The chronology of Cenozoic volcanism and deformation in the Yerington area, western Basin and Range and Walker Lane

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ABSTRACT

High-precision $^{40}Ar/^{39}Ar$ isotopic ages obtained from Cenozoic volcanic rocks and subvolcanic intrusions document the age of initiation and the temporal evolution of extensional and strike-slip faulting in the western Basin and Range Province. In the northern Wassuk Range, faulting began between ca. 26 and 24.7 Ma; both normal and strike-slip faults are bracketed between 23.1 and 22.2 Ma, and between 15 and 14 Ma. These ages document inception of the Ancestral Walker Lane, a northwest-trending zone of right-transtensional faulting in western Nevada that separated extending crust on the east from the unextended Sierra Nevada block on the west at lat 39°N. We speculate that the southwesterly migrating, episodic Oligocene–early Miocene, east-west extensional faulting in the Basin and Range thinned and weakened the crust, allowing right-slip faults to develop in the Walker Lane in response to San Andreas right-shear in California.

Southwest of the Walker Lane there was no faulting prior to 15 Ma. Here, in the Yerington district, andesitic magmatism began at ca. 15 Ma and was followed by >150% east-west extension along closely spaced (1–2 km) normal faults with up to 4 km of offset each (Proffett, 1977). These faults tilted older Cenozoic rocks 35°–40°W. Our new $^{40}Ar/^{39}Ar$ ages substantially revise earlier K-Ar ages of the timing of extension and establish that andesite lava flows cut by normal faults are 13.8–15 Ma, and that these faults are intruded by 12.6–13.0 Ma dacites. Rapid extension is thus bracketed to a 0.7–1.7 m.y. interval at 95% confidence, indicating local, east-west strain rates of 2–4 × 10^{-14}/s (5–10 mm/yr). Following this period, lower rates of extension prevailed near Yerington along more widely spaced normal oblique-slip faults that localized clastic sedimentation of the Wassuk Group between 11 and 8 Ma. These faults and sedimentary rocks are more abundant southwest of Yerington in a belt parallel to the Walker Lane in previously little-extended crust. From 7 Ma to present, normal right-oblique slip faults with a lower rate of extension than the previous two periods produced the modern ranges near Yerington and extend 100 km southwest of the Walker Lane, which continues to be the locus of strike-slip faulting. Thus, since 15 Ma the margin of the Basin and Range has moved progressively 100 km west creating the broad Walker Lane belt and lower strain rates near Yerington.

INTRODUCTION

Proffett (1977) described the Cenozoic structural geology of the Yerington district, located at the western margin of the Basin and Range Province (Fig. 1). His careful geologic mapping documented extreme (>150%) east-west crustal extension along normal faults that penetrated to ≥8 km depth, originated with ≥60° dips, and rotated to lesser dips during their movement and during movement along two younger sets of normal faults. On the basis of K-Ar ages of volcanic rocks and subvolcanic intrusions, Proffett (1977) concluded that the extensional faulting began at 19–17 Ma, proceeded rapidly until ca. 11 Ma, and then slowed along the younger normal faults between 11–8 Ma and the present.

At about the same time as Proffett's studies, but 50–100 km east of Yerington, Nielsen (1965), Hardyman (1980), Ekren et al. (1980), Ekren and Byers (1984), and Hardyman (1984) described the structure of the central Walker Lane, a 40-km-wide by >100-km-long zone of northwest-striking strike-slip faults with an estimated 48–60 km, and perhaps 60–75 km (Oldow, 1993), of right-slip displacement. The central Walker Lane as used herein and by Hardyman and Oldow (1991) represents the eastern part of what Stewart (1988) has termed the Walker Lane belt, a 100- to 300-km-wide by 700-km-long zone extending north-northwest along the California-Nevada border from the vicinity of Las Vegas, Nevada, to Oregon (inset, Fig. 1). The age and inception of faulting within the central Walker Lane is poorly constrained, but Ekren and Byers (1984) estimated inception at ca. 24 Ma on the basis of fault-associated landslide breccias overlain by late Oligocene tuffs. Faulting has continued to the present, exemplified by the 1932 right-lateral Cedar Mountain earthquake (Gianella and Callaghan, 1934). The southern portion of the Walker Lane belt may have cumulative displacement of 100 km right-slip in the Death Valley region, as reviewed by Stewart (1988). Current right-slip shear is 1.1 ± 0.1 cm/yr between the Sierra Nevada and the North American craton to the east (Argus and Gordon, 1991) and is largely accommodated by the Walker Lane belt. Active normal faults bounding the ranges in the Walker Lane belt commonly strike N10°–20°W (Stewart, 1988), and many have a significant component of right oblique-slip (e.g., Zoback, 1989).

The timing and relationships of normal faults to strike-slip faults in and adjacent to the Walker Lane are not well known, nor is the relation of the Basin and Range extensional province to the San Andreas and related strike-slip faults. This paper contributes to understanding of these problems by presenting high-precision $^{40}Ar/^{39}Ar$ isotopic ages of volcanic and

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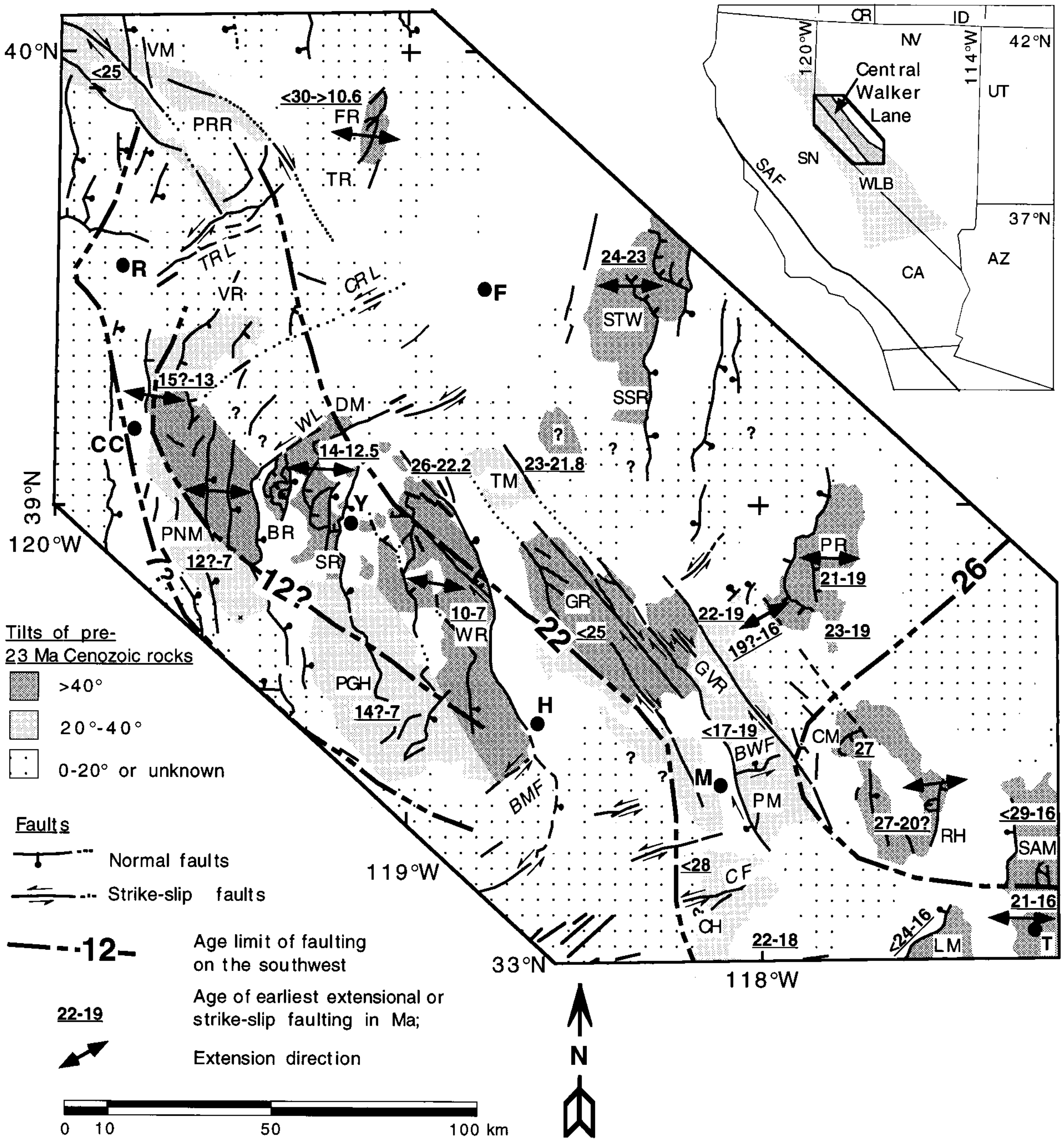


Figure 1. Simplified Cenozoic fault and tilt map of western Nevada, showing age range of oldest faulting and isochrons marking westward limit of faulting at various times (see text for sources). The 12? and 7? Ma isochrons are very approximate and are based on the distribution of the syntectonic Wassuk Group and equivalents. The extent of >26 Ma faulting (26 Ma isochron) is not well known. Tilt angle domains are based largely on the dips of pre-faulting Oligocene ignimbrites. Inset shows (central) Walker Lane of Hardyman and Oldow (1991) and this paper, Walker Lane belt (WLB) of Stewart (1988), Sierra Nevada (SN), and San Andreas fault (SAF). Cities are Carson City, CC; Fallon, F; Hawthorne, H; Mina, M; Reno, R; Tonopah, T; and Yerington, Y. Left-lateral faults southwest of the Walker Lane proper are Borealis Mine fault, BMF; Bettles Well fault (BWF); Carson River lineament, CRL; Candelaria fault, CF; Truckee River lineament, TRL; and Wabuska lineament, WL. Mountains and ranges (references in text) are Buckskin Range, BR; Candelaria Hills, CH; Cedar Mountains, CM; Desert Mountains, DM; Fireball Ridge, FR; Gillis Range, GR; Gabbs Valley Range, GVR; Lone Mountain, LM; Pine Grove Hills, PGH; Pilot Mountains, PM; Pine Nut Mountains, PNM; Paradise Range, PR; Pah Rah Range; PRR; Royston Hills, RH; San Antonio Mountains, SAM; Singatse Range, SR; Sand Springs Range, SSR; southern Stillwater Range, STW; Terrill Mountains, TM; Truckee Range, TR; Virginia Mountains, VM; and Virginia Range, VR.

TABLE 1. $^{40}Ar/^{39}Ar$ AGE DATA

Sample*	Rock type	Lat (°N)	Long (°W)	WMPA (Ma)†	% ^{39}Ar§	Isochron (Ma)	Total fusion age (Ma)	Comments#
Ar-Ar step-heating extractions								
YR-240B hbl	Ash bed, Buckskin Range	38°59′52.5″	119°22′44″	6.17 ± 0.15	96.9 (5)	6.16 ± 0.18	6.00 ± 0.52	Beds are tilted 5°–10°W
YR-1 plag (+)	Basaltic andesite flow	38°56′18″	119°14′57″	7.54 ± 0.17	95.7 (8)	7.53 ± 0.33	7.59 ± 0.20	Basal lava at McConnell Canyon; equiv. to JMP 431 = 10.8 ± 1.0
93-87-S6 plag	Basaltic andesite flow	38°50′23″	118°48′17″	9.23 ± 0.77	90.0 (7)	9.09 ± 2.08	11.30 ± 1.86	15 m below JM2 = 8.4 ± 1.2; 80 m above JM1 = 9.44 ± 0.22 Ma
110JD91 hb1	Ash bed in Wassuk group	38°54′17″	119°00′27″	8.86 ± 0.08	78.8 (4)	8.86 ± 0.09	8.68 ± 0.39	Lower part of section, dips 25–30°W
YR13B bi	Ash bed in Wassuk group	38°55′50″	118°59′10″	8.91 ± 0.06	93.3 (7)	8.98 ± 0.14	8.77 ± 0.14	Beds tilted 20°W, Black Mtn. Well
74JD91 hbl	Ash bed in Wassuk group	38°53′06″	118°54′13″	11.88 ± 2.76**	73.8 (2)	−14.07 ± 8.44††	34.05 ± 0.28	Lower part of section, dips 30°WSW
YR-7B bi	Lincoln Flat dacite intrusion	39°00′10″	119°19′41″	12.64 ± 0.07	97.5 (7)	12.79 ± 0.12	12.48 ± 0.17	P&P bi = 14.2 ± 0.6 Ma
YR-7H hbl	Lincoln Flat dacite intrusion	39°00′10″	119°19′41″	12.12 ± 0.36	98.7 (6)	12.38 ± 0.41††	11.85 ± 0.55	P&P hbl = 18.7 ± 2.5 Ma
108JD89B bi (+)	Lincoln Flat dacite intrusion	38°59′06″	119°22′42″	13.03 ± 0.02	99.5 (10)	13.01 ± 0.03	13.03 ± 0.02	southern Buckskin Range, intrudes fault
YR-6 hbl	Lincoln Flat andesite flow	38°59′11″	119°15′20″	13.83 ± 0.17	95.8 (6)	13.86 ± 0.21	13.67 ± 0.29	P&P hbl = 17.7 ± 2.4 Ma
88JD87 hbl	Lincoln Flat andesite intrusion	39°00′09.5″	118°53′52″	12.85 ± 0.33	84.8 (5)	13.45 ± 0.36	12.74 ± 0.55	Intrudes Walker Lane
77JD90 hbl	Lincoln Flat andesite flow	39°00′35″	118°56′08″	14.08 ± 0.23	99.1 (7)	14.08 ± 0.30	13.82 ± 0.36	5°–10° tilted along Walker Lane
41JD89 hbl	Lincoln Flat andesite breccia	38°59′04″	118°57′04″	14.95 ± 0.24	98.3 (8)	15.03 ± 0.33	14.74 ± 0.52	40°W, tilted in Wassuk Range
73JD90 wr	Pyroxene andesite dike	39°00′46″	118°56′38″	22.16 ± 0.27	81.9 (8)	22.87 ± 0.54††	21.55 ± 0.36	Intrudes older Walker Lane fault
140JD90 bi	Hu-Pwi rhyodacite ignimbrite	38°59′27″	118°54′36″	23.09 ± 0.04	99.0 (8)	23.14 ± 0.08	23.04 ± 0.07	Poinsettia Tuff Member?
				Age/1 std. err.	Grains fused			
Ar-Ar laser extractions								
36JD90 san	Ash-flow in Bluestone Mine	39°02′04″	118°57′48″	24.604 ± 0.025	5			Red Tuff? of John (1992); overlies Tlt
33JD90C san	Ash-flow in Bluestone Mine	39°02′11″	118°57′43″	24.659 ± 0.020	5			Lower White Tuff? of John (1992); overlies Nine Hill T.
46JD90 san	Rhyolite ash-flow tuff	39°01′57″	118°57′37″	28.579 ± 0.038	5			Disconformably overlain by Mickey Pass Tuff (27.1 Ma)
42JD90 san	Ash blocks, in breccia	39°02′24″	118°56′40″	23.734 ± 0.039	5			From Quaternary Walker Lane fault zone
61JD89 san	Ash bed, upper Wassuk group	36°58′38″	118°59′27″	24.164 ± 0.112	6			Within conglomerates of upper part of Wassuk Group
YR-4 san	Ash bed, reworked, Wassuk	38°56′23″	119°13′06″	24.5				Underlies 8–11 Ma basalts of Proffett (1977)
K-Ar age								
208JD88 hbl	Ash bed, Wassuk group	39°00′15″	118°59′43.5″	9.5 ± 1.2				Within sandstones in upper part of Wassuk Group

*Abbreviations here and in text are: plag = plagioclase; hbl = hornblende; bi = biotite; wr = whole rock; san = sanidine. Samples were analyzed at Stanford (see text) except two (+) analyzed in Gans's lab at University of California, Santa Barbara, using similar methods.
†WMPA is weighted mean plateau age; for laser analyses, the mean is used as analytical errors are similar; cited errors are given by one stanard error of the mean of individual analyses.
§% ^{39}Ar is percentage of total ^{39}Ar released used in WMPA; number in parentheses is number of heating steps used in WMPA.
#JM-1 at 38°50′16″N, 118°48′19″W (K-Ar bi); JM-2 at 38°50′24″N, 118°48′20″W (hbl single crystal $^{40}Ar/^{39}Ar$); from McIntyre (1990), determinations by A. Deino, Institute for Human Origins. P&P = Proffett and Proffett (1976); JMP = Proffett (1977).
**Not a true plateau age.
††Indicates an isochron that yields a non-atmospheric intercept.

subvolcanic rocks in the Yerington district and the northern Wassuk Range to the east. These data revise the ages of normal faulting and hence estimates of the rate of extension in the Yerington district and, combined with new field geologic evidence (Dilles, 1993a), establish the age of initiation of normal and strike-slip faulting in the northern Wassuk Range portion of the Walker Lane.

METHODS

The geologic database is provided by detailed mapping at 1:12 000 or larger scale in the Yerington district (Singatse Range and vicinity), the Buckskin Range to the west, and the northern Wassuk Range to the east (Fig. 1). Mapping was principally by Proffett in the Yerington district (Proffett, 1977; Proffett and Proffett, 1976; Proffett and Dilles, 1984a); by Dilles and Proffett (unpubl. mapping) and McIntyre (1990) in the northern Wassuk Range, revising a map of Bingler (1978a); and by Proffett and Dilles (unpubl. mapping) in the Buckskin Range, revising a map of Hudson and Oriel (1979). Figure 1 shows the major Cenozoic faults and areas of stratal tilt of pre-Miocene Cenozoic rock units.

The geochronology is provided by 15 new $^{40}Ar/^{39}Ar$ plateau ages and 6 new $^{40}Ar/^{39}Ar$ laser-fusion ages, as well as previously published ages (Table 1 and Fig. 2). All but two of the $^{40}Ar/^{39}Ar$ analyses were done in the Stanford University laboratory of Mike McWilliams. Two others were analyzed in Gans's laboratory. The Stanford lab is equipped with an M.A.P. 216 mass spectrometer with a Bauer Signer source and a Johnston multiplier, an all-metal extraction/gas purification manifold, and both a continuous Ar ion laser (0.25–70 W) and a Staudacher type double vacuum resistance-type furnace for heating samples. The sensitivity of the mass spectrometer at typical operating gains is ~2–3 × 10^{-14} mol/V. Typical blanks for the laser line (5 min isolation period) are ~5.0 × 10^{-17} mol ^{40}Ar and 1.5 × 10^{-18} mol ^{36}Ar, whereas on the resistance furnace, blanks are typically 1–3 × 10^{-16} ^{40}Ar and 2–3 × 10^{-18} mol ^{36}Ar. Analytical procedures generally follow those outlined by Little et al. (1992). High purity, sized separates of biotite, hornblende, sanidine, plagioclase, and groundmass were made using standard magnetic, density, and handpicking techniques. Samples, 2–20 mg in size, were packaged in Al foil packets, stacked and sealed in a silica glass vial, and irradiated in the U.S. Geological Survey TRIGA reactor in Denver, Colorado. The neutron flux was monitored using sanidine from Taylor Creek Rhyolite (85G003), an internal standard developed by the U.S. Geological Survey in Menlo Park, California, with an assigned age of 27.88 Ma (Dalrymple and Duffield, 1988). Typical uncertainties in J (flux parameter) are ~0.1%. Reactor constants for the production of interfering isotopes were not directly measured for this irradiation but were assigned the nominal values for the U.S. Geological Survey TRIGA reactor determined by Dalrymple et al. (1981). Data were reduced using a computer program of B. Hacker.

The single crystal $^{40}Ar/^{39}Ar$ ages listed are means of five or more individual analyses of 1–5 sanidine grains shown with a 1σ standard error of the mean, which is

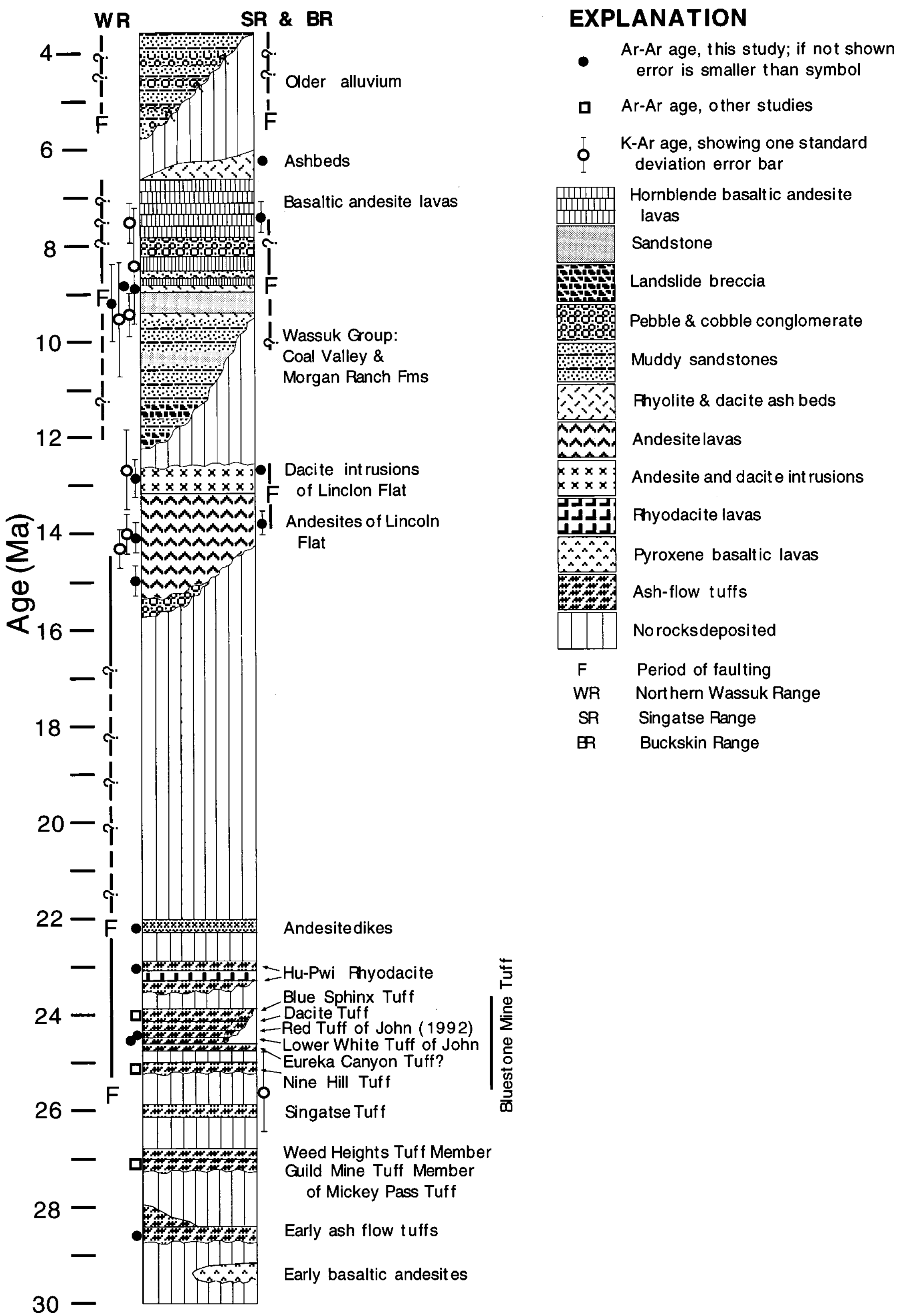


Figure 2. Time-stratigraphic column summarizing $^{40}Ar/^{39}Ar$ and K-Ar ages for the Wassuk Range (WR, left side) and Singatse and Buckskin Ranges (SR and BR, right side), Yerington area, principally from this study. Errors are smaller than symbol or are shown by one standard deviation ticks. We have omitted older K-Ar ages of Proffett and Proffett (1976) and Proffett (1977) for the Singatse Range due to large uncertainties. The Wassuk Range chronology includes ages of 7–15 Ma rocks reported by Bingler et al. (1980), Dilles (1989), and McIntyre (1990).

<0.2% (Table 1; Appendix). The $^{40}Ar/^{39}Ar$ ages for step-heating experiments are presented as the weighted mean plateau ages, with an error representing one standard error of the mean (Table 1, Fig. 3, and Appendix). Fourteen of the 15 step-heating experiments yielded true plateaus as defined by at least 50% of the ^{39}Ar released in three or more contiguous heating steps from the 9–11 heating steps performed as illustrated in Figure 3. In the non-plateau sample, two heating steps containing 74% of ^{39}Ar from a hornblende separate from a fluvially reworked ash in the Wassuk Group yielded an age of 11.88 ± 2.76 Ma; this age may represent multiple hornblende age-populations from reworked sources and is not considered further herein. The largest error for a plateau age is 8% for plagioclase from sample 93-87-S6 due to the small radiogenic ^{40}Ar fractions (Appendix); hornblende and whole rock yielded <3% errors; biotite yielded <1% errors. All of the true plateau ages are also within one standard deviation error of the isochron ages. For comparison, the isochron and total fusion ages are also given (Table 1 and Fig. 3).

Previously published K-Ar ages discussed below are recalculated using IUGS decay constants (Steiger and Jäger, 1977).

REGIONAL GEOLOGIC SETTING

The central Walker Lane region is underlain principally by Mesozoic crystalline rocks, which include Triassic–Lower Jurassic metasedimentary and metavolcanic rocks, Middle Jurassic granodiorite to granite plutons and associated silicic volcanic rocks, and Cretaceous granites (Speed, 1978; Dilles and Wright, 1988). Cenozoic deposits unconformably overlie the crystalline bedrock and may be divided on the basis of lithology and age into five rock series (cf. Hardyman and Oldow, 1991): (1) Oligocene–lowest Miocene silicic ash-flow tuffs (e.g., Ekren et al., 1980); (2) Miocene andesite and dacite lavas and hypabyssal intrusions including the Kate Peak, Alta, and Lincoln Flat lithologies (Thompson, 1956; Proffett and Proffett, 1976); (3) upper Miocene clastic sedimentary rocks filling fault-bounded basins (e.g., the Coal Valley Formation and Wassuk group; Axelrod, 1956; Gilbert and Reynolds, 1973); (4) upper Miocene basaltic andesite lavas; and (5) Pliocene–Holocene alluvium, sand, and fanglomerate deposits of modern fault basins.

Cenozoic Stratigraphy

In the Yerington district, the Buckskin Range, and the Wassuk Range, the Cenozoic stratigraphy is similar and is considered together below with variations noted (Fig. 2).

Oligocene Ash-Flow Tuffs. The oldest Cenozoic deposits are up to 2-km-thick silicic ash-flow tuffs that are thickest where they overlie conglomerates, landslide breccias, and small volumes of basaltic andesite lava flows deposited within Oligocene river valleys (Proffett and Proffett, 1976). Erosional remnants of a series of thin rhyolite ash-flow tuffs are the oldest tuffs; one tuff with abundant carbonate lithics yielded an $^{40}Ar/^{39}Ar$ age of 28.58 ± 0.04 Ma on sanidine (18, Table 1), similar to a biotite K-Ar age of 29.5 Ma reported by Proffett and Proffett (1976) for an ash-flow tuff boulder in the basal Tertiary conglomerate.

Unconformably overlying the earliest deposits are the voluminous dacite to rhyolite ash-flow tuffs of the Mickey Pass Tuff, 27.1 ± 0.1 Ma by $^{40}Ar/^{39}Ar$ (McIntosh et al., 1992). They are overlain by the Singatse Tuff, a 3500 km^3 quartz latite ash-flow tuff. The Singatse is ca. 26 Ma based on stratigraphic position above the 27.1 Ma tuff and below a 25.1 Ma tuff (Fig. 2) and K-Ar ages with large errors: 27.9 ± 1.1 (biotite) and 32.5 ± 1.8 (hornblende) (S-29; Proffett and Proffett, 1976), 26.6 ± 0.8 (biotite) (Bingler et al., 1980), and 29.2 ± 1.1 Ma (biotite) (Bingler, 1972).

The Bluestone Mine Tuff (in part called the tuff of Gabbs Valley by Ekren et al., 1980) disconformably overlies the Singatse Tuff in its type section near Yerington and consists of 200 m of vitric ash-flow and air-fall tuffs and minor tuffaceous sedimentary rocks containing two thin ash-flow tuffs (Proffett and Proffett, 1976). Deino (1985, p. 9) has correlated the lower ash-flow tuff with the Nine Hill Tuff and the upper with the Eureka Canyon Tuff of Bingler (1978b). The Bluestone Mine Tuff thickens northward; in the northernmost Wassuk Range it contains at least five ash-flow tuffs, which lie in angular unconformity on the Mickey Pass and Singatse Tuffs and Mesozoic basement (Dilles, 1993a). The oldest of these ash-flow tuffs is correlated here on the basis of its rheomorphic texture, sparse anorthoclase phenocrysts, and elevated Nb and Zr contents with the Nine Hill Tuff, 25.11 ± 0.017 Ma by $^{40}Ar/^{39}Ar$ (sanidine) (Deino, 1985, 1989). Locally, tuff of Hackett Canyon overlies the Nine Hill (Deino, 1985). Elsewhere, an unnamed biotite rhyolite ash-flow tuff overlies Nine Hill. The biotite tuff is overlain by a 24.66 ± 0.02 Ma (sanidine, 17, Table 1) white, lithic-rich rhyolite ash-flow tuff with 10% crystals, which is tentatively correlated with the lower white tuff of John (1992) of the Paradise Range. The uppermost tuff is a 24.60 ± 0.03 Ma (sanidine, 16, Table 1) thin, red rhyolite ash-flow tuff with 2%–5% crystals and elevated Nb content, and it may correlate with the red tuff of John (1992). In the northern Wassuk Range, but not in the Yerington district to the west, the Bluestone Mine Tuff is disconformably overlain by a unnamed biotite dacite ash-flow tuff (Bingler, 1978a), which is in turn overlain disconformably by the Blue Sphinx Tuff. The tuff and breccia of Gallagher Pass in the Yerington district (Proffett and Proffett, 1976) and the equivalent Hu-pwi Rhyodacite in the Wassuk Range (Bingler, 1978a; Ekren et al., 1980) are locally derived lava flows and domes, ash-flow tuffs, and tuff-breccias that disconformably overlie the older tuffs. A Hu-pwi ash-flow tuff overlying a lava flow yielded a $^{40}Ar/^{39}Ar$ age of 23.09 ± 0.04 Ma (biotite, 15, Table 1). The ash-flow tuff and the lava may be respectively equivalent to the Poinsettia Tuff Member and the Ghost Dance Lava Member in the Gillis Range of Ekren et al. (1980).

Miocene Andesites. Andesites of two ages are exposed in the area. The older, volumetrically minor, pyroxene andesite dikes dated by $^{40}Ar/^{39}Ar$ at 22.16 ± 0.27 Ma (groundmass, 14, Table 1) intrude northwest-striking faults in the northern Wassuk Range. In the Yerington district, thin olivine pyroxene basalt flows overlying the tuff and breccia of Gallagher Pass and underlying the andesites of Lincoln Flat may have a similar age.

The younger hornblende andesites and related dacites of the Lincoln Flat unit are widely exposed in the Singatse, Buckskin, and Wassuk Ranges where they are temporally associated with faulting. In the northern Wassuk Range, a hornblende andesite breccia at the base of the unit has an age of 14.95 ± 0.24 Ma (hornblende, 13, Table 1) and lies in a fault-graben disconformably upon the Hu-pwi Rhyodacite and locally upon older Oligocene tuffs. The contact is marked by a red paleosol and breccia containing up to 5-m-diameter boulders of Hu-pwi and Oligocene tuffs. At another Wassuk Range locality, a gently dipping andesite lava flow conformably overlying similar andesite breccia has an age of 14.08 ± 0.23 Ma (hornblende, 12, Table 1), and both lava

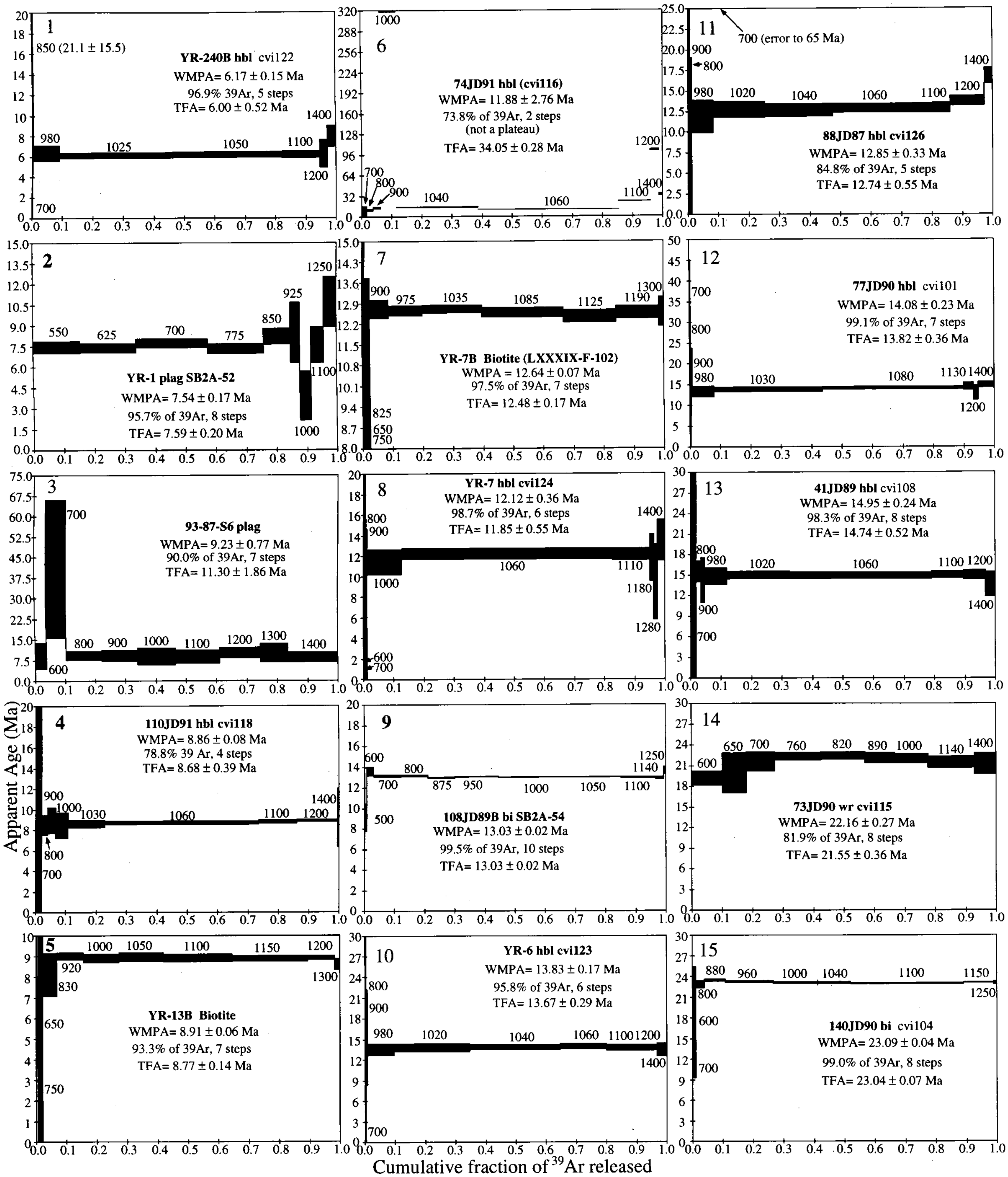


Figure 3. $^{40}Ar/^{39}Ar$ age-spectra, showing cumulative fraction of ^{39}Ar released plotted versus age, with one standard deviation errors (without error in J flux) given by vertical width of each temperature (°C) step. Numbers in upper left correspond to numbers in text, Table 1 (location, rock type, and age summaries), and Appendix (isotopic data).

flow and breccia lie in angular unconformity—locally marked by a red, bouldery paleosol—upon faulted, fault-brecciated, and previously tilted Hu-pwi and Oligocene tuffs. An andesite dike intrusive into a northwest-striking strike-slip fault has an age of 12.85 ± 0.33 Ma (hornblende, 11, Table 1). These three ages are similar to previously reported K-Ar hornblende ages of 14.3 ± 0.4 Ma for an andesite lava flow and of 14.0 ± 0.4 Ma on an andesite dike intruding a fault in the northern Wassuk Range (Bingler et al., 1980).

In the Singatse and Buckskin Ranges, hornblende andesite lava flows of Lincoln Flat are up to 400 m thick and lie in disconformity or slight angular unconformity on the uppermost part of the Oligocene–early Miocene tuff section. The hornblende andesite lava flow sampled by us in the Singatse Range dips ~41°W, similar to the 42°W dip of the underlying Bluestone Mine Tuff, indicating there is no significant angular discordance between older tuffs and younger andesites (Proffett, 1977; cross-section A–A′ of Proffett and Dilles, 1984a). This andesite has a $^{40}Ar/^{39}Ar$ age of 13.83 ± 0.17 Ma (hornblende, 10, Table 1), substantially younger than the 18.2 ± 2.4 Ma K-Ar age of hornblende reported by Proffett and Proffett (1976) and Proffett (1977) from the same lava. They also reported K-Ar ages of 18.1 ± 2.4 Ma (hornblende) for a second flow, and 18.9 ± 2.5 Ma (hornblende) and 19.3 ± 2.8 Ma (plagioclase) for an andesite dike and thus concluded that the andesite of Lincoln Flat is ca. 18–19 Ma. A hornblende-biotite dacite plug inferred to intrude the earliest normal faults in the Yerington district was also resampled and redated: the new $^{40}Ar/^{39}Ar$ ages of biotite and hornblende are 12.64 ± 0.07 Ma and 12.12 ± 0.36 Ma (7 and 8, Table 1), respectively, whereas the K-Ar ages determined by Proffett and Proffett (1976) and Proffett (1977) for these two minerals are 14.5 ± 0.6 Ma and 19.1 ± 2.5 Ma, respectively, and for plagioclase, 18.9 ± 2.7 Ma. We also obtained an age of 13.03 ± 0.02 Ma (biotite, 9, Table 1) on a dacite plug intruding a normal fault in the Buckskin Range. Hudson and Oriel (1979) reported a K-Ar age of 15.7 ± 1.5 Ma (hornblende) for a similar dacite there. We prefer to use the $^{40}Ar/^{39}Ar$ biotite ages of 12.64 and 13.03 Ma for the dacite based on the smaller analytical error compared to the hornblende $^{40}Ar/^{39}Ar$ age (at a 2σ level, the hornblende and biotite ages 7 and 8 are concordant; Table 1). Comparison of the new $^{40}Ar/^{39}Ar$ and old K-Ar ages suggests that the K-Ar ages of andesite of Lincoln Flat and older tuffs reported by Proffett and Proffett (1976) and Proffett (1977) on hornblende and plagioclase are too old by 10%–50%, most likely due to incorrectly low K_2O analyses of these low-K minerals; in contrast, their K-Ar ages on high-K phases biotite and sanidine are within two standard deviation error of the new $^{40}Ar/^{39}Ar$ ages, excepting the biotite age of dacite of Lincoln Flat, which is 15% too old.

Wassuk Group. Up to 2 km of fluvial and lacustrine sedimentary rocks of the Wassuk Group are exposed in fault-bounded basins in the Wassuk Range. They generally dip 25°–45°W and lie in 5°–25° angular unconformity upon older Cenozoic rocks. The Wassuk Group is widespread to the south and west where it has yielded ages of ca. 8–12.5 Ma (Gilbert and Reynolds, 1973; Stewart, 1993). In the northern Wassuk Range, the Wassuk Group consists largely of alluvial fan sandstones and conglomerates (McIntyre, 1990), with lesser landslide breccia and lacustrine mudstone. Two thin rhyolite-to-dacite ash and pumice beds intercalated in the lower part of the sections yielded $^{40}Ar/^{39}Ar$ ages of 8.91 ± 0.06 Ma (biotite) and 8.86 ± 0.08 Ma (hornblende), within error of K-Ar ages of biotites from similar beds elsewhere of 9.4 ± 0.4 Ma (McIntyre, 1990) and 9.5 ± 1.2 Ma (Dilles, 1989; analyses 4, 5, and 22, Table 1). Three other ash-rich beds from the Wassuk and Singatse Ranges contain sanidines that yielded ca. 24 Ma single crystal $^{40}Ar/^{39}Ar$ ages (19, 20, and 21, Table 1), implying that sanidine was principally derived from erosion of the uppermost Oligocene rhyolite ash-flow tuffs—for example, the Blue Sphinx and Bluestone Mine Tuffs.

Basaltic Andesites. Basaltic andesite lava flows up to 60 m thick with plagioclase and sparse oxyhornblende and pyroxene phenocrysts overlie in local slight angular unconformity, or are intercalated with, the uppermost sedimentary rocks of the Wassuk Group and dip 5°– 12°W in the Wassuk and Singatse Ranges. One lava flow in the Wassuk Range that yielded a $^{40}Ar/^{39}Ar$ age of 9.23 ± 0.77 Ma (plagioclase, 3, Table 1) lies 80 m above the Wassuk Group ash bed dated by K-Ar at 9.44 ± 0.22 Ma and 15 m below a similar lava flow dated at 8.4 ± 1.2 Ma (McIntyre, 1990). The ages of these lava flows are slightly older than a K-Ar whole rock age of 7.5 ± 0.4 Ma on another lava flow in the northern Wassuk Range (Bingler et al., 1980) and K-Ar ages of 6.9–7.8 Ma to the south in the Pine Grove Hills (Gilbert and Reynolds, 1973), but similar to a K-Ar whole-rock age of 9.2 ± 0.6 Ma to the north in the Desert Mountains (Bell et al., 1984). In the Singatse Range, we obtained an age of 7.54 ± 0.17 Ma on plagioclase (2, Table 1) from the lowest basaltic andesite lava flow overlying up to 100 m of Wassuk Group sedimentary rocks. K-Ar whole-rock ages obtained by Proffett (1977) from this flow sequence are within error or older: 10.8 ± 1.0 Ma (lowest lava), 8.6 ± 1.3 Ma, and 8.4 ± 1.2 Ma (uppermost lava). We suspect that the 10.8 Ma age may be slightly too old due to an inaccurate K_2O analysis, similar to the old K-Ar ages of the Lincoln Flat unit discussed above. On the west side of the Buckskin Range, which lacks basaltic andesite flows, an ash bed within a gently dipping (0°–15°W) sequence of fine-grained fluvial and lacustrine sedimentary rocks yielded an $^{40}Ar/^{39}Ar$ age of 6.17 ± 0.15 Ma (hornblende, 1, Table 1); these sedimentary rocks unconformably lie on steeply west-tilted Miocene hornblende andesite and older rocks.

Pliocene and Holocene Deposits. Alluvial fanglomerates and sandstones, as well as lesser playa and windblown sand and silt deposits, lie in the modern, fault-bounded basins. The basins are principally half-grabens, bounded on the west by large normal faults along the eastern escarpments of the Pine Nut Mountains and the Singatse, Buckskin, and Wassuk Ranges. The basins east of the Pine Nut Mountains and Singatse Range contain ~1 and 0.8 km of sedimentary fill, respectively, on the basis of gravity data (Erwin, 1970); the Walker Lake basin east of the Wassuk Range may have 2–4 km of fill (Dilles, 1993a). Up to 120 m of gravel and conglomerate occur at the northernmost portion of the Wassuk Range, uplifted along a northwest-striking right-slip fault zone.

Structure

30–12 Ma. The oldest Cenozoic features of the Yerington–Wassuk Range are northwest-trending river valleys containing thick deposits of the Oligocene ash-flow tuffs (Fig. 4 of Proffett and Proffett, 1976), including the basal 28.6 Ma tuff dated by us. Landslide breccias, paleotopographic slopes up to 30°, and minor discordance between the 28.6 Ma tuff and overlying Mickey Pass Tuff suggest faulting, but none has been positively identified.

Northern Wassuk Range. The oldest recognized faults lie in the N40°W-striking, 2- to 3-km-wide White Mountain and Wassuk

Spur fault zones (Dilles, 1993a; Dilles et al., 1993; John et al., 1993), which are referred to herein as faults of the Ancestral Walker Lane because they are now inactive. The major faults strike northwesterly, dip steeply, have minor to major (>1 km) stratigraphic separation, step left en echelon, have horizontal slickensides, and apparently had right-slip motion (Dilles, 1994). A second set of spatially associated, more numerous faults moved synchronously, and these dip moderately, have normal displacement, and commonly have slickensides and fault intersections indicating oblique-slip displacement with east-southeast–west-northwest net slip. These normal oblique-slip faults have dips alternately to the northeast, southwest, and west, and have accommodated tilting to the southwest, northeast, and east, respectively. Mismatch of Mesozoic plutonic and metasedimentary rocks, as well as the thickness of the Oligocene ash-flow tuff section across the northwest-striking fault zones, indicates significant lateral displacement. Dilles (1993a, 1993b, 1994) proposed that the west-northwest–east-southeast strain accommodated by associated normal faults is consistent with right-lateral shear, but Bingler (1978a) proposed left-lateral offset.

The age of the northwest-striking Ancestral Walker Lane faults is bracketed between ca. 26 and 14 Ma. The oldest faults cut the 27.1 Ma Mickey Pass Tuff and the ca. 26 Ma Singatse Tuff, which are hydrothermally altered and associated with landslide breccias with hydrothermally altered clasts. These faults, altered tuffs, and breccias are overlain in angular unconformity up to 70° along a surface with substantial paleotopography by the 24.7 and 24.6 Ma unnamed rhyolite ash-flow tuffs of the Bluestone Mine Tuff. The 25.1 Ma Nine Hill Tuff (basal Bluestone Mine Tuff) lies unconformably on Mesozoic basement, which suggests uplift and erosion of older tuffs, possibly associated with earliest faulting. Younger movement on steeply dipping strike-slip and moderately dipping oblique-slip faults offsets the 23.09 Ma Hu-pwi Rhyodacite, and these faults were subsequently intruded by the 22.2 Ma pyroxene andesite dikes. There are no deposits for the next 7 m.y., but 15–13.5 Ma hornblende andesites mark the end of this early period of Ancestral Walker Lane faulting. The andesite breccias and tuffaceous rocks (14.95 Ma) and overlying andesite lava flows lying southwest of the Wassuk Spur fault zone are cut by normal-oblique slip faults, one of which has been intruded by the 14.0 ± 0.3 Ma andesite dike. The <15°-dipping, 14.08 Ma andesite lava flow overlies and buries both normal and strike-slip faults of the Wassuk Spur fault zone of the Ancestral Walker Lane, and overlies extensive fault and landslide breccias. The 14.08 Ma lava is not cut by faults of the Wassuk Spur fault zone. The 12.85 Ma andesite dike intrudes a strand of the White Mountain fault zone of the Ancestral Walker Lane. We conclude that strike-slip and normal faulting began in the Walker Lane here at ca. 26–25 Ma, was active from 23 to 22 Ma, was active again prior to and during the period 15–14 Ma, and was inactive by 14 Ma.

Yerington District. In contrast to the northern Wassuk Range, in the Singatse Range there is no evidence of faulting prior to 14 Ma. The ca. 29 Ma northwest-trending valleys and minor erosional disconformities beneath the Bluestone Mine Tuff and the tuff and breccia of Gallagher Pass (Hu-pwi) suggest very slight deformation, but no faults have been identified (Proffett and Proffett, 1976; Proffett, 1977).

Proffett (1977) described initiation of normal faulting at Yerington as being synchronous with hornblende andesite and dacite magmatism of Lincoln Flat. The earliest normal faults cut hornblende andesite lava and breccia, now dip 0°–10°E, but initiated with ≥60°E dips and rotated to shallower angles (20°–25°E) during movement. These faults penetrated to >8 km crustal depth, were slightly concave upward (0.3°–0.7°/100 m), were spaced 1–2 km apart, and had displacements up to 4 km; hornblende andesite intrusions are displaced by most faults, but a few intrude fault planes and have fault gouge on their contacts (Proffett, 1977). Thus, the hornblende andesite lava dated by us at 13.83 ± 0.17 Ma, which is cut by the Singatse fault, places a maximum age on the initiation of normal faulting. Plagioclase, hornblende, biotite, ± quartz phenocryst–bearing dacites dated at 13.03 ± 0.02 Ma clearly intrude these shallowly dipping faults in the Buckskin Range (Hudson and Oriel, 1979; J. M. Proffett and Dilles, unpubl. mapping); the dacite dated at 12.64 ± 0.07 Ma is inferred to intrude a similar fault in the western Singatse Range. Therefore, using the 12.64 Ma age of dacite, the earliest normal faults are tightly constrained to have moved between 13.83 and 12.64 Ma or, using a 2σ error at 95% confidence, between 14.2–13.5 and 12.8–12.5 Ma. These ages substantially revise Proffett's (1977) estimates of movement between 17–18 and 11 Ma. The new brackets yield a very narrow, 0.7–1.7 m.y. time interval for the earliest extension and correspondingly higher strain rates. Restoration of cross-section A–A′ of Proffett and Dilles (1984a) across the Singatse Range yields a strain of 1.63 (163%) for this interval, and high instantaneous strain rates for east-west extension of 4.4×10^{-14}/s and 1.8×10^{-14}/s for 0.7 and 1.7 m.y. intervals, respectively. The 163% strain corresponds to a net east-west stretch from an initial 4.46 km length to a final 11.72 km length, corresponding to extension rates of 10.2 and 4.5 mm/yr over 0.7 and 1.6 m.y. intervals, respectively. Higher strain rates over a shorter interval would result from using the 13.03 Ma age of dacite. Inclusion of the Buckskin Range and eastern Yerington district could add up to 50% to the strain estimates.

11–8 Ma. *Northern Wassuk Range.* Faults of this age lie south and west of the zone of earlier faulting in the Ancestral Walker Lane. The faults cut and bound clastic sedimentary basins of the Wassuk Group. Syntectonic landslide breccias intercalated within the sedimentary rocks and localized adjacent to faults occur along moderately east-dipping normal right-oblique slip faults that strike north to northwest, along north-northwest–striking, steeply dipping faults with possibly strike-slip offset, and along northeast-striking, east-dipping left-oblique slip faults (Proffett and Dilles, 1984b; Dilles, 1989; McIntyre, 1989, 1990; Dilles, 1993a). Faults of this age accommodated extension in a west-northwest–east-southeast direction and tilted syntectonic Wassuk Group sediments variably but an average of 30°–35°W (Dilles, 1989, 1993a; McIntyre, 1990). The largest faults are the north-northwest–striking faults, one of which has ~2.7 km normal and ~2.5 km right-lateral displacement (Dilles et al., 1991; Dilles, 1993a; John et al., 1993). These faults are constrained to postdate the 13–15 Ma hornblende andesites and predate the ca. 8–9 Ma basaltic andesites. The two 8.9 Ma ash beds from the syntectonic Wassuk Group date faulting, but because the clastic sediments probably accumulated quickly, substantial faulting prior to 9 Ma seems unlikely. Because the Wassuk Group beds display decreased tilts up section from ~45° to ~10°–15° to where they are overlain in slight angular unconformity or are intercalated with ca. 8–9 Ma basaltic andesite lava flows tilted <15°W, most faulting and associated tilting was synsedimentary in a short interval (e.g., Gilbert and Reynolds, 1973; McIntyre, 1990). The geochronology indicates deposition and faulting in the Wassuk Range probably took place in about a 1 m.y. interval, and certainly less than a 5 m.y. interval. Taking an average 30°W-tilting and initial fault dips of 75°E and 65°E along these extensional normal faults, use of the block fault model of Thompson (1960) yields net strain of ~37%–58%, respectively; these yield estimated strain rates from a maximum of 1.5×10^{-14}/s to a minimum of 4.3×10^{-15}/s over 1 and 3 m.y. intervals, respectively, corresponding to 7.2 and 1.7 mm/yr east-west stretch rates over a final distance of 36 km.

Yerington District. Tectonism was limited during the 11–8 Ma interval in the Singatse Range. A second set of normal faults now dips ~30°E and offsets the earliest (ca. 13 Ma) normal fault set slightly (Proffett, 1977); ~2°–5° of westward tilting and 5% east-west extension may be related to these faults. The faults offset the 13.8 Ma andesite lava flows and were not intruded by andesite or dacites of Lincoln Flat, whereas they predate the 7.5 Ma basaltic andesite lava flow. Wassuk Group sedimentary rocks are thin and tilted only slightly more (~5°) than the overlying basaltic andesites; these data suggest little synsedimentary faulting. Assuming faulting has the same time brackets as in the Wassuk Range and 5% net strain, strain rates in the Singatse Range were an order of magnitude lower (1.5×10^{-15}/s to 5.4×10^{-16}/s); over an ~36 km length, these correspond to east-west stretch rates of 1.7–0.6 mm/yr, respectively, over 1–3 m.y. intervals.

7 Ma to Present. After the eruption of basaltic andesite lava flows in the Singatse and Wassuk Ranges at ca. 7.5–9 Ma, movement began on a third set of down-to-the-east normal faults and has continued since to create the modern ranges. The normal fault on the east side of the Singatse Range strikes north-south, dips 60°E, has a net slip direction of S65°–70°E (Proffett, 1977), and has had ~2 km of normal offset. A similar fault, with less displacement, bounds the Buckskin Range. The N20°E-striking, 50°E-dipping fault bounding the east side of the Wassuk Range has at least 2 km of normal offset on the basis of offset of basaltic andesite lava flows to the valley surface and more probably 4–6 km offset on the basis of an estimated 2–4 km of basin fill. This fault has slickensides pitching 60°SE, indicating a S50°E slip direction (Zoback, 1989). Two N50°W-striking faults in the northern Wassuk Range cut Quaternary alluvium with a right-slip displacement of >2.5 km (Dilles, 1993b). One fault merges southeasterly into the Wassuk Range front fault (John et al., 1993). The 8–9 Ma basalts and ashes are tilted an average of 10°W as a result of this normal faulting. Net east-west strain is estimated at ~11%, which yields an average strain rate of 4.6×10^{-16}/s over the past 7 m.y., or an east-west extension rate of 0.8 mm/yr in the 60 km distance from the east side of the Pine Nut Mountains to the east side of the Wassuk Range.

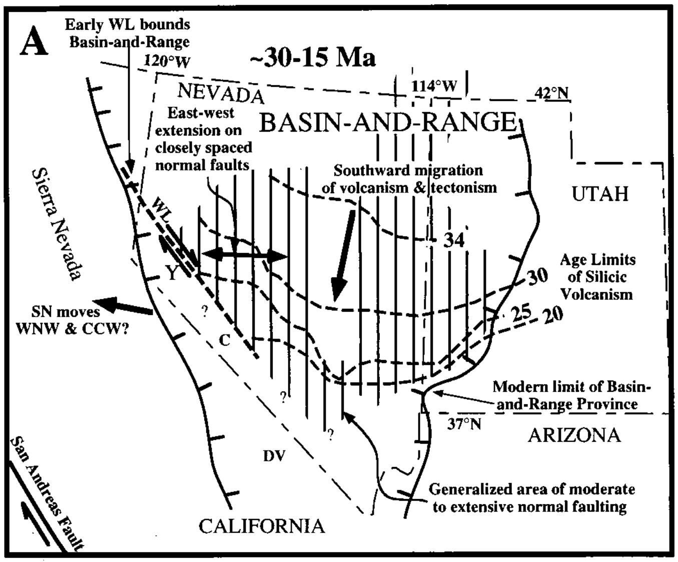
DISCUSSION

The $^{40}Ar/^{39}Ar$ ages reported here resolve several questions regarding the age and duration of faulting in the Yerington district and the adjacent central Walker Lane. Field relations and new ages establish that the Ancestral Walker Lane strike-slip and normal faults became active in the northern Wassuk Range between ca. 26 and 25 Ma, and continued to be active in the intervals from 23 to 22 Ma and from 15 to 14 Ma. In the Yerington district immediately to the west, our new ages tightly bracket the normal faulting and tilting between 14 and 12.5 Ma based on ages of the pre-fault andesites and post-fault dacites of Lincoln Flat; these andesites and dacites were previously dated by K-Ar at 18–19 Ma and 14–19 Ma, respectively (Proffett, 1977). Thus, there is no evidence for faulting in the Yerington district prior to 14 Ma. Extreme strain rates (>10^{-14}/s) in the Yerington district between 14 and 12.5 Ma gave way to lower strain rates of ~10^{-15}/s during Wassuk Group sedimentation at 11–8 Ma and slightly lower strain rates of 5×10^{-16}/s due to active normal faults since 7 Ma.

The Yerington area lies in a region in which normal faulting and characteristic east-west extension of the Basin and Range Province interact with strike-slip faults of the Walker Lane region. As reviewed by Stewart (1988), strike-slip faulting in the Walker Lane belt began ca. 25 Ma and has extended to the present in a broad northwest-trending band also characterized by normal faulting at the western margin of the Basin and Range. The relationship between the early history of faulting along the Walker Lane and the early east-west extension farther east is not entirely clear, in part because the time-space patterns of extension in the Great Basin remain controversial. One interpretation is that the initiation of normal faulting and extension in the Nevada Basin and Range is time-transgressive beginning in the late Eocene in northeastern Nevada and becoming younger to the south and southwest (e.g., Zoback et al., 1981; Wernicke et al., 1987; Armstrong and Ward, 1991; Gans et al., 1989, Seedorff, 1981, 1991a) in general concert with the sweep of magmatism (e.g., Christiansen and Lipman, 1972; Best et al., 1989). An alternative interpretation is that extension is episodic and not correlated with volcanism (Best and Christiansen, 1991; Axen et al., 1993). In the first hypothesis, the initiation of extension reached the Walker Lane area ca. 25 Ma, when strike-slip faulting also began (Fig. 4A).

In westernmost Nevada, areas of moderate and extreme extension as evidenced by 20°–40° and >40° stratal dips, respectively, and gently dipping normal faults form up to 50% of the exposures of pre–23 Ma rocks shown in Figure 1. Northeast of the Walker Lane in western Nevada, several areas of extreme extension formed synchronously with or closely following silicic ash-flow tuff volcanism representing the southwestward sweep of magmatism in the Basin and Range. The earliest closely spaced normal faulting, extreme extension, and tilting, bracketed by pre- and post-fault ash-flow tuffs, are documented at 27 Ma in the Royston Hills (Seedorff, 1991b) and Cedar Mountains (Hardyman et al., 1993) and 24–23 Ma in the Stillwater Range (John, 1993). Faults postdating ash-flow tuffs and predating or associated with andesitic magmatism are bracketed between 29 and 16 Ma in the San Antonio Mountains (Shaver and McWilliams, 1987) and ca. 22–16 Ma in Tonopah–Lone Mountain areas (Nolan, 1935; Bonham and Garside, 1979) and Paradise Range (John et al., 1989). Similar normal faults that may be this age postdate ca. 25–30 Ma tuffs in the Sand Spring Range and Fireball Ridge (Dilles, unpubl. mapping).

The central Walker Lane fault zone also initiated at ca. 25 Ma, as shown by our age brackets of ca. 26–24.7 Ma and 23.1–22.2 Ma for the northern Wassuk Range, ca. 23–21.8 Ma in the Terrill Mountains (Hardyman et al., 1993; John et al., 1993), and ca. 24 Ma in the Gabbs Valley Range (Ekren et al., 1980). In all these areas, strike-slip displacement along northwest-striking, steeply dipping faults is associated with normal or "detachment" faults that extend and rotate Tertiary strata to moderate (~30°) and locally steep (>60°) dips (Hardyman, 1980; Ekren et al., 1980; Keller et al., 1987, 1989; Hardyman and Oldow, 1991). These geologists proposed that the Tertiary section is cut by normal faults and tilted but is everywhere separated from untilted Mesozoic basement rocks by detachment faults in the central Walker Lane. In contrast, in the



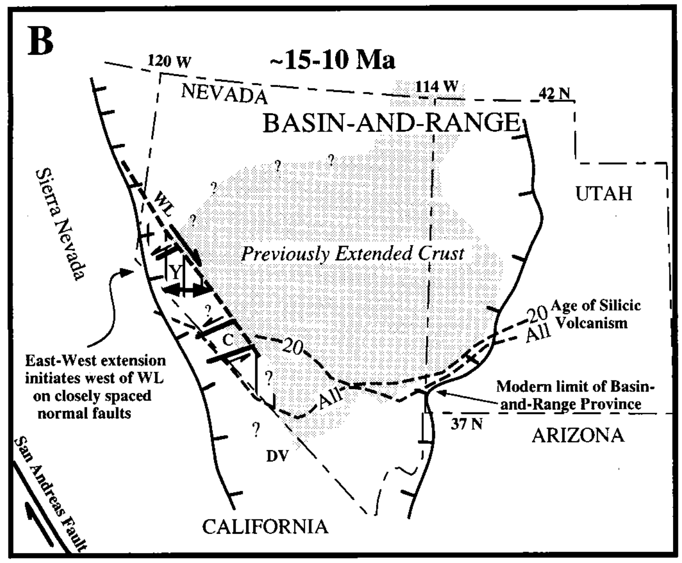
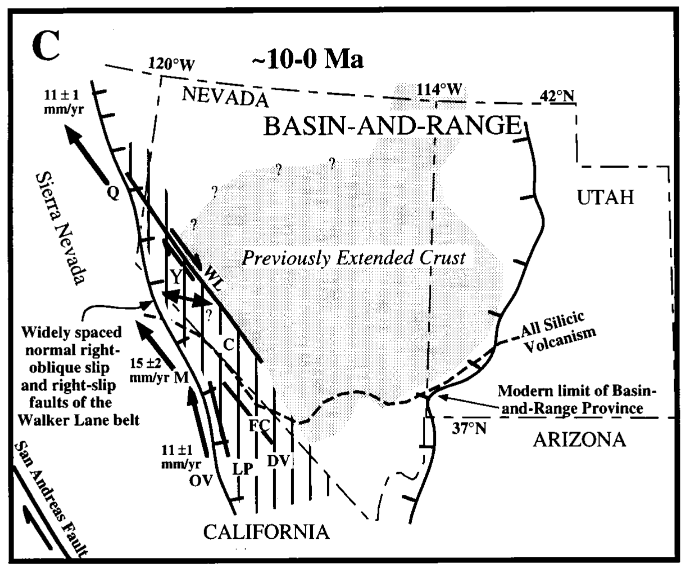


Figure 4. Time-tectonic model for relationship of Walker Lane to Basin and Range extension, with isochrons of southwest limit of silicic volcanism modified from Axen et al. (1993) and data from John (1993) and this study. (A) 40–15 Ma interval illustrates south and west migration of volcanism and tectonism from 40 to 15 Ma leading to initiation of the Walker Lane (WL) fault zone at 26–25 Ma. Right-lateral movement on the San Andreas fault began at 23–22 Ma, and right-transtensional faulting earlier. As discussed in text, we support the published models in which extensional tectonism of the Basin and Range was episodic and migrated southwesterly in general concert with the sweep of magmatism during this time interval (e.g., Seedorff, 1991, Figs. 6 and 7). Closely spaced normal faults occur east of the Walker Lane and moved beginning ca. 27 Ma (see text and Fig. 1). From ca. 25 to 15 Ma, the Walker Lane served as western boundary of Basin and Range. (B) 15–10 Ma interval illustrates beginning of extension west of the Walker Lane, characterized by the Yerington (Y) extreme extensional zone, and development of northeast-striking left-lateral faults, including ca. 15–20 Ma faults at Candelaria (C). (C) 10 Ma to present interval illustrates migration of the normal faulting west to the Sierra Nevada, development of the broad Walker Lane belt extending from northeast California to Death Valley and characterized by right-slip faults in the Walker Lane and (Lone Pine, LP; Furnace Creek, FC) in the Death Valley (DV) region. Current Sierra Nevada–North America relative motion is shown by arrows for Quincy (Q), Mammoth Lakes (M), and Owens Valley (OV) stations from Argus and Gordon (1991).



northern Wassuk Range Dilles (1993a) mapped the Tertiary section in depositional contact atop Mesozoic rocks with both units cut by Ancestral Walker Lane normal and strike-slip faults that accommodated west-northwest–east-southeast strain. Based on the temporal and spatial associations of extensional and strike-slip faulting in the northern Wassuk Range and elsewhere in the Walker Lane at ca. 25–22 Ma and the synchronous initiation of normal faulting directly to the northeast, we hypothesize that Walker Lane faulting was kinematically linked to westward migration of normal faulting across the Nevada Basin and Range. We speculate that right-lateral strike-slip faulting initiated in the extended, thinned, and weakened crust of western Nevada in response to plate margin tectonics. Right-lateral faulting along the San Andreas system of California began ca. 23–22 Ma and was preceded from 26 to 22 Ma by right-oblique extension (Fig. 4; Yeats et al., 1989; Powell and Weldon, 1991; Powell, 1993).

After 25 Ma the southwestward migration of extensional faulting apparently ceased until 15 Ma at lat 39°N. Thus, during the interval 25–15 Ma, normal faulting was bounded on the southwest by the Walker Lane (Fig. 4A). The nature of early movement in the central Walker Lane is controversial and poorly constrained. Keller et al.

(1987, 1989) and Hardyman and Oldow (1991) proposed that early movement was left-lateral on the basis of left-oblique slip faults in the Gabbs Valley Range (Diner, 1983; C. Boyer, p. 33–34 *in* Craig et al., 1992) and possibly synchronous east-west elongated pull-apart basins at Bettles Well in the southeast Gabbs Valley Range and Candelaria (Fig. 1). Dilles (1993a, 1993b, 1994) has argued that normal faults associated with the strike-slip faults in the northern Wassuk Range indicate west-northwest–east-southeast extension compatible with right-slip movement. Regardless of sense of slip, the Walker Lane faults are not thoroughgoing features characteristic of major transform faults with large lateral displacement; rather, they strike N40°W, dip steeply, have subhorizontal slickensides, step left en echelon, and are connected to one another by normal or detachment faults (Hardyman, 1980; Ekren and Byers, 1984; Dilles, 1993a). We propose that the Ancestral Walker Lane was a transtensional accommodation zone separating the extending crust on the east from the intact Sierra Nevada block on the west.

West of the Walker Lane extreme to moderate extensional faulting began at ca. 15 Ma at lat 39°N (Fig. 4B). Near Yerington, this rapid extension is restricted to the Singatse, Buckskin, and northwestern Wassuk Ranges, is bracketed between 14 and 12.5 Ma, and is closely associated with andesite-dacite magmatism. Moderate extension at this time is well documented for the southern Virginia Range and the area east of Carson City, Nevada, and is likely in the Pine Nut Mountains, Pine Grove Hills, and southern Wassuk Range where andesites and older silicic ash-flow tuffs were tilted 5°–30° prior to deposition of 12–8 Ma Wassuk Group (Fig. 1). In the southern Virginia Range ages of 13–14 Ma for andesites and dacites of the Kate Peak Formation date normal faulting (Thompson, 1956; Whitebread, 1976; Vikre et al., 1988). As reviewed by John et al. (1989), for the southeast portion of Figure 1 within and northeast of the Walker Lane, andesite lava flows are commonly slightly older than 15 Ma and closely associated with extension: 20–15 Ma in the southwest Paradise Range (John et al., 1989), 17–19 Ma in the northern Pilot Mountains (Dockery, 1982; Meinwald, 1982; Hardyman and Oldow, 1991), 23–15 Ma in the eastern Gabbs Valley Range (Ekren et al., 1980; Ekren and Byers, 1984); and 17–15 Ma in the Tonopah area (Nolan, 1935; Bonham and Garside, 1979; Silberman et al., 1979). The zones of rapid extension associated with andesitic magmatism form a N60°W belt crossing the Walker Lane at a small angle and with slightly younger ages to the northwest (Fig. 1).

A series of left-lateral and left-oblique slip faults striking N50°–70°E lie west of the Walker Lane but within the broader Walker Lane belt (Stewart, 1988). These faults initiated synchronously with andesitic magmatism and normal faulting at 19–12 Ma: the Bettles Well fault initiated at 17–19 Ma and was inactive by 15–17 Ma (Hardyman and Oldow, 1991); the Candelaria fault initiated after 28 Ma (Speed and Cogbill, 1979); the Borealis Mine fault initiated prior to 16–17 Ma and has Quaternary movement (J. H. Dilles *in* Eng, 1991); the Wabuska lineament has Quaternary displacement (Stewart, 1988), but initiated at 12.5–14 Ma in the Buckskin Range (Fig. 4). The Wabuska lineament may be an accommodation zone between domains of differing extension and tilting at 14–12.5 Ma: 35–40°W in the Yerington area and 10°–30°W to the northwest.

In the period from ca. 11 to 8 Ma, magmatism waned west of the Walker Lane and includes small volumes of basaltic andesite lavas and lesser rhyolite and dacite tuffs. Widespread, moderate magnitude extension along normal oblique-slip faults with both northwest and northeast strikes localized thick clastic sedimentary section of the Wassuk Group and tilted them up to 35°W. These sections are thin or absent in the belt of 12.5–14 Ma moderate to extreme extension from Yerington northwest to the southern Virginia Range. The 11–8 Ma faulting occurs principally in a belt parallel to the Walker Lane but southwest of the 14–12.5 Ma belt and extends from the southern and central Wassuk Range northwestward through the Pine Grove Hills (Gilbert and Reynolds, 1973) and western Pine Nut Mountains into the Reno, Nevada, area (Bonham, 1969), indicating a farther southwestward migration of faulting. These relationships suggest that areas that had previously undergone moderate to extreme extension were less susceptible to renewed extension.

Normal faults responsible for the morphology of the modern ranges west of the Walker Lane became active near Yerington after ca. 7 Ma, similar to the Mono Basin 50 km south (Gilbert et al., 1968) and about the same time as strike-slip and normal faulting in the Death Valley (ca. 10–5 Ma; Reheis, 1993) and Owens Valley regions (3–5 Ma; Bachman, 1978). Sparse bimodal basalt and rhyolite magmatism occurs in the Yerington region. The faults commonly strike N10°–20°W, have right-oblique slip movement (Zoback, 1989), and extend through areas of earlier faulting but also an additional 25 km west to the Sierra Nevada at long 120°W (Figs. 1 and 4C). Thus, the Basin and Range normal faulting at lat 39°N has moved 100 km southwest since 15 Ma. In contrast, right-lateral strike-slip faulting has remained localized in the Walker Lane since ca. 25 Ma.

SUMMARY

We propose that zones of high extension beginning 27 to ca. 22 Ma northeast of the Walker Lane are part of the inferred southwestward temporal migration of episodic Basin and Range normal faulting, associated with or postdating voluminous silicic ash-flow magmatism. This faulting is kinematically linked with normal and strike-slip faulting in the Walker Lane beginning by 26 to 25 Ma and well-documented by 23 to 22 Ma, and continuing at 15 to 14 Ma. The nature of the early, 25–15 Ma Ancestral Walker Lane is poorly understood, but we infer that it was a right-lateral transtensional fault zone separating extending crust on the east from the unextended Sierra Nevada block on the west. Inception of voluminous andesitic magmatism was associated with extension west of the Walker Lane in the Yerington area at 14–12.5 Ma. The rapid, extreme extension (>150%) at Yerington is bracketed between 13.83 ± 0.17 (1σ) Ma and 12.64 ± 0.07 Ma, a 0.7–1.7 m.y. (2σ) interval, indicating very high strain rates corresponding to ~5–10 mm/yr east-west stretching. This rate is similar to the modern northwest-southeast strain rate of 11 ± 1 mm/yr for the Basin and Range at this latitude (Fig. 4C; Argus and Gordon, 1991), suggesting that such extensional zones may briefly accommodate most Basin and Range extension or that the Miocene Basin and Range extensional rate was greater. In the succeeding interval from 11 to 8 Ma, extensional faulting migrated southwest to a zone paralleling the Walker Lane that was characterized by widely spaced faults, clastic sedimentation, and lower strain rates. Since 7 Ma, normal right-oblique-slip faulting has been diffused over a zone >100 km wide west of the Walker Lane, resulting in lower extensional strain rates for given areas. At the latitude of Yerington, in both the 11–8 and 7–0 Ma intervals, the east-west stretching rates when summed over the width of

the Walker Lane belt are similar to the 11 mm/yr strain rate for entire Basin and Range. From 11 Ma to present, strike-slip faulting has remained focused in the Walker Lane despite the westward migration of the normal fault front and has created the broad Walker Lane belt of right-oblique slip faulting.

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APPENDIX: $^{40}Ar/^{39}Ar$ AND K-Ar ISOTOPIC DATA[1]

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[1]GSA Data Repository item 9515 (Appendix) is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

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