0.57	0.17	2.25	6.91	93.27	100.00
±s; n=19	0.34	0.12	0.09	0.01	0.03	0.03	0.04	0.12	0.19	0.46	
96TT134	76.36	12.08	1.81	0.03	0.03	0.55	0.16	2.26	6.72	93.42	100.00
±s; n=15	0.45	0.13	0.1	0.01	0.02	0.03	0.06	0.18	0.19	0.57	
96TT136	75.25	12.51	2.15	0.09	0.04	0.67	0.27	2.39	6.63	93.1	100.00
±s; n=19	0.54	0.22	0.12	0.02	0.02	0.05	0.05	0.21	0.25	0.55	
96TT137	75.5	12.40	2.03	0.08	0.04	0.62	0.24	2.30	6.78	93.04	99.99
±s; n=19	0.59	0.27	0.13	0.02	0.03	0.05	0.06	0.16	0.15	0.50	
96TT138	76.13	12.40	1.84	0.06	0.03	0.55	0.21	2.42	6.37	94.09	100.01
±s; n=20	0.61	0.20	0.14	0.02	0.02	0.05	0.04	0.21	0.16	0.47	
96TT139	76.30	12.20	1.78	0.06	0.03	0.53	0.22	2.28	6.61	94.19	100.01
±s; n=20	0.35	0.18	0.15	0.01	0.02	0.03	0.04	0.15	0.19	0.43	
96TT151	75.96	12.27	1.94	0.07	0.04	0.58	0.21	2.57	6.35	93.50	99.99
±s; n=18	0.83	0.24	0.17	0.02	0.04	0.07	0.04	0.21	0.36	0.63	
96TT153	75.65	12.62	2.04	0.08	0.03	0.61	0.26	2.60	6.11	93.53	100.00
±s; n=20	0.62	0.27	0.22	0.02	0.01	0.09	0.05	0.15	0.31	0.39	
96TT154	74.73	12.41	2.6	0.08	0.05	0.7	0.23	2.39	6.79	93.4	99.98
±s; n=15	0.55	0.15	0.18	0.01	0.03	0.05	0.05	0.17	0.24	0.4	

Shards were analyzed using the JEOL8900* instrument.

Standard deviation calculated from individual analyses of shards. Oxide values given are recalculated to a 100% fluid-free basis.

Total(O) - original total on analysis; Total (R) - total recalculated to a 100% fluid-free basis.

analyses. Silicic volcanic rocks of both the McDermitt and Juniper Mountain volcanic centers have low abundances of mafic minerals, but high Fe_2O_3 contents (McKee, 1976; Rytuba and McKee, 1984; Ekren and others, 1984). The mean Fe_2O_3 content of the glass shards of the Carlin tuffs of 1.99 percent is very high for rhyolite glasses at 76 percent SiO_2, such as those of the Owyhee Plateau region (Ekren and others, 1984), but slightly lower than the less silicic volcanic rocks of the McDermitt and Lake Owyhee fields. Based on the subalkaline character and range of ages extending to less than 14 Ma (Ekren and others, 1984), the Juniper Mountain tuffs of the Owyhee Plateau are a more favorable candidate as the source for the Carlin tuffs than the peralkaline centers of McDermitt and Lake Owyhee. The oldest ages reported in tables 1 and 2 for Carlin tuffs are compatible with a 15-Ma source such as the McDermitt or Lake Owyhee fields, but rhyolitic volcanism younger than 15 Ma is more common in the Juniper Mountain tuffs (Ekren and others, 1984). Attributing the tuffs studied here to any of these identified calderas, however, is tentative without better chemical and age studies of the tuffs. In addition to more detailed study of glass chemistry of the larger volcanic fields of McDermitt, Lake Owyhee, and Juniper Mountain, the chemistry of sources more local to the Carlin area, such as in the Snowstorm and Sheep Creek Mountains, also needs evaluation.

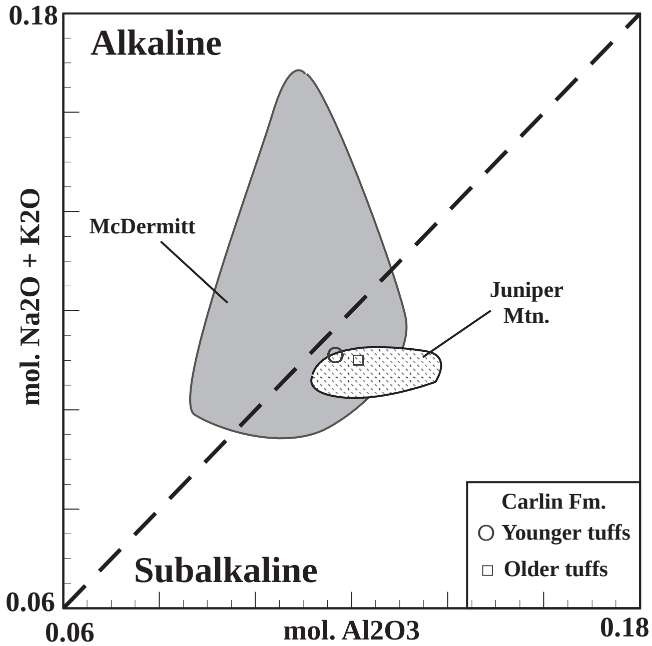


Figure 5. Al_2O_3 versus total alkalies diagram for glass shards from air-fall tuffs of the Miocene Carlin Formation, demonstrating the subalkaline character of these glasses. The younger group of tuffs of the Carlin Formation (locations 1-2 with an age of about 14.4 Ma) have slightly lower Al_2O_3 than the older group (locations 4-7 with ages between 14.8 and 15.1 Ma), but identical alkalies. Note the extremely-low compositional variation of the glass. Fields are shown for analyses reported by Rytuba and McKee (1984) for the McDermitt volcanic field and by Ekren and others (1984) for the Juniper Mountain volcanic field of the Owyhee Plateau. Both volcanic centers contain rocks of similar composition, but the Juniper Mountain field has a very restricted range of compositions, all within the field of subalkaline magmas.

DISCUSSION

North and east of Battle Mountain, Nev., the Carlin Formation post-dates 15- to 16-Ma volcanic rocks associated with the northern Nevada rift (NNR), an over 500-km long zone of north-northwest-trending dikes and lava flows that extends from near the Nevada-Oregon border to southeastern Nevada (Zoback and Thompson, 1978; McKee and Noble, 1986; Blakely and Jachens, 1991; Zoback and others, 1994). The NNR is well defined by both gravity and aeromagnetic anomalies and modeled as a swarm of near vertical mafic dikes (Philbin and others, 1963; Mabey, 1966; Zoback and Thompson, 1978; Blakely and Jachens, 1991). Basaltic flows and dikes, marking the surface expression of the rift between the Roberts Mountains in the south to Midas, Nev. in the north, yield ages between 18.6 and 13.6 Ma with the majority between 17 and 14 Ma (Zoback and others, 1994). North of Midas, rhyolite dikes, flows, and domes belonging to two sequences of silicic volcanic rocks are present along the NNR (Wallace, 1993). The older group is interbedded and approximately coeval with basalts and basaltic andesite flows associated with the rift (Zoback and Thompson, 1978; Wallace, 1993; Zoback and others, 1994). Synchronous with magmatism along the NNR, eruption of the bulk of the voluminous flood basalts of the Columbia Plateau occurred between 16 and 15 Ma from north-northwest-trending feeder dikes aligned generally along the trend of the NNR (Bottomley and York, 1976; Pierce and Morgan, 1992; Zoback and others, 1994). Midway between the Columbia Plateau and the southern end of the NNR, the McDermitt and Owyhee volcanic centers are identified with the initial position of the Yellowstone hotspot (Pierce and Morgan, 1992; Zoback and others 1994). The Lake Owyhee volcanic field is 100-150 km north of the McDermitt volcanic field and the track of the Yellowstone hotspot. The spatial and temporal trace of the hotspot along the eastern Snake River Plain has been studied by numerous authors, who document the progress of volcanism, faulting, and crescent-shaped uplift from the McDermitt-Owyhee area at about 16 Ma to its present position at the Yellowstone Plateau (Armstrong and others, 1975; Pierce and Morgan, 1992; Anders and Sleep, 1992; Zoback and others, 1994; Perkins and others, 1995). These authors provide persuasive evidence of a common origin for the northern Nevada rift, the flood basalts of the Columbia Plateau, and the silicic and basaltic volcanism at the McDermitt and Owyhee volcanic centers as resulting from the interaction of the head of a mantle plume with the base of the lithosphere at about 16 Ma. Pierce and Morgan (1992) and Zoback and others (1994) present a model of rift formation north-northwest and south-southeast of the McDermitt volcanic center as the rift propagated rapidly away from the plume head normal to the direction of plate motion. That west-southwest motion of the North American plate corresponds precisely with the N70-75°E orientation of the hotspot track between 16 and 10 Ma (Pierce and Morgan, 1992). Based on the 14.4- to 15.1-Ma ages obtained from the tuffs of the Carlin Formation in the Santa Renia Fields quadrangle, an Owyhee Plateau source would be most consistent with the timing and location determined for the hotspot during that period. Although the hotspot model presents an internally consistent argument for the location of a currently-unknown source region for the tuffs, we recognize that the actual source might be either more distant, as in the volcanic centers of the western Snake River plain (e.g. McKee and Noble, 1986; Rytuba and VanderMeulen, 1991) or more local, related to volcanism responsible for the many silicic volcanic units of the northern Nevada area (e.g., McKee and others, 1974; Wallace and others, 1990).

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