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Character and Chronology of Basin Development, Western Margin of the Basin and Range Province

ABSTRACT

Near the western margin of the Basin and Range Province in an area encompassing some 1,500 km^2 between Mono Lake, California, and Yerington, Nevada, six structural basins contain thick accumulations of Miocene-Pliocene sedimentary and volcanic rocks. From approximately 22 to 18 m.y. ago, the area was a highland from which ignimbrite flows of Oligocene age were generally eroded. Subsequent eruptions of andesitic rocks blanketed the area with flows and breccia. Between about 12.5 and 9 to 8 m.y. ago, the area became an integrated basin of sedimentation in which some 2,500 m of strata accumulated. During this period, faulting, along west and northwest trends, and volcanism occurred. Within the basin, surface environments varied from fluvial to lacustrine, and basin margins fluctuated, the maximum extent of the basin having been reached about 10.5 m.y. ago, but a single integrated basin persisted. By approximately 7.5 m.y. ago, the region had been disintegrated by normal faulting into existing structural blocks. Faults of this episode generally trend northeast, east, and northwest. Relative tectonic quiescence ensued for about 4 m.y. During this time a well-graded erosional surface evolved and was locally covered by basic volcanic flows and silicic protrusions, commonly emplaced along faults of the earlier episode. Broad upwarping and block faulting during the Quaternary Period produced the present topography. In contrast to trends of faulting prior to 7.5 m.y. ago, Quaternary normal faults have a north orientation. These faults terminate en echelon in structural warps or by abrupt decrease in displacement to define a northeast-trending lineament across the area, parallel to the Mono Basin–Excelsior zone to the south and the Carson lineament to the north.

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INTRODUCTION

The region studied for this report includes a thick sequence of stratified rocks, both sedimentary and volcanic, that is exposed over an area large enough to encompass six existing structural basins in the western part of the Basin and Range Province. The sedimentary rocks in the sequence vary sufficiently in lithology and facies characteristics to provide a stratigraphic basis for interbasin correlation and for interpretation of depositional environments. Furthermore, many of the rocks are datable by radiometric means, and the sequence is nearly continuous from about 12.5 to 6 m.y. ago. Coupled with the younger sequence involved in studies made in the adjacent Mono Basin area (Gilbert and others, 1968; Christensen and others, 1969), a nearly continuous record of the last 13 m.y. is provided for this general region. The report that follows describes first the character, age, and relations of the various rock units, and then considers the chronology and character of the late Cenozoic deformation.

The area that has been mapped extends more or less continuously from Fletcher and Lucky Boy Pass on the south to Smith and Mason Valleys on the north, and from the western flank of the Wassuk Range to the western part of the Pine Grove Hills (Fig. 1). Mapping on a scale of 1:62,500 or larger was completed in most areas where late Tertiary sedimentary and volcanic rocks are exposed; less attention was given to older volcanic rocks, and basement rocks were not differentiated.

An extensive gravity survey was made to supplement surface mapping, the results of which will be reported in a later publication. It is expected that the gravity data will provide

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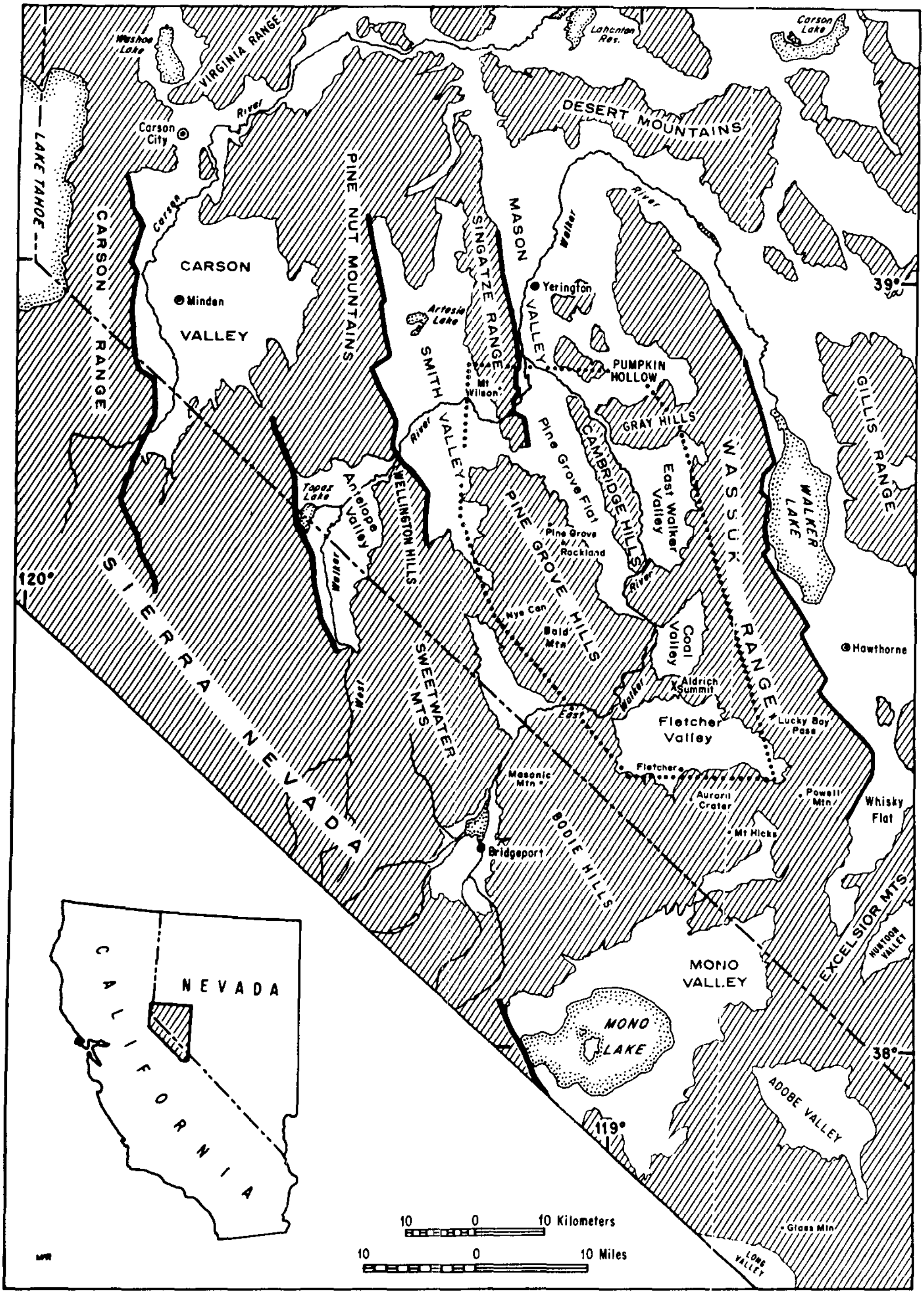

Figure 1. Index map showing part of the western margin of the Basin and Range Province. Dots outline the approximate area mapped during this study, and heavy lines are Quaternary normal faults referred to in the text.

additional information on the depth and configuration of existing structural basins in which the younger sedimentary rocks are preserved.

GENERAL CHARACTER AND AGE OF ROCK UNITS

Regional Basement

Granitic, metavolcanic, and metasedimentary rocks of Mesozoic age are the basement rocks of the region. Over large areas they are buried unconformably by thick accumulations of Cenozoic sedimentary and volcanic rocks. Most of the exposed basement within the region studied for this report consists of quartz monzonite or granodiorite together with a variety of more mafic intrusive rocks. Metamorphic rocks occur as small remnants or pendants in the granitic intrusive rocks. They are undoubtedly of Triassic and Jurassic age (Moore, 1960, 1969), but they were not differentiated.

Quartz monzonite masses in the western Pine Grove Hills have been dated radiometrically as 87 and 90 m.y. old (Krueger and Schilling, 1971, p. 11). These dates correlate the Pine Grove Hills pluton with the Cathedral Range intrusive epoch of Late Cretaceous age in the Sierra Nevada (Evernden and Kistler, 1970). A Late Cretaceous age has also been reported for plutons in the Wassuk Range at Lucky Boy Pass and near Powell Mountain, but a pluton at the northern end of the Wassuk Range has a Late Jurassic age of 140 m.y. (Evernden and Kistler, 1970). Clearly, more than one intrusive epoch is represented by the granitic rocks of the area.

Older Volcanic Rocks

The oldest Cenozoic rocks are rhyolitic ignimbrite flows that are probably correlative with the Hartford Hill rhyolite tuff in the Virginia Range (Moore, 1969). Within the area mapped, these ignimbrites occur in thin sequences in the western Pine Grove Hills, near Morgan Ranch, and at two localities along the eastern margin of Coal Valley (Fig. 2). They are more widespread and thicker to the north along the northeast margin of East Walker Valley and on the northern flank of the Gray Hills, southeast of Yerington. West of Yerington, in the northern Singatze Range, a thick sequence of rhyolitic ignimbrites was mapped in detail by Proffett (1972), who reported K-Ar ages for them ranging from 25 to 28 m.y. The ages of two ignimbrites in the western Pine Grove Hills were determined by Eastwood (1969) as 22.8 and 28.8 m.y. Farther south, similar rocks having similar ages were mapped east of Mono Lake (Gilbert and others, 1968). During early Miocene time, rhyolitic ignimbrites probably covered most of this part of western Nevada and adjacent parts of California. Within approximately 5 to 7 m.y., however, they had been deformed and extensively eroded, for Miocene andesite overlaps them and rests directly on eroded basement over most of the area mapped for this study.

Andesitic flows and clastic rocks of Miocene age are widespread and locally thick in western Nevada and in the Sierra Nevada northward from Mono Lake (Ross, 1961; Slemmons, 1966; Gilbert and others, 1968; Bonham, 1969; Moore, 1969). Flows and coarse breccia predominate, but tuff and andesitic sandstone and conglomerate are interbedded in many places. Locally, at the base of the sequence in the southern Singatze Range and in the western part of the Wassuk Range, bouldery sedimentary lenses containing a variety of basement rocks represent drainage channels across the underlying surface. These channels appear to trend roughly east.

The K-Ar age of a hornblende andesite flow about 15 m above granitic basement in the central Cambridge Hills is approximately 15 m.y. (KA2493, Table 1). Proffett (1972) reported K-Ar ages of andesite flows in the northern Singatze Range from 17.0 to 18.9 m.y. In the Mono Basin area, the oldest andesite flows are interbedded with rhyolitic ignimbrite about 22 m.y. old (Gilbert and others, 1968; samples KA1974, KA2000, KA2074).

Andesitic rocks of equivalent age in the southern part of the area mapped have been silicified, argillized, and propylitized almost beyond recognition. Extensive exposures of these altered rocks occur in the canyon of the East Walker River southeast of the Pine Grove Hills, and along the western flank of the Wassuk Range for several kilometers north and south of Lucky Boy Pass. Near the East Walker River (N. 38°26.45′, W. 118°58.5′), hydrothermally altered andesite is overlain unconformably by unaltered remnants of a hornblende-biotite andesite flow having an average K-Ar age of 12.2 m.y. (KA2362, KA2364, KA2368, Table 1). A dikelike mass of similar andesite in the same area, also unaltered, was intruded along a fault between altered andesite and basement; it has an average age of 12.65 m.y. (KA2372,

TABLE 1. ANALYTICAL DATA FOR POTASSIUM-ARGON AGE DETERMINATIONS

SAMPLE 1/	ROCK TYPE LOCATION (latitude - longitude)	MINERALS ANALYZED	K WEIGHT PERCENT	SAMPLE WEIGHT IN GRAMS	$^{40}Ar_{rad}$ moles/g x 10^{-11}	$\frac{^{40}Ar_{rad}}{^{40}Ar_{total}}$ x 100	CALCULATED AGE 10^6 YEARS
		Older andesite					
KA2493	Andesite N38°43.1' - W119°01.8'	Hornblende	0.6550	2.76115	1.7956	41.0	14.88 ± 0.47
		Hornblende-biotite andesite dike and flow					
2/ KA2362	Andesite (flow)	Plagioclase	0.5377	5.19389	1.1611	40.95	12.11 ± 0.39
KA2364	N38°26.45' - W118°58.35'	Hornblende	0.6159	4.63701	1.3254	28.53	12.07 ± 0.50
KA2368		Biotite	6.123	1.05060	13.4685	31.36	12.33 ± 0.31
KA2372	Andesite (dike)	Biotite	5.489	0.99832	12.1607	41.66	12.42 ± 0.17
KA2373	N38°27.3' - W118°58.55'	Hornblende	0.631	5.14858	1.4556	36.03	12.93 ± 0.45
		Aldrich Station Formation					
KA2379R	Tuff N38°24.8' - W118°56.5'	Biotite	6.111	0.19171	12.4257	17.6	11.40 ± 0.54
KA2375	Tuff	Plagioclase	0.5239	5.00115	1.2121	46.03	12.97 ± 0.39
KA2380	N38°28.8' - W118°58.7'	Hornblende	0.66895	4.01535	1.1467	28.33	12.00 ± 0.50
KA2381	Tuff	Plagioclase	0.5795	5.06752	1.2102	48.94	11.71 ± 0.34
KA2440	N38°37.2' - W118°54.9'	Hornblende	0.5837	2.92661	1.3381	21.50	12.46 ± 0.67
KA2438	Tuff	Plagioclase	0.4154	3.09160	0.7931	7.8	10.55 ± 1.45
KA2503	N38°36.97' - W118°56.3'	Hornblende	0.6593	3.42699	1.5483	36.10	12.76 ± 0.45
KA2501	Tuff	Hornblende	0.7205	4.31707	1.4797	63.7	11.15 ± 0.24
KA2434	N38°43.85' -W119°10.63'	Biotite	6.627	0.91006	11.3416	60.9	9.30 ± 0.09
KA2581	Andesite N38°47.9' - W119°12.1'	Plagioclase	0.6165	3.62521	1.2649	25.7	11.15 ± 0.52
		Coal Valley Formation					
KA2431	Tuff	Plagioclase	0.6051	3.38040	1.0250	28.7	10.23 ± 0.44
KA2432	N38°41.15' - W119°05.3'	Hornblende	0.6479	1.01648	1.2248	25.0	10.42 ± 0.49
KA2439	Tuff N38°41.85' - W119°04.5'	Hornblende	0.5538	3.22236	0.9318	24.0	9.14 ± 0.44
		Basalt flows					
KA2341	N38°40' - W119°12.5'	Whole rock	2.014	5.86923	2.4435	19.4	6.80 ± 0.30
KA2365	N38°36.05' - W119°03.4'	Whole rock	1.824	5.53146	2.1949	63.73	6.76 ± 0.06
KA2366	N38°34.5' - W118°58.3'	Whole rock	2.127	5.20183	2.4895	20.22	6.57 ± 0.27
KA2367	N38°33.67' - W119°10.8'	Whole rock	1.906	5.43180	2.2352	41.23	6.59 ± 0.12
KA2369	N38°35.4' - W118°55.15'	Whole rock	1.740	5.11579	2.2303	65.60	7.20 ± 0.07
KA2496	N38°42.5' - W119°06.4'	Whole rock	1.6185	2.98161	2.2062	42.0	7.41 ± 0.15
KA2497	N38°42.75' - W119°09.7'	Whole rock	1.384	2.85923	1.8124	24.5	7.12 ± 0.24
KA2582	N38°52.65' - W119°12.55'	Whole rock	1.053	8.94159	1.4035	26.13	7.25 ± 0.30
		Rhyolitic protrusions and intrusions					
KA2370	Perlite	Biotite	6.272	1.04844	8.2547	25.0	7.39 ± 0.24
KA2502	N38°34.9' - W119°07.4'	Sanidine & Plagioclase	2.584	2.48456	2.6246	60.3	5.57 ± 0.06
KA2435	Perlite	Biotite	6.6045	0.91486	8.2698	41.7	6.74 ± 0.12
KA2437	N38°36.5' - W119°02.7'	Sanidine & Plagioclase	3.788	4.00287	4.4882	17.2	6.44 ± 0.34
KA2428R	Perlite	Biotite	6.400	0.98639	8.1397	32.8	6.92 ± 0.16
KA2427	N38°37.0' - W119°02.3'	Sanidine & Plagioclase	4.183	5.47083	4.4248	74.2	5.82 ± 0.05
KA2494	Dacite N38°40.5' - W119°02.8'	Plagioclase	0.6686	0.87441	0.6859	8.5	5.58 ± 0.70
KA2436	Rhyolite N38°39.6' - W119°05.25'	Biotite	7.165	1.12696	8.6362	60.2	6.56 ± 0.05
		Unnamed sedimentary rocks, Smith Valley					
KA2491	Tuff	Hornblende	0.7365	1.13548	0.4204	21.3	5.02 ± 0.26
KA2513	N38°45.63' - W119°13.8'	Biotite	5.803	0.90156	5.1695	13.1	4.97 ± 0.35

1/ K-Ar Laboratory, Department of Geology and Geophysics, University of California, Berkeley, sample number

2/ Dates on sample from same hand specimen

KA2373, Table 1). Unconformities between altered and unaltered andesite were also mapped some 15 km farther south, by Johnson (1951) and Al-Rawi (1969) north of Bodie and again south of Aurora, where one of the younger unaltered andesites has a K-Ar age of 12.5 m.y. This unconformity represents a distinct period of faulting, hydrothermal alteration, and erosion during late Miocene time. In this paper the term "older andesite" refers to andesitic

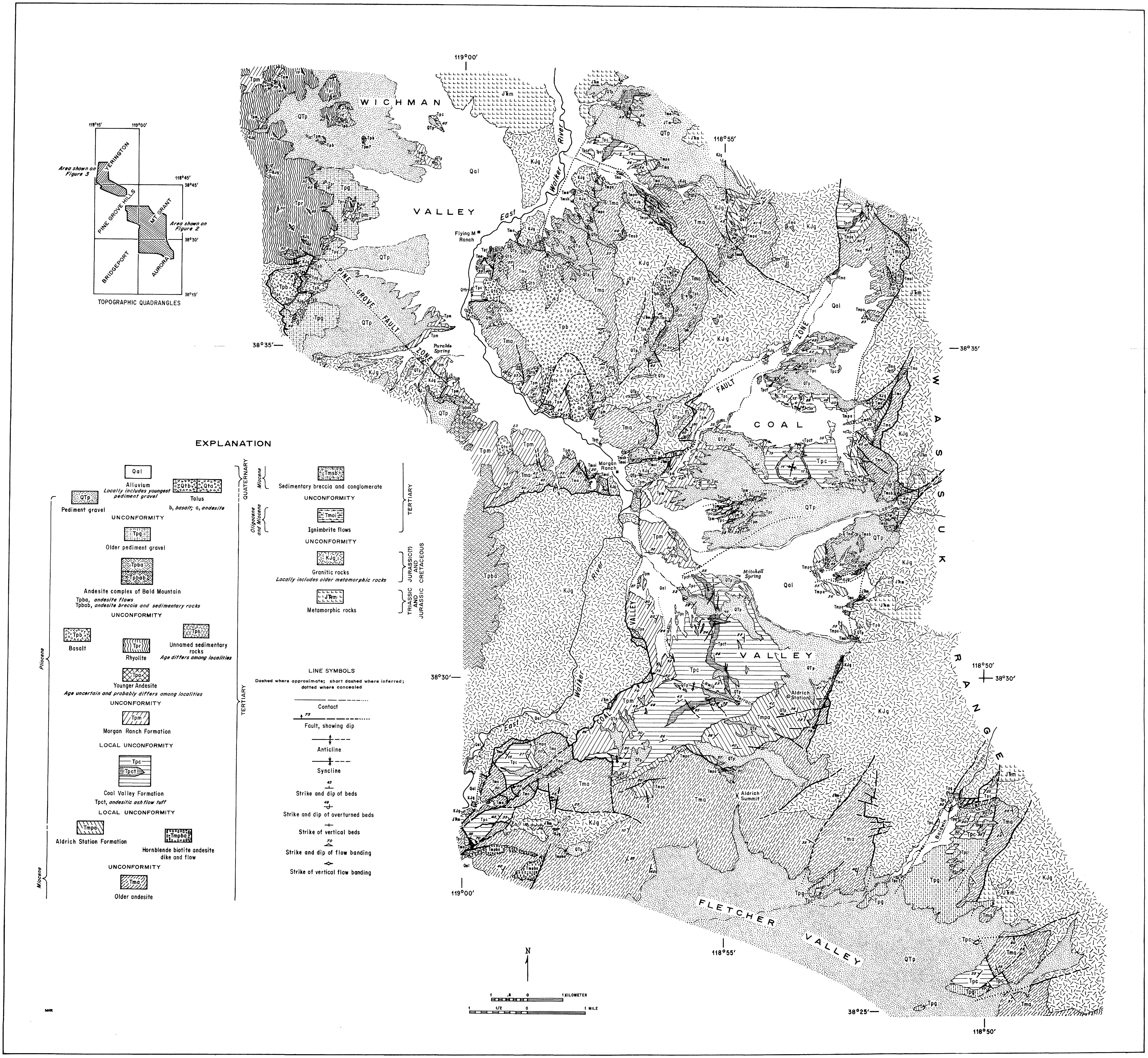

Figure 2. Geologic map of the East Walker River area, Lyon and Mineral Counties, Nevada.

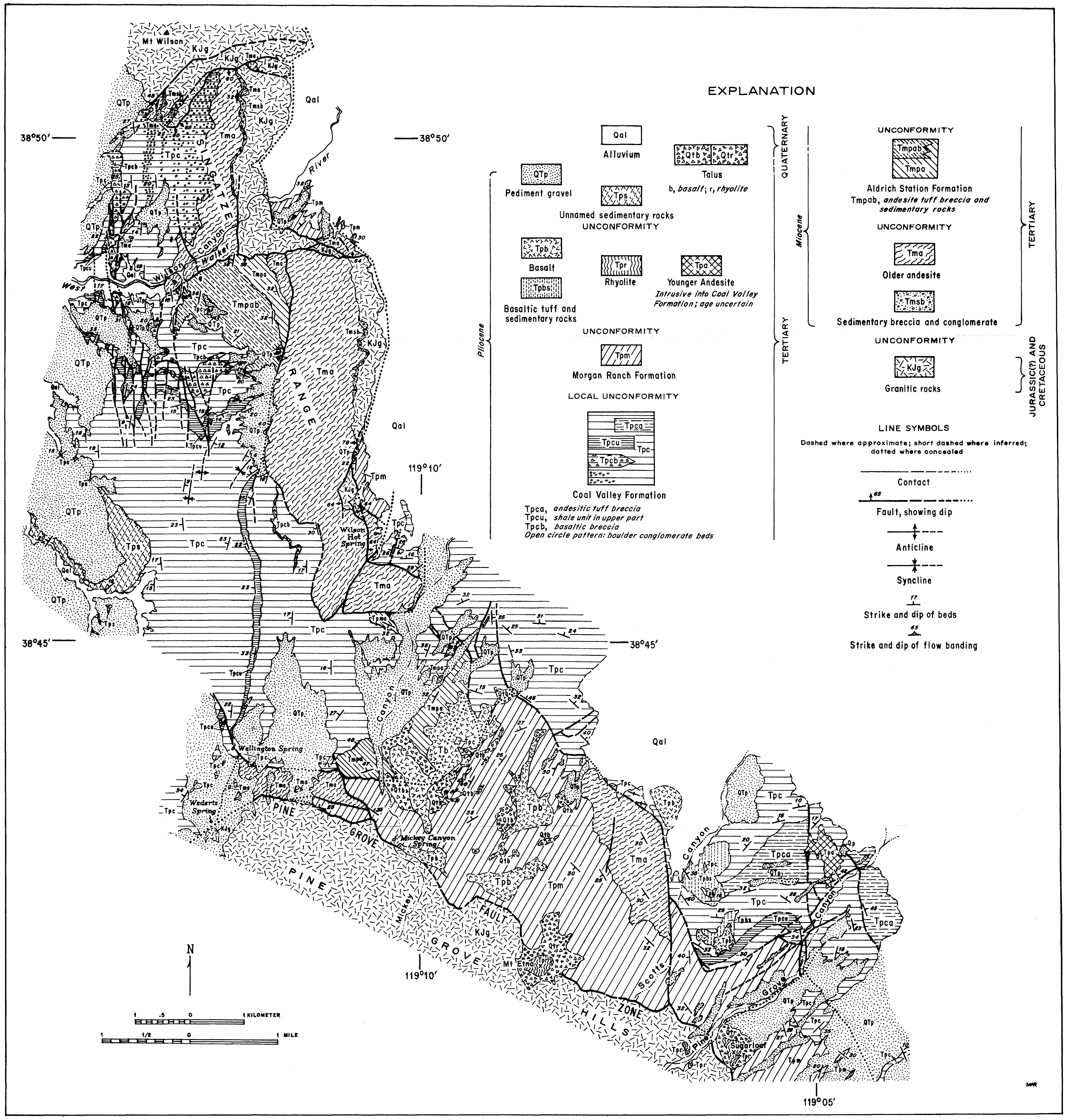

Figure 3. Geologic map of the northern Pine Grove Hills and southern Singatze Range, Lyon County, Nevada.

rocks that antedate this discontinuity and are older than about 15 m.y.

Upper Miocene and Pliocene Sedimentary Formations

Axelrod (1956) named and described three sedimentary formations in Coal Valley which together measure approximately 2,500 m in thickness and constitute the Wassuk Group. The two oldest of these, the Aldrich Station and Coal Valley Formations, are fluviolacustrine deposits consisting largely of andesitic detritus and containing numerous tuff beds. The younger Morgan Ranch Formation consists largely of basement detritus; it contains numerous coarse sedimentary breccias and a few tuff beds. Fossil floras and mammalian faunas collected from these formations have led to age assignments of upper Barstovian–lower Clarendonian for the Aldrich Station Formation, Clarendonian–lower Hemphillian for the Coal Valley Formation, and Hemphillian for the Morgan Ranch Formation (Axelrod, 1956, p. 61; Evernden and others, 1964, p. 162–164).

Four K-Ar ages determined for biotite from tuff beds in the uppermost part of the Aldrich Station Formation, as defined by Axelrod (1956), average 11.0 m.y., and a date for biotite from a tuff bed near the base of the Coal Valley Formation is 10.8 m.y. (Evernden and others, 1964). The boundary between Aldrich Station and Coal Valley Formations is hereby redefined, and all of the foregoing tuff beds are considered to be lower Coal Valley. Biotite from tuff near Wilson Canyon in the southern Singatze Range in what is now recognized as the upper part of the Coal Valley Formation has a K-Ar age of 9.3 m.y. (Evernden and others, 1964). During the present study, K-Ar ages were determined for tuff beds at different localities in the Aldrich Station and Coal Valley Formations (Table 1). These dates taken in conjunction with those reported by Evernden and others (1964) indicate for the Aldrich Station Formation, as presently defined, an age of about 12.5 to 11 m.y., and for the Coal Valley Formation an age of about 11 to 9 m.y. The overlying Morgan Ranch Formation is itself overlain unconformably by olivine basalt flows as old as 7.4 m.y.; it has also been intruded by rhyolitic rocks approximately 7 m.y. old.

Formations of the Wassuk Group extend the length and breadth of the area mapped, but they now are preserved in separate structural basins. From south to north, these basins are Fletcher Valley and Baldwin Canyon, Coal Valley, Wichman Valley, East Walker Valley, Pine Grove Flat, and Smith Valley (Fig. 1). Stratigraphic relations show, however, that the formations accumulated in a single large basin having a northwest trend and extending at times beyond the limits of our mapping.

Younger Volcanic Rocks

Tuff and andesite breccia and flows in the Aldrich Station and Coal Valley Formations testify to continuing volcanism during late Miocene and early Pliocene time. The large volume of volcanic debris in these formations was partly derived from erosion of older andesites, but much of it was supplied by contemporary volcanism. One center of contemporary eruption has already been mentioned, a dike and flow of hornblende-biotite andesite near the East Walker River south of Coal Valley, which has an age of about 12.5 m.y. A few other eruptive centers are inferred near localities where flows or coarse eruptive breccia are interbedded in the sedimentary formations, for example, at the northeastern end of Coal Valley and south of Wilson Canyon. Other areas of active volcanism during this period, between about 8 and 12.5 m.y. ago, have been reported to the south in the Bodie Hills and eastern Mono Basin (Gilbert and others, 1968; Silberman and Chesterman, 1972), to the west in the Sierra Nevada (Slemmons, 1966), and to the north in the Virginia Range (Bonham, 1969).

Volcanic rocks younger than the Morgan Ranch Formation include flows of olivine basalt and andesite and irregular intrusive bodies and protrusions of flow-banded rhyolite and dacite. Small flows of olivine basalt ranging in age from 6.6 to 7.4 m.y. (Table 1) occur north and east of Morgan Ranch, at a number of localities around the Pine Grove Hills, and in the Singatze Range. Intrusions and protrusions of flow-banded rhyolite and dacite, many of them glassy and perlitic, are abundant in the central and eastern parts of the Pine Grove Hills and along the eastern margin of the range. The average of four K-Ar ages for feldspar in these rocks is 5.8 m.y.; the average age for biotite is 6.9 m.y. (Table 1). The southern portion of the Pine Grove Hills structural block, known as Bald Mountain, was the center of late andesitic eruptions, and most of the range south of Nye Canyon is covered by andesite flows. Along the south side of Nye Canyon and at the southwest margin of Wichman Valley, andesite flows of the Bald

Mountain complex overlie olivine basalt flows having ages of 6.6 and 6.8 m.y. (KA2365, KA2367). The andesite flows represent a distinctly younger volcanic episode than both the basalt and rhyolite, for in Nye Canyon they are unconformable against rhyolite and are separated from the dated basalt by gravel and lenticular shale. Reliable radiometric dating of the Bald Mountain andesite complex has not been possible, presumably because of abundant inclusions of glass throughout feldspar phenocrysts and widespread oxidation of mafic minerals; however, we consider an age of at least 5 m.y. likely. Our judgment is based on the fact that the Bald Mountain rocks were erupted prior to the upwarp which has produced rejuvenation and extensive dissection in the area. A small, completely separate andesitic complex intrudes the upper part of the Coal Valley Formation north of the mouth of Pine Grove Canyon and may have been erupted during this same interval.

Volcanic rocks younger than the Bald Mountain complex have not been recognized within the area mapped during the present study. Pleistocene basalt flows occur along the southern margin of the area, near Fletcher, and volcanic rocks younger than 3.5 to 4 m.y. are widespread farther south (Gilbert and others, 1968). Pleistocene volcanic rocks, mostly basaltic flows, also occur farther north in the area between Truckee and the Virginia Range; reports of these were summarized by Bonham (1969, p. 39).

Younger Sedimentary Deposits and Erosional Surfaces

Tuff interbedded with arkosic sandstone and conglomerate at the southeast margin of Smith Valley (Fig. 3; N. 38°46′, W. 119°14′) has a K-Ar age of about 5 m.y. (KA2491, KA2513, Table 1). These strata are, therefore, late Hemphillian (Evernden and others, 1964, Table 6). They overlie upper Coal Valley strata unconformably and have themselves been tilted to the northwest by as much as 20°. The exposed thickness is approximately 60 m.

Pediment gravel and alluvium cover most of the surface in the large structural depressions where the Miocene-Pliocene sedimentary formations are preserved. In Coal Valley, three pediment levels can be distinguished, the highest and oldest of which has been named the Lewis Terrace by Axelrod (1956, Fig. 2). This surface now stands 250 m above the East Walker River; near Aldrich Station it has been dissected by tributary streams to a depth on the order of 150 m (Fig. 4). Two lower and younger pediments are evident above the level of present drainage channels in many parts of Coal Valley. Also, along the eastern margin of the Pine Grove Hills, three pediment levels can be distinguished, and at least two can be distinguished in East Walker Valley, Fletcher Valley, and along the southeast margin of Smith Valley. Wherever the pediment surfaces have not been dissected and remain intact, the underlying rocks are concealed by pediment gravel, but the gravel is everywhere only a veneer. In most parts of the area, extensive bedrock exposures are to be found in the numerous gulches that have been cut into the pediments.

Remnants of the Lewis Terrace are preserved on hilltops and ridges south and west of Aldrich Station, where they truncate tilted flows of older andesite and strata of the Aldrich Station, Coal Valley, and Morgan Ranch Formations (Fig. 2). The surface is remarkably even and is mantled by coarse, subangular gravel from 1 to 25 m thick which was derived from local basement rocks and Miocene andesite. The broad extent and general accordance of the Lewis Terrace with erosion surfaces cut across basement both north and west of Coal Valley are evident and impressive when viewed from the terrace level just north of Aldrich Summit (Fig. 4). The surface slopes generally westward toward the East Walker River, approximately 50 m per km near the base of the Wassuk Range and less steeply farther west. Near the river at the southwest corner of Coal Valley, accordant surfaces on granitic rock have little apparent slope, and west of the river, they slope eastward. Taken together, these remnants of the Lewis surface suggest a very broad, well-graded valley, presumably the valley of the East Walker River at an earlier stage in its history.

A detailed structural chronology requires that the age of the Lewis surface be estimated as closely as possible. It is older than the regional uplift which has caused the youthful dissection of the area, and that uplift was presumably coincident with the late period of deformation in Mono Basin, which began between 3 and 4 m.y. ago (Gilbert and others, 1968). The Lewis surface was the landscape at that time, but it undoubtedly had evolved during a considerable period of tectonic stability and erosion. A surface of low relief, in places cut across tilted Morgan Ranch strata and buried locally by basalt flows 6.6 to 7.4 m.y. old, probably represents the early part of that period of erosion, for that surface west of Coal Valley and west of Morgan Ranch is accordant with the Lewis Terrace. North of Coal Valley, however, remnants of basalt flows stand 60 to 90 m above adjacent parts of the Lewis surface cut across granitic basement, indicating some further evolution of the surface after outpouring of the flows in that area (Fig. 4). Furthermore, the occurrence of sedimentary deposits about 5 m.y. old and as thick as 60 m in Smith Valley indicates at least local downwarping and basin filling while the Lewis surface evolved. Thus, we regard the Lewis surface to be the product of slow erosion during a period of relative tectonic quiescence that lasted about 4 m.y. Probably the surface evolved more rapidly and was largely developed during the early part of this period and thereafter was but little modified until regional rejuvenation began 3 to 4 m.y. ago.

A fossil mammalian fauna from pockets of sandstone in the northern part of Wichman Valley (Fig. 2) is reported to be of Blancan age, approximately 1.5 to 3.5 m.y. (Macdonald, 1956; Evernden and others, 1964, Table 6). The deposits containing these fossils are, therefore, younger than the Lewis surface, and they presumably accumulated during the period of regional rejuvenation while a younger pediment graded to the rejuvenated river was developing across Wichman Valley. In the vicinity of the fossil locality (N. 38°37.8′, W. 119°0.8′), strata as thick as 200 m and tilted westward are exposed beneath younger, coarse pediment gravels. The tilted strata include mudstone, arkosic sandstone and siltstone, pebble conglomerate, diatomite, and tuff. Exposures are fragmentary so that the structure and relations of the deposits are uncertain. Coal Valley beds crop out farther east, and the tilted beds at the fossil locality appear to be in an overlying position. Farther west, a small, isolated remnant of olivine basalt (undated) overlies pebble conglomerate similar to that near the fossil locality, and near the western margin of Wichman Valley, small exposures of tilted tuffaceous mudstone and arkosic sandstone and conglomerate are intruded and overlain by rhyolitic perlite having an average age of 6.5 m.y. (KA2435, KA2437, KA2428R, KA2427). We regard the deposits containing the Blancan fossils as being a local accumulation lying unconformably on older tilted strata, which are probably Morgan Ranch.

STRATIGRAPHY OF THE WASSUK GROUP

The three formations assigned to the Wassuk Group by Axelrod (1956) are of special importance to this report because their distribution and internal facies changes provide

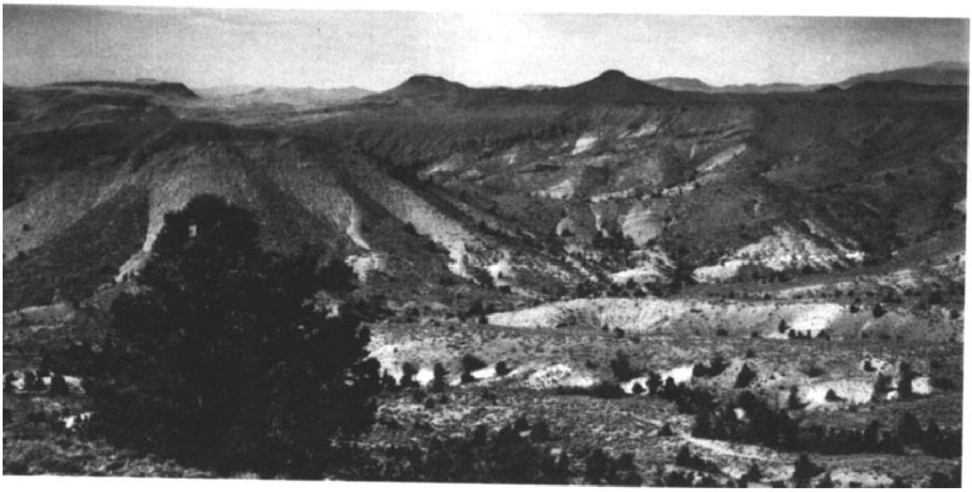

Figure 4. Lewis Terrace, viewed north from equivalent surface on the north side of Aldrich Summit. Pediment gravel mantling the surface rests on tilted beds of the Coal Valley Formation. Peaks rising above the surface in the background are capped by a basalt flow 7.2 m.y. old.

evidence concerning the times and extent of basin development and, locally, of faulting. These formations, the Aldrich Station, Coal Valley, and Morgan Ranch, crop out more widely than Axelrod described in his treatise on the flora of the type locality. Characteristics of the formations at their type localities were summarized by Axelrod (1956, p. 23–35, Fig. 3). This portion of our report describes the areal extent, important characteristics, and intrabasinal correlation of the formations. We conclude that they were deposited successively in a basin that differed in size and configuration during late Miocene and Pliocene time. The maximum extent of the basin was reached about 10.5 m.y. ago during deposition of the Coal Valley Formation. During deposition of each formation the basin was significantly larger than present basins in this portion of the Basin and Range Province.

Aldrich Station Formation

This formation crops out in separate fault blocks from near Aldrich Station northward to Wilson Canyon (Figs. 2, 3, 5). It is composed of an easily recognizable sequence of carbonaceous mudstone and siltstone, diatomaceous shale, lithic arenite, and pebbly lithic arenite beds; the finer grained rocks are dominant. Thin vitric tuff beds are present in all sections, and units of vitric crystal tuff, locally reaching thicknesses of 55 m, are present at Aldrich Station, Lapon, Mickey, and Wilson Canyons (Fig. 5). Correlation of specific tuff units, however, is not always possible among sections, but generally similar sequences can be identified. Stratified and massive andesite tuff breccia units are interbedded in the upper part of the formation in the southern part of the Singatze Range south of Wilson Canyon, and thin lenses of tuff breccia are present southwest of Aldrich Station. An undated sequence of andesite tuff breccia, tuff, thin carbonaceous shale, and lithic arenite, underlying a thin sequence of typical Aldrich Station rocks in the northeast corner of Coal Valley, may be correlative with a part of the formation at other sections.

We concur with the interpretation of Axelrod (1956, p. 26–28) that the rocks were deposited in alternating lacustrine and fluviatile environments, with lacustrine conditions prevailing across the basin for longer durations than fluviatile conditions. Eruptions of andesite tuff breccia occurred near the basin margins late in Aldrich Station time.

The terrigenous rocks are generally pale brown and upon weathering or drying assume a characteristic white or very pale-orange color. Beds split shaly to produce smooth slopes locally interrupted by ledges of resistant sandstone or tuff beds. Red beds, at places containing cobbles and boulders of older andesite, mark the base of the formation southwest of Aldrich Station, in the East Walker Valley, and south of Wilson Canyon.

The formation rests unconformably on the sequence of older andesite flows and tuff breccia. Generally, the contact is sharp and relief along it seems to be low. Elsewhere the formation is faulted along high-angle faults against various units including the Morgan Ranch Formation (Mickey Canyon; Fig. 3) and Mesozoic granitic or metamorphic rocks (south of Lapon Canyon; Fig. 2).

At Aldrich Station the formation is about 755 m thick.[1] Northward along the west flank of the Wassuk Range to the East Walker Valley the formation thins, and in the last exposures it is about 300 m thick (N. 38°37.2′, W. 118°-54.67′). Within a distance of 2.4 km westward from that locality, the formation thins to about 185 m. Such abrupt thinning, largely at the expense of diatomaceous claystone and mudstone near the center third of the formation, may reflect incipient uplift near the Cambridge and Gray Hills. At Mickey Canyon the Aldrich Station is 370 m thick, but it thickens northward to about 730 m at Wilson Canyon as tuff breccia beds appear in the formation. The most marked thickness change occurs at the southern exposures of the formation where the formation thins from 610 to about 70 m across a fault that was active during deposition.

Uniformly fine-grained rocks comprising the formation across the area attest to a nearly continuous depositional basin surrounded by land areas of low relief. The approximate positions of the southern and northern margins of the basin can be defined by facies and thinning relations (Fig. 5). From Aldrich Station southwest to the limits of the exposure west of Aldrich Summit, the formation thins abruptly across a west-northwest-trending fault (N. 38°28.67′, W. 118°55′ to N. 38°29.05′, W. 118°56.3′; Fig. 2). Most of the thinning occurs in the lower half of the formation, seemingly by the loss through convergence or

[1] Axelrod (1956, p. 24) measured 1,235 m, but this thickness includes some beds (his unit A_6) assigned in this report to the Coal Valley Formation.

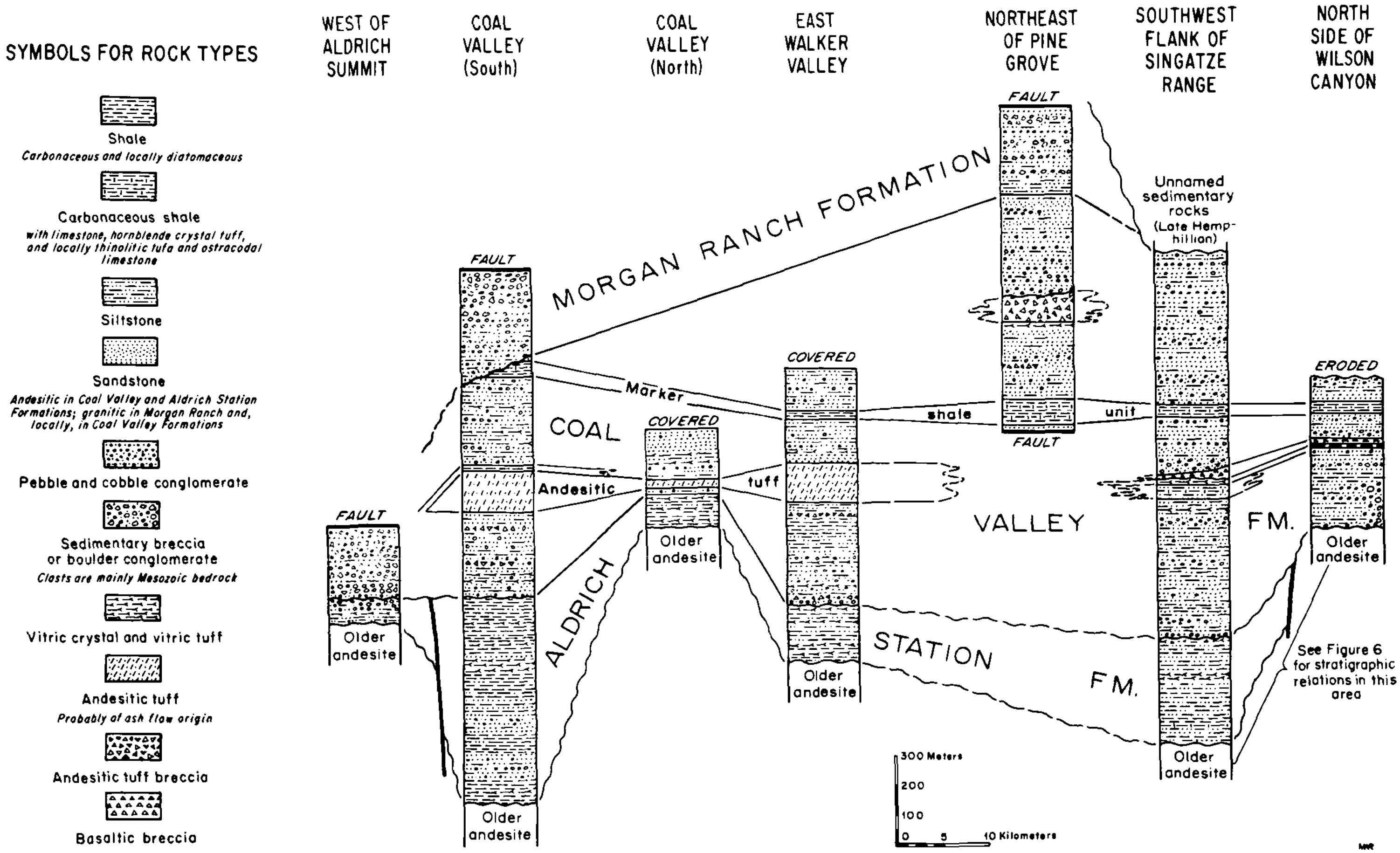

Figure 5. Correlation of Wassuk Group strata from Coal Valley to the southern part of the Singatze Range.

nondeposition of the finer deposits. Coincident with the thinning is a marked coarsening of sediments and an increase in the amount of conglomerate in the formation. Lenses of andesite pebble conglomerate crop out north of the fault, but south of the fault cobble and boulder conglomerate beds are the dominant rocks in the thinned stratigraphic section. Clasts are andesite, altered andesite, and granite; the matrix is usually andesitic or arkosic sand. Clearly, the fault was active during deposition. About 4.8 km farther southwest near the East Walker River and east at Baldwin Canyon, the formation is absent. Thus the southern margin seems to be defined by an east-northeast-trending highland through Aldrich Summit. The presence of the growth fault, described above, nearby to the north suggests that the southern margin of the basin may have owed its elevation to faulting.

Another abrupt facies change south of Wilson Canyon in the Singatze Range implies a basin margin nearby on the north. The lower portion of the formation contains typical mudstone, siltstone, and carbonaceous shale beds with lenses of lithic arenite and pebble conglomerate. Upward, the abundance of pebble conglomerate increases and beds of lapilli tuff are present; a conspicuous unit of water-reworked biotite crystal tuff present both in this sequence and in the finer-grained section of the Aldrich Station Formation at Mickey Canyon demonstrates equivalence of the rocks. About 85 m stratigraphically above the tuff at Wilson Canyon, units of stratified andesite tuff breccia, which pass laterally and vertically into massive units of tuff breccia, are interbedded with carbonaceous and porcellaneous shale, siltstone, and pebbly conglomerate. These units contain very common fragments of petrified wood. Tuff breccia near the top of the formation at Wilson Canyon is dated radiometrically as 11.15 m.y. (KA2581), thus confirming the temporal equivalence of these rocks with fine-grained sedimentary rocks in the formation to the southeast. The northern margin of the sedimentary basin seems to have been north of Wilson Canyon where a center of andesitic volcanism existed.

Late Tertiary and Quaternary uplift and erosion across the Wassuk Range on the east and Pine Grove Hills on the west preclude close definition of the basin margins in those directions. Fine-grained facies of the Aldrich Station Formation immediately adjacent to the present ranges indicates that the basin extended at least partway across the sites of the ranges. Only at the center of the present Wassuk Range (N. 38°36.67′, W. 118°52.8′) is a possible margin suggested by thinning of the formation and interfingering of volcanic breccia and tuff.

The identified approximate margins suggest a depositional basin elongate in a northwest direction and encompassing the area of four present valleys and parts of three present mountain ranges.

Coal Valley Formation

The Coal Valley Formation is the most widespread formation of the Wassuk Group as it now crops out in five separate basins. The southernmost outcrops of the formation are along Mud Spring Creek at the south edge of Fletcher Valley where only a thin portion of the formation is exposed; more extensive exposures in that present basin are in Baldwin Canyon. From its type section in Coal Valley the formation crops out discontinuously from Morgan Ranch northward to the north flank of Mount Wilson in the Singatze Range, north of which it is absent (Proffett, 1972). The northwest end of the Pine Grove Hills and the west flank of the Wassuk Range define the known west to east extent, respectively, of the formation (Figs. 2, 3).

Andesitic sandstone, pebble and cobble conglomerate, and mudstone and siltstone are dominant rocks in the formation (Fig. 5). Beds of vitric or crystal tuff are scattered through the formation, and lenses or thick accumulations of andesite breccia are interbedded, particularly in Coal Valley and east of Pine Grove. For mapping, the base of the formation is defined to include the lowest sequences of andesite pebble conglomerate and sandstone overlying the highest continuous thick sequence of mudstone beds typical of the Aldrich Station Formation. This horizon marks an unconformity identifiable across the southern end of Coal Valley. Coupled with the lithologic change, it is our basis for revising downward the formation boundary initially described by Axelrod (1956, p. 29–30). We place the boundary at the base of his uppermost (A_6) Aldrich Station unit.

In detail, the stratigraphic succession varies vertically and laterally as strata of fluviatile and locally lacustrine origin interfinger at all scales. Near the Lewis Terrace, the formation is a monotonous succession of interbedded bluish-gray or olive-gray weathering andesitic sandstone, pebble conglomerate, and tuffaceous siltstone. These same rocks characterize the major part of the formation across the region. Several distinctive units can, however, be traced from valley to valley to facilitate correlation among sections now separated by bedrock uplifts (Fig. 5).

One such unit in the lower part of the formation is a remarkable bed of andesitic tuff (unit C_2 of Axelrod, 1956, p. 30), interpreted here as being an ash-flow tuff. The base of the bed is coarse grit composed of angular fragments of andesitic tuff, granite, and feldspar. In the coarse-grained part are angular blocks and fragments as much as 35 m long, torn from underlying portions of the formation and incorporated at odd angles within the bed. The grain size decreases uniformly upward to the top, which consists of silt and clay-sized particles. The center of the bed weathers to reveal closely spaced tubules aligned normal to the contacts of the bed, which are interpreted as being formed by channels of gas-streaming during cooling of the bed. The bed thickens from a feather edge to about 150 m south of Lewis Terrace, but northward as far as East Walker Valley the thickness ranges from 5 to 125 m. In general, the thinner sections are farther east than the thicker ones.

A second unit, important for correlation in the upper part of the Coal Valley Formation along the east flank of the Pine Grove Hills and west flank of the Singatze Range, consists of a sequence of white-weathering tuffaceous siltstone and shale beds, containing a few thin layers of buff aphanitic, ostracodal limestone and hornblende pumice tuff. Calcareous sandstone and fine-pebble conglomerate beds locally interfinger with the finer grained rocks, and the upper part of the unit contains beds of distinctive thinolitic tufa. In Coal Valley the unit is 45 m thick; limestone and tufa beds are absent, but shale and hornblende pumice tuff beds persist. There the younger Morgan Ranch Formation rests unconformably on the unit but truncates it 0.5 km farther south (N. 30°30′, W. 118°56′). On the east flank of the Pine Grove Hills, the unit is about 100 m thick and is overlain by as much as 550 m of typical rocks of the Coal Valley Formation. The unit then thins northward to 50 m on the north side of Wilson Canyon, where it is separated below by about 55 m of andesitic siltstone, sandstone, and pebble conglomerate beds from a conspicuous biotite crystal tuff and basalt breccia unit. Evernden and others (1964, p. 178; KA485) dated the crystal tuff as 9.3 m.y. old, although following Axelrod (1956, p. 67), they assigned the unit to the Morgan Ranch Formation. Clearly, these rocks belong to the Coal Valley Formation, and the date establishes an early Hemphillian age for the upper part of the formation. The lower part of the formation, dated at approximately 11 m.y., is of Clarendonian age.

Several facies changes can be defined in the Coal Valley Formation using the two described units for reference. Southwest from Lewis Terrace, increasing amounts of coarse sedimentary breccia interfinger with sandstone and conglomerate beds. At the southwesternmost exposures of the formation (N. 38°27.5′, W. 119°0′), massive beds of sedimentary breccia form the entire preserved part of the formation. Rock fragments in the breccia units include andesite and propylitized andesite of Miocene age and metavolcanic, metasedimentary, and granitic rocks of Mesozoic age. The edge of the basin along which basement rocks were exposed lay only a short distance west and southwest. Farther southwest, slightly younger latite ignimbrite units (about 9.5 m.y.) are separated from Miocene andesite or Mesozoic basement rocks by only a veneer of andesitic sandstone and conglomerate (Gilbert and others, 1968, p. 286).

In the lower part of the Coal Valley Formation, mudstone and siltstone beds and carbonaceous siltstone beds are common between Lewis Terrace on the south and near Lapon Canyon on the north. These rocks grade southward into andesitic sandstone interbedded with andesitic tuff breccia and northward into andesitic sandstone and siltstone. These relations suggest that the deepest part of the basin, in which lacustrine and paludal environments prevailed, lay in the area of the present Coal Valley. A similar unit consisting of diatomaceous mudstone, siltstone, and very fine-grained sandstone, as much as 25 m thick, overlies the marker andesitic tuff from Lewis Terrace to Lapon Canyon. South and north of these localities the unit thins and grades into sandstone and siltstone beds of fluviatile origin. Apparently, for a second time during deposition of the Coal Valley Formation, a lacustrine environment persisted in the Coal Valley area long enough for a significant thickness of sediment to accumulate before fluviatile sediments again blanketed the area.

A pronounced facies change occurs in the lower part of the formation in the vicinity of Wilson Canyon (Figs. 5, 6). At the north end

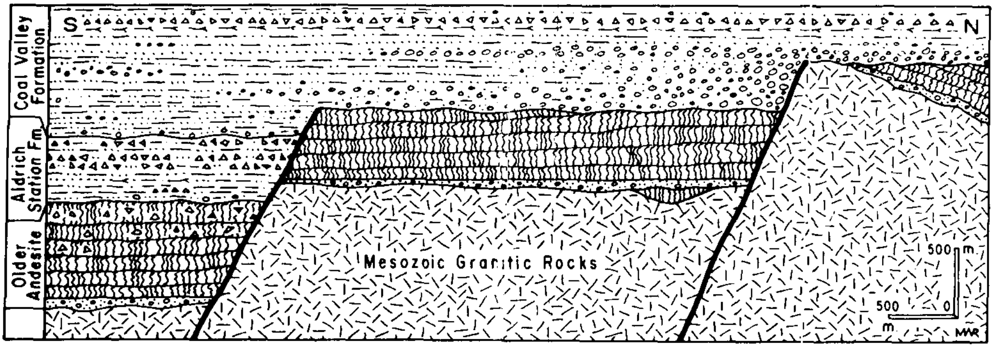

Figure 6. Schematic representation of Aldrich Station and Coal Valley strata across late Clarendonian–early Hemphillian faults in the southern Singatze Range near Wilson Canyon and Mount Wilson. Northward coarsening of Coal Valley strata reflects proximity of the basin margin.

of the Pine Grove Hills, the lower part of the formation contains dominantly fine-grained rocks including siltstone and fine-grained sandstone, locally tuffaceous, that weather to form smooth, soft slopes. The lowermost beds are juxtaposed against older andesite along a fault just south of Wilson Canyon (N. 38°48.5′, W. 119°13.0′), but the upper portion of these beds extends continuously across the fault and across Wilson Canyon. This relation dates movement along the east-trending fault (Figs. 3, 6) as latest Clarendonian. Finer grained rocks that are not offset by the fault interfinger rapidly northward across Wilson Canyon with coarse sandstone, conglomerate, and bedded sedimentary breccia. Clasts include granodiorite and granitic debris, metavolcanic rocks, and Miocene andesite.

On the south flank of Mount Wilson, clasts coarsen to as large as 4 m across adjacent to a northeast-trending fault. There the Coal Valley Formation is composed mostly of granodiorite boulder conglomerate. Along the fault nearly all of the conglomerate sequence on the south abuts granodiorite on the north (Fig. 3). However, the uppermost beds of boulder conglomerate and overlying beds, including the distinctive biotite crystal tuff and basalt tuff breccia, can be mapped unbroken across the projection of the fault. Southward the boulder bed interfingers in a succession of sandstone and siltstone beds. The fault was active during deposition of part of the formation with the upthrown block of basement rock on the north contributing granitic debris to the basin adjacent on the south (Fig. 6).

Although most rock fragments in the Coal Valley Formation are andesite and altered andesite, clasts of granitic composition or minerals derived from granitic rocks are locally important constituents and are significant in interpreting the tectonic history of the region. As noted, coarse granitic debris is abundant near the identifiable margins of the basin on the southwest and north. Within the basin the lowermost 185 m and the uppermost 275 m of the formation on the north flank of the Pine Grove Hills contain granitic clasts. Similarly, the upper quarter of the formation in Coal Valley is locally arkosic. These occurrences indicate that basement rocks were exposed, possibly by recurrent faulting west of the basin, during early and late Coal Valley time. Both the granitic debris and the thick sections of andesitic sediments in the upper part of the formation suggest the possibility that progressive uplift along the western margin of the basin led to erosion of previously deposited Coal Valley sediments there, and to their redeposition together with granitic debris farther east in the continuously subsiding deeper portion of the basin. The apparent near conformity between the Coal Valley and overlying Morgan Ranch Formation in the deeper part of the basin lend support to this interpretation of progressive, rather than abrupt, uplift to the west.

Complete sections of the Coal Valley Formation are exposed only at the north end of the Pine Grove Hills and at the southern end of Coal Valley; elsewhere in the area only partial sections are present, owing to later faulting or erosion. At the former locality the formation is about 1,350 m thick, whereas at the latter we measured 970 m.

At most localities the Coal Valley Formation rests unconformably on older units. North of Mount Wilson it rests on granitic basement rocks; south of Mount Wilson and also west of Aldrich Summit, it rests on older andesite. Disconformity with the underlying Aldrich Station Formation is evident near Aldrich Station and at Lapon Canyon where cobble conglomerate comprises the basal Coal Valley beds. Unconformable relations are especially evident in the southern part of the Singatze Range where the Coal Valley rests on progressively older beds of the Aldrich Station from north to south (Fig. 3).

The Coal Valley Formation was deposited in a basin that extended beyond the present limits of its outcrop. The eastern basin margin is unknown, but judging from the thickness and extent of beds along the west flank of the Wassuk Range, it must have been east of the range. Similarly, the western margin is unknown; coarser facies in the vicinity of the Pine Grove Hills suggest a margin not far beyond the present hills. On the south a margin must have extended east-southeast from Fletcher toward Powell Mountain. During deposition the northern margin migrated progressively northward with time, overstepping fault blocks rising across the southern part of the Singatze Range (Fig. 6). It is likely that the final northern margin lay at the latitude of the present central part of the range. Thus, the basin seems to have been elongate in a northwest direction. Uplands composed primarily of andesitic volcanic rocks must have been rising to the southwest, west, and northwest, with faulting and erosion at least locally exposing crystalline basement rocks. Within the basin, localized volcanic eruptions produced andesite breccias interbedded in the formation.

Morgan Ranch Formation

At the type locality the Morgan Ranch Formation consists of coarse clastic sediments overlying Coal Valley strata and in fault contact with granitic basement along the western margin of Coal Valley. It measures as much as 400 m thick in this area. The primary basis for distinguishing the sequence is a change from tuff and andesitic sandstone, which characterize the Coal Valley Formation, to arkosic sandstone and breccia derived principally from granitic and metamorphic basement rocks. The general color of the two units also differs, being gray to light brown in the Coal Valley and orange-brown to yellow-brown in the overlying Morgan Ranch strata. The Morgan Ranch sequence coarsens upward, and the uppermost portion is largely coarse, poorly sorted breccia, which Axelrod (1956) interpreted as fanglomerate deposited against a rising escarpment in front of a basement high. Feldspathic sandstone, commonly coarse and pebbly, is interbedded with breccia units and predominates in the lower part of the formation. The sandstone beds are as much as 3 to 6 m thick; many are cross-bedded and show scour along upper and lower surfaces.

The name Morgan Ranch is used in this study also for arkosic strata that crop out extensively west and north of Morgan Ranch and along the northeastern margin of the Pine Grove Hills (Fig. 3); limited exposures occur at the northeast end of Coal Valley. These rocks are composed largely of debris derived from local basement rocks with a variable admixture of andesitic debris. They are generally similar in character and age to type Morgan Ranch strata, but they are thicker and tend to be finer grained. Along the northeast flank of the Pine Grove Hills, Morgan Ranch strata are approximately 1,225 m thick, and most of the exposed sequence consists of well-bedded, brown sandstone, siltstone, and shale or mudstone. Beds of coarse, poorly sorted breccia are also present and are as characteristic of the formation here as they are in the type locality, particularly in the upper part of the formation, but in most exposed sections the breccia beds are fewer and thinner than they are in Coal Valley. Breccia units are interbedded with friable, brown sandstone, and they contain principally granitic and metamorphic debris and relatively little andesitic debris. The coarse breccia beds contain blocks 1 to 2 m across, with sporadic larger blocks, and they occur in units as much as 15 to 25 m thick. Typically, such units are graded without distinct stratification, and the upper portions are made up of fragments no larger than 5 or 6 cm. Fine-grained breccia also occurs separately in units as much as 1 m thick.

The relation between Morgan Ranch and Coal Valley Formations is variable. In most places, exposed contacts are faults. Where depositional contacts can be mapped, as in Coal Valley, stratification is generally approximately parallel in the two formations, and they appear conformable. Axelrod (1956) reported that they are conformable. Careful mapping in Coal Valley shows, however, that stratal units in the underlying Coal Valley Formation are progressively overlapped southward. To the north the two do indeed appear to be conformable, but at the northwestern margin of Coal Valley a pronounced local unconformity occurs. Both formations are truncated along a fault against granitic basement east of Morgan Ranch (Fig. 2). On the upthrown block north of this fault, Coal Valley strata are absent, and the Morgan Ranch Formation rests directly on older andesite. Both formations have been displaced, but Coal Valley strata together with any Aldrich Station strata originally present had been removed from the upthrown block before Morgan Ranch strata were deposited. A similar unconformity is evident across the fault at the mouth of Scotts Canyon (Fig. 3). South of Pine Grove Canyon (N. 38°41.3′, W. 119°5.3′), Morgan Ranch strata disconformably overlie the Coal Valley Formation.

Facies changes in the Morgan Ranch Formation along the northeast flank of the Pine Grove Hills are evident but can be delineated only in a general way. Part of the section exposed northeast of Mickey Canyon Spring consists primarily of thin-bedded, gray, silty shale which is commonly carbonaceous; the section coarsens to the southwest. Breccia is a lithofacies particularly characteristic in the upper part of the formation, but it also varies laterally and is partly controlled by proximity to the fault bounding the basement block. Many individual breccia units terminate abruptly. For example, northeast of Mickey Canyon Spring, where the exposed section strikes toward the fault (Fig. 3), breccia units increase in number, coarseness, and thickness as the fault is approached. South of Pine Grove Canyon, the upper part of the exposed section contains abundant units of coarse breccia; traced northwestward toward Pine Grove Canyon, breccia units lens out and the equivalent section becomes largely sandstone with only a few interbedded breccia beds.

Units of porous limestone and calcite-cemented breccia are interbedded in the Morgan Ranch Formation at several localities along the Pine Grove Hills fault zone. They have the appearance of tufa-type deposits and were probably produced by springs emerging along the fault. They are interbedded through about 100 m of section, indicating that the fault was presumably active during deposition of the strata. Best exposures of these rocks are to be found on the southeast flank of Mount Etna (Fig. 3); others occur northwest of Mickey Canyon Spring.

These facies relations suggest to us that the fault bounding the Pine Grove Hills basement block approximately delineates the western margin of Morgan Ranch deposition. The formation probably accumulated, as Axelrod (1956) inferred, in front of a rising basement block, the breccia representing both the times and the places of most active colluvium and fanglomerate deposition, the finer facies representing the more distal depositional environments on the subsiding block to the northeast. Such origin would probably produce thicker sections to the west near the fault and thinning to the east, but this cannot be established from existing surface exposures.

PERIODS OF FAULTING AND WARPING

Quaternary movement along normal faults has produced steep escarpments and delineated a number of the most prominent ranges and valleys in this general region, notably the escarpment near Topaz Lake facing Antelope Valley, and the eastern escarpments of the Carson Range facing Carson Valley; the Pine Nut Mountains and Wellington Hills facing Smith Valley; the Singatze Range facing Mason Valley; and the Wassuk Range facing Walker Lake and Whisky Flat (Fig. 1). These escarpments are all steep and lofty and have been relatively little eroded. Their youthful age has been demonstrated in a number of places. Along the southern part of the Wassuk Range, olivine basalt flows having an age of about 3.5 m.y. have been displaced the full height of the range front (Gilbert and others, 1968). The escarpment of the Sierra Nevada facing Mono Basin is younger than basaltic flows having a K-Ar age of about 3 m.y. and also younger than the earliest glacial stage (Curry, 1966; Gilbert and others, 1968). Recent movement along the front of the Carson Range has long been recognized (Lawson, 1912; Moore, 1969, Fig. 8). A basalt flow that caps the Singatze Range and is offset by the frontal fault about 7 km north of Wilson Canyon has a K-Ar age of 7.25 m.y. (KA2582).

By contrast, geologic relations mapped during the present study demonstrate that the faults delineating the Pine Grove Hills and Coal Valley structural blocks are older than about 7.5 m.y. and have not been reactivated during the Quaternary deformation of the region. The eastern front of the Pine Grove Hills, for example, is not a Quaternary fault scarp despite the fact that the margin of the basement block is a fault of large displacement; nor has the fault zone that bounds the basement block west and northwest of Coal Valley had Quaternary movement.

Deformation during early or middle Miocene is indicated by the unconformity between rhyolitic ignimbrite 22 to 28 m.y. old and andesite 15 to 18 m.y. old. The wide regional distribution of the ignimbrite units suggests that they formed a more or less continuous terrane during the time of eruptions, but they are lacking in many parts of the area mapped during the present study. Younger andesite flows lie directly on basement rocks in the southern Singatze Range, in the Cambridge Hills, on the structural high between Coal Valley and East Walker Valley, and along the margins of Fletcher Valley (Figs. 2, 3). It appears that the area mapped was structurally high and eroded during the period between about 18 and 22 m.y.

Faults of late Miocene age have been mapped near the southern margin of Coal Valley and in the southern Singatze Range. One near the East Walker River, south of Coal Valley (N. 38°27.4′, W. 118°59.9′), is the contact between altered andesite and granitic rock and has been followed by a dikelike intrusion of younger andesite having an age of about 12.5 m.y. The younger andesite has not been sheared, as is evident from its glassy contact selvages, and fault movement must have occurred between about 12.5 and 15 m.y. This fault trends approximately east and is nearly vertical. A second fault cutting Aldrich Station and lower Coal Valley strata north of Aldrich Summit trends west-northwest to northwest, dips steeply, and was active during deposition of the displaced strata. In the Singatze Range, two east-northeast-trending faults, one just south of Wilson Canyon and the other on the south flank of Mount Wilson, displaced lower Coal Valley strata but are overlapped by upper Coal Valley beds only slightly older than 9.3 m.y. (Figs. 3, 6). Major displacement along the southern fault occurred during an interval between deposition of Aldrich Station and Coal Valley strata. On the downthrown block to the south, Coal Valley beds unconformably overlie an Aldrich Station sequence 740 m thick, whereas on the upthrown block to the north, Coal Valley beds rest directly on older andesite flows. The uppermost Aldrich Station strata have a K-Ar age of 11.15 m.y. (KA2581), and the oldest unfaulted Coal Valley strata are only slightly older than tuff dated as 9.3 m.y. old.

Movement along many of the faults began before and continued after Morgan Ranch deposition. Along some of these faults, such as near Morgan Ranch and at Scotts Canyon, earlier movement followed by erosion of Coal Valley and Aldrich Station strata from the upthrown blocks has resulted in local unconformities where younger Morgan Ranch beds overlap the faults. The evidence for both pre- and post–Morgan Ranch movement along these faults is indisputable, and a similar history is probable along many other faults in the area. Along the Pine Grove Hills fault zone, movement during Morgan Ranch deposition is indicated by facies relations of Morgan Ranch strata, but pre–Morgan Ranch movement cannot be proved, because all of the sedimentary formations are confined to the downthrown block. This very fact, however, suggests that movement along the Pine Grove Hills fault zone probably began during pre–Morgan Ranch time, resulting in removal of older strata and exposure of basement rocks west of the fault by the time Morgan Ranch strata were accumulating. Perhaps movement along the fault zone was more or less continuous. Arkosic Morgan Ranch strata would then have accumulated east of the uplifted block when and where basement detritus became predominant. If such was indeed the history, one must conclude that the boundary between Coal Valley and Morgan Ranch Formations is a lithologic boundary that is probably not the same age throughout the area.

Morgan Ranch strata, as well as older strata, have been faulted and tilted, locally to high angles. This deformation was completed before eruption of the younger volcanic rocks 6 to 7 m.y. ago. East of Mickey Canyon Spring, a flow of olivine basalt having a K-Ar age of 7.1 m.y. (KA2497) unconformably overlies the tilted and faulted formations of the Wassuk Group, and a dikelike mass of the basalt is intruded along the Pine Grove Hills fault southeast of the spring. In the southern Singatze Range north of Mount Wilson, olivine basalt having a K-Ar age of 7.25 m.y. (KA2582) unconformably overlies tilted Coal Valley beds faulted against granitic basement. Likewise, north of Morgan Ranch, tilted and faulted Morgan Ranch Strata are buried by relatively undeformed basalt having an age of 6.6 m.y. (KA2366). An andesite flow belonging to the Bald Mountain complex buried tilted Morgan Ranch Formation and older andesite in fault contact with granitic basement west of Morgan Ranch (Fig. 2). Furthermore, rhyolitic protrusions have been emplaced along and across the Pine Grove Hills fault. The largest and most numerous of these occur west of Wichman Valley, where they have obscured the fault boundary between granitic basement and Morgan Ranch Formation (Fig. 2). The northernmost is a small protrusion situated squarely on the fault at Mount Etna north of Scotts Canyon (Fig. 3).

The structural history of this area during the last 7 m.y., since the eruption of basalt and andesite flows and rhyolitic protrusions, does not include reactivation of earlier faults. Broad uplift has occurred, however. This is clear from the rejuvenation of the East Walker River along its course between Bridgeport and Mason Valley. The river is incised below the Lewis surface by as much as 250 m in the area west and southwest of Coal Valley. The amount of incision decreases northward and is negligible at the southern end of Mason Valley, so that the uplift has the appearance of a broad upwarp. The sequence of dissected younger pediments below the Lewis Terrace testifies to some periodicity in the upwarping movement.

A more pronounced and local upwarp has produced the higher elevation of the old erosion surface on the summit of the Pine Grove Hills and is responsible for the present relief of that range. Specific evidence of the upwarp can be seen along the northern flank of the range. Here, young basalt flows were erupted onto surfaces of low relief cut across relatively nonresistant sedimentary formations. The flows are now tilted northward at angles as high as 20° and have been deeply dissected. Even here, however, older faults were not reactivated despite the proximity of the Singatze fault block which was uplifted during Quaternary time. Displacement along the young fault zone at the eastern front of the Singatze Range diminishes southward from Wilson Canyon and disappears at the Pine Grove Hills upwarp, about 8 km south of Wilson Canyon.

Other local Quaternary upwarps may be present in the region but are not clearly distinguishable. The Cambridge Hills may be one, but exposures along its margins are so poor that structure and history are uncertain. Along the eastern side of the Cambridge Hills, relatively small escarpments trending north are suggestive of normal faulting, and this may be a small Quaternary fault block, tilted westward like others in the region.

GEOMETRY OF STRUCTURES

Regional Configuration

Faulting prior to 7.5 m.y. produced structurally low areas in which the Miocene-Pliocene sedimentary formations are preserved, and intervening structurally high areas where older rocks are now exposed and elevations are generally higher. Each large structural block is itself complexly faulted, but the gross configuration of structural highs and lows reflects the structural trends characteristic of the earlier period of Basin-Range deformation. These trends are typically northeast to east and northwest. Coal Valley, for example, is separated from Fletcher Valley and Baldwin Canyon to the south and from Wichman Valley and East Walker Valley to the north by structural highs that trend east-northeast and northeast, respectively. The Gray Hills trend nearly east and separate two structural lows, East Walker Valley to the south and Pumpkin Hollow to the north. The Pine Grove Hills trend northwest.

By contrast, all of the Quaternary fault block ranges in the region have general trends that are north or north-northwest (Fig. 1). These younger fault blocks stand prominently in the general topography, and they tend to obscure the earlier structures and structural trends. However, many faults within the young-range blocks are of earlier (Tertiary) age and trend northeast or northwest at marked angles to the general north trend of the range as a whole. Over most of the area mapped during the present study, Quaternary faulting was minimal or did not occur, and the major fault zones trend either northwest or northeast.

Miocene-Pliocene Faults

Most of the faults mapped during the present study are normal faults that have displaced formations of the Wassuk Group and older volcanic rocks but have not been active during the last 7.5 m.y. Most dip at angles between 50° and 70°, but dips range from 40° to vertical. Most individual faults of this age, as well as major structures, trend northeast, but some individual faults and fault segments trend nearly north. Of the latter, only a few have large displacement and seem significant. One of these on the west flank of the southern part of the Singatze Range (Fig. 3) forms the east boundary of the sedimentary section in that area. Another at the mouth of Scotts Canyon had both pre- and post-Morgan Ranch movement, and another at the southern end of East Walker Valley truncates a sequence of Aldrich Station strata 300 m thick against granitic basement. Several north-trending faults along the eastern margin of Coal Valley are relatively small and may have had Pleistocene movement. The most extensive fault zones having the largest displacements are the Pine Grove Hills fault zone forming the northeastern margin of the Pine Grove Hills basement block and the Coal Valley fault zone forming the northwest margin of the Coal Valley block and the southeast margin of the Pine Grove Hills block. These fault zones consist of fault segments that strike in different directions producing an irregular fault trace that is locally zig-zag. Because of this irregularity, we conclude that movement along the zones has been dip-slip without significant strike slip.

Along the Pine Grove Hills fault zone, the basement complex forming the higher part of the range is faulted against Morgan Ranch strata, except along the northernmost and southernmost parts where older andesite is faulted against granitic rocks (Fig. 3). The trace of the fault can be mapped in detail from a little south of Pine Grove Canyon to the northernmost part of the range; farther south, it is obscured by rhyolitic protrusions that bury or intrude it (Fig. 2), so that only the general location of the fault can be determined. Northwestward from Pine Grove Canyon, the general trend of the fault zone is N. 60° W., but the trace is irregular and consists of segments as long as 2 km which strike northwest, north, and east-northeast. Where the attitude of the fault surface can be determined, it dips away from the range at an angle of about 60°. Southeastward from Pine Grove Canyon, the general trend is S. 35°, E. 40° as far as the southern margin of Wichman Valley. There the fault bounding the basement block turns west-southwest beneath andesite breccia units and flows of the Bald Mountain complex and reappears 3.5 km to the south where it strikes east through Morgan Ranch to an intersection with the Coal Valley fault zone (Fig. 2).

The Coal Valley fault zone is the margin of the basement complex west of Coal Valley. Its general trend is northeast, but its trace is irregular. For about 3 km east of Morgan Ranch, the trace is zig-zag, consisting of short east, northeast, and northwest-trending segments (Fig. 2). In this area the fault surface dips toward Coal Valley at an angle of 40° to 45°. Farther east, poor exposures preclude detailed mapping, but the general trend continues northeast. South of Morgan Ranch, the general trend of the fault zone for about 5 km is approximately north, and again the trace is very irregular. The fault surface dips steeply eastward in this area, but at one locality the dip is steeply westward. The fault turns again toward the southwest and continues across the East Walker River toward the structurally low area south of the Pine Grove Hills. South of Morgan Ranch, the Coal Valley fault zone is the southeastern terminus of the Pine Grove Hills structural block.

Fault structures on the western flank of the Wassuk Range between Lucky Boy Pass and Aldrich Station are a series of northeast-trending horsts and grabens bounded by steeply dipping normal faults (Fig. 2). Most noteworthy is the Baldwin Canyon graben within which about 600 m of Coal Valley strata are exposed between granitic basement on the northwest side of the graben and older andesite and basement rocks on the southeast. Farther north also, the eastern margin of Coal Valley is cut by faults trending northeast into the Wassuk Range, although some north-trending faults occur here as well. Faults cutting sedimentary strata within Coal Valley most commonly have northeast trends.

The structure east of the Cambridge Hills is obscured by pediment gravel and alluvium. Rocks exposed at the southern end of East Walker Valley have been displaced along faults trending northeast, northwest, and north. To the north, our gravity traverse across the Gray Hills shows a pronounced negative anomaly in the north end of East Walker Valley relative to gravity values over basement in the Gray Hills. These data are not yet fully analyzed, but a fault along the southern margin of the Gray Hills, trending approximately east, is probably to be inferred with a buried sequence of Miocene-Pliocene sedimentary rocks south of it.

Major Miocene-Pliocene faults cross the southern Singatze Range near Wilson Canyon and along both the north and south flanks of

Mount Wilson. All are normal faults having dips between 45° and 70° and trends that are east-northeast or northwest. They are demonstrably older than 7.5 to 9.3 m.y. Moore (1969, p. 19) reported that a major fault zone trending east-northeast marks the southern end of the Pine Nut Mountains and suggested that this may be the same as the east-northeast-trending fault zone crossing the Singatze Range at Wilson Canyon. Whether the two are the same fault zone cannot be established, but they probably are of similar age and have had little or no Quaternary movement. The present study demonstrates conclusively that the fault crossing the Singatze Range at Wilson Canyon was active during late Miocene time (Clarendonian) and has not been active since. Present relief at the southern end of the Pine Nut Mountains is probably to be attributed to relatively deep erosion of nonresistant sedimentary rocks on the downthrown block to the south rather than to late fault movements.

Folds Related to Miocene-Pliocene Faulting

Low-amplitude folds, approximately 0.5 to 3 km across, are associated with faults in Coal Valley and near Pine Grove Canyon (Figs. 2, 3). The folds undoubtedly developed as normal faulting deformed the margins and floors of the present basins. Axes of the folds trend N. 30° E. to N. 90° E., although a fold at Lewis Terrace trends N. 70° W. Several are cross folded into asymmetric basins. For example, northwest of Lapon Canyon (Fig. 2), two such folds whose dominant axes trend northeast parallel to the Coal Valley fault zone are arranged en echelon between east-northeast–trending faults within Coal Valley; their minor axes trend nearly due east. Beds of the Wassuk Group at Lewis Terrace are folded in a westward-plunging syncline, the axis of which is normal to a strong basinward salient in the Coal Valley fault zone (Fig. 2). Folding there seems to have occurred as basement rocks were forced prowlike along the fault into the sedimentary section.

Small folds south of Wilson Canyon, whose axes trend north to northeast, appear to be related to movements along a swarm of small north-trending faults that cut the upper Coal Valley strata in that area (Fig. 3).

Quaternary Faults

Range-front fault zones bordering the north-trending ranges of Quaternary age characteristically have zig-zag traces, and the fault scarps show topographic salients and re-entrants. These features are clearly depicted by Moore (1969) for the Carson Range, Pine Nut Mountains, and Singatze Range. Of these young fault blocks, only the southernmost portion of the Singatze Range has been mapped during the present study. Here, the surface of the frontal fault dips toward Mason Valley at angles between 50° and 60°. The zig-zag trace of the east-facing escarpment and of the frontal fault is evident, particularly just south and north of Wilson Canyon. At least some of the jogs in the range front coincide with locations of large Miocene-Pliocene faults within the range block. For example, the earlier east-northeast fault just south of Wilson Canyon probably controlled the prominent east trend of the range front at that point. Similarly, the easterly jog of the frontal fault zone 3 km farther north coincides with an earlier east-northeast-trending fault that crosses the range on the south side of Mount Wilson, and the succeeding northwesterly jog is approximately in line with an earlier northwest-trending fault that crosses the range north of Mount Wilson and along which west-dipping Coal Valley strata have been faulted down against the granitic basement of the range summit. In similar fashion, the Pine Nut Mountains–Wellington Hills frontal escarpment shows an easterly jog at the juncture between the two blocks, where an east-northeast fault zone of presumably pre-Pleistocene age crosses the ranges.

SUMMARY AND CONCLUSIONS

Cenozoic History

The earliest Cenozoic rocks in the area studied are rhyolitic ignimbrite flows of early Miocene age; these are succeeded by widespread andesitic flows and breccia. Deformation during early and middle Miocene time is indicated by an unconformity between the Miocene andesite flows and underlying rhyolitic ignimbrite. Few details are known about this early deformation, but the absence of rhyolitic ignimbrite over much of the area mapped indicates that this area was relatively high. By approximately 12.5 m.y. ago, however, the same area was the site of sedimentation in an extensive basin. The record of events thereafter is preserved more completely in a thick sequence of upper Miocene and Pliocene sedimentary and volcanic strata that accumulated in the basin. Stratigraphy and facies characteristics of these strata, which now are preserved in separate fault blocks, indicate that all the strata were deposited in a single large basin that was much more extensive than present basins in the area. Volcanism was contemporaneous with sediment accumulation, for many strata are volcanogenic; centers of eruption were mostly close to the margins of the basin of accumulation or beyond them.

Fault movements contemporaneous with sediment deposition have been established at a number of localities. By approximately 7.5 m.y. ago, the original basin and the extensive sedimentary formations that accumulated in it had been disintegrated into the separate structural blocks that now characterize the region. We conclude that the fault movements that accomplished the breakup of the once continuous sedimentary terrane were in progress during an interval between approximately 10 and 8 m.y. ago; that is, they began during Coal Valley deposition and continued during Morgan Ranch deposition. Faulting had ceased and an erosion surface of low relief had developed by about 7.5 m.y. ago. Basic flows and rhyolitic protrusions were erupted locally onto this surface. During a period of tectonic inactivity which lasted until 3 to 4 m.y. ago, a well-graded erosion surface evolved. Broad pediments extended across the less-resistant sedimentary rocks preserved on the lower structural blocks, and accordant surfaces of low relief developed on the higher blocks where older rocks are exposed. Across this graded surface, the courses of the East and West Walker Rivers were established.

During the Quaternary period, warping and faulting resumed. Young fault-block ranges and valleys, which are the most prominent features of the present regional topography, developed at that time, and the rivers were incised across the upwarped and upfaulted areas.

Basin-Range Deformation

At least two distinct periods of late Cenozoic deformation can be recognized in this portion of the western Basin and Range Province. Data from the area mapped during the present study establish an earlier period of faulting and tilting prior to 7.5 m.y. ago. Data from the adjacent Mono Basin area establish another period later than 3 to 4 m.y. ago (Gilbert and others, 1968). Development of the extensive and remarkably even Lewis erosion surface between these two periods of deformation indicates that they were separated by an interval of little tectonic activity that lasted about 4 m.y. Significantly, this interval was also an interval of minimum volcanic activity in the Mono Basin area, where volcanism has otherwise been essentially continuous during the last 12 m.y. (Gilbert and others, 1968). The only volcanism recorded in the Mono Basin area during that interval is a small volume of rhyolite in the western Bodie Hills which has been dated at 5.3 to 5.7 m.y. (Silberman and Chesterman, 1972).

Stress relief during the later period of Basin-Range deformation did not follow the pattern established prior to 7.5 m.y. ago. The earlier period was characterized by normal faults and fault blocks having northeast and northwest trends. The more recent deformation has been characterized by tilted fault blocks that trend north to north-northwest and by broad areas of warping with little faulting. Zig-zag traces of young range-front fault zones are at least partly a reflection of earlier fault structures within the range blocks, but the north trend of zones along which major Quaternary displacements occurred is in marked contrast to the trends of earlier fault structures. A similar variation between early and late fault patterns in the western Basin and Range Province has been reported by Ekren and others (1968) at the Nevada Test Site, but there the change in pattern occurred about 10 m.y. earlier, between 14 and 17 m.y. ago.

The pattern of Quaternary deformation in the area of this report is distinctive and is separated from adjacent segments of the western Basin and Range Province by two major northeast-trending structural zones (Fig. 7). To the south is the Mono Basin–Excelsior Mountains zone (Shawe, 1965, Fig. 7; Gilbert and others, 1968) in which left lateral movement during Pleistocene and Holocene time has been recognized. The zone also has been a locus of Quaternary volcanic activity. South of the Mono Basin–Excelsior Mountains zone, Quaternary deformation has been characterized by large, continuous horsts and grabens trending approximately north: Owens Valley graben, Inyo–White Mountains horst, and Fish Lake Valley graben. The junction of the zone and the fault structures to the south is marked by a structural "knee" where trends change from north to northeast (Gilbert and others, 1968, p. 313–314). To the north is the Carson lineament,

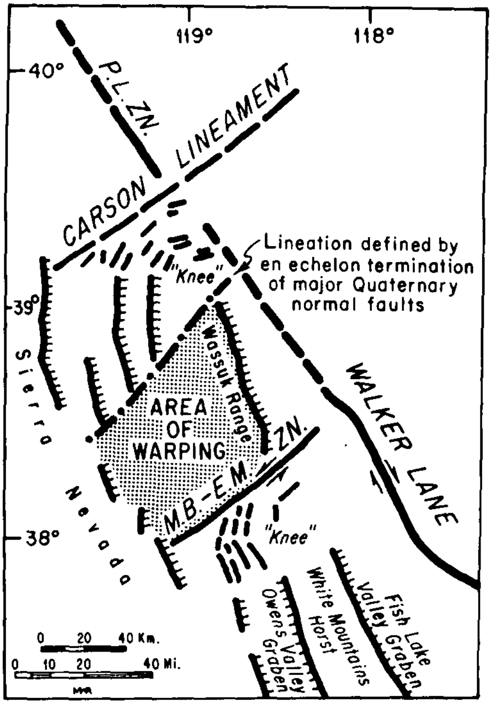

Figure 7. Sketch map showing major fault zones and lineaments near the western margin of the Basin and Range Province and the pattern of Quaternary faulting and warping. P.L. ZN. is zone of faulting in the Pyramid Lake area, and M.B.-E.M. ZN. is Mono Basin–Excelsior Mountains structural zone. Traces of the Walker Lane, Pyramid Lake zone, and Carson lineament are after Shawe (1965, Fig. 8), and traces of short faults south of the Carson lineament are after Moore (1969, Pl. 1).

extending as much as 150 km northeastward from Carson City (Shawe, 1965, p. 1373–1375) and forming the northern boundary of the regional block including the area of this report. Quaternary structural trends north of this lineament are north or northeast, except near Pyramid Lake where a northwest-trending zone of Quaternary faults (Bonham, 1969) seems to be a continuation of the Walker Lane described to the southeast (Shawe, 1965, p. 1374).

Within the block bounded by the Mono Basin–Excelsior Mountains zone, the Carson lineament, and the Wassuk Range, Quaternary deformation has included a broad southern area of warping with minimal faulting and a northern area of block faulting (Fig. 7). Most of the mapping during this study has been in the southern area where broad warping has been the characteristic style of Quaternary deformation. Quaternary fault-block ranges occur en echelon in a belt that extends southwestward from the northern end of the Wassuk Range. The alignment of the southern ends of these fault blocks establishes a northeast-trending lineament that is approximately parallel to the Mono Basin–Excelsior Mountains zone and to the Carson lineament (Fig. 7). The fault blocks are much smaller than those south of the Mono Basin–Excelsior Mountains zone, and they have all been tilted westward and are separated by east-dipping normal faults. Range-front fault zones typically terminate in areas of warping (Moore, 1969, p. 16); one example of this, the southern terminus of the Singatze fault block, has been documented in the present report.

Near the Carson lineament, at the northern ends of the Pine Nut Mountains and the Singatze and Wassuk Ranges, the structural trend changes from north to northeast and east (Fig. 7; Moore, 1969, Pl. 1). This change in trends seems to define a structural "knee" adjacent to the Carson lineament similar to the "knee" along the southern margin of the Mono Basin–Excelsior Mountains zone. If so, the lineament defined by en echelon termination of Quaternary fault zones near the center of the regional block described here may represent a break at depth in the crust between a relatively more stable block to the south deformed by warping and a block to the north deformed primarily by horizontal shear at depth resulting in normal faulting at the surface.

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