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TIMING OF TERTIARY EXTENSION IN THE RAILROAD VALLEY-PIOCHE TRANSECT, NEVADA: CONSTRAINTS FROM $^{40}Ar/^{39}Ar$ AGES OF VOLCANIC ROCKS

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Abstract. Time-space relations of extension and volcanism place critical constraints on models of Basin and Range extensional processes. This paper addresses such relations in a 130-km-wide transect in the eastern Great Basin, bounded on the east by the Ely Springs Range and on the west by the Grant and Quinn Canyon ranges. Stratigraphic and structural data, combined with $^{40}Ar/^{39}Ar$ isotopic ages of volcanic rocks, document a protracted but distinctly episodic extensional history. Field relations indicate four periods of faulting. Only one of these periods was synchronous with nearby volcanic activity, which implies that volcanism and faulting need not be associated closely in space and time. Based on published dates and the analyses reported here, the periods of extension were (1) prevolcanic (pre-32 Ma), (2) early synvolcanic (30 to 27 Ma), (3) immediately postvolcanic (about 16 to 14 Ma), and (4) Pliocene to Quaternary. The break between the second and third periods is distinct. The minimum gap between the first two periods is 2 Ma, but the separation may be much larger. Temporal separation of the last two periods is only suggested by the stratigraphic record and cannot be rigorously demonstrated with present data. The three younger periods of faulting apparently occurred across the entire transect. The oldest period is recognized only at the eastern end of the transect, but appears to correlate about 150 km northward along strike with extension in the Northern Snake Range-Kern Mountains area. Therefore the oldest period also is regional in extent, but affected a different area than that affected by younger periods. This relation suggests that distinct extensional structures and master detachment faults were active at different times. The correlation of deformation periods of a few million years duration across the Railroad Valley-Pioche transect suggests that the scale of active extensional domains in the Great Basin may be greater than 100 km across strike.

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Introduction

Timing relations of deformation and magmatism are among the most powerful tests of tectonic models. In the Tertiary evolution of the Great Basin of the western United States, fundamental questions regarding timing of tectonic processes include whether tectonic extension and magmatism occurred coevally, and whether deformation was episodic or occurred gradually as a temporal continuum. In this study we address these questions within a 130 km wide transect in the eastern Great Basin, combining detailed stratigraphic and structural field data with $^{40}Ar/^{39}Ar$ isotopic ages of Tertiary volcanic rocks in critical contact relations.

In this paper, we address the patterns of extension-related magmatism in part of the Great Basin by looking at volcanism, because the plutonic parts of the systems are rarely exposed. We assume that the patterns of volcanism give a reasonable first-order image of major crustal magmatic events.

The study area, which we call the Railroad Valley-Pioche transect (see Figure 1 for location), was chosen because it offers important stratigraphic relations in the Great Basin for determining time-space relations of Tertiary faulting and volcanism. Early work by Cook [1965] showed that, in this transect, Oligocene ash flow tuffs present mainly north of the transect are overlapped by Miocene tuffs that are thicker south of the transect. Therefore this transect exposes a long Tertiary stratigraphic record. Based on older work and this study, this record extends from roughly 32 to 15 Ma. The small age range of the rocks of interest and the scatter of existing conventional K/Ar dates indicated that more precise dates were needed to resolve the relative ages of rocks that do not occur in stratigraphic contact in the field. The $^{40}Ar/^{39}Ar$ incremental-release method has rarely been used to date young volcanic rocks, but was chosen for this study because it permits better accuracy and analytical precision than the K/Ar method. Data for all $^{40}Ar/^{39}Ar$ analyses are shown in Table 1.

In this paper, we distinguish local "episodes" of faulting, in which a particular fault or group of faults is found in a specific

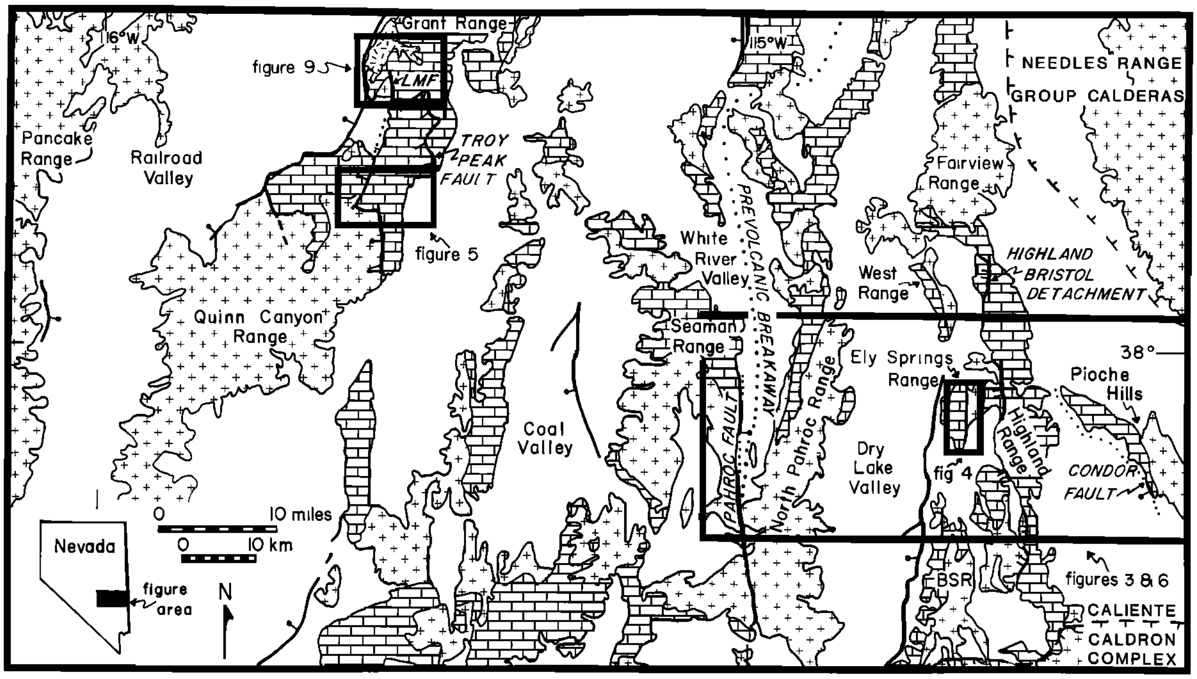

Fig. 1. Location map of the studied transect with features mentioned in the text. Paleozoic rocks shown by block pattern. Mesozoic stock shown by random dashes. Tertiary rocks undivided shown by plus pattern. Pliocene to Quaternary rocks shown by no pattern. BSR represents Burnt Springs Range. LMF represents the Little Meadows fault. Locations of Figures 3, 4, 5, 6, and 9 are shown.

time-bracketing relation at a specific locality, from regional "periods" of faulting, in which extensional faults, over a period of at most a few million years, were active across an area encompassing several mountain ranges (i.e., thousands of square kilometers). Each period of faulting is distinguished by recognition of one or more faulting episodes that are closely related in time.

Regional Geology

Recent Work

Recent field work in the Railroad Valley-Pioche transect has focused near its ends, around Dry Lake Valley on the east and in the Quinn Canyon and southern Grant Ranges on the west. Earlier work on the Tertiary of the Dry Lake Valley area was by Tschanz and Pampeyan [1970] and Ekren et al. [1977]. Recent detailed mapping by Axen [1986] in the Ely Springs Range and Taylor [1989] in the North Pahroc Range has significantly improved understanding of both stratigraphy and structure of Tertiary rocks in this area. These results demonstrate that extension began before the mid-Oligocene and continued episodically until the Quaternary [Axen, 1986; Taylor and Bartley, 1986; Taylor, 1989]. The isotopic ages presented below place constraints on the timing of these episodes.

Early work on the structure and stratigraphy in the Quinn Canyon Range and southern Grant Range was by Sainsbury and Kleinhampl [1969] and Cebull [1970] and was recently summarized by Kleinhampl and Ziony [1985]. However, these authors concentrated on evidence for Mesozoic compression recorded in these ranges and tended to minimize the importance of Tertiary extension [Fryxell, 1984; Bartley et al., 1985, 1987]. The latter has been mitigated by recent work of Fryxell [1984, 1988], Bartley et al. [1988], and Gleason [1988], which suggests an episodic extensional history from Oligocene to Recent. Stratigraphic constraints on timing at the west end of the transect are not as tight as in the Dry Lake Valley area.

Stratigraphy

Understanding of map-scale structures depends upon knowledge of stratigraphy. Dacitic to rhyolitic ash flow tuffs are the predominant mid-Tertiary rocks of much of the Basin and Range Province of the western United States [Cook, 1965; Lipman et al., 1972]. Commonly, different ash flow tuffs are petrographically quite similar, and their distinction in the field requires detailed knowledge of phenocryst modes, distinctive phenocryst characteristics such as crystal habit or color (e.g., smoky quartz or amethyst), and relative sizes of phenocrysts, as well as the nature of pumice inclusions, type(s) of lithic fragments present, and vertical zonal variations. For example, large crystal-rich dacitic ash flow tuffs of Oligocene age, including the Monotony Tuff [Ekren et al., 1971] and the Needles Range Group (Cottonwood Wash Tuff, Wah Wah Springs Formation, and Lund Formation [Best and Keith, 1983]) are closely similar and widely known to be easily confused. In this regard, it is worth noting that the tripartite division of Needles Range Group dacites by Best and Keith [1983], mainly using hand-specimen phenocryst observations, is strongly supported by our

TABLE 1.

Temperature, °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	Cummulative ^{39}Ar, (%)	Age, Ma
QC5-10B, Shingle Pass Tuff, t_p=26.2 +/- 0.5 Ma, J=0.004631					
600	125.2302	0.0822	0.4166	0.4	17.40 +/- 10.19
700	24.1672	0.03724	0.07104	1.4	26.04 +/- 7.68
800	8.8792	0.0118	0.01919	4.5	26.30 +/- 1.18
850	5.6074	0.006943	0.008002	9.8	26.57 +/- 0.73
900	5.6282	0.005413	0.00827	16.6	26.09 +/- 0.68
950	5.0049	0.00727	0.006109	25.4	26.22 +/- 0.43
1025	4.2171	0.01529	0.003484	46.1	26.12 +/- 0.37
1100	4.025	0.01371	0.002845	75.9	26.10 +/- 0.27
FUSE	4.1126	0.02578	0.00307	100.1	26.28 +/- 0.29
QC5-10S, Shingle Pass Tuff, t_p=26.2 +/- 0.5 Ma, J=0.004545					
600	100.9109	0.03155995	0.3298981	0.8	27.58 +/- 5.83
825	4.8371	0.01232	0.0056577	6.7	25.46 +/- 0.58
888	4.2012	0.009528	0.0032581	13.0	26.05 +/- 0.51
950	3.898701	0.008171	0.001999	21.5	26.61 +/- 0.83
1000	3.9606	0.007917	0.002446	31.7	26.04 +/- 0.56
1050	3.6873	0.007633	0.001431	44.6	26.26 +/- 0.32
1100	3.9348	0.007463	0.002266	61.5	26.27 +/- 0.34
1130	3.6352	0.007512	0.001287	84.0	26.18 +/- 0.28
FUSE	3.665	0.007646	0.001342	99.9	26.29 +/- 0.28
4.139-658H, unnamed tuff, t_p=29.6 +/- 1.2 Ma, J=0.005816					
750	118.96	0.5359	0.3933	1.2	28.58 +/- 19.03
825	61.95	0.858	0.1829	2.2	81.43 +/- 20.35
865	163.2	1.611	0.5407	2.5	36.55 +/- 194.47
935	42.33	4.046	0.1263	4.0	54.92 +/- 16.02
1000	7.807	5.134	0.01815	17.8	29.48 +/- 0.42
1025	6.647	5.323	0.01407	35.3	30.12 +/- 1.24
1050	4.342	5.688	0.00670	90.9	29.10 +/- 0.36
1100	7.198	0.687	0.01456	98.9	34.64 +/- 2.07
FUSE	42.05	5.716	0.1142	100.1	89.72 +/- 34.42
4.139-658B, unnamed tuff, t_p=31.3 +/- 1.0 Ma, J=0.005745					
500	17.55	0.02422	0.05410	6.3	15.78 +/- 1.11
600	8.52	0.01895	0.02123	19.7	22.70 +/- 0.28
700	6.72	0.01916	0.01357	32.9	27.48 +/- 0.48
800	6.10	0.02179	0.01059	43.5	30.11 +/- 1.01
850	6.40	0.03187	0.01117	50.0	31.48 +/- 1.64
900	5.75	0.04134	0.00907	55.5	31.17 +/- 0.48
950	5.23	0.04910	0.00730	69.7	31.25 +/- 0.43
1025	5.45	0.08205	0.00778	76.8	31.98 +/- 0.74
FUSE	5.13	0.18490	0.00713	99.9	30.83 +/- 0.39
4-109-2B, t_p=31.3 +/- 0.4 Ma, J=0.005167					
600	32.7763	0.01877	0.1013	4.2	25.96 +/- 0.97
700	14.9484	0.01122	0.0394	7.6	30.20 +/- 0.72
800	7.4946	0.006165	0.01384	11.5	31.11 +/- 1.75
850	6.2207	0.003676	0.009117	17.5	32.22 +/- 0.42
900	5.1257	0.003721	0.005479	28.2	32.04 +/- 0.78
950	4.3865	0.005499	0.003318	42.0	31.12 +/- 0.57
1025	4.3491	0.008096	0.003107	62.8	31.35 +/- 0.35
1100	4.1211	0.01044	0.002349	86.8	31.32 +/- 0.34
FUSE	4.7915	0.01176	0.004569	100.1	31.45 +/- 0.49

TABLE 1. (Continued)

Temperature, °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	Cummulative ^{39}Ar, (%)	Age, Ma
5-95-1B, t_p=15.3 +/- 0.2 Ma, J=0.0067					
500	84.6313	0.04183	0.274	0.7	43.34 +/- 6.23
600	12.2956	0.02574	0.03176	1.9	34.40 +/- 6.47
700	4.5243	0.007853001	0.01032	6.8	17.28 +/- 0.77
800	3.3593	0.006662	0.006647	12.6	16.32 +/- 0.30
850	3.5939	0.006977	0.007515	17.9	16.06 +/- 0.30
900	3.3111	0.007844	0.006687	23.5	15.61 +/- 0.37
950	2.3558	0.01704	0.003551	32.5	15.27 +/- 0.38
1025	1.735	0.03796	0.001444	58.3	15.31 +/- 0.17
1100	1.63	0.03264	0.001114	89.2	15.22 +/- 0.18
FUSE	2.3399	0.05645	0.00347	100.1	15.41 +/- 0.23
4.143-697P, tuff of Hamilton Spring, t_p=27.4 +/- 2.5 Ma, J=0.005788					
600	39.069	2.908	0.118	1.6	45.44 +/- 24.33
650	5.579	3.286	0.011	10.2	26.56 +/- 1.60
880	5.475	3.367	0.0104	19.3	27.39 +/- 1.61
950	5.086	3.362	0.0087	30.3	28.55 +/- 0.97
1000	5.333	3.3356	0.01026	41.0	26.32 +/- 3.29
1050	8.513	3.349	0.021	51.5	26.40 +/- 0.76
1100	6.196	3.347	0.01265	63.1	27.95 +/- 1.54
1130	5.669	3.307	0.00106	72.5	28.73 +/- 2.32
2500	4.703	3.342	0.0071	99.9	29.46 +/- 0.90
QCR-5-84B, t_p=27.3 +/- 0.4 Ma, J=0.00526					
500	43.3917	0.03576	0.1401	0.7	18.47 +/- 4.69
600	35.7725	0.0387	0.1125	1.5	23.50 +/- 4.44
700	8.5539	0.01418	0.019197	4.3	26.78 +/- 1.08
800	5.115	0.008395001	0.007257	11.8	27.61 +/- 0.46
850	4.2175	0.006266	0.00415	21.3	27.80 +/- 0.30
950	3.8882	0.009831	0.00319	34.7	27.38 +/- 0.43
1025	3.8114	0.01694	0.00294	47.5	27.36 +/- 0.29
1100	3.6844	0.01627	0.002603	74.8	27.10 +/- 0.30
FUSE	3.8641	0.0111	0.0031299	100.0	27.32 +/- 0.34
QC-33.1B, Windous Butte Formation, t_p=32.2 +/- 0.4 Ma, J=0.004233					
600	31.9076	0.01265	0.0968	3.3	24.76 +/- 2.79
800	8.238401	0.004442	0.01329	17.0	32.34 +/- 0.99
900	6.5609	0.004751	0.007728	35.3	32.08 +/- 0.83
1025	5.836	0.009460001	0.005163	73.4	32.33 +/- 0.36
1100	6.6702	0.02159	0.008066	96.0	32.16 +/- 0.36
FUSE	12.6699	0.05099	0.02766	100.0	33.75 +/- 2.57
QC=33.1S, Windous Butte Formation, t_p=31.2 +/- 0.6 Ma, J=0.005169					
600	27.60065	0.0309	0.08382	0.4	25.88 +/- 7.82
825	5.3891	0.01471	0.006735	3.1	31.07 +/- 2.05
898	4.9133	0.009600001	0.004916	6.4	31.64 +/- 1.18
950	5.074	0.008067	0.005577	10.8	31.32 +/- 0.99
1000	4.4182	0.007101	0.003409	16.7	31.18 +/- 0.76
1050	3.7816	0.006196	0.001317	24.8	31.01 +/- 0.36
1100	3.7568	0.006207	0.00124	35.4	30.99 +/- 0.35
1130	3.655	0.005705	0.0008025	51.4	31.24 +/- 0.39
FUSE	3.5273	0.005747	0.0005703	100.0	30.70 +/- 0.35

TABLE 1. (Continued)

Temperature, °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	Cummulative ^{39}Ar, (%)	Age, Ma
		68.9-83B, t_g=14.2 Ma, J=0.005708			
500	8.5	0.024	0.027	6.6	4.98 +/- 0.96
600	5.405	0.018	0.015	11.0	9.60 +/- 0.87
700	3.735	0.0181	0.008	18.4	13.68 +/- 0.29
800	2.698	0.0145	0.004	30.9	15.16 +/- 0.41
850	2.308	0.012	0.003	49.0	14.19 +/- 0.21
900	2.371	0.017	0.003	64.6	14.84 +/- 0.22
950	2.658	0.023	0.004	75.0	14.76 +/- 0.66
1025	2.527	0.044	0.003	87.4	16.45 +/- 0.20
FUSE	2.503	0.204	0.003	100.2	16.34 +/- 0.28
		5-4-83B, t_p=27.8 +/- 0.4 Ma, J=0.005765			
500	11.2195	0.0227	0.0312	8.9	20.30 +/- 0.28
600	7.836	0.0181	0.01797	14.9	25.70 +/- 1.50
700	6.06	0.0135	0.0113	20.7	27.69 +/- 1.90
800	4.727	0.0127	0.0067	29.4	27.96 +/- 0.50
850	4.281	0.0142	0.0052	38.0	27.93 +/- 0.67
900	4.83	0.02	0.00708	45.2	27.87 +/- 0.36
950	4.546	0.0251	0.00612	54.4	27.87 +/- 0.55
1025	4.519	0.0322	0.00609	67.9	27.69 +/- 0.36
1500	3.663	0.0476	0.00324	100.0	27.56 +/- 0.32
		3.144-527B, Monotony Tuff, t_p=27.1 +/- 0.6 Ma, J=0.006665			
500	50.188	0.05117	0.1633	0.8	22.68 +/- 7.85
600	29.2149	0.05095	0.0917	1.5	24.87 +/- 6.07
700	8.3635	0.0209	0.02099	4.2	25.36 +/- 3.78
800	3.9459	0.01358	0.005732	8.8	26.43 +/- 0.53
850	3.2301	0.008641	0.00307	14.7	27.26 +/- 0.69
900	3.5779	0.006422	0.004238	24.1	27.29 +/- 0.58
950	3.2199	0.006084	0.003164	38.1	26.81 +/- 0.34
1025	3.6487	0.010296	0.004594	52.1	26.89 +/- 0.53
1100	3.3094	0.01239	0.003407	74.9	27.03 +/- 0.28
FUSE	3.5184	0.01401	0.004039	100.1	27.29 +/- 0.29
		3.144-527H, Monotony Tuff, t_p=26.7 +/- 0.3 Ma, J=.006753			
875	85.04901	1.594	0.2779	1.3	36.47 +/- 27.11
925	26.5497	3.706	0.08	3.5	38.34 +/- 7.28
963	6.219	4.606	0.0136	9.5	30.73 +/- 9.77
1000	3.63	4.842	0.00601	57.0	26.80 +/- 0.51
1012	4.649	4.842	0.0095	82.3	26.66 +/- 1.69
1025	6.781	4.8095	0.0161	90.3	28.81 +/- 7.94
1038	11.573	4.722	0.03	91.9	36.94 +/- 14.56
1050	29.755	4.767	0.089	92.6	45.92 +/- 32.91
1100	62.086	4.842	0.202	95.2	33.31 +/- 22.50
1500	17.606	4.944	0.0499	100.0	38.99 +/- 12.11
		4.139-662B, Hiko Tuff, t_p=18.5 +/- 0.4 Ma, J=0.00512			
600	99.2564	0.882464	0.3293	0.6	18.22 +/- 4.93
700	26.18128	0.2262338	0.0811	1.0	20.09 +/- 8.57
800	21.7734	0.04967316	0.0675	1.8	16.48 +/- 2.28
850	10.08035	0.03486369	0.0255	3.3	22.92 +/- 1.32
900	4.720517	0.02642442	0.0089	7.3	18.81 +/- 1.37
950	3.83705	0.02115643	0.0061	17.3	18.29 +/- 0.41
1025	2.835087	0.02612195	0.0026	38.4	18.54 +/- 0.19
1100	2.572538	0.02864528	0.0017	76.5	18.46 +/- 0.20
FUSE	2.843541	0.04332928	0.0026	99.9	18.63 +/- 0.21

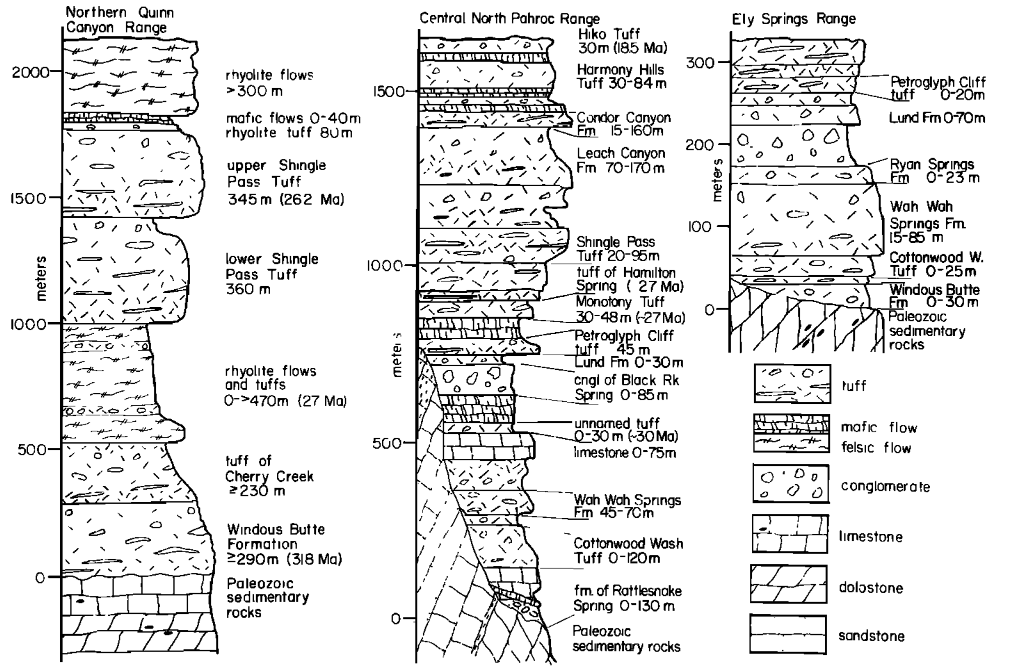

Fig. 2. Generalized and simplified composite stratigraphic columns of Tertiary units in the Ely Springs Range area, North Pahroc Range, and the Grant and Quinn Canyon ranges. Note scale changes between columns.

mapping of Needles Range Group outflow sheets throughout the Dry Lake Valley area. We adopt Best's [1986] nomenclature and ages for these units.

Detailed descriptions therefore are needed for consistently correct identification. Many of the recommendations of Hildreth and Mahood [1985] were used in discriminating and correlating tuffs in this study. Petrographic descriptions, modes, and precise sample locations may be obtained from the authors.

Because of the limited lateral extent of some individual volcanic units, the exact sequence of Tertiary volcanic rocks varies across the transect. Tertiary stratigraphic columns from the Ely Springs Range, North Pahroc Range, and Quinn Canyon Range are shown in Figure 2. The columns have been simplified and generalized but show the relative stratigraphic positions of the volcanic units. There is a general trend in all columns, passing from Oligocene to Miocene rocks, from intermediate composition ash flow tuffs toward a broadly bimodal assemblage of rhyolitic tuffs and subordinate mafic to intermediate lava flows [cf. Christiansen and Lipman, 1971; Taylor and Bartley, 1986]. However, the transition, to the extent that it can be recognized, is gradual. Further, as is discussed below, this transition does not coincide with the onset of any phase of extension.

The vents from which the major volcanic units were derived lie at the edges of the transect (Figure 1). The multiple calderas from which the Needles Range Group was erupted lie directly to the northeast [Best and Grant, 1987]. Major caldrons in the Pancake and Quinn Canyon ranges, the boundaries of which are poorly constrained, were the sources of the Windous Butte Formation and the Monotony and Shingle Pass tuffs [Sargent and Hauser, 1970; Ekren et al., 1971, 1974]. The Caliente Caldron Complex, located at the southeast corner of the transect, was the source of several early Miocene ash flow tuffs [Ekren et al., 1977]. Our field study has dealt mainly with outflow sheets of ash flow tuffs, which provide by far the best stratigraphic and structural markers in the Tertiary stratigraphic section. The paucity of vents within the transect implies that most structures can be assumed to be of tectonic origin and not related to volcanic vents. However, the geographic proximity of the volcanic centers to the transect and the regional extent of the extensional periods documented here imply that the volcanic and structural events we report record the Tertiary history of the same crustal region.

Ages of Structures

The principal objective of this study was to constrain the timing of Tertiary deformation in the Railroad Valley-Pioche transect. For this reason, geochronological data are presented and discussed below in the context of the periods of deformation defined by field data. Extensional episodes in the transect can be grouped into four periods: prevolcanic (> 32 Ma), early synvolcanic (30 to 27 Ma), immediately postvolcanic (about 16 to 14 Ma), and Quaternary. Normal faults of the last three periods occur throughout the transect; however, the precise age of fault episodes within each period of faulting is not necessarily the same across the entire transect.

Prevolcanic Faulting

Prevolcanic normal faults were mapped in the Ely Springs Range (Figure 3) [Axen, 1986] and probably are present in the North Pahroc Range

[Taylor, 1988]. Faulting of this age in the North Pahroc Range also is suggested by Tertiary conglomerates and lacustrine limestones that were deposited at the base of the Tertiary section in a major paleotopographic low [Taylor and Bartley, 1988; Bartley et al., 1988]. Further, cross-section reconstructions require prevolcanic normal offsets and rotations within the Devonian to Permian section [Taylor, 1989]. Based on our reconnaissance and on mapping by Langenheim et al. [1969, 1971], prevolcanic normal faults in Paleozoic rocks also occur north and south of the Ely Springs Range in the Fairview Range, West Range, and probably in the Burnt Springs Range (see Figure 1 for locations). Major prevolcanic normal faults have not been identified in the part of the Seaman Range mapped during this study or farther west in the transect.

Sub-Tertiary Unconformity

Characteristics of the unconformity between Tertiary and Paleozoic rocks constrain prevolcanic deformation. In the Dry Lake Valley area, rocks ranging in age from Silurian to Permian underlie the unconformity, with an angular discordance ranging up to 60°. Westward, progressively younger units are preserved beneath the unconformity. However, across White River Valley in the Seaman Range, the unconformity is low angle and developed on Mississippian and uppermost Devonian rocks with at least 300 m of topographic relief buried beneath the Tertiary section. The area of pronounced discordance at the sub-Tertiary unconformity coincides with the area of prevolcanic extension (Figure 3). We therefore attribute the pronounced angular discordance across the unconformity in the Dry Lake Valley area to prevolcanic extensional rotation. The absence of Pennsylvanian and Permian rocks, absence of prevolcanic Tertiary sedimentary units, relatively thin volcanic units at the base of the Tertiary section, and the deeply incised prevolcanic paleotopography in the Seaman Range suggest this Seaman Range block was uplifted and eroded adjacent to the extended area.

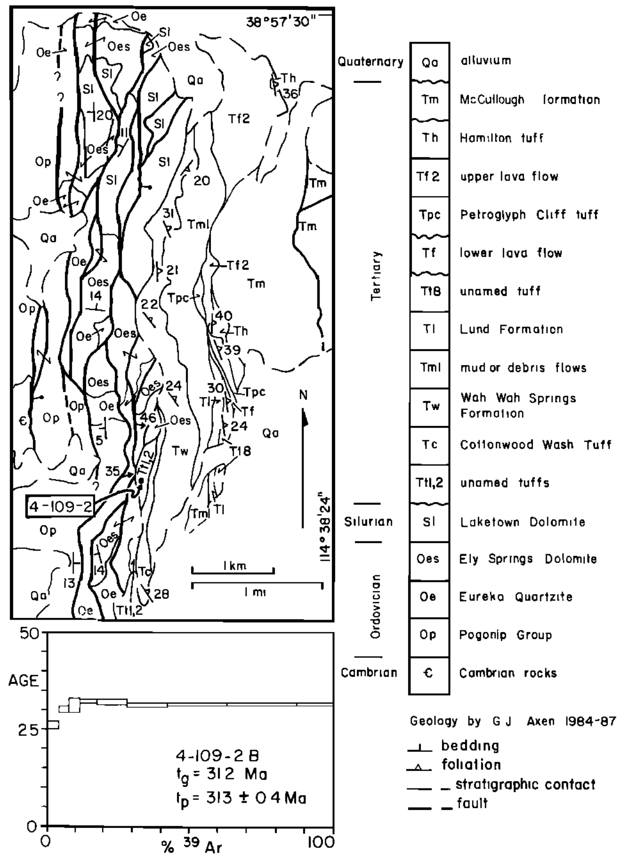

Fig. 4. Simplified geologic map of the Ely Springs Range [Axen, 1986 and unpublished mapping, 1987]. $^{40}Ar/^{39}Ar$ spectra and sample locations are shown for oldest volcanic rock (4-109-2) in Ely Springs Range. The unit Tt1,2 may include the Windous Butte Formation.

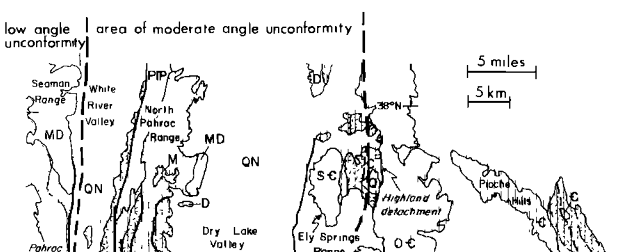

Fig. 3. Known areal distribution of prevolcanic extension underlies ruled pattern. Area of pronounced angular discordance (>30°) between Tertiary and Paleozoic units shown in middle of map. Area of small angular discordance (<20°) between Tertiary and Paleozoic rocks lies in western end of map. Note the areal coincidence of the pronounced angular unconformity and prevolcanic faulting. Base map is the same as in Figure 6. Standard letter abbreviations used for Paleozoic units. QN (Quaternary-Neogene) is used for Quaternary and Pliocene units. Stipple pattern on 31 to 27 Ma units. Random dashes on 27 to 14 Ma units.

Paleozoic rocks in the North Pahroc and Seaman ranges are overlain by clastic and volcanic units ranging in age from 30.6 to about 27 Ma (Figure 3). These volcanic units include the Cottonwood Wash Tuff and Wah Wah Springs Formation of the Needles Range Group [Best et al., 1973] and some of the Pahroc sequence units [Cook, 1965; Taylor, 1989]. The 29.5 Ma Wah Wah Springs Formation [Best and Grant, 1987] overlies the areally largest part of the unconformity in this vicinity.

The sub-Tertiary unconformity is not as widely exposed at the western end of the transect, but the base of the Tertiary section is exposed, deposited upon Ordovician rocks, in the northern Quinn Canyon Range [Murray, 1985; Bartley et al., 1985]. Structural elevation of Ordovician rocks along a Mesozoic thrust appears to be responsible for the sub-Tertiary unconformity cutting so deeply into the Paleozoic section here [Bartley et al., 1985]. The effects of both Mesozoic thrusting and prevolcanic extension resulted in considerable stratigraphic relief beneath the sub-Tertiary

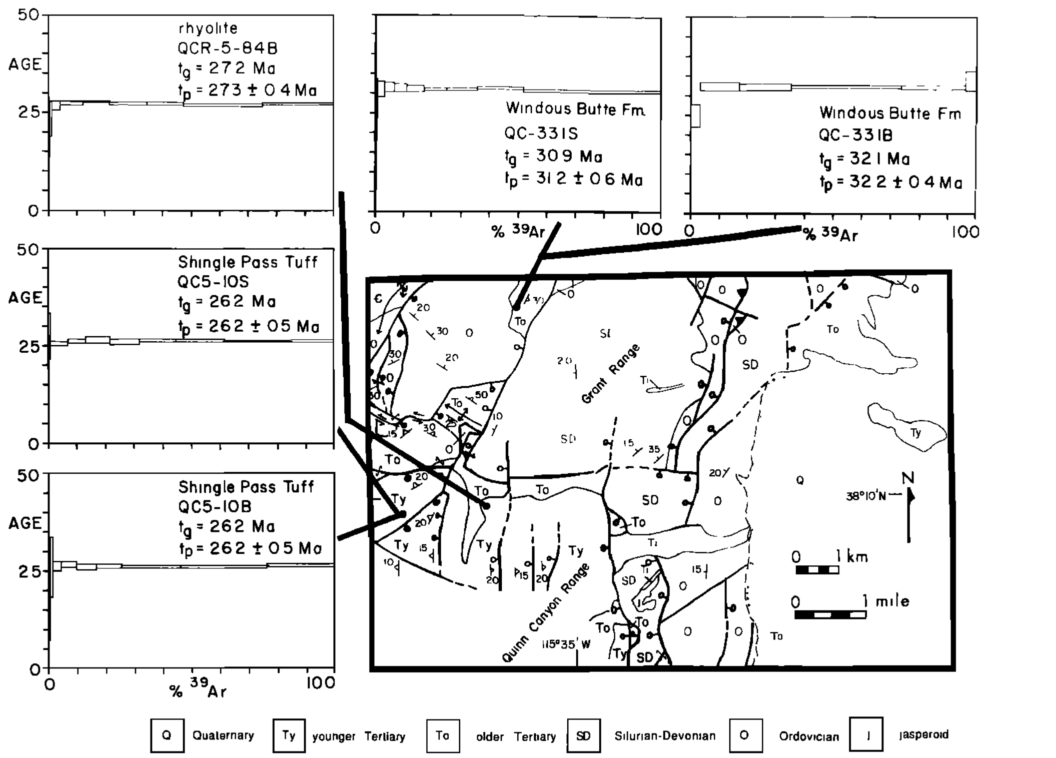

Fig. 5. Sample locations in the Quinn Canyon Range and $^{40}Ar/^{39}Ar$ spectra for the Windous Butte Formation, Shingle Pass Tuff, and a rhyolite. The geology is from Bartley and Gleason [1989].

unconformity in this transect, in contrast to farther north in Nevada [Armstrong, 1972; Gans and Miller, 1983].

Three new $^{40}Ar/^{39}Ar$ ages (Figures 2 and 4), in conjunction with K/Ar ages (recalculated with 1977 constants where appropriate) from Armstrong [1970] and Best and Grant [1987], indicate that the oldest volcanic rocks above the unconformity throughout the transect were erupted between 31 and 32.5 Ma. In the Ely Springs Range, an unnamed tuff (Figure 4) that directly overlies faulted Paleozoic rocks yielded a biotite plateau age of 31.3 +/- 0.4 Ma. This age is stratigraphically consistent, in that the tuff lies below the Cottonwood Wash Tuff, to which Best and Grant [1987] assigned an age of 30.6 Ma.

In the Quinn Canyon Range, the Windous Butte Formation unconformably overlies Ordovician rocks (Figure 2) [Murray, 1985]. Samples of the vitrophyre of the lower ignimbrite of the Windous Butte Formation yielded plateau ages of 32.2 +/- 0.4 Ma (biotite) and 31.2 +/- 0.6 Ma (sanidine) (Figure 5). The error ranges of these ages barely overlap at 31.8 Ma, which is our best estimate of the age of the Windous Butte Formation. This age agrees well with previous K/Ar ages from the Windous Butte Formation (corrected to International Union of Geological Sciences (IUGS) constants) of 31.4 +/- 0.6 on sanidine, 31.0 +/- 0.6 on a 97% biotite separate [Armstrong, 1970], 31.1 on sanidine (average of five dates), and 32.0 on biotite (average of four dates [Gromme et al., 1972]) .

Early Synvolcanic Faulting

Dry Lake Valley Area

Minor faulting occurred during activity in the Needles Range Group calderas at the eastern end of the transect. The best exposures of synvolcanic faults are in the North Pahroc Range where two temporally distinct fault sets are defined by field relations (Figure 6) [Bartley et al., 1988]. These fault sets probably represent two episodes of movement within one fault system, because they have similar trends and are quite close in age. Both fault sets appear to have small, mainly dip-slip offsets. The younger fault set is truncated by a low-angle unconformity (about 10^{o} of discordance). This surface was eroded and cut by channels, so that it is quite irregular and units deposited upon it are laterally discontinuous.

The first set of faults formed in this period offset a tuff that is only locally present in the North Pahroc Range. $^{40}Ar/^{39}Ar$ incremental-release spectra were determined on both hornblende and biotite separates from this tuff (Figure 7). The biotite spectrum includes a statistical plateau of 31.3 +/- 1.0 Ma but indicates that the biotite Ar system was disturbed. Also, the plateau contains less than 50% of the total gas released. The hornblende spectrum lacks a plateau and is saddle shaped, which usually is interpreted to indicate the presence of extraneous ^{40}Ar in both low- and high-temperature increments [Lanphere and Dalrymple, 1971; Harrison and McDougall,

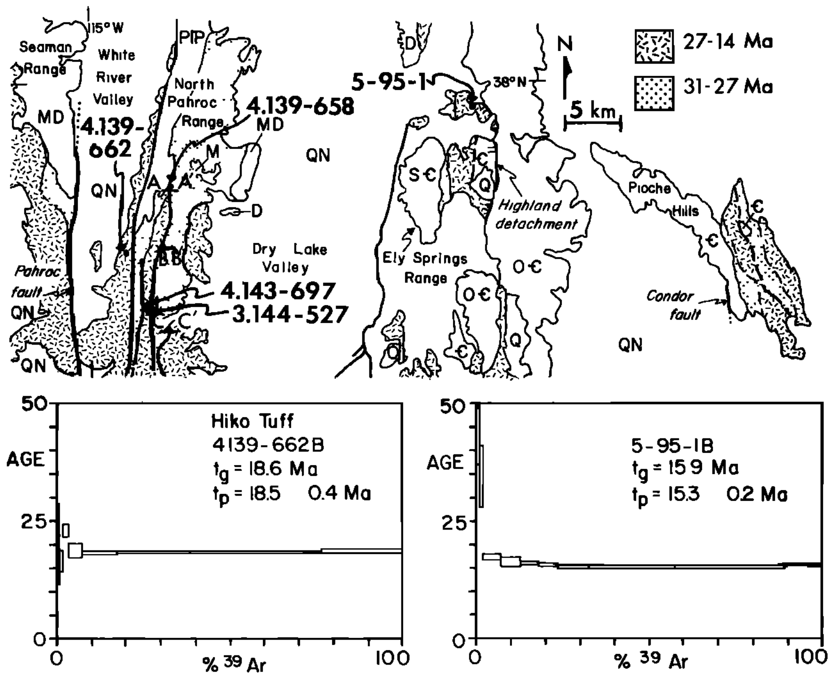

Fig. 6. Simplified and generalized geologic map of the region surrounding Dry Lake Valley. The youngest faults in the North Pahroc Range cut the Hiko Tuff and may be related to the Highland detachment. Some faults younger than 18.6 Ma are shown. Spectrum for Hiko Tuff and sample location for sample 4.139-662 shown. Spectrum and sample location shown for sample 5-95-1. Sample 5-95-1 is from an air fall tuff intercalated with syntectonic conglomerates of the McCullough Formation. Locations of cross sections and samples in Figures 6 and 7 shown. Standard letter abbreviations used for Paleozoic units. QN (Quaternary-Neogene) is used for Quaternary and Pliocene units.

1981]. The minimum age increment of the hornblende spectrum (29.6 +/- 1.2 Ma) therefore is interpreted to be a maximum age of the tuff. The relatively large error ranges of the two dates overlap, but neither is an excellent date. Together, they suggest that the tuff was erupted at about 30 Ma. The local tuff lies stratigraphically above the Wah Wah Springs Formation, for which Best and Grant [1987] reported an age of 29.5 Ma, based on a mean of 16 conventional K/Ar dates (Figure 2). Given the large uncertainties in our dates (1.0 and 1.2 Ma) for the local tuff and the 1.0 Ma or greater errors associated with the K/Ar dates on the Wah Wah Springs Formation, the conflict may be more apparent than real. It appears that the Wah Wah Springs Formation and the unnamed tuff are close in age (about 30 Ma).

The early faults that cut this unnamed tuff are overlapped by conglomerate that stratigraphically underlies the Lund Formation (Figure 2), to which Best [1986] assigned an age of 27.9 Ma. Therefore timing of the first episode of synvolcanic faults is bracketed between approximately 30 and 27.9 Ma.

A second set of synvolcanic faults offsets the Lund Formation and two younger, but undated units. These two units were not dated because they do not contain minerals favorable for $^{40}Ar/^{39}Ar$ dating or they contain xenocrysts, which would render a date unreliable. The faults are overlapped by two tuffs from which we analyzed mineral separates. Based on stratigraphic position as well as petrographic and outcrop characteristics, we correlate the lower of these tuffs with the Monotony Tuff of central Nevada [Ekren et al., 1971], although Cook [1965] included this tuff in his informal Pahroc sequence. Ekren et al. [1977] estimated the age of the Monotony Tuff to be 26 to 27 Ma. Both hornblende and biotite were analyzed from this unit. The hornblende spectrum is saddle shaped, suggesting the presence of extraneous ^{40}Ar, but includes a plateau at 26.7 +/- 0.3 Ma (Figure 8). The minimum age increment is also 26.7 Ma. These observations suggest that incremental release completely resolved the extraneous ^{40}Ar component and the plateau age is the emplacement age. This date is further supported by concordance with the biotite plateau age of 27.1 +/- 0.6 Ma (Figure 8). We conclude that this tuff was emplaced at approximately 27 Ma, which corroborates our correlation with the Monotony Tuff. This occurrence of the Monotony Tuff significantly increases the outcrop area of that ash flow sheet. It also helps to resolve any uncertainty about the stratigraphic relations of the Monotony Tuff and Needles Range Group.

The stratigraphically higher tuff we dated also belongs to the Pahroc sequence of Cook [1965]. We refer to this tuff informally as the tuff of Hamilton Spring, for exposures in the North Pahroc Range about 1.6 km south-southwest of Hamilton Spring. Its phenocryst mode closely resembles that of the Isom Formation [Mackin,

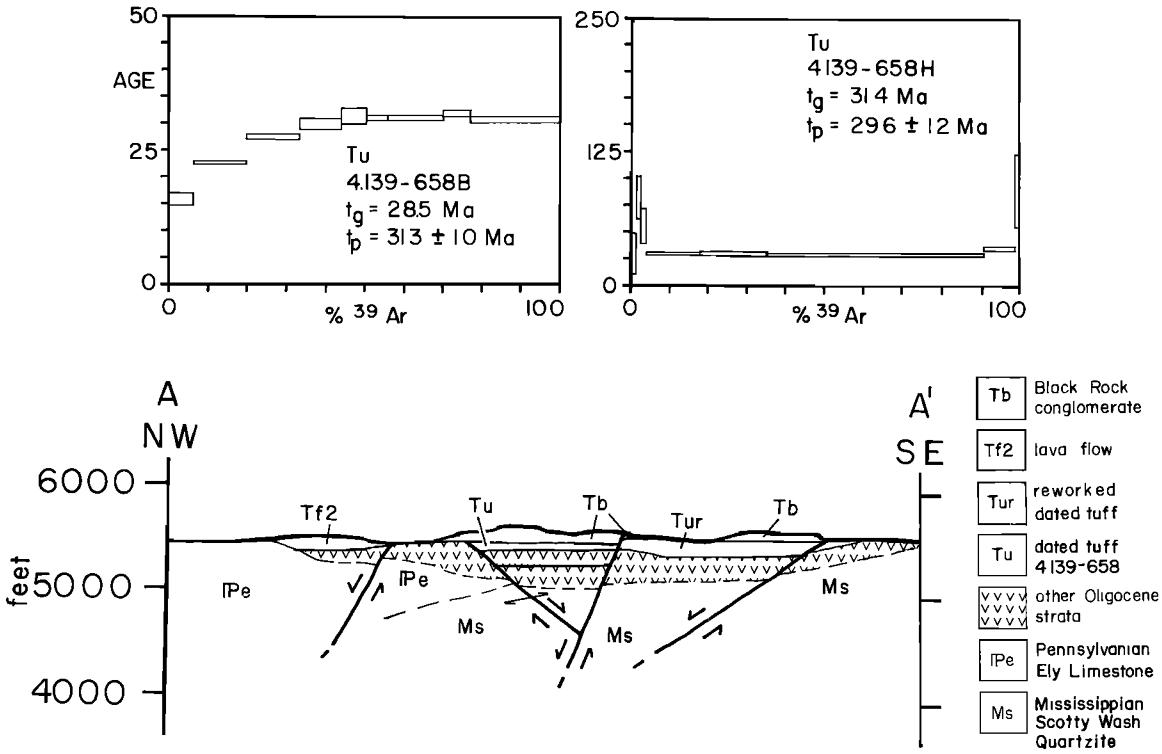

Fig. 7. Cross section showing late Oligocene unconformity and a fault of the first episode of the second period of faulting lapped by conglomerate. In order of decreasing age the units depicted are Tf2, a lava flow; Tb, Black Rock conglomerate; Tu, the unnamed tuff from which sample 4.139-658 was collected; Tur, reworked unnamed tuff; V pattern, tuffs between 30 and 31 Ma; lPe, Pennsylvanian Ely Limestone; Ms, Mississippian Scotty Wash Quartzite. Spectra are from the unnamed tuff of local distribution that is the youngest tuff cut by faults of the first episode of the second period of faulting. Sample location and location of cross-section line is in Figure 6.

1960], but the tuff of Hamilton Spring has yielded older isotopic ages than the Isom Formation. The Isom Formation yielded conventional K/Ar dates of 25.3 +/- 0.5 and 26.1 +/- 0.5 on whole rocks [Armstrong, 1970], and 25.3 +/- 0.4 and 25.5 +/- 0.4 Ma on plagioclase separates [Fleck et al., 1975]. The tuff of Hamilton Spring yielded a $^{40}Ar/^{39}Ar$ plateau age of 27.4 +/- 2.5 Ma on plagioclase (Figure 8). This spectrum may be slightly disturbed. The large error associated with this date is probably a result of using a sample too small for the low content of K and high content of Ca in the plagioclase, necessitating a large correction for extraneous ^{36}Ar and ^{40}Ar generated by irradiation of Ca [Dalrymple et al., 1981]. The ages permit that either the tuff of Hamilton Spring correlates with the Isom Formation or that it is older.

Therefore the second fault set is bracketed between 27.9 and about 27 Ma. An angular unconformity of this same age occurs above the Lund Formation and below the Petroglyph Cliff tuff and the tuff of Hamilton Spring in the Ely Springs Range [Axen et al., 1988].

Grant and Quinn Canyon Ranges

Late Oligocene normal faults also are present in the Grant and Quinn Canyon Ranges (Figure 1), although stratigraphic constraints are less precise than in the North Pahroc Range. A northwest trending normal fault in the southern Grant Range cuts the 31.8 Ma Windous Butte Formation (see above), but it and several other mainly west dipping, high- to low-angle normal faults are truncated by an east-west trending felsite intrusion (Figure 5) [Bartley et al., 1988]. The felsite intrusion is quite hydrothermally altered and therefore not amenable to isotopic dating; however, geologic relations suggest an age of about 26-27 Ma. The emplacement of the intrusion probably was related to a major caldron inferred in the adjacent Quinn Canyon Range [Sargent and Hauser, 1970; Ekren et al., 1977]. The caldron was probably the source of the Shingle Pass Tuff [Sargent and Hauser, 1970; J. M. Bartley, unpublished mapping, 1985]. Ages for the Shingle Pass Tuff and associated rhyolite lava flows in the Quinn Canyon Range may give an approximate age for the felsite intrusion, and therefore an approximate minimum age bracket for these early normal faults. It is possible that the Quinn Canyon volcanic center was active after 26 Ma and the dikes are younger, but we as yet have no younger ages from igneous rocks in the area to suggest it.

Biotite and sanidine separates from the basal vitrophyre of the Shingle Pass Tuff in the northern Quinn Canyon Range yielded excellent and identical plateau ages of 26.2 +/- 0.5 Ma.

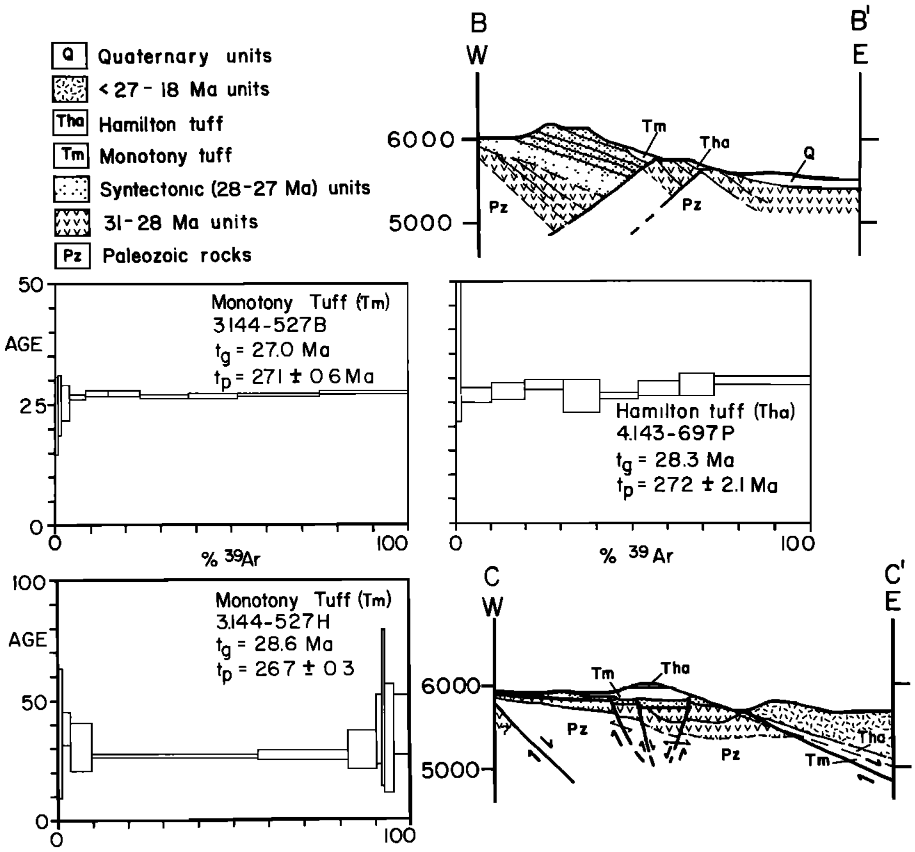

Fig. 8. Cross sections showing faults of second episode of second period of faulting and late Oligocene unconformity. Sample location and location of cross-section line shown in Figure 6. Spectra show dates of the tuff of Hamilton Spring and Pahroc sequence 2a. Pahroc sequence unit 2a correlates with the Monotony Tuff.

In each, more than 90% of the total gas contributed to the plateau. Intercept $^{40}Ar/^{36}Ar$ ratios from correlation diagrams computed from the release spectra are 294.3 +/- 1.5 and 294.5 +/- 4.4, indicating that the only significant source of nonradiogenic ^{40}Ar was the atmosphere. These data indicate strongly that the age of the Shingle Pass Tuff is very close to 26.2 Ma and thus is late Oligocene, not Miocene as has been inferred based on conventional K/Ar ages [e.g., Ekren et al., 1977]. Also dated was a rhyolite flow that stratigraphically underlies the Shingle Pass Tuff. The flow occurs in normal fault contact with the felsite intrusion; field relations suggest that the intrusion may have been a conduit that fed rhyolite flows in the northern Quinn Canyon Range. Biotite from the rhyolite flow yielded an excellent plateau age of 27.3 +/- 0.4 Ma. This date is presently our best estimate of the age of the intrusion that cuts the early normal faults. Therefore fault movement is bracketed between about 32 and 27 Ma.

Indications of late Oligocene extension also are found in the Troy Canyon area in the central Grant Range. Fryxell [1984, 1988] showed that slices of Tertiary welded tuffs occur along the Troy Canyon low-angle normal fault, which places Ordovician limestone upon metamorphosed Cambrian rocks. Biotite from a welded tuff in one of these slices yielded a plateau age of 27.8 +/- 0.4 Ma (Figure 9). A Cretaceous stock in the footwall of the fault has yielded conventional K/Ar mica ages of 25.3 +/- 0.5 and 23.1 +/- 0.5 Ma (from Armstrong [1970] recalculated with IUGS constants from Steiger and Jager [1977]), and $^{40}Ar/^{39}Ar$ incremental-release mica ages of 24-26 Ma (J. E. Fryxell, personal communication, 1986). These mica ages have been interpreted to date cooling after tectonic denudation of the Troy stock by low-angle normal faults [Fryxell, 1984; Bartley et al., 1984].

Postvolcanic Faulting

Dry Lake Valley Area

The volcanic stratigraphy of the North Pahroc Range clearly documents a period of volcanic activity in a tectonically quiescent regime that lasted at least 8 Ma after the end of early synvolcanic faulting [Taylor and Bartley, 1986]. Numerous ash flow tuffs and lava flows accumulated from 27 to 19 Ma without stratigraphic or structural evidence of syndepositional faulting. Much of this activity was centered in the Caliente Caldron Complex, although more locally distributed tuffs and lava flows document closer volcanic sources as well.

Post-27 Ma faults cut all Tertiary units, including rocks as young as 18.6 to 15.3 Ma.

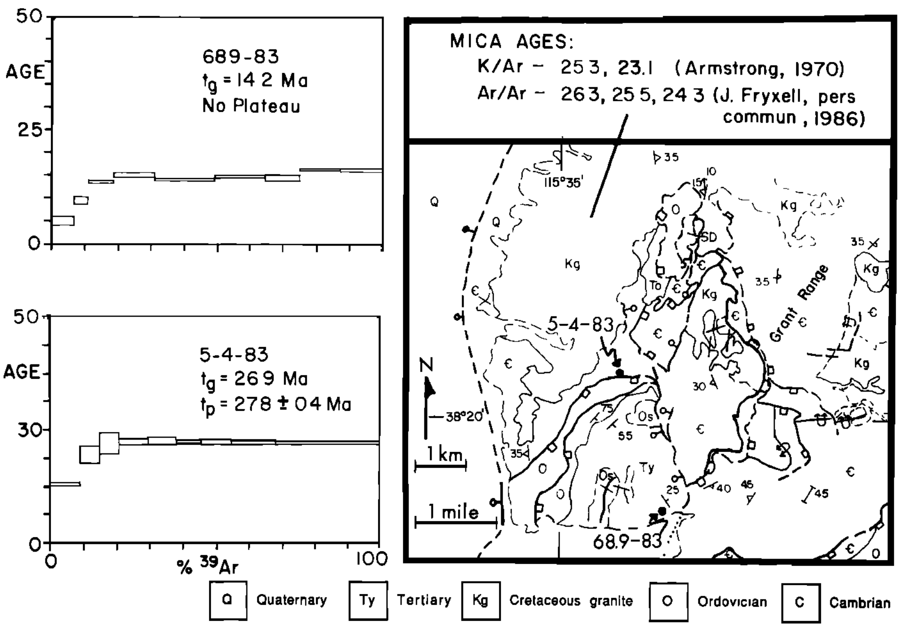

Fig. 9. The 68.9-83 spectrum on biotite and 5-4-83 spectrum on biotite. The welded tuff from which sample 5-4-83 was collected is cut by a fault which in turn is cut by a fault that tilts the air fall tuff from which sample 68.9-83 was collected. Geology of this part of the Grant Range simplified from Fryxell [1988].

The third period of extension therefore postdates nearly all major volcanic eruptions, aside from the Kane Wash Tuff (14 Ma, Noble [1968]). However, the Kane Wash Tuff was erupted from a volcanic center that is well to the south of the transect, although that center is generally considered a part of the Caliente Caldron Complex.

The north-south trending Highland detachment, exposed in the Highland Range (Figure 1), cuts and tilts a recently recognized sequence of conglomerates and breccias, called the McCullough formation, that overlies the youngest ash flow tuff in this area [Axen et al., 1988]. These deposits are interpreted as syntectonic clastic sediments shed from the tectonically denuded footwall of the detachment. Biotite from an airfall tuff intercalated in the syntectonic sedimentary rocks yielded a plateau age of 15.3 +/- 0.2 Ma (Figure 4). These data indicate that the Highland detachment was active at, and after, about 15 Ma. This age supercedes the Oligocene age previously inferred for the Highland detachment [Axen, 1986].

In the North Pahroc Range, three structurally distinct fault sets cut the Hiko Tuff. Biotite from the upper part of the Hiko Tuff in the North Pahroc Range gave a plateau age of 18.5 +/- 0.4 Ma (Figure 6); 18.6 Ma is the average of several ages determined from Hiko Tuff samples collected in Rainbow Canyon, nearer its inferred vent in the Caliente Caldron Complex (Figure 1) [D. R. Lux, unpublished data, 1987]. Taking these data together, we consider 18.6 Ma to be the best estimate of the age of the Hiko Tuff.

These faults in the North Pahroc Range therefore are younger than 18.6 Ma. The only rigorous minimum age constraint is given by the observation that none of these faults cuts Quaternary deposits. However, regional relationships indicate that at least some of these faults probably are mid-Miocene in age. The Highland detachment projects westward beneath the North Pahroc Range. The orientations and kinematics of the post-18.6 Ma faults in the North Pahroc Range are consistent with the hypothesis that some or all of the faults reflect internal extension of the hanging wall of the Highland detachment [Bartley et al., 1988].

Grant Range

Stratigraphic data from the central Grant Range supply only loose age brackets for Miocene faults, but indicate significant fault displacements at about 14 Ma. The Little Meadows fault [Fryxell, 1984, 1988] lies within the Grant Range at Troy Canyon, but farther south forms the western boundary of the range. This fault truncates late Oligocene faults, and also cuts and tilts conglomerate at Little Meadows Creek [Cebull, 1970; Fryxell, 1984, 1988]. Biotite from an air fall tuff intercalated at the top of this conglomerate section yielded a total-gas age of 14.2 Ma (Figure 9). The release spectrum is disturbed and lacks a statistical plateau. However, all increments are middle to late Miocene, and seven increments that constitute more than 80% of the gas give dates near 15 Ma. Therefore the total-gas age is only approximate and probably a minimum value, but indicates that the conglomerates probably are mid-Miocene.

Syntectonic clastic deposits similar to those at Little Meadows Creek also occur at the northern end of the Grant Range (Horse Camp Formation of Moores [1968] and Moores et al. [1969]). Fryxell [1984] tentatively correlated these two clastic sections based on similar lithologies and structural positions. Fossils recovered from the Horse Camp Formation led Moores to propose an age near the Miocene-Pliocene boundary, but the fossils all have large biostratigraphic ranges and do not appear to exclude an age as old as early Miocene. Therefore the isotopic age we report, though imprecise, may still be the most precise age constraint upon Grant Range syntectonic conglomerate.

Pliocene to Quaternary Faults

Faults that cut Pliocene and Quaternary deposits occur in most of the basins in the Railroad Valley-Pioche transect (Figure 1). At least one of these, the Pahroc fault, was initiated in Pliocene or Quaternary time (see below). In contrast, faults that cut mid-Miocene deposits consistently are overlapped by Quaternary deposits. Therefore, Quaternary faulting may compose a period of extension distinct from that in the mid-Miocene. The paucity in most of the transect of exposed deposits that give late Miocene-Pliocene ages makes this possibility difficult to assess. The only known post-14 Ma volcanic eruptions near or within the transect are Pliocene-Quaternary basalts from the Lunar Crater area of the Pancake Range.

The Pahroc fault [Tschanz and Pampeyan, 1970] cuts exposed late Cenozoic basin-fill sediment on the west side of White River Valley (Figure 1) [DiGuiseppi, 1987]. The basin-fill sediment is flat lying and poorly indurated and contains mid-Pliocene to Quaternary invertebrate fossils [DiGuiseppi and Bartley, 1987; DiGuiseppi, 1988]. The Pahroc fault can be traced southward into a bedrock fault within the North Pahroc Range, where the fault separates Miocene volcanic rocks the same amount as Quaternary strata. Therefore the Pahroc fault was active entirely within Pliocene-Quaternary time.

The Condor fault, near the east end of the transect (Figure 1), cuts the lower Panaca Formation and is lapped by the upper Panaca Formation [Bartley et al., 1988]. The lower part has been assigned a late Clarendonian to Hemphillian age (upper Miocene to lower Pliocene) based on vertebrate fossils [Phoenix, 1948]. The upper Panaca Formation was assigned an age of 3.7 to 3.2 Ma based on microtine rodent fossils [Repenning, 1988]. These relations suggest the fault was active in the Pliocene. Therefore it appears that at least some of the young faults were active in the Pliocene.

Discussion

The contact relations and ages of Tertiary volcanic rocks in the Great Basin constrain the timing of extension, and the temporal relation of extension to magmatism. However, implications of the age data may be limited if the time-space distribution of volcanism does not reflect closely the distribution of magmatism in general. Specifically, large amounts of magma could be intruded into and trapped within the lower crust without volcanic expression. In this case, the time-space patterns of volcanism would be unreliable in determining the relation of magmatism to tectonics. However, it seems unlikely to us that major crustal magmatism could be so cryptic, particularly in the thin and actively deforming crust of the Great Basin. Therefore we assume that the patterns of volcanism give a reasonable first-order image of major crustal magmatic events.

Episodic Extension

The results of our work indicate that extension was distinctly episodic. Multiple sets of faults in this area commonly reflect quite different periods of deformation rather than successive phases in a continuum of deformation [cf. Proffett, 1977; Gans and Miller, 1983]. Kellogg [1964] and Axen [1986] previously suggested that distinct periods of extension occurred in this region.

It is uncertain whether a major hiatus in faulting existed between the prevolcanic and the 30 to 27 Ma periods of normal faulting because there is only a minimum bound on the age of the prevolcanic faults. However, if the prevolcanic faults correlate with the approximately 35 Ma old faults to the north in the Ely area [Gans and Miller, 1983], then there may be a hiatus of about 5 Ma.

A period of tectonic quiescence between 27 and 19 Ma is clear in the Dry Lake Valley area. No fault movements are recorded in the section from the Monotony Tuff (about 27 Ma) to the Hiko Tuff (18.5 Ma). Irregularities of thickness and discontinuous units appear to reflect erosional and constructional-volcanic topography rather than tectonic movements. Data from the western part of the transect suggest a similar hiatus, but we presently lack comparable stratigraphic resolution in the Grant and Quinn Canyon ranges.

Although it is uncertain, we suggest a tectonic hiatus also separates faults of mid-Miocene and Quaternary ages. Because rocks are lacking that give ages between upper Miocene and Quaternary, it is possible that faulting continued through the intervening time. On the other hand, no documented 14 to 16 Ma faults can be traced along strike into Quaternary fault scarps. Also, we have found syntectonic sedimentary deposits associated with each of the earlier periods of faulting in the transect. The Condor fault cuts the Clarendonian to Hemphilian lower Panaca Formation, and is lapped by 3.2 to 3.7 Ma upper Panaca fine-grained lacustrine deposits. This relation suggests that faults were active during the Pliocene or perhaps the very latest Miocene. The apparent lack of late Miocene syntectonic deposits seems to require either a break in tectonism within the interval from mid-Miocene to the Pliocene, or that areas of post-15 Ma tectonic subsidence coincide precisely with modern basins and are concealed therein. The latter is a reasonable hypothesis that cannot be tested without detailed subsurface data from basin-fill deposits.

We are yet unable to make comprehensive extension estimates for each period across the transect. In the Dry Lake Valley area, prevolcanic extension is a minimum of 7 km across about 10 km of exposed width; the amount of extension recorded in intervening concealed areas can only be conjectured. Only minor extension (about 1 km) resulted from the synvolcanic period at Dry Lake Valley, but coeval extension within the Grant and Quinn Canyon ranges probably exceeds 10 km [Fryxell, 1988; Bartley and Gleason, 1989]. Postvolcanic extension related to the Highland detachment exceeds 10 km [Axen et al., 1988; Taylor, 1988]. Synchronous extension across the Little Meadows fault in the Grant Range is a minimum of 3 km [Fryxell, 1988]; it is likely that more, and perhaps larger, faults of this age are concealed under Railroad Valley [cf. Effimoff and Pinezich, 1986]. It therefore appears that each of the periods resulted in a significant amount of crustal extension across some part of the transect.

Correlation of Faulting Episodes Across the Transect

Major pre-32 Ma normal faults have been found or inferred in the transect only east of a line through southern White River Valley (Figure 1). This distribution of faults suggests that the prevolcanic normal faults are related to a different extensional system than all younger faults in the transect. The contrasting relations of the sub-Tertiary unconformity across southern White River Valley require a major concealed prevolcanic normal fault. Because all normal faults of that age are exposed east of there, this concealed fault may be the breakaway of an east dipping prevolcanic detachment beneath the Dry Lake Valley area [Taylor and Bartley, 1988; Taylor, 1989]. The detachment that correlates with this breakaway may be the Stampede detachment, fragments of which are exposed east of Dry Lake Valley [Axen et al., 1988]. These suggestions are consistent with our hypothesis that the pre-32 Ma faulting correlates with early Oligocene extension north of the transect in the Snake Range and environs. Oligocene upper crustal extension in the Snake Range area has been inferred above a major east dipping extensional detachment [Wernicke, 1981; Bartley and Wernicke, 1984; Lee et al., 1987; Gaudemer and Tapponier, 1987]. We further suggest that a significant portion of western Utah lies within this belt of east-vergent Oligocene extension (W. Taylor and J. Bartley, manuscript in preparation, 1989), based on widespread prevolcanic normal faults on published geologic maps [Hintze, 1978; Best et al., 1987a, b].

Faults bracketed between 30 and 27 Ma are exposed throughout the entire transect, indicating regional extension at that time. Two episodes of faulting documented in the North Pahroc Range result in a late Oligocene angular unconformity (Figures 5 and 6). The unconformity and syntectonic conglomerates also appear in this part of the section in the Ely Springs Range (Figure 2). The age brackets in the western part of the transect are looser; most faults are between 32 and 27 Ma. The timing nonetheless is consistent with regional contemporaneity.

Another regional period of normal faulting occurred about 14 to 16 Ma. At this time, the Little Meadows fault tilted syntectonic deposits in the Grant Range that contain the approximately 14 Ma air fall tuff. The Highland detachment cut and tilted syntectonic conglomerates with an intercalated 15 or 16 Ma tuff. The three episodes of post-18.6 Ma faults in the North Pahroc Range may be related to the Highland detachment because they have a strike similar to the detachment and the detachment projects under them. Therefore these faults may be upper plate faults related to the Highland detachment. Quaternary faulting is documented throughout the transect, clearly indicating that faulting of this age is regionally important. However, the time of onset of this youngest period of faulting is poorly constrained.

Major deformation episodes, typically of a few million years duration, span the Railroad Valley-Pioche transect. We interpret each period of extension to have occurred along a large-scale extensional shear zone [e.g., Wernicke, 1981; Davis, 1983], such that each extensional period corresponds to the initiation, evolution, and deactivation of a major shear system. Specifically, prevolcanic extension took place along an eastward rooting extensional shear system that was later crosscut by the westward rooting Highland detachment. The geometries and magnitudes of extension during the other periods are less clear, and therefore we are uncertain of their relation to those two shear systems.

The areal extent of a given period thus should indicate the scale of the shear system it reflects. Correlation of extensional episodes for at least 100 km across strike along the transect, and our proposed correlation of at least the prevolcanic extension for 200 km along the strike, imply a minimum scale for individual extensional shear systems. A further implication is that the Great Basin formed as a mosaic of diachronous and overlapping extensional shear systems. At scales ranging up to that characteristic of major shear systems, deformation will be episodic, but the precise timing of episodes is likely to be diachronous across the Great Basin.

Significance of Timing Relations of Volcanism and Faulting

Age relations between volcanism and faulting carry implications for models of time-space relations of magmatism and tectonism in the Basin and Range. Christiansen and Lipman [1971] proposed a widely embraced model in which a transition from dominantly intermediate volcanism to fundamentally basaltic or bimodal volcanism marked the initiation of Basin and Range extension. They suggested that, in the area of the transect, the transition occurred at about 20 Ma, between eruption of the dominantly dacitic Needles Range Group and the dominantly rhyolitic early Miocene tuffs.

More recent data suggest several reasons to question this scenario. Because extension began before volcanism, the onset of extension clearly was earlier than any volcanic compositional transition in this area. Further, in the Dry Lake Valley area voluminous rhyolitic ash flow tuffs and lavas, and significant amounts of mafic lavas, first appear interstratified with the upper Needles Range Group, while the youngest widespread dacitic ash flow tuff is the Harmony Hills Tuff, nearly 10 m.y. younger. This "transitional" interval encompasses most of the volcanic section (Figure 2), rendering moot any distinction of an intermediate to bimodal transition in the area. Finally, the source locations of the major volcanic units are sufficiently known to make it clear that units in the sequence came from several compositionally diverse systems of different but overlapping ages. Consequently, chemical trends in a single section mix information regarding the evolution of several different unrelated magmatic systems. The fact that simple compositional trends are not apparent therefore suggests that evolution of these magmatic systems was not coordinated in time, even though these systems are located as close to each other as adjacent ranges (Needles Range and Caliente caldron complexes, Figure 1); also see Ekren et al. [1977] and Best and Grant, [1987].

The relative timing of volcanism and extension also bears on kinematic and dynamic relations between magmatism and extension. Upper crustal extension by faulting has been inferred to be compensated kinematically at depth by intrusion of magma [Thompson, 1959; Wright and Troxel, 1973; Cape et al., 1983; Gans and Miller, 1983]. Instances where magmatism is syntectonic with respect to extension have been cited as supporting this view [Wright and Troxel, 1973; Gans et al., 1986]. This kinematic argument complements the "active rifting" dynamic model of extension, in which heat advected by rising magma causes topographic uplift and drives extension [e.g., Sengor and Burke, 1978]. It is important to note that the kinematic and dynamic models are independent, in that verification of one does not require the other to be correct.

The presence of significant extension before Tertiary volcanism, and the general lack of correlation between ages of extension and volcanism, argue against, but do not preclude, both of these hypotheses in the Railroad Valley-Pioche transect. Extension predating volcanism favors the "passive rifting" dynamic model, in which tectonic thinning of the lithosphere causes magmatism, perhaps by decompression melting. However, pre-32 Ma plutonism without coeval volcanism, perhaps as a precursor to volcanism, cannot be ruled out. Therefore the evidence is suggestive rather than compelling.

The lack of temporal correlation between faulting and volcanism may be interpreted in a variety of ways. Most major volcanic eruptions in and near the transect occurred during periods of relative tectonic quiescence. The simplest interpretation of this relation is that volcanism and faulting simply were not closely coupled, though they probably were related. Alternatively, the lack of correlation between faulting and volcanism may indicate that, during active magmatism, extension was concentrated in vent areas, which mainly lie outside the transect. A test of this hypothesis is to seek evidence for synvolcanic extension in and around major vents. Such a situation occurs in the Kern Mountains area [Gans et al., 1986]. However, this model would predict that the synvolcanic extension at Dry Lake Valley, in close proximity to the Needles Range Group calderas, should be large, yet the amount of extension at this time is small.

Conclusions

Detailed geologic mapping and $^{40}Ar/^{39}Ar$ dating allowed documentation of the time-space relations of Tertiary extension and volcanism in a part of the Great Basin. This documentation leads to the following conclusions.

1. Extension was episodic in the Railroad Valley-Pioche transect. Four temporally distinct regional periods of faulting are distinguished: prior to volcanism (pre-32 Ma), between 30 and 27 Ma, about 14-16 Ma, and Pliocene to Quaternary. The three younger periods of faulting are correlative across the transect, but shorter episodes of faulting may be regionally restricted. The area affected by each period of faulting extends beyond the limits of the transect (>4000 km^2). The characteristic time scale of tectonic episodes in this area appears to be roughly 5 to 10 Ma.
2. Extension began prior to volcanism, which favors a passive rifting model for initial Basin and Range extension.
3. There is a general lack of correlation between extensional periods and volcanism. This indicates that the genetic relationship between volcanism and extension is not simple and direct.
4. Individual periods of extension are regional in extent, but the regions affected do not always coincide. This spatial distinction suggests that different extensional detachment systems were active at different times. The older faults occur only in the eastern part of the transect and may lie in the upper plate of an originally east dipping detachment. Faults active from 14 to 16 Ma are exposed across the transect, and many of them are probably related to the west dipping Highland detachment.

Appendix: Analytical Methods

Samples for geochronology were collected within the same structural block as exposures of the structure or unconformity to be dated. This procedure removes one critical inference otherwise required in dating structures, i.e., stratigraphic correlation between the sample locality and the rock actually found in the key contact relation, which is particularly valuable because of the difficulties inherent in tuff correlations noted above.

Samples were crushed and sieved to uniform grain sizes chosen to yield the largest possible dominantly individual rather than composite grains. Standard physical methods were used to extract mineral separates of biotite, sanidine, hornblende, and plagioclase with an estimated purity of >99.9%. These separates were encapsulated in aluminum foil, sealed in silica glass vials, and irradiated in the nuclear reactor at the Phoenix Memorial Laboratory at the University of Michigan. An interlaboratory standard, Hornblende 3946, was used as an irradiation monitor. It was calibrated to a widely accepted mineral standard, MMhb-1 [Alexander et al., 1978].

Isotope measurements were made at the University of Maine. Procedures used in isotope analyses are described by Hubacher and Lux [1987]. Individual ages and errors, calculated using equations from Dalrymple et al. [1981], are two sigma, plus 0.5% uncertainty in the J value (the nuclide conversion parameter), which is neglected by some workers in estimating analytical uncertainty. The IUGS decay constants and the recommended isotopic composition of K were used for age calculations [Steiger and Jäger, 1977]. The criteria used for determining plateaus are from Fleck et al. [1977]. The critical value test [Dalrymple and Lanphere, 1969] was used to test concordance between successive increments using only analytical uncertainties. The total gas age (t_g) is a weighted average based on the total amount of ^{39}Ar in each increment. A plateau age (t_p) is the mean of the ages considered concordant. A plateau age was considered reliable if (1) the plateau contained >75% of the total ^{39}Ar released, (2) it consisted of four or more increments, and (3) the plateau age agreed with the age determined by the $^{39}Ar/^{40}Ar$ versus $^{36}Ar/^{40}Ar$ isotope correlation method computed from gas increments from that sample, with a $^{40}Ar/^{36}Ar$ intercept value that was between 285 and 305. The last criterion is an independent check that the only source of nonradiogenic ^{40}Ar in the sample was atmospheric Ar, in which $^{40}Ar/^{36}Ar = 295.5$.

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