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The geology and structural significance of the Arch Mountain area, northern Black Mountains, Mohave County, Arizona

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THE GEOLOGY AND STRUCTURAL SIGNIFICANCE OF THE ARCH MOUNTAIN AREA, NORTHERN BLACK MOUNTAINS, MOHAVE COUNTY, ARIZONA

by

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ABSTRACT

The Arch Mountain area of northwestern Mohave County, Arizona, is typified by rocks that range from Precambrian to Quaternary in age. Arch mountain is a north-trending horst bounded on the west by the Petroglyph Wash graben and on the east by the Virgin Basin. A low-angle normal fault, herein named the Arch Mountain detachment fault, is exposed for 6 km along strike just below the ridge crest of Arch Mountain, and it is typified by a 2-20 cm thick zone of hematite-impregnated breccia and cataclasite. The detachment fault places an upper plate of Precambrian gneiss, Paleozoic quartzite, shale and dolomite, and Tertiary intrusive rock on a lower plate composed of quartz monzonite that is geochemically similar to quartz monzonite of the Wilson Ridge pluton. The western margin of the horst is cut by en echelon, west-dipping, high-angle normal faults that step the detachment fault to the west and rotate it to the east. The Ransome fault forms the western boundary of the horst and separates Arch Mountain from Precambrian gneiss and Tertiary volcanics. The eastern margin of the horst is cut by en echelon, east-dipping, high-angle normal faults that step the detachment fault to the east and rotate it to the west. The Boulder Wash fault forms the eastern boundary of the horst and separates Arch Mountain from Tertiary Muddy Creek sediments in the Virgin Basin-Detrital Wash area.

The Ransome and Boulder Wash faults may be genetically related to and may have formed synchronously with the left-lateral Lake Mead fault system at approximately 12 Ma. Crosscutting relationships indicate that the Arch Mountain detachment fault is older than the Lake Mead fault system. The Arch Mountain detachment fault is possibly related to the development of the Las Vegas Valley shear zone, and it is interpreted to be correlative with the Saddle Island detachment fault.

I propose that the Arch mountain detachment fault represents the brittlely deformed, upper crustal part of a regional detachment fault system that has a breakaway zone adjacent to the Grand Wash Cliffs. I interpret the detachment fault and lower plate mylonites at Saddle Island to be the plastically deformed, deep level part of the regional detachment fault system that became exposed by progressive structural denudation, isostatic uplift and erosion. The fault history of the regional detachment system is complicated and poorly constrained but I suggest the following scenario: (1) regional uplift and arch formation south of Lake Mead during the late-Cretaceous to early Tertiary; (2) early to mid Tertiary detachment faulting, development of the Las Vegas Valley shear zone and westward transport of the Paleozoic and Mesozoic rocks represented at Petroglyph Wash, Boulder Canyon, the Frenchman Mountain and Sheep Mountain structural blocks and at the Spring Mountains; (3) continued detachment faulting and westward transport of the River Mountains volcanics, and the development of the Lake Mead fault system with related high-angle normal faults.

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"Humility is perpetual quietness of heart. It is to have no trouble. It is never to be fretted, or vexed, of irritated, or sore, or disappointed.

It is to expect nothing, to wonder at nothing that is done to me, to feel nothing done against me. It is to be at rest when nobody praises me, and when I am blamed and despised.

It is to have a blessed home in myself, where I can go in and shut the door, and kneel to my Father in secret, and be at peace as in a deep sea of calmness, when all around and above is troubled."

-Unknown

INTRODUCTION

Location

The Arch Mountain area is located in the northern Black Mountains, south of Boulder Canyon and east of Wilson Ridge, in Mohave County, northwestern Arizona (Figure 1). The 60-square-km study area is in the Lake Mead National Recreational Area and is bounded on the north and east by Lake Mead and on the south and west by Petroglyph Wash. Motor vehicle access is restricted to the Petroglyph Wash Road, which passes through the south and west parts of the study area. Travel to the northern and eastern parts of the area is possible only by foot or by boat.

Previous Work

Ransome (1923) mapped, in reconnaissance, the geology adjacent to the Colorado River in Boulder Canyon to evaluate the suitability of the canyon for the proposed Boulder Canyon dam and reservoir. During his study, he assigned the Precambrian biotite schist, Paleozoic limestone and shale, Tertiary (?) intrusive quartz diorite and quartz monzonite, and volcanic rocks of the Boulder Canyon area to the Boulder Wash group, and he noted the presence of north-striking normal faults, fault breccia, joints, and dikes.

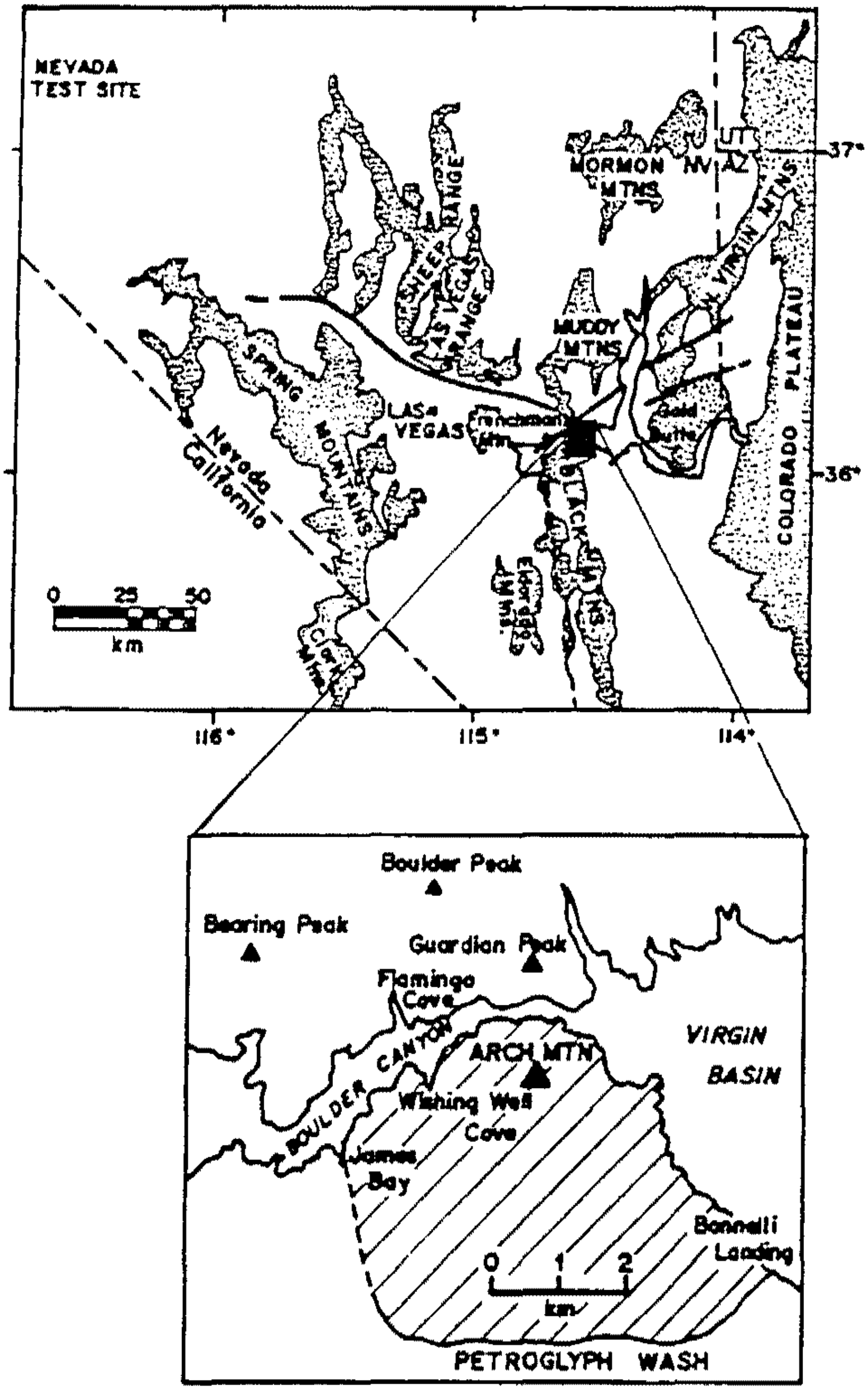

Figure 1. Location map of the Arch Mountain area (striped), northern Black Mountains, Mohave County, northwestern Arizona.

Longwell (1936), mapped the geology of the Boulder reservoir floor to document important geological relationships that would be covered by Lake Mead. Part of his map includes Boulder Canyon and the adjacent Black Mountains. Longwell mapped the granitic rocks south of Boulder Canyon as Precambrian biotite granite, quartz monzonite, granodiorite, and hornblende syenodiorite. He also described the structure of the Black Mountains horst, tilted blocks of Paleozoic sediments south of Boulder Canyon, and a several hundred foot thick waterlain breccia composed of andesite porphyry clasts, near Wishing Well Cove.

Wilson and Moore (1959) compiled a geologic map of Mohave County at the scale of 1: 375,000. They mapped the Arch Mountain horst as Precambrian granite and were the first to recognize isolated blocks of Paleozoic sediments near Gilbert Canyon, within the Petroglyph Wash graben.

Longwell (1963), interpreted the Black Mountains horst block as a 12 km-wide belt of north-trending horsts and grabens bounded on the east by the Boulder Wash Fault and on the west by the Indian Canyon fault. He described the Arch Mountain block of the Black Mountains as a horst bounded on the east and west by the north-trending Boulder Wash and Ransome faults, respectively. Longwell suggested that the occurrence of blocks of Paleozoic sediments in the hanging wall of the Ransome fault, south of the Colorado River, requires that the throw on that fault to be at least 1000 km. He also recognized the

Petroglyph Wash graben as a large structural block between the Ransome and Emery faults.

Anderson (1971) was the first to recognize the importance of low-angle faults in the extended Tertiary rocks of southeastern Nevada. He also provided K-Ar dates for selected Tertiary rocks in the Lake Mead area (Anderson et al.,1972). Anderson (1973) recognized the Lake Mead fault system north of Lake Mead. He provided models showing the relationship between strike-slip and high-angle normal faults and he suggested that the Black Mountains south of Lake Mead should provide important clues to the synchronous development of strike-slip and high-angle normal faults in the Lake Mead region.

Feuerbach (1986) mapped the area adjacent to and west of Arch Mountain from James Wash east to Wilson Ridge. He recognized several phases of the Wilson Ridge Pluton and mapped in detail a large, fault-bounded, Paleozoic carbonate block in Petroglyph Wash that was previously recognized by Wilson and Moore (1959).

Naumann (1987) mapped the Boulder Canyon area north of Lake Mead and Arch Mountain and described an unusual breccia, first noted by Longwell (1936), and he named it the Boulder Canyon Breccia. The breccia is apparently 400 m thick and crops out over a 3-km-square area north of Lake Mead, west of the Boulder Wash fault and east of the Ransome fault. The massive breccia is composed of angular fragments and rounded clasts of Precambrian rapakivi granite, gneiss and schist, Cambrian Bonanza King dolomite, and Tertiary quartz monzonite. These clasts are supported by a highly indurated and ferrically altered matrix of crushed rock. The breccia locally intrudes the country rock including overlying Paleozoic carbonates. Naumann proposed that the breccia had a hydromagmatic origin and that it formed by the second boiling and decompression of a hydrous magma or by the interaction of magma with ground water.

Purpose

The purposes of this study are :

1. To produce a detailed geologic map of the Arch Mountain area. The geology of the Arch Mountain area has not been previously mapped at a scale greater than 1:375,000. The map produced in this study is at a scale of 1:24,000 and provides greater detail than the small scale map of Wilson and Moore (1959).

2. To Describe the structural geometry of the area. Arch Mountain lies in a structurally complex region cut by Tertiary strike-slip, high-angle and low-angle normal, and detachment faults.

3. To Determine the regional significance of Arch Mountain. Arch Mountain lies in a structurally complex region near the western edge of the Colorado Plateau and on the eastern edge of the Basin and Range province. The two major strike-slip fault systems of the area project to the north of Arch Mountain, and exposures of a major detachment fault system lie to the west. The presence of a detachment fault on Arch Mountain that is cut by high-angle normal

faults provides an opportunity to evaluate the significance of Arch Mountain with respect to the major structural features of the Lake Mead region.

4. To Constrain the models for the evolution of the Lake Mead area proposed by previous workers, and to present a new model that incorporates the geologic information from the Arch Mountain area.

Methods Of Study

The southern half of the Boulder Canyon 7.5-minute quadrangle and the northern half of the Petroglyph Wash 7.5-minute quadrangle maps were mapped at a scale of 1:24,000 (Plate 1). Petrographic thin sections of selected rock specimens were studied (Appendix A) and mineral percentages were visually determined by using the visual percentage estimation method (Scholle, 1978). Selected specimens were analyzed for major-element geochemistry (Appendix B).

REGIONAL GEOLOGIC SETTING

Introduction and Generalized Geology

Arch Mountain is located in the southwestern Basin and Range physiographic province approximately 50 km west of the Colorado Plateau province. Arch Mountain is situated in an area that lacks the thick sequences of Paleozoic, Mesozoic, and Cenozoic sedimentary rocks which are abundant to the north of Lake Mead (Figure 2). This area of the Black Mountains is composed mainly of mid-Miocene (?) quartz monzonite of the Wilson Ridge Pluton, dacite, diorite, and mid-Miocene to Pliocene basalt (Anderson et al., 1972; Mills, 1985; Feuerbach, 1986). Precambrian gneiss crops out in the southern part of Wilson Ridge, on the flanks of Wilson Ridge, and on Arch Mountain. Paleozoic and Mesozoic rocks are rare; however, Paleozoic sandstone, shale, and carbonate rocks crop out in the Petroglyph Wash graben near Gilbert Canyon (Wilson and Moore, 1959; Feuerbach, 1986) and at the Cohenour Mine (this study), near Boulder Canyon (Longwell, 1936; Naumann, 1987a), in the River Mountains (Timm, 1985), and at Saddle Island (Sewall, 1988). Also, small xenoliths of Paleozoic limestone occur in the Kingman Wash Road basalt of the Hoover Dam area (Mills, 1985).

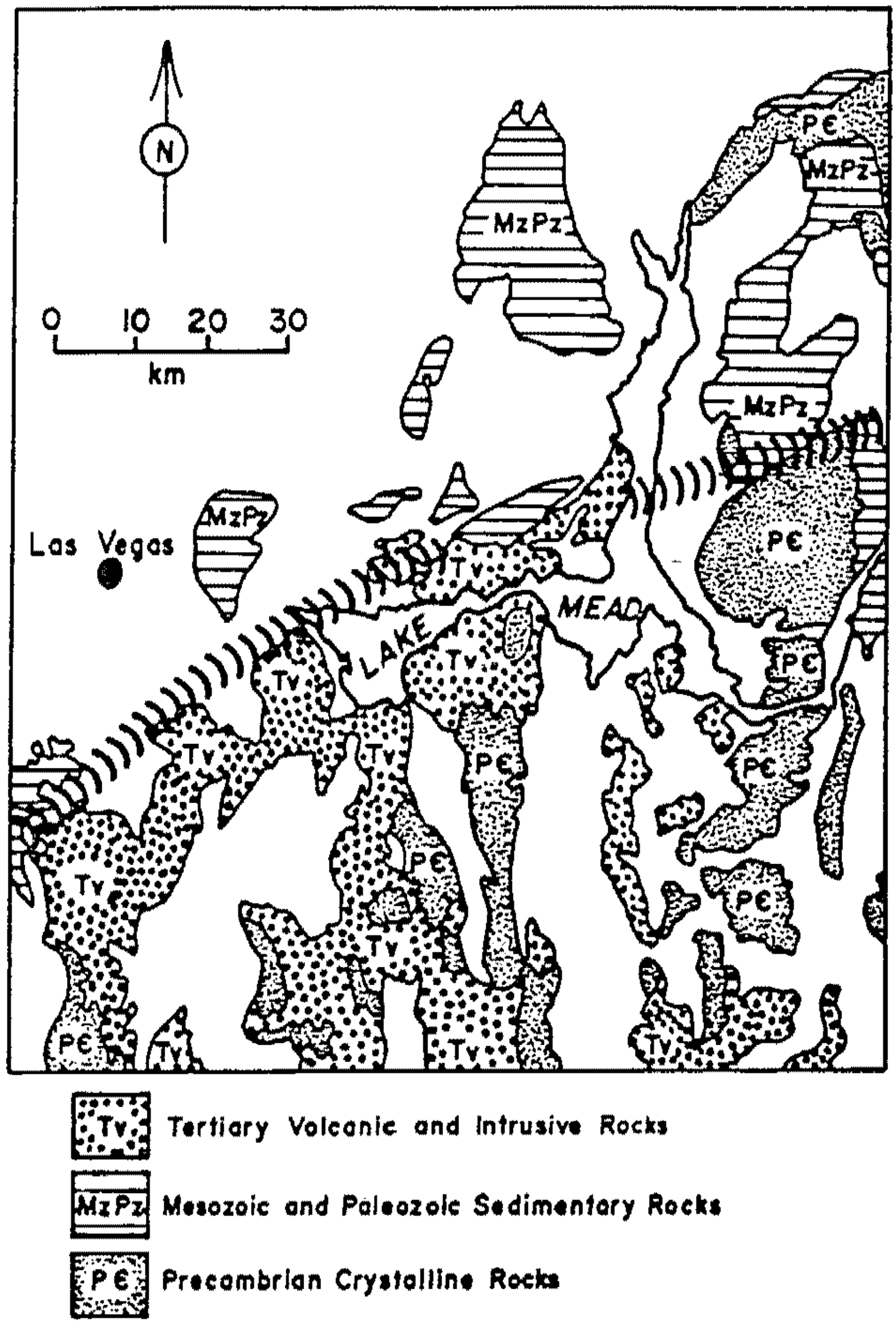

Figure 2. Generalized index map showing regional geology of the Lake Mead area. Hatchured line marks boundary between Paleozoic, Mesozoic, and Tertiary sedimentary rocks to the north of Lake Mead and Precambrian crystalline and Tertiary igneous rocks to the south (modified after Anderson, 1973, and Bohannon, 1984)

Detachment Faults

As defined by Reynolds (1985) the term "detachment fault" describes a low-angle normal fault that represents a major structural discontinuity with at least one of the following four characteristics:

1. It is a zone of major displacement as revealed by a pronounced lithologic mismatch between upper and lower plates.

2. It separates rocks with contrasting structural styles; faulted, rotated, and brittlely distended upper-plate rocks are juxtaposed against less faulted lower-plate rocks;

3. The upper plate contains normal faults that are cut by or merge with the detachment fault.

4. It is underlain by a zone of hydrothermally altered breccia and microbreccia derived from lower-plate rocks.

Detachment faults, and low-angle normal faults, have been widely recognized in the Lake Mead and lower Colorado River trough regions (Longwell, 1945; Anderson, 1971; Smith, 1982; Frost and Martin, 1982; Choukroune and Smith, 1985; Myers, 1984; Smith et al., 1987b). Locally, detachment faults are exposed at Arch Mountain (Eschner and Smith, 1988), in the James Bay and the Petroglyph Wash regions near Gilbert Wash (Feuerbach, 1986), and north of Boulder Canyon (Naumann, 1987a) between Boulder Wash and Flamingo Cove (Figure 3).

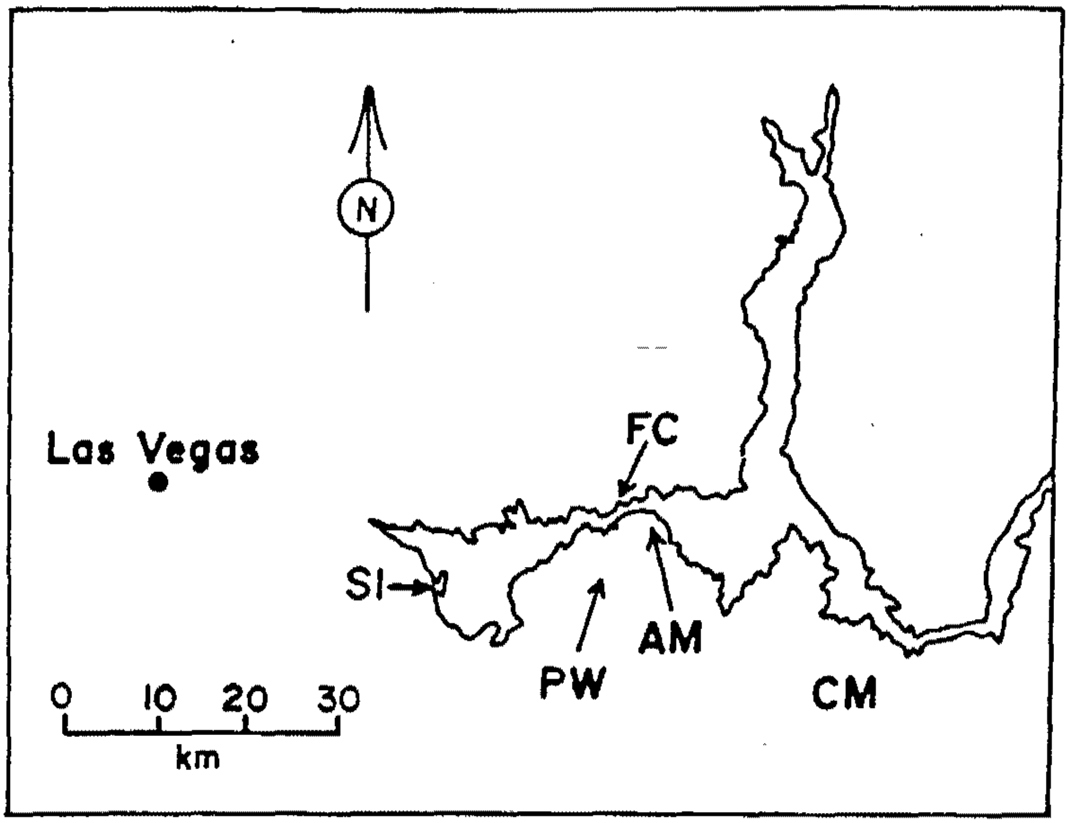

Figure 3. Location of detachment faults exposed in the Lake Mead Area. AM = Arch Mountain, PW = Petroglyph Wash, FC = Flamingo Cove, CM= Cyclopic Mine, SI = Saddle Island.

Strike-Slip Faults

Studies examining the role of strike-slip faults in an extensional setting indicate that such faults may form between regions of variable extension in the upper plates of detachment fault systems (Lister et al. 1986). In continental regimes this type of strike-slip fault is called a transfer fault (Gibbs, 1984). In the Lake Mead region, apparent strike-slip faulting began at approximately 17-15 Ma (Bohannon, 1979; Wernicke et al.1984) along two zones: the northwest-striking, right-lateral Las Vegas Valley shear zone, and the northeast-striking, left-lateral Lake Mead fault system. Guth (1981) and Wernicke et al. (1982) suggested that the Las Vegas Valley shear zone is a transfer fault that separates a northern detached and tilted fault block terrain (e.g., Sheep Range, Black Hills, Desert Range) from a southern detached "stable" terrain (e.g., Spring Mountains).

Weber and Smith (1987) suggested the Hamblin Bay fault, a strand of the Lake Mead fault system that offsets the mid-Miocene Hamblin-Cleopatra stratovolcano, is also a transfer fault that separates the Eldorado Mountains from the River Mountains.

Southeast of the Frenchman Mountain block, the Las Vegas Valley shear zone is not easily recognized (Anderson, 1973; Bohannon, 1979). The southwest projection of the Lake Mead fault system is also nebulous south of the Frenchman Mountain block; however, Weber and Smith (1987) hypothesized that the Hamblin Bay fault projects across Lake Mead and becomes a high-angle, west-dipping normal fault buried by alluvium in Eldorado Valley. This geometry is possibly repeated to the north, where the Bitter Spring Valley fault, a splay of the Lake Mead fault system, may turn to the south to become the

Saddle Island detachment (Sewall and Smith, 1986; Weber and Smith, 1986, 1987).

South of Lake Mead, high-angle normal faults, rather than strike-slip faults, are the dominant structures, although both types of faults occurred synchronously between 12 and 10.6 Ma (Anderson, 1973). High-angle normal faults that bound the northern part of the Black Mountains structural block either merge with or are truncated by the Hamblin Bay fault (Figure 4).

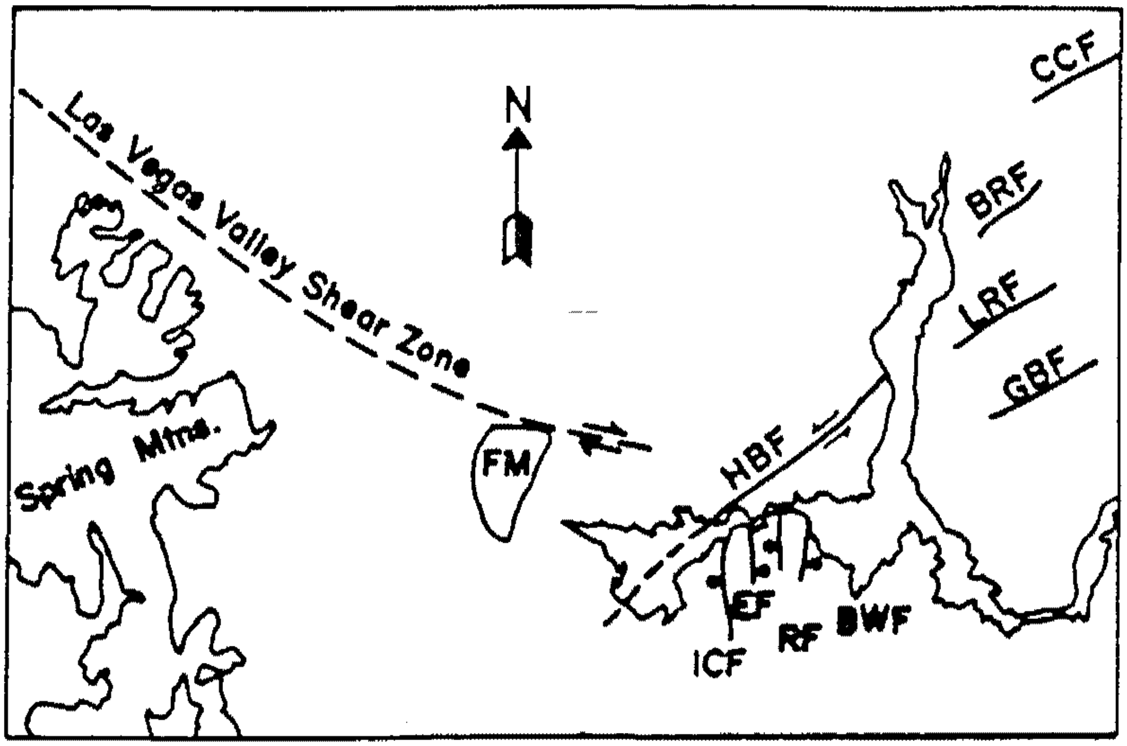

Figure 4. Location of strike-slip faults and high-angle normal faults. FM = Frenchman Mountain, HBF = Hamblin Bay fault, CCF = Cabin Canyon fault, BRF = Bitter Ridge fault, LRF = Lime Ridge fault, GBF = Gold Butte fault, BWF = Boulder Wash fault, RF = Ransome fault, EF = Emery fault, ICF = Indian Canyon fault.

DESCRIPTION OF ROCK UNITS

Precambrian Rocks (P€)

Precambrian (?) gneiss crops out in the Arch Mountain klippe where it is exposed along the crest and on the east and west flanks of Arch Mountain. The gneiss is well foliated with mafic bands of hornblende separated by felsic bands of plagioclase and quartz. The klippe also contains exposures of diorite that ranges in texture from aphanitic to phaneritic (Appendix A). North-striking, white and pinkish, coarse grained pegmatite dikes cut the gneiss and contain quartz, plagioclase and biotite. The dikes are typically about 1 m wide.

Gneiss and granite are exposed along the east flank of the Arch Mountain horst, from the head of Boulder Canyon near Boulder Wash, south to Petroglyph Wash. Precambrian rock on the west side of the horst forms a north-trending block of dark grayish black gneiss and biotite schist.

Paleozoic Rocks (Pz)

Exposures of Paleozoic sandstone, shale, and limestone that are correlative with Cambrian Tapeats Sandstone, Bright Angel Shale, and Muav Limestone, respectively, crop out to the east of Wishing Well Cove. At this outcrop, approximately 5 m of buff-tan, well-indurated, medium- to coarse-grained Tapeats Sandstone is exposed above lake level. In the steep slope above the lake, the sandstone grades upward into a 5 m thick section of platy, greenish red, ripple-marked, micaceous Bright Angel Shale.

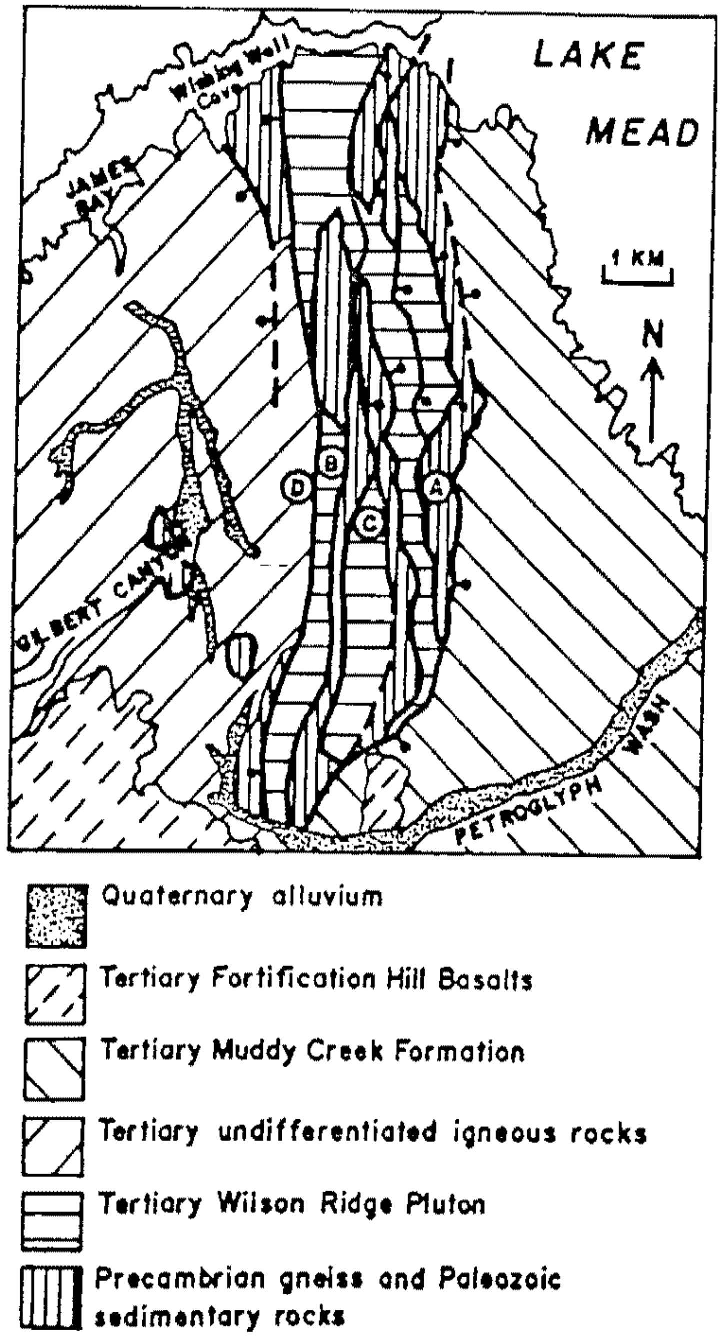

Figure 5. Geographic locations and generalized geology of the Arch Mountain Area

A thick section of grayish brown Muav (?) limestone with layers of chert nodules overlies the shale (Plate 1). In addition to this exposure, other exposures of Paleozoic sedimentary rocks that are similar in lithology to the rocks east of Wishing Well Cove occur near the junction of Gilbert Canyon and James Bay Wash (Wilson and Moore, 1959; Feuerbach, 1986). These carbonate exposures lie in a klippe above a low-angle fault. Similar outcrops of greyish-brown, massive Paleozoic limestone are also exposed in the alluviated valley east of James Bay Wash.

At the Cohenour mine, white quartzite, greenish shale, and brownish gray limestone that are likely correlative with the Muav Limestone, Bright Angel Shale, and Tapeats Sandstone, are complexly faulted and may form another klippe. The quartzite is massive to poorly bedded and is composed of medium to coarse, rounded quartz grains. The shale is laminated, and well indurated but fissile; it is composed of silt and micaceous minerals. The limestone is massive, grainy, and locally dolomitized. The exposures of Paleozoic limestone in the area of the mine are locally mineralized and contain hematite, barite, chalcopyrite, malachite, azurite, sphalerite, epidote, and druzy quartz. Tertiary dacite and andesite intrude the blocks of Paleozoic rocks.

Tertiary Rocks

Horse Spring Formation (Ths)

A sedimentary section containing breccia with limestone clasts, quartz sandstone, bedded limestone, and blocks of Precambrian (?) granite crops out east of the Cohenour mine at hill 886T (Plate 1).

This section is about 40 m thick and is tentatively correlated with the lithologically similar Thumb Member of the Horse Spring Formation. Ash layers from the Horse Spring Formation in the Lake Mead region yield K-Ar dates of 24, 23.5, and 19.6 Ma (Lucchitta, 1966; Anderson, 1973), but the Horse Spring Formation may be as young as 20 to11.9 m.y. (Bohannon, 1984).

Most of the upper 25 m of the sedimentary section is a well indurated pebble conglomerate. In outcrop the conglomerate is reddish brown, but the individual clasts are gray and brown or white. About 90 percent of the clasts are 0.1 to 5 cm in diameter, subangular to subround limestone. The other 10 percent of the clasts are subangular sandstone, chert, or granitic rock fragments supported by a red-brown calcareous matrix. A highly indurated, well-sorted, fine-grained quartz sandstone with stringers of coarse grained quartz conglomerate is interbedded with the carbonate breccia. Megabreccia blocks of Precambrian granite (?) as much as 8 m thick are also exposed at the top and bottom of the section.

Approximately 4 m of resistant gray, well bedded, limestone underlies or is interbedded with the clastic section. The beds are 5 to 25 cm thick, and are interlayered with 1 to 10 cm thick beds of fairly well sorted, fine-grained, rounded quartz sandstone. The strike of the bedding in the limestone is coplanar with bedding in the overlying breccia. Similar limestones formed in the Tertiary Horse Spring Formation elsewhere in the Lake Mead region (Bohannon, 1984).

Interpretation of the Horse Spring Formation

The Horse Spring Formation was deposited in basins that formed during active extension (Longwell et al., 1965). Outcrops of the Horse Spring Formation at Arch Mountain, in the Rainbow Gardens area east of Frenchman Mountain (Anderson, 1973; Parolini,1986), and on Saddle Island (Sewall and Smith, 1988), contain large blocks of distinctive Precambrian granite clasts. Although the Precambrian exposures in the Black Mountains have been suggested as a possible source for the coarse, clastic, debris-flow deposits (Schmitt and Rice, 1988), the only exposed source with lithologies that match those of the debris flows at Rainbow Gardens is the Precambrian complex in the South Virgin Mountains, near Gold Butte (Volborth, 1962; Longwell, 1974; Parolini, 1986; Parolini and Rowland, 1988). Sewall and Smith (1987) correlated a Tertiary fanglomerate in the upper plate of the Saddle Island detachment fault with the Rainbow Gardens and Thumb members of the Horse Spring Formation exposed in the Rainbow Gardens area east of Frenchman Mountain. They also suggested that the Horse Spring Formation exposed in the upper plate of the Saddle Island detachment fault was transported to the west by the Saddle Island detachment. I suggest that the occurrence of Horse Spring Formation in the upper plate of the Arch Mountain and Saddle Island detachment faults and in the Rainbow Gardens area may indicate that these rocks were transported westward from the South Virgin Mountains in the upper plate of a west-dipping regional detachment system.

Wilson Ridge Pluton (Twr)

The granitic suite exposed at Arch Mountain is chemically similar to the granitic rocks of the Wilson Ridge pluton (Appendix B). The Wilson Ridge pluton is a composite granite-quartz monzonite pluton of mid-Tertiary age that forms a north-trending belt in the central part of the study area (see Figure 5). The age of the pluton is based primarily on two K-Ar dates (15.1 ± .06 Ma and 13.6 ± .06 Ma) from samples that were collected from the west flank of Wilson Ridge (Anderson et al., 1972). Weber and Smith (1987) chemically correlated the Wilson Ridge pluton to the River Mountains volcanic section, which is dated between 15 and 12 Ma.

The eastern flank of the Arch Mountain horst is composed mainly of grayish white, fine-grained quartz monzonite (Appendix A) that contains less than 5 percent biotite and hornblende (see location A in Figure 5). The quartz monzonite grades to the west into a hornblende-biotite-sphene-bearing quartz monzonite that locally contains abundant inclusions of hornblende-rich diorite (see location B in Figure 5). The diorite inclusions range from angular blocks to circular blobs as much as 40 cm in diameter. The hornblende occurs as delicate acicular crystals and coarse blocky crystal aggregates in a matrix of white plagioclase. In the south-central part of the horst the diorite inclusions are particularly well exposed and abundant (see location C in Figure 5).

The western flank of the Arch Mountain horst is composed mostly of white, coarse-grained granite and fine-grained hypabyssal quartz monzonite (Appendix A). Occasional xenoliths of hornblende-rich diorite also occur within the quartz monzonite. North-striking basalt and lamprophyre dikes (Appendix A) that are less than 1 m thick contain 1-3 mm wide euhedral books of biotite that intrude the western part of the pluton mainly along joints and faults; they are best exposed near the southern trace of the Ransome fault (see location D in Figure 5). South of Petroglyph Wash, the horst is overlain by the Fortification Hill basalt member of the Muddy Creek Formation.

Diorite containing hornblende and plagioclase (Appendix A) crops out sporadically in the central part and along the west flank of the horst, adjacent to the north-trending belt of Precambrian (?) banded gneiss. The diorite varies in texture from fine to coarse grained. Hornblende occurs as conspicuous, blocky crystals ranging in size from 1 mm to 2 cm. The age of this unit is uncertain. Joan Fryxell (personal communication, 1988) indicated that in the Southern Virgin Mountains, a similar unit with conspicuous blocky hornblende crystals is involved in Precambrian basement deformation. However, the diorite at Arch Mountain may be as young as Tertiary. Feuerbach (1986) and E.I. Smith and L. Larson (personal communication, 1988) indicate that a similar hornblende diorite is exposed in the southern part of the Wilson Ridge pluton near Horse Thief Canyon. They interpret the diorite as a part of the mid-Miocene Wilson Ridge pluton.

Undifferentiated Igneous Rocks (Tui)

Green and brown vesicular basalt is exposed in the James Bay region. The basalts are fine to medium-grained and contain abundant quartz amygdules as much as 4 cm wide. The basalts intrude light gray, fine- to medium-grained porphyritic diorite (Appendix A). The diorite contains phenocrysts of plagioclase, quartz, and hornblende and spherical inclusions of basalt that are generally 10 cm in diameter, with cuspate margins. Naumann and Smith (1987) observed similar basalt inclusions in a dacite north of Boulder Canyon and they suggested that the basalt inclusions are evidence of the mixing of basaltic and granitic magmas.

Dacite flows, ranging from light gray to red, crop out adjacent to the James Wash Road (see location C in Figure 5). Locally, the dacite is highly hydrothermally altered and is bright red. The dacite contains quartz, plagioclase, biotite, and hornblende. In addition, a plug of dark reddish brown to blackish andesite porphyry, with small white angular to tabular plagioclase phenocrysts (Appendix A) crops out approximately 0.5 km north of the Cohenour Mine. A similar porphyritic andesite is the main clast type of a conglomerate that is well exposed in the Wishing Well Cove area.

Interpretation of the James Bay Volcanics

Volcanic rocks that may be equivalent to the River Mountains volcanics are widely exposed near James Bay. Feuerbach (1986) suggested that the James Bay volcanic section lies in the lower plate of the Arch Mountain detachment, and he provided an elegant model, after Spencer (1985), that explains how the volcanics could have intruded as a dike swarm during detachment faulting. An alternative interpretation, however, is that the section lies in the upper plate of the Arch Mountain detachment fault and that the section was transported from a source east of Arch Mountain.

The Boulder Wash stratovolcano (Naumann, 1987) and the Hamblin-Cleopatra volcano (Anderson, 1973; Thompson, 1985) are located to the east of the James Bay area, therefore it is possible that the James Bay volcanic section was detached from one of those sources.

Wishing Well Cove Breccia (Twcb)

The reddish brown, resistant volcaniclastic breccia at Wishing Well Cove, here named the Wishing Well Cove Breccia, extends approximately 6 km to the south of Wishing Well Cove. At Wishing Well Cove the unit is massive, clast supported, well indurated, and it is at least 100 m thick where it is exposed in cavernous weathering vertical cliffs (Figure 6). Approximately 2 km south of Wishing Well Cove the unit becomes bedded and thins to approximately 10 m. Bedding is formed by alternating layers, as much as 0.5 m thick, of poorly sorted cobbles and gravels. The unit is composed of angular to sub-rounded, brown, gray and purple andesite porphyry containing tabular plagioclase phenocrysts 1 to 3 mm in size. Clasts range in size from gravel, 1 cm in diameter, to cobble, 5 cm in diameter, to boulder, 25 cm in diameter. Cobble-size clasts are the most abundant and represent about 90 percent of the clasts.

Interpretation of the Wishing Well Cove Breccia

Erosion of volcanic rocks resulted in the deposition of the monolithologic Wishing Well Cove breccia. The source of the clasts is unknown. The lack of nonvolcanic clasts in the unit suggests that the quartz monzonite and gneiss of the Arch Mountain horst were not exposed during to the deposition of the volcaniclastic unit, thus plutonic and metamorphic rocks were not availiable for deposition. The breccia also apparently lies in the upper plate of the Arch

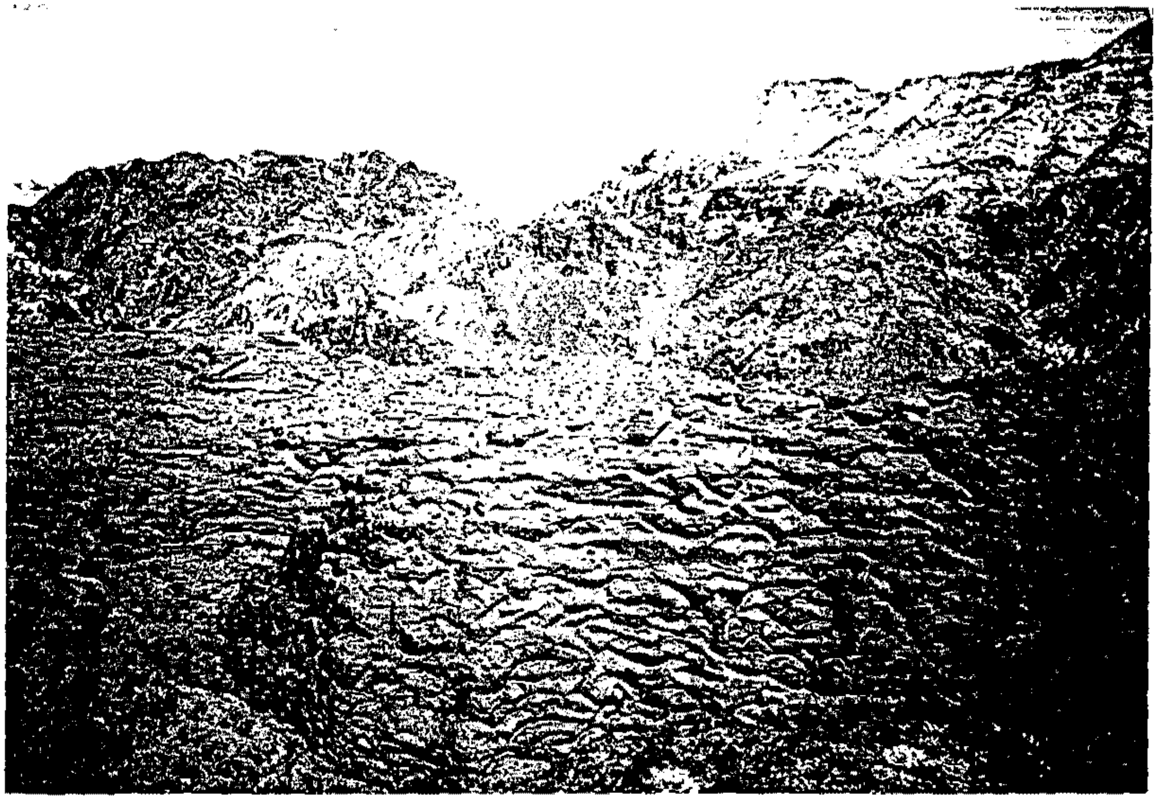

Figure 6. At Wishing Well Cove the unit is massive, clast supported, well indurated, and it is at least 100 m thick where it is exposed in cavernous weathering vertical cliffs. View looking northeast with Gaurdian Peak to the left of center in the background.

Mountain detachment, therefore it, and the James Bay volcanics, may have been transported from the east.

Muddy Creek Formation (Tmc)

The Muddy Creek Formation crops out in a deeply incised alluvial apron along the east flank of Arch Mountain. The Muddy Creek Formation is a 10 m.y. old basinal deposit (Bohannon, 1984) that varies considerably in lithology. Proximal, medial, and distal lithofacies are recognized in the exposure east of Arch Mountain. The proximal facies crops out adjacent to the range front as a poorly sorted, coarse clastic fanglomerate composed of angular cobbles and boulders of gneiss and quartz monzonite. The lithology of the fanglomerate clasts varies vertically such that the clasts in the lower and middle parts of the fan are mainly Precambrian gneiss, but clasts of Tertiary quartz monzonite are present in the upper part of the fan. The clast size becomes finer down-fan, toward the east, and grades into the medial facies. The medial facies is mostly a poorly sorted gravel with 5 to 30 cm thick interbeds of angular, cobble size clasts. Farther to the east, the medial facies grades from bedded gravel to alternating layers of gravel and sand that interfinger with a fine-grained, reddish siltstone unit. The siltstone unit is approximately 10 m thick and is composed mainly of massive, friable silt with well-defined 0.25 to 1 m thick interbeds of poorly indurated, well-sorted sandstone. The siltstone and the sandstone are cemented with carbonate. Also, a channel fill deposit 10 m thick, containing 1 to 3 m thick crossbeds of well-rounded cobbles composed of

Paleozoic fossiliferous limestone and pebbles of chert, is cut into the upper portion of the reddish siltstone unit.

Locally, olivine basalt dikes (Appendix A) intrude the red siltstone and basalt flows overlie the Muddy Creek sediments. The basalt is assumed to be the Fortification Hill member of the Muddy Creek Formation. A 10 m thick section of east-dipping, bedded white gypsum interbedded with 10 cm thick waterlain ash layers underlies the reddish siltstone unit. The gypsum unit is at least 180 m thick (Ransome, 1923), but the waters of Lake Mead cover the lower 170 m of the section.

Interpretation of Muddy Creek Formation

Based on my preliminary observations of the Muddy Creek Formation I suggest that the section exposed east of Arch Mountain provides a record of the unroofing of the Wilson Ridge pluton. Much of the fanglomerate facies is composed of Precambrian gneiss clasts; Tertiary quartz monzonite clasts are abundant only in the upper part of the fan and in the Holocene river channels. This suggests that during the initial stages of fan development mainly Precambrian rock was exposed to erosion and that Tertiary quartz monzonite was not widely exposed until later in the fan-building episode (Figure 7a). When the quartz monzonite was exposed, due to erosion and activity on the Boulder Wash fault zone, quartz monzonite clasts were deposited over the detritus of the Precambrian rock (Figure 7b). Continued faulting and erosion produced steep cliffs in the exposed belt of resistant quartz monzonite. The development of the steep cliffs halted sheet flow and debris flow deposition on the fans and initiated stream channels that cut down into the fan material (Figure 7c). Some of these river channels are deeply incised into the Muddy Creek Formation, thereby exposing the stratigraphy of the fans. The fans exhibit a proximal facies of coarse, poorly sorted breccia that grades down-fan into a medial facies of interfingered cobbles, gravels, and sands that in turn interfinger with a distal playa facies of gypsiferous silts and gypsum beds. This relationship indicates that alluvial fans were developing at the margin of the Virgin Basin synchronously with playa development near the basin center. Layers of tuff that are interbedded with thick gypsum deposits suggest that volcanic activity was occurring concurrently with gypsum precipitation.

Channel fill deposits that are cut into the Muddy Creek fan and playa sequence are composed of rounded cobbles and pebbles of Paleozoic carbonates, quartzites, and cherts. These deposits were probably laid down by the Colorado River at about 5 Ma. It seems likely that the cobbles were laid down about the same time that the Colorado River was cutting its channel through Boulder Canyon, thus connecting the Virgin and Boulder basins and creating an integrated drainage system.

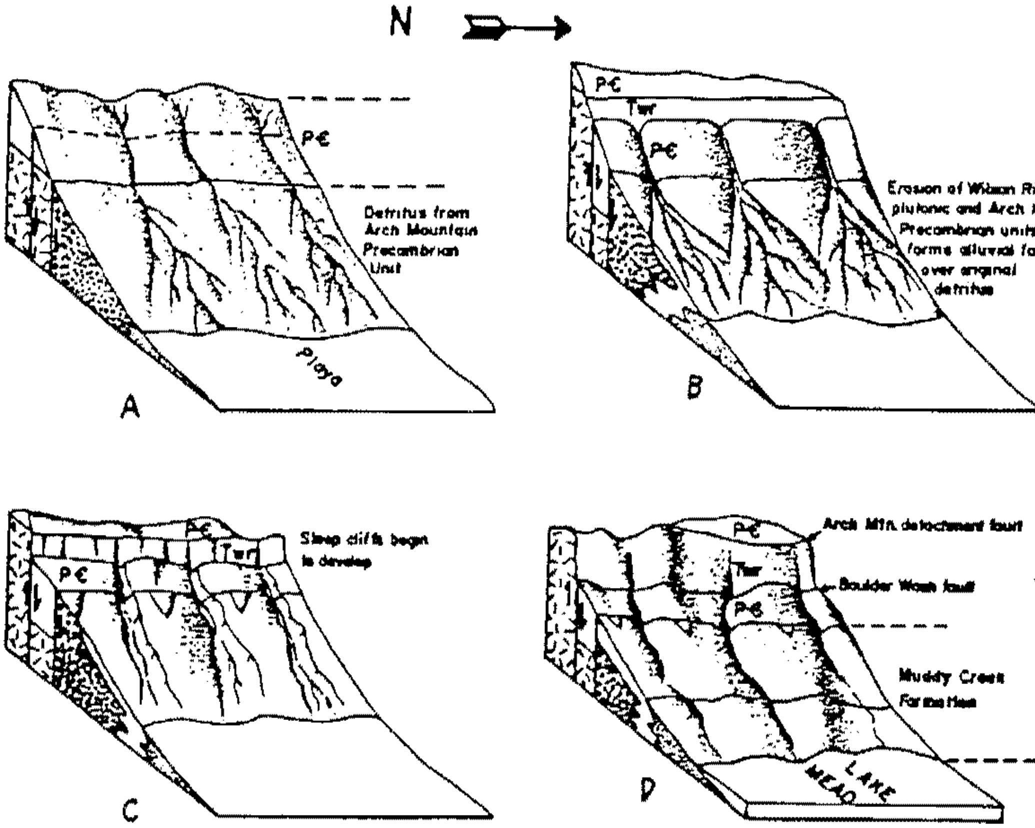

Figure 7. Interpretive development of the syntectonic Tertiary Muddy Creek Formation on the east side of Arch Mountain beginning with the initial uplift and erosion of the Precambrian rocks of the Arch Mountain horst (A) and ending with the present outcrop configuration (D) of Precambrian rocks (PЄ), Tertiary Wilson Ridge pluton (Twr) and Muddy Creek Formation.

Quaternary Rocks

Older Alluvium (Qol)

Alluvium occurs mainly on the east and west flanks of the horst. Older alluvial deposits are distinguished from younger alluvial deposits on the basis of superposition. Recent stream channels are usually incised into the older alluvial deposits. The surface of the buff-colored older alluvial deposits is commonly covered by a varnished desert pavement. These older alluvial deposits are often flat lying or slightly inclined and are composed of loosely consolidated and poorly sorted sediments that range in clast size from silt to boulder. The clasts are mostly angular to subangular and are mainly derived from the Precambrian basement and the Tertiary Wilson Ridge pluton. Tertiary volcanic clasts are locally abundant.

Younger Alluvium (Qal)

The thin veneer of sediments deposited in the major drainages of intermittant streams was mapped as younger alluvium (Qal). It consists of light colored sand, gravel, cobbles, and boulders derived from the recent erosion of the local terrane. The unit is unconsolidated and poorly sorted and the angular and subangular clasts are composed of Precambrian granite, gneiss,and Tertiary plutonic and volcanic rocks.

STRUCTURE

Arch Mountain Detachment Fault

A low-angle normal fault, herein named the Arch Mountain detachment fault, crops out over a lateral distance of 6 km just below the ridge crest of Arch Mountain. The fault strikes N10° W and dips 5° to 35° west. The fault can be easily identified from a distance because it corresponds to a distinctive dark-light contact produced by the color contrast between the dark, upper plate rocks and the light, lower plate rocks (Figure 8). The dark-light contact is also identifiable on LANDSAT imagery of northwestern Arizona. In the south-central part of the horst the fault trace is difficult to identify, and the color contrast is not well defined because only narrow outcrops of upper-plate rocks exist as erosional remanents above a diorite, inclusion-rich lower plate.

The Arch Mountain detachment fault is planar and lacks the undulations that are typical of detachment faults along the Colorado River trough in Arizona and southeastern California (Frost and Martin, 1982). On the west side of Arch Mountain, however, othe fault surface exhibits west-trending mullion structures with amplitudes of approximately 1 m (Figure 9). The fault surface is typified by a 2 to 20 cm thick zone of breccia and cataclasite impregnated with hematite. The breccia zone is formed by angular fragments of the Wilson Ridge pluton that range in size from 1 mm to 10 cm and that are supported by a black matrix composed of highly indurated rock flour (Figure 10).

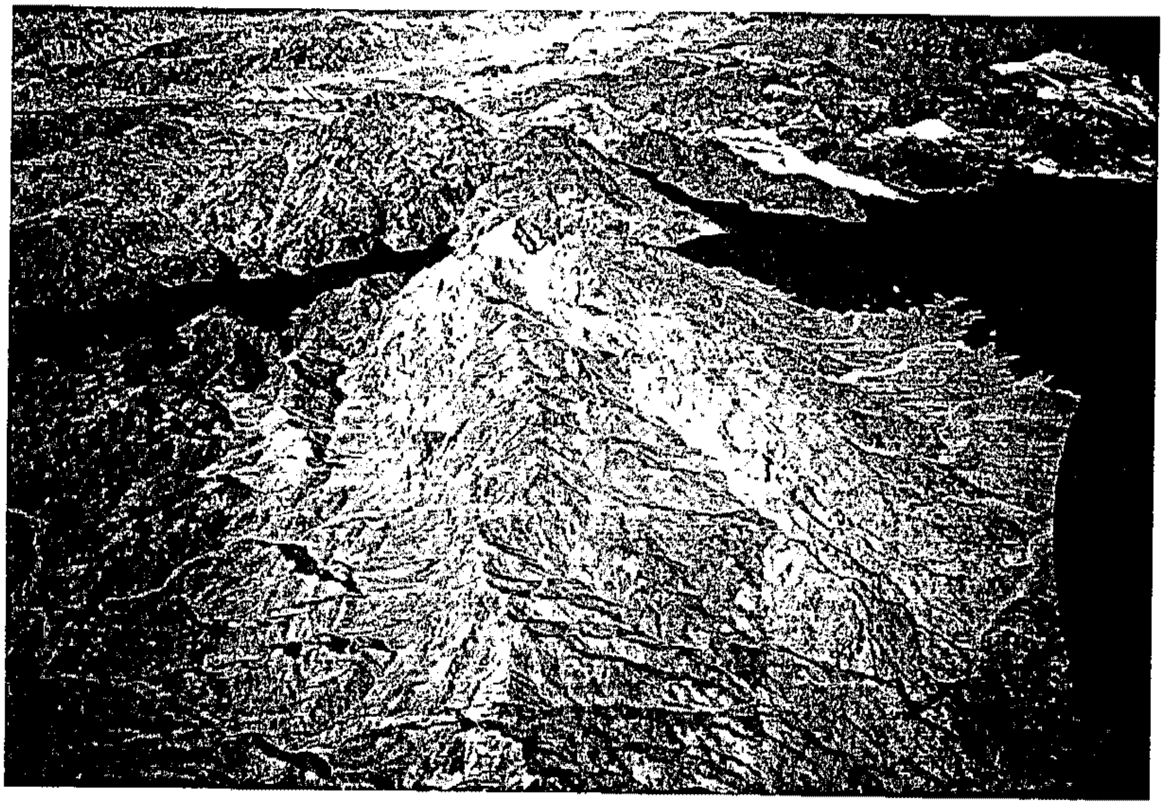

Figure 8. The Arch Mountain detachment fault can be easily identified from a distance because it corresponds to a distinctive dark-light contact produced by the color contrast between the dark, upper plate rocks and the light, lower plate rocks. View looking north (photo courtesy of Dr. E. I. Smith).

Figure 9. On the west side of Arch Mountain the detachment fault surface exhibits west-trending mullion structures with amplitudes of approximately 1 m (rock hammer for scale is left of center in lower part of photo). View looking west.

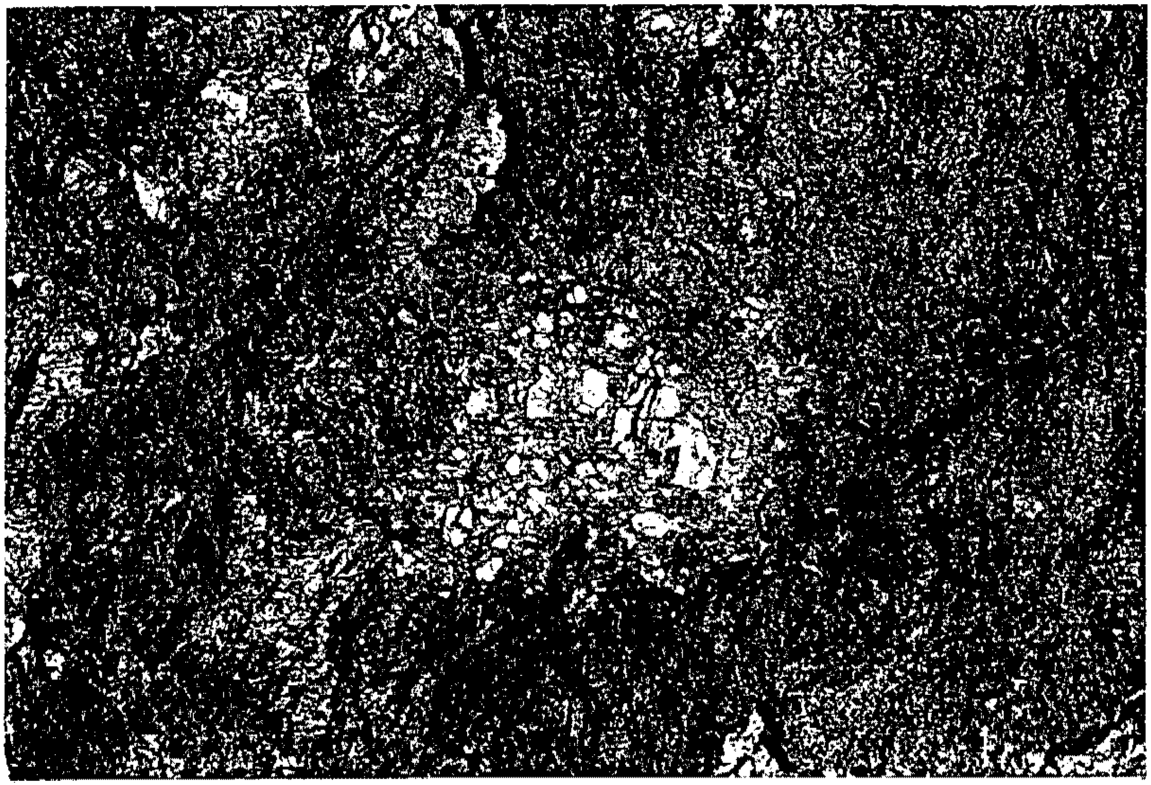

Figure 10. Photograph of a typical exposure of the breccia zone of the Arch Mountain detachment fault. The breccia is formed of angular fragments of Wilson Ridge pluton that range in size from 1 mm to 10 cm and that are supported by a black matrix composed of highly indurated rock flour.

The lower plate of the detachment fault is cut by anastomosing faults and by a pervasive set of fractures that are coplanar with the detachment fault (Figure 11). West-directed offset of the faults is demonstrated by the westward offset of mafic dikes that are cut and displaced as much as several meters to the west. Although the offset on individual faults is small, the cumulative offset along these numerous faults is estimated to be greater than 100 m.

Stacks of low-angle, west-dipping faults are also present in James Bay Wash; however, there is no cataclasis associated with them. Instead, these faults are discrete, slickensided planes of slippage that have been stained red by hydrothermal alteration. Again, cummulative displacement on these faults may be large, but the absolute offset could not be determined.

Figure 11. The quartz monzonite (Twr) in the lower plate of the Arch Mountain detachment fault is cut by anastomosing faults and by a pervasive set of fractures that are coplanar with the detachment fault. View looking south from east side of Arch Mountain, rock hammer for scale in lower part of photo.

Boulder Wash Fault Zone

The Boulder Wash fault crops out along the east side of Arch Mountain, from north of Petroglyph Wash to Boulder Canyon. North of Boulder Canyon the fault follows Boulder Wash and terminates against the Hamblin Bay Fault (Longwell, 1963; Naumann, 1987). Directly south of Boulder Canyon the fault dips 40° east and separates Precambrian granite from Quaternary fanglomerate. A few kilometers south of Boulder Canyon the dip of the fault increases to 45° east, and the fault zone contains a 10 m zone of highly altered, multicolored gouge. Farther south, near Petroglyph Wash, the fault dips 82° east, and the width of the gouge zone narrows to about 1 m.

Anderson (1971) suggested that at least 800 m of displacement was accommodated along the Boulder Wash fault. My mapping, however, demonstrates that the displacement on the Boulder Wash fault was distributed across a series of en echelon, east-dipping faults that are coplanar with the Boulder Wash fault. These faults crop out in a broad zone that extends approximately 1 km east and 2 km west of the trace of the Boulder Wash fault. Faults of this zone to the west of the Boulder Wash fault generally dip 75° or greater and place a hanging wall of Precambrian rocks (from the upper plate of the Arch Mountain detachment) against a footwall of Tertiary quartz monzonite (in the lower plate of the Arch Mountain detachment). Several of these east-dipping, high-angle faults cut and rotate the Arch Mountain detachment 30° to 35° to the west (Figure 12).

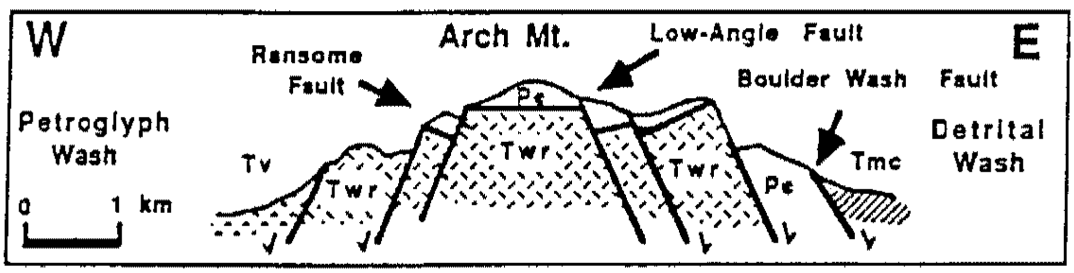

Figure 12. The Boulder Wash and the Ransome faults are major normal faults that cut the Arch Mountain detachment and bound the Arch Mountain horst on the east and west, respectively (from Eschner and Smith, 1988).

East of the Boulder Wash fault, Muddy Creek sediments are cut and rotated by a series of coplanar faults that dip 50° to 70° eastward (Figure 13). Some of these faults exhibit a well-cemented and resistant gouge zone (approximately 5 cm wide) that stands several cm in relief (Figure 14). Also, a north-plunging anticline parallels the Boulder Wash fault zone within the Muddy Creek sediments. Much of the eastern limb of the anticline is covered by the waters of Lake Mead. Longwell (1963) mapped several attitudes in the Muddy Creek section west of the anticline. Based on Longwell's mapping, I suggest that a syncline lies to the east of, and parallels, the anticline mapped by me but the syncline is now covered by Lake Mead. It is possible that the syncline northeast of Boulder Canyon (Naumann, 1987) is the northward projection of the concealed syncline.

Ransome Fault Zone

The Ransome fault strikes north along the western range front of Arch Mountain, from Petroglyph Wash to north of Boulder Canyon where it is truncated by, or merges with, the Boulder Wash fault. The fault forms a steep 100 m high escarpment that extends from Boulder Canyon approximately 3 km to the south; however, from approximately 4 km south of Boulder Canyon to Petroglyph Wash the escarpment is only 1 to 3 m high. The marked decrease in the height of the escarpment 4 km south of Boulder Canyon may indicate that the fault hinges as a scissor fault. Alternatively, erosion may have removed more of the hanging wall block near Boulder Canyon, thus exposing more of the fault.

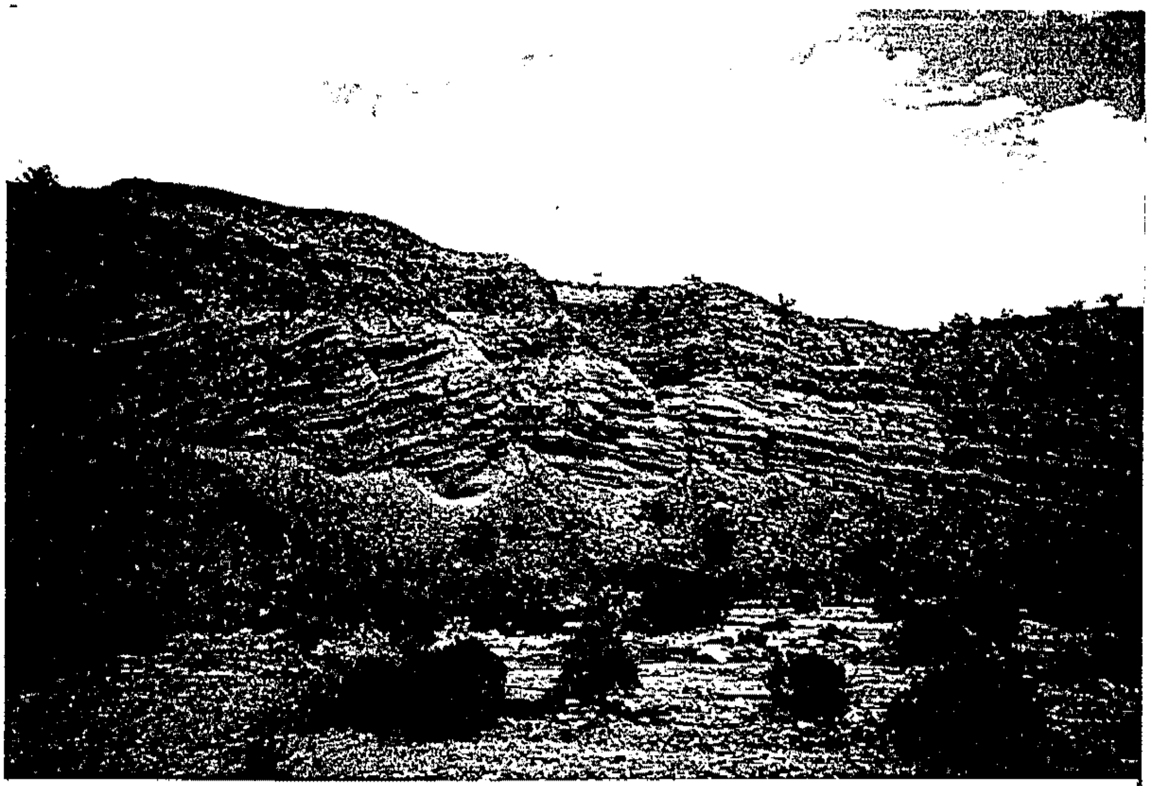

Figure 13. East of the Boulder Wash fault, Muddy Creek sediments are cut and rotated by a series of coplanar faults that dip 50° to 70° eastward. View looking north-down axis of anticline.

Figure 14. Some of the faults that cut the Muddy Creek Formation exhibit a well cemented and resistant gouge zone (approximately 5 cm wide) that stands several centimeters in relief. View looking south from east flank of Arch Mountain.

South of Boulder Canyon, the Ransome fault juxtaposes a 2.5 km - long block of Precambrian and Paleozoic rock against Tertiary Wilson Ridge pluton in the lower plate of the Arch Mountain detachment fault. The down-dropped block of Precambrian rock is offset at least 500 m from similar rocks in the upper plate of the Arch Mountain detachment fault. The block of Precambrian rock is bounded on the west by a west-dipping, high-angle normal fault, here named the Wishing Well Cove fault. The Wishing Well Cove fault juxtaposed and dragged volcaniclastic rocks against the block of Precambrian rock (Figure 15). Several smaller blocks of Precambrian rock are also displaced by the Ransome fault and by faults synthetic to the Ransome fault. The displaced blocks crop out along the west flank of Arch Mountain (see Plate 1).

In the James Bay region, west of the Wishing Well Cove fault , the section of hypabyssal quartz monzonite and dacite that is intruded by numerous, low-angle basaltic dikes is cut by north-striking, high-angle faults that dip 50° to 55° westward. Some of the high-angle faults are cut by north-striking, low-angle faults that dip 10° to 15° west-ward. No offset features were found that could be used to estimate the total amount of displacement across the low-angle faults; however, at one locality several en echelon, high-angle faults cut a quartz-monzonite dike, and each fault shows approximately 10 cm of down-to-the-west displacement (Figure 16).

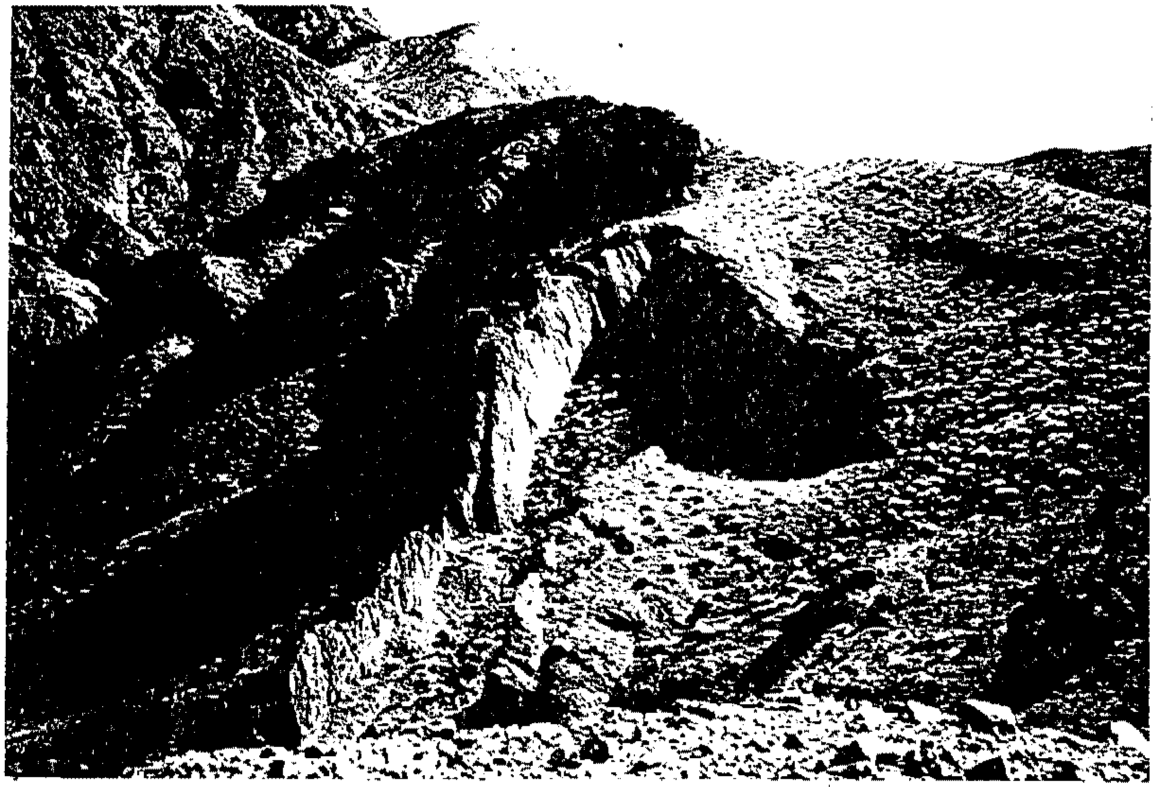

Figure 15. View looking southeast from south of Wishing Well Cove. The steeply west-dipping scarp of the Wishing Well Cove fault is exposed from the lower left of the photo to the upper right.The Wishing Well Cove fault juxtaposed and dragged volcaniclastic rocks, exposed in the right half of photo, against the block of Precambrian rock, exposed in the left half of photo.

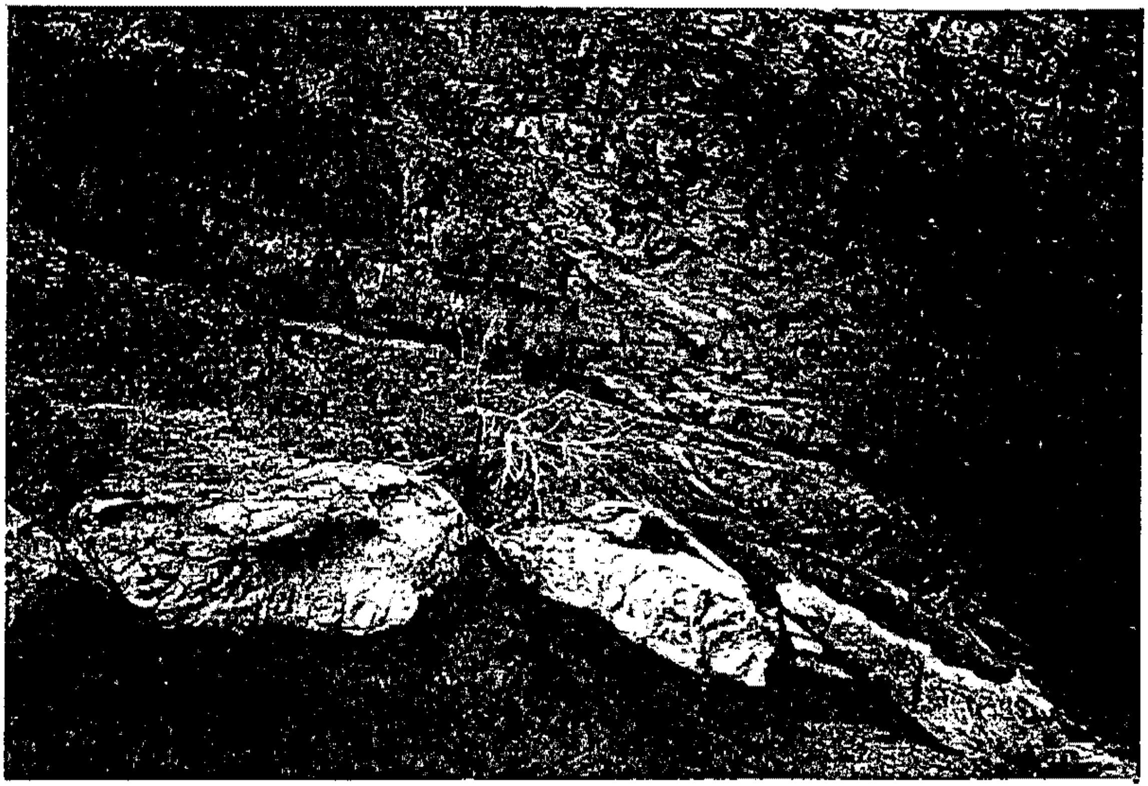

Figure 16. View looking south from James Bay wash. West-dipping, en echelon, high-angle normal faults cut a quartz monzonite dike, and each fault shows approximately 10 cm of down-to-the-west displacement. For scale, the dike is approximately 20 cm wide.

Structural Trends

North-striking, low-angle, normal faults and high-angle normal faults, and joints, are the major structural features of the Arch Mountain area. The poles to the planes of the faults and joints are plotted on Schmidt net lower hemisphere projection plots (Figures 17 and 18). The poles for the north-trending faults plot along an east-west belt, and thus reflect east-west regional extension. The poles for the north-trending joints also reflect east-west extension. No low-angle joints were observed. The poles plot in two groups centered on the east-west axis of the net, one on the eastern side and the other on the western side of the net (Figure 18). The data for the faults and the data for the joints indicate that the faults and joints are the result of a vertical maximum principal stress (sigma 1) and of a horizontal, east-west directed, minimum stress (sigma 3).

Interpretation of High-Angle Normal Faults and Strike-Slip Faults

Multiple north-striking horsts and grabens formed south of the Lake Mead region synchronous with strike-slip faulting of the Lake Mead fault system (Anderson, 1973). The Black Mountains block, including the Arch Mountain horst, the Petroglyph Wash graben, and the Wilson Ridge horst was uplifted approximately 2000 m (Anderson, 1973) relative to the Colorado River trough, the Boulder basin, and the Virgin Basin. The Black Mountains are bounded by high-angle faults that formed as the range uplifted.

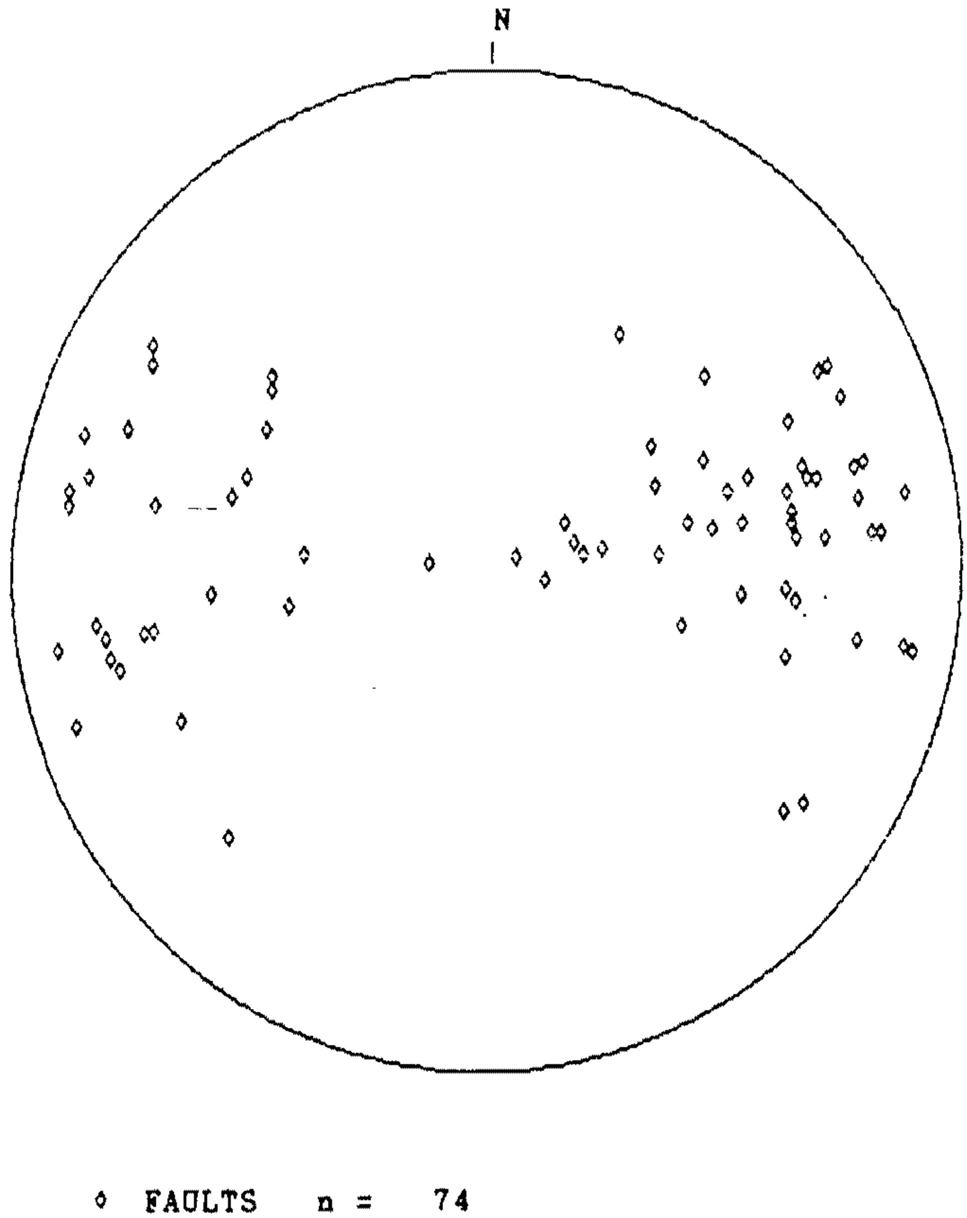

Figure 17. Poles to the planes of the faults plotted on a Schmidt net, lower hemisphere projection.

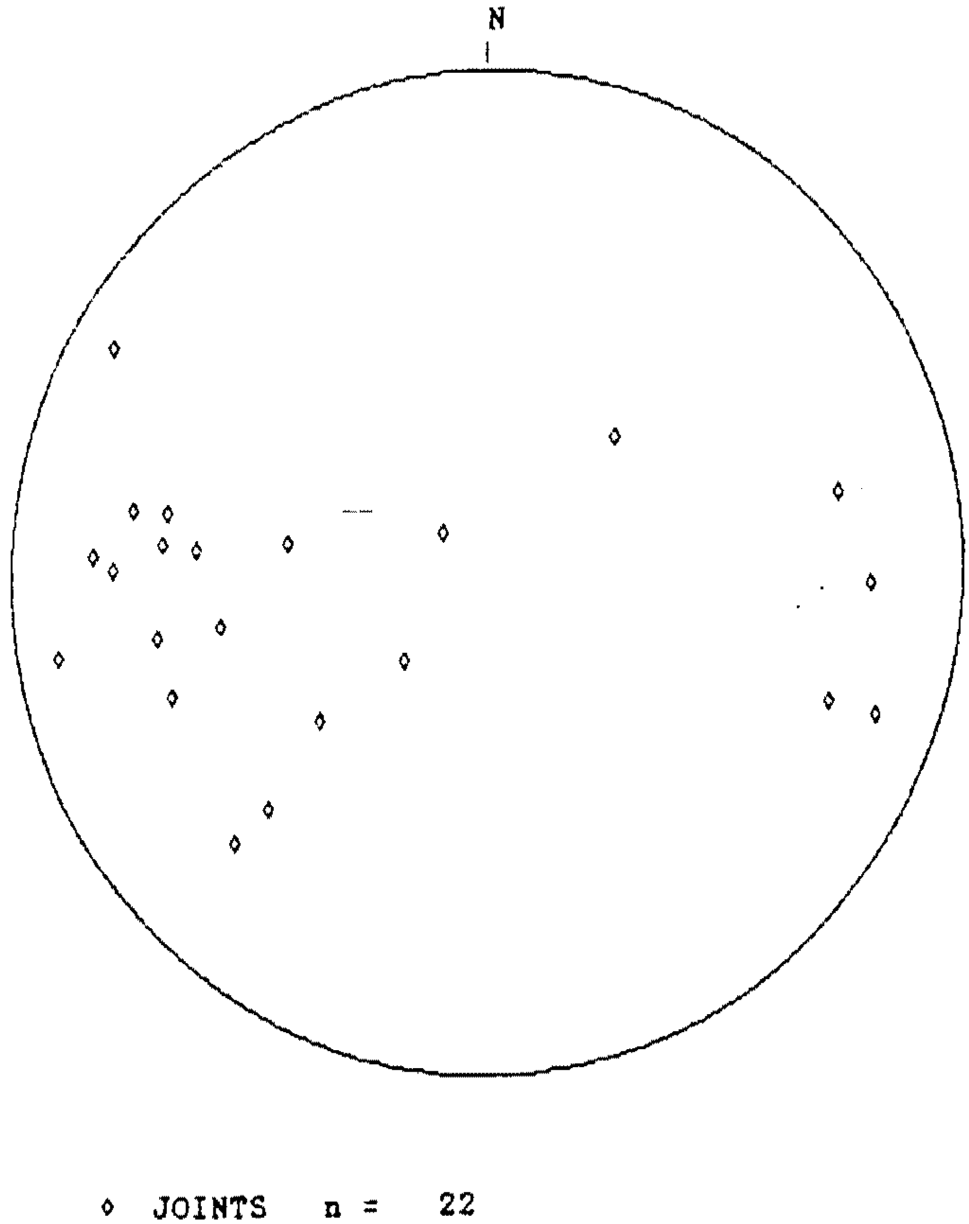

Figure 18. Poles to the planes of the joints plotted on a Schmidt net, lower hemisphere projection.

The Indian Canyon fault is the west-dipping, high-angle normal fault that bounds the west flank of the Black Mountains, adjacent to Wilson Ridge; the fault projects north of Lake Mead and bends eastward into the Lake Mead fault system along the Hamblin Bay fault (Longwell, 1936; Angelier et al., 1985). The Boulder Wash fault bounds the east flank of the Black Mountains, adjacent to Arch Mountain, and intersects the Hamblin Bay fault. The Virgin Basin (Detrital Valley block) is bounded to the west and north by the Boulder Wash and Hamblin Bay faults, respectively (Figure 19). The high-angle faults that cut the Black Mountain block may have formed in the upper plate of a detachment system that is structurally younger and deeper than any detachment faults that are exposed in the region (Smith et al., 1987b). Conversely, the high-angle faults may have formed in response to isostatic uplift of the Black Mountains block resulting from the tectonic denudation of the Arch Mountain-Saddle Island detachment system or from an older detachment system. Axen (1987) and Wernicke and Axen (1988) documented similar structural geometries in the Mormon and East Mormon Mountains, the Tule Spring Hills, the Beaver Dam Mountains and the Virgin Mountains. In those areas, approximately 60 km of WSW-directed extension occurred above three detachments. The detachment faulting was followed by isostatic rebound that caused high-angle faults to accommodate 5-20 km of footwall uplift.

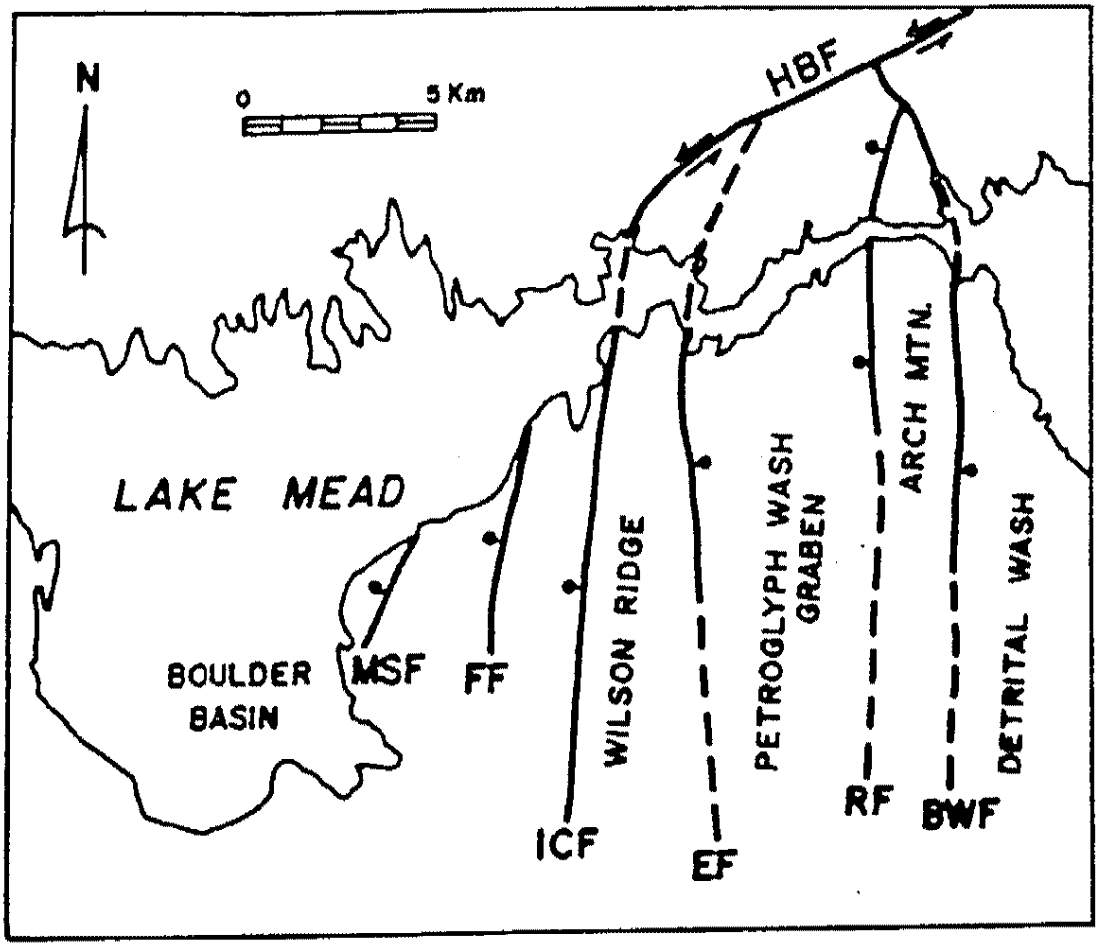

Figure 19. Generalized structure map of the Lake Mead area showing relationship between the left-lateral Hamblin Bay fault and the high-angle normal faults (bar and ball on down-dropped side) to the south (modified after Longwell, 1936; Anderson, 1973; Angelier et al., 1985). HBF = Hamblin Bay fault; BWF = Boulder Wash fault; RF = Ransome fault; EF = Emory fault; ICF = Indian Canyon fault; MSF = Mead Slope fault; FF = Fortification fault.

REGIONAL STRUCTURAL MODELS

Introduction

Several models have been proposed to explain the geology of the Lake Mead area, but these models need updating as new geologic relationships are discovered. I present here a discussion of the models of the Lake Mead area geology.

Strike-slip models

Early models of the area addressed the significance of large-magnitude strike-slip faults. Two opposing schools of thought emerged, one in favor of right-lateral strike-slip faulting and another in favor of left-lateral faulting. Longwell (1971; 1974) recognized that the Gold Butte pluton in the South Virgin Mountains is the closest known source for the rapakivi-granite megabreccias in the Horse Springs Formation east of Frenchman Mountain. He proposed that the right-lateral Las Vegas Valley shear zone was responsible for approximately 65 km of right-lateral displacement of the Frenchman Mountain Block (Figure 20), and he presented several other independent estimates of lateral movement that support approximately 65 km of right-lateral offset on the Las Vegas Valley shear zone. Longwell's work indicated that at approximately 17 Ma, before the development of the Lake Mead fault system, the Las Vegas Valley shear zone extended to the southernmost South Virgin Mountains and that at 12 Ma the northeast trending faults of the Lake Mead system offset the Las Vegas Valley shear zone.

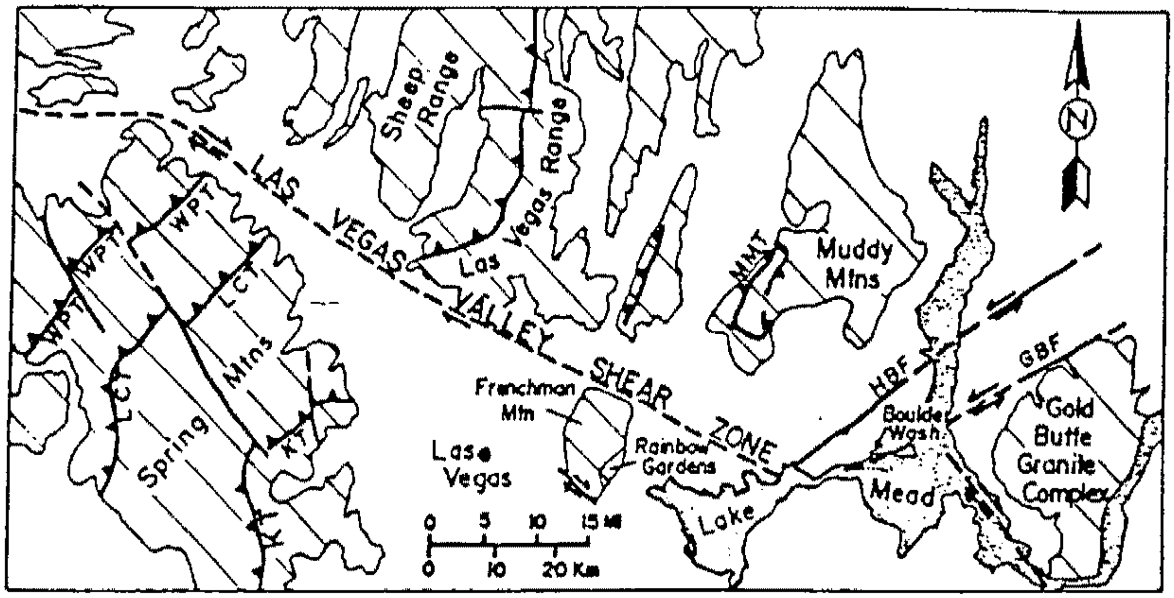

Figure 20. Right-lateral strike-slip model showing approximately 65 km of seperation between the Frenchman Mountain block and the Gold Butte granite complex (after Longwell, 1974)

Anderson (1973) and Bohannon (1979) did not support Longwell's interpretation. They chose to ignore the implications of large-magnitude right-lateral strike-slip faulting in the Lake Mead area based on the poor exposure of the southeastward projection of the Las Vegas Valley shear zone (Figure 21). They suggested that the left-lateral Lake Mead fault system was responsible for the emplacement of the Frenchman Mountain block. They also concluded that perhaps the Las Vegas Valley and Lake Mead strike-slip systems formed coevally, between approximately 15 to 10.7 Ma, and that strike-slip displacement on the Lake Mead fault system is transferred into vertical displacement and crustal extension south of Lake Mead (Figure 22). It is still unclear whether the Las Vegas Valley shear zone was active at the same time as the Lake Mead fault system, but Salyards and Shoemaker (1987) indicate that in the region southeast of Frenchman Mountain, where the two fault systems intersect, the Las Vegas Valley shear zone is consistently offset by the Lake Mead fault system.

Detachment Models

Anderson (1973) realized that the large horizontal transport of the Frenchman Mountain block and the geometry of the northeast-striking fault ridges within and about the block were inadequately explained by classical fault mechanics acting within a rigid crust. He speculated that these upper-crustal deformational features must be the result of mantle convection. Low-angle, normal-slip, crustal shear zones, however, can also explain these upper-crustal features.

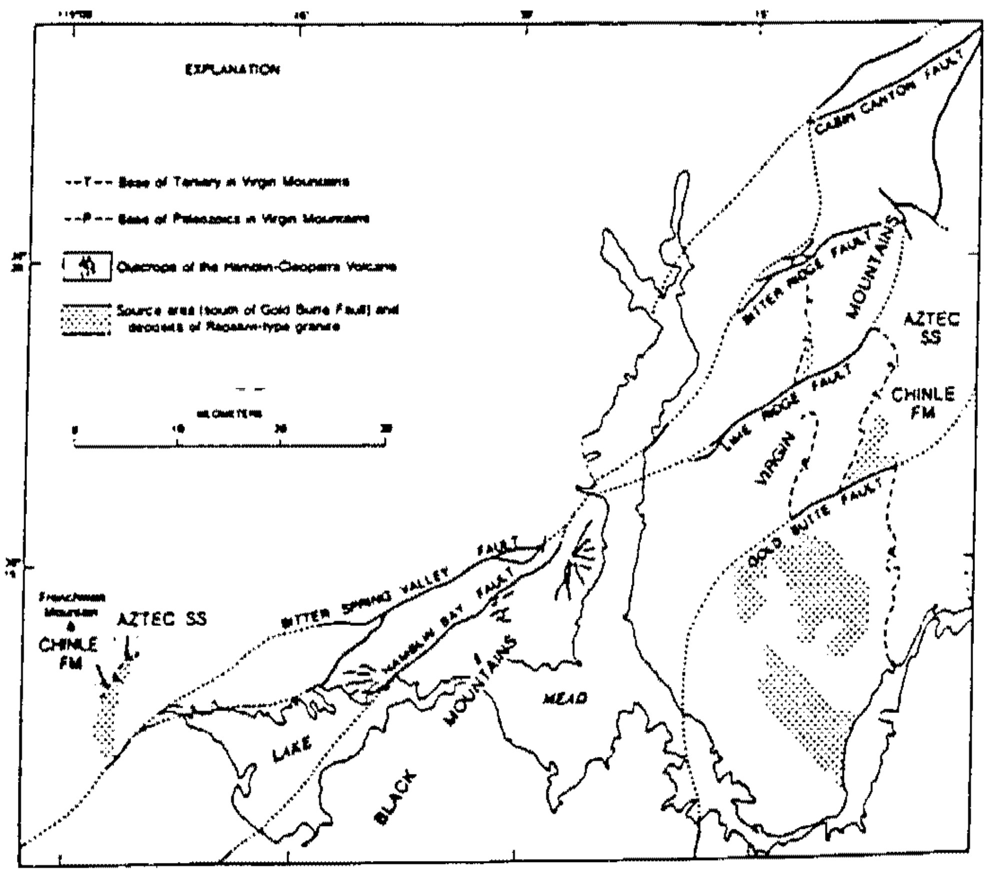

Figure 21. Left-lateral strike-slip model showing approximately 20 km of separation of the Hamblin-Cleopatra volcano (from Bohannon, 1979).

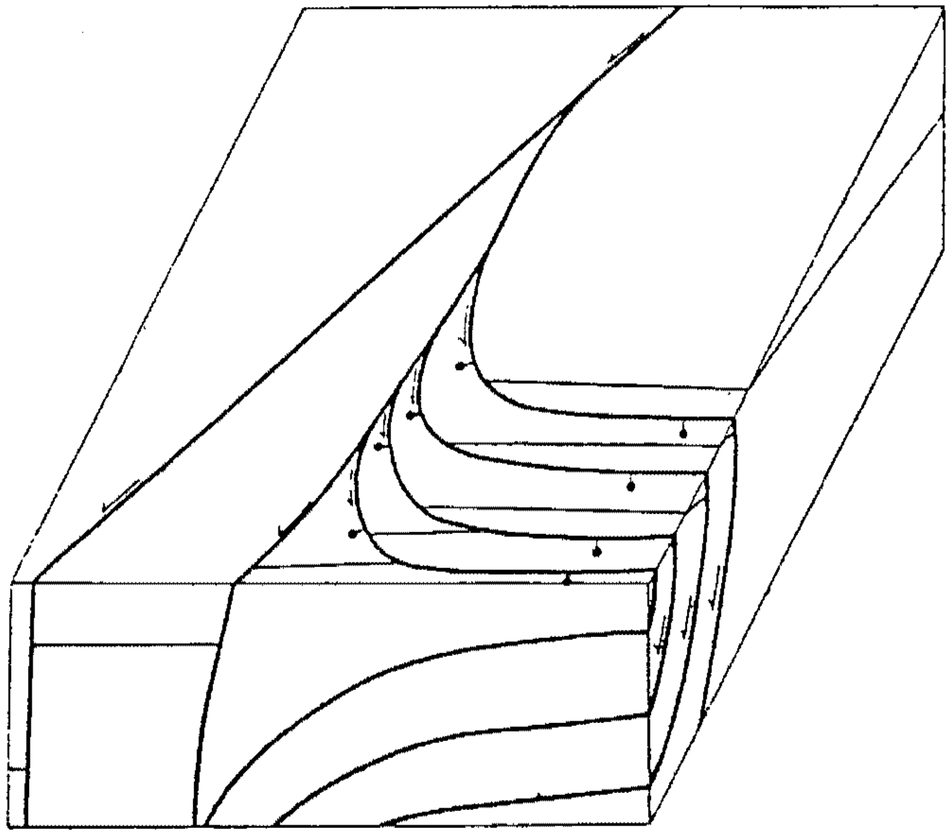

Figure 22. Block diagram illustrating the relationship of strike-slip faults and normal faults in the Lake Mead area. The normal faults are shown with bar and ball on the down-thrown side. Displacement on the strike-slip system decreases toward the viewer (from Anderson, 1973).

With the recognition of detachment faulting in the Lake Mead region (Smith, 1982; Choukroune and Smith, 1985) new models were developed, and a new school of thought is emerging that emphasizes the importance of detachment faults and their relationship to strike-slip and high-angle normal faults.

Weber and Hardy (1986) disagreed with Bohannon's (1984) model of broad arching in the Lake Mead region and suggested that the similarities in thickness and depositional environment of the lower to middle Cambrian sequences exposed at the Colorado Plateau, Frenchman Mountain, and Sheep Mountain indicated that those areas, now widely separated, were originally deposited in close proximity. They applied the models of Spencer (1985) and Wernicke (1985) and suggested that Frenchman Mountain, and Sheep Mountain may represent isolated blocks that broke off the margin of the Colorado Plateau during the mid-Miocene and were transported westward as the Precambrian basement in the Lake Mead area was pulled from beneath the Colorado Plateau in the lower plate of an east-rooted detachment structure. They argued that the Paleozoic sedimentary section was never deposited on the Precambrian basement of the Lake Mead area.

Parolini (1986) studied the Thumb Member of the Horse Spring Formation in the Rainbow Gardens area east of Frenchman Mountain and suggested that the angularity of the clasts in the Rainbow Gardens member precludes Bohannon's (1984) interpretation that the megabreccias were deposited 30 km from their proposed source in the Gold Butte area of the South Virgin Mountains before lateral transport by the Lake Mead fault system.

Alternatively, Parolini called on the Wernicke (1985) model of an east-rooted detachment beneath the Colorado Plateau and suggested that the source for the Thumb Member megabreccias was pulled from beneath the Colorado Plateau, and that the megabreccia was deposited in an allochthonous basin .

Parolini concurred with Longwell (1974) that the Horse Spring basin formed prior to 17.5 Ma and he suggested that the initiation of faulting and basin formation was at least 3 m.y. before the initiation of activity on the Lake Mead fault system at 14.5 Ma.

Weber and Smith (1987) used geochemical data from volcanic rocks and volcanic stratigraphy to suggest that high-angle normal faults and the faults of the Lake Mead fault system formed at the boundaries between areas of variable extension in the upper plate of a regional detachment structure. They also suggested that the high-angle normal faults and the faults of the Lake Mead fault system sole into the upper plate of a regional detachment structure and that the detachment structure and strike-slip faults of the Lake Mead fault system are temporally and kinematically related (Figure 23).

Smith et al. (1987a) suggested that the detachments exposed at Saddle Island, Petroglyph Wash, and Arch Mountain may be correlative.

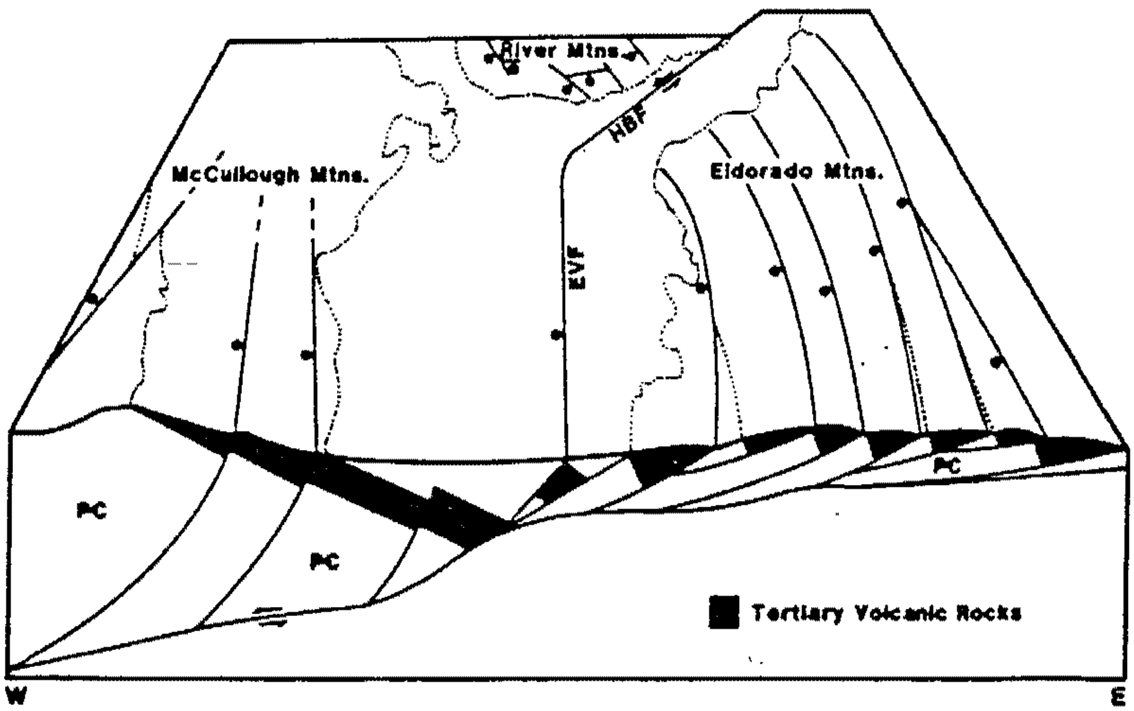

Figure 23. Interpretive block diagram showing upper plate of the proposed Lake Mead-Eldorado Valley detachment system. EVF = Eldorado Valley fault; HBF = Hamblin Bay fault (from Weber and Smith, 1987).

Also, they suggested that the high-angle normal faults that cut the detachments to form a series of north-striking horsts and grabens may be related to a structurally younger and deeper detachment (Figure 24). Duebendorfer et al. (1988) examined the mylonitic Precambrian rocks in the lower plate of the Saddle Island detachment, and they determined a top-to-the-west sense of shear for the mylonites and the low-angle normal faults that cut the lower plate rocks. They suggested that Saddle Island represents a metamorphic core complex.

Rowland et al. (in press) examined Paleozoic and Tertiary strata exposed in the Frenchman Mountain block and similar rocks adjacent to the Colorado Plateau. They suggested that the Frenchman Mountain block was detached from an area east of the South Virgin Mountains. Before large-magnitude tectonic transport of the Frenchman Mountain block, the megabreccias of Precambrian rapakivi granite that are now exposed in the Horse Spring Formation east of Frenchman Mountain were likely calved from a structurally exposed headwall in the South Virgin Mountains and were deposited into a proximal episutural basin.

Any new structural models of the Lake Mead area must honor the implications of detachment faulting and recognize that high-angle normal faults and strike-slip faults in the region may be adjustment features in the upper plate(s) of detachment structures (Guth and Smith, 1987).

LAS VEGAS VALLEY–DETRITAL WASH TRANSECT

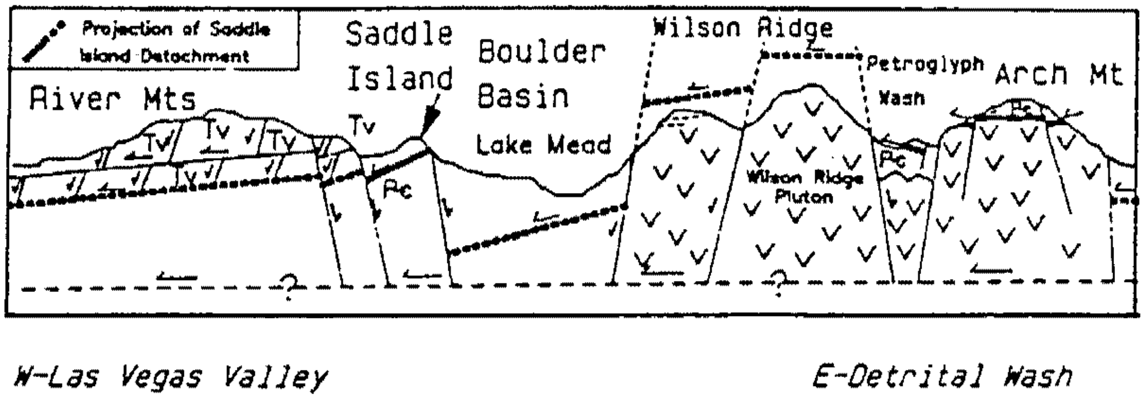

Figure 24. Las Vegas Valley-Detrital Wash transect showing horst and graben nature of the region and the projection of the Arch Mountain and Saddle Island detachment faults (after Smith et al., 1987a).

IMPLICATIONS AND CONSTRAINTS

Introduction

The geology of the Arch Mountain area provides data that are useful for constraining structural models of the Lake Mead area. Evaluating the models induces critical questions about the Cenozoic history of the Lake Mead area. These questions include:

1. Were the Paleozoic and Mesozoic sedimentary rocks that are now virtually missing south of Lake Mead removed by erosion or by faulting

2. What is the significance of major structural features such as the the Saddle Island detachment, the Arch Mountain detachment, the Las Vegas Valley shear zone, and the Lake Mead fault system?

I will next discuss each question using constraints based on my field work at Arch Mountain and on a synthesis of regional studies.

1. Lack of Paleozoic and Mesozoic Rocks South of Lake Mead

The absence of Paleozoic and Mesozoic cover in the area south of Lake Mead suggests the removal of approximately 3000 m of section by erosion or by faulting, or by a combination of the two processes.

Bohannon (1984) suggested that, during the late Cretaceous to early Tertiary, a large north-striking arch formed in the Lake Mead area (Figure 25) and that in the core region of the arch, between the Grand Wash Cliffs and the eastern Spring Mountains, erosion denuded the Precambrian basement of virtually all Paleozoic and Mesozoic cover before the Patsy Mine Volcanics were deposited at approximately 20 Ma. In the Lake Mead-Eldorado Valley area, mid Miocene plutons served as the source for the volcanic rocks that were deposited on the basement of Precambrian metamorphic rocks locally covered by as much as 10 m of conglomerate (Anderson, 1971; Anderson et al. 1972; Weber and Smith, 1987). Unfortunately, Tertiary erosion and faulting preclude unequivocal reconstruction of the arch, but sedimentologic and stratigraphic evidence suggest that a topographic high existed in the area of the proposed arch before 20 Ma (Longwell, 1963; Young, 1966; Lucchitta, 1966; Anderson, 1971). Xenoliths of Paleozoic rocks near Kingman Wash (Mills, 1985), large blocks of Paleozoic rocks in the Petroglyph Wash graben (Wilson and Moore, 1959; Feuerbach, 1986) and in the River Mountains (Timm, 1985), and the Paleozoic-Mesozoic section at Frenchman Mountain indicate that isolated blocks of Paleozoic rocks were present in the Lake Mead area during the episode of mid-Tertiary plutonism and volcanism between approximately 15 to12 Ma. Therefore erosion did not remove all of the pre-Tertiary rocks as Bohannon (1984) suggested. Alternatively, the presence of Paleozoic rocks in the upper plate of the Arch Mountain detachment fault, and the presence of detachments in Petroglyph Wash and at Saddle Island, suggest that detachment faulting was an important factor in removing Paleozoic-Mesozoic strata from the area. The Horse Spring Formation apparently formed during this faulting event between 24 to10 Ma.

Weber and Hardy (1986) disagreed with the arch theory and proposed that the Precambrian basement south of Lake Mead is an exhumed tectonic surface that was pulled from beneath the Colorado Plateau; they concluded that Paleozoic rocks were *never* deposited on the basement of the Lake Mead area.

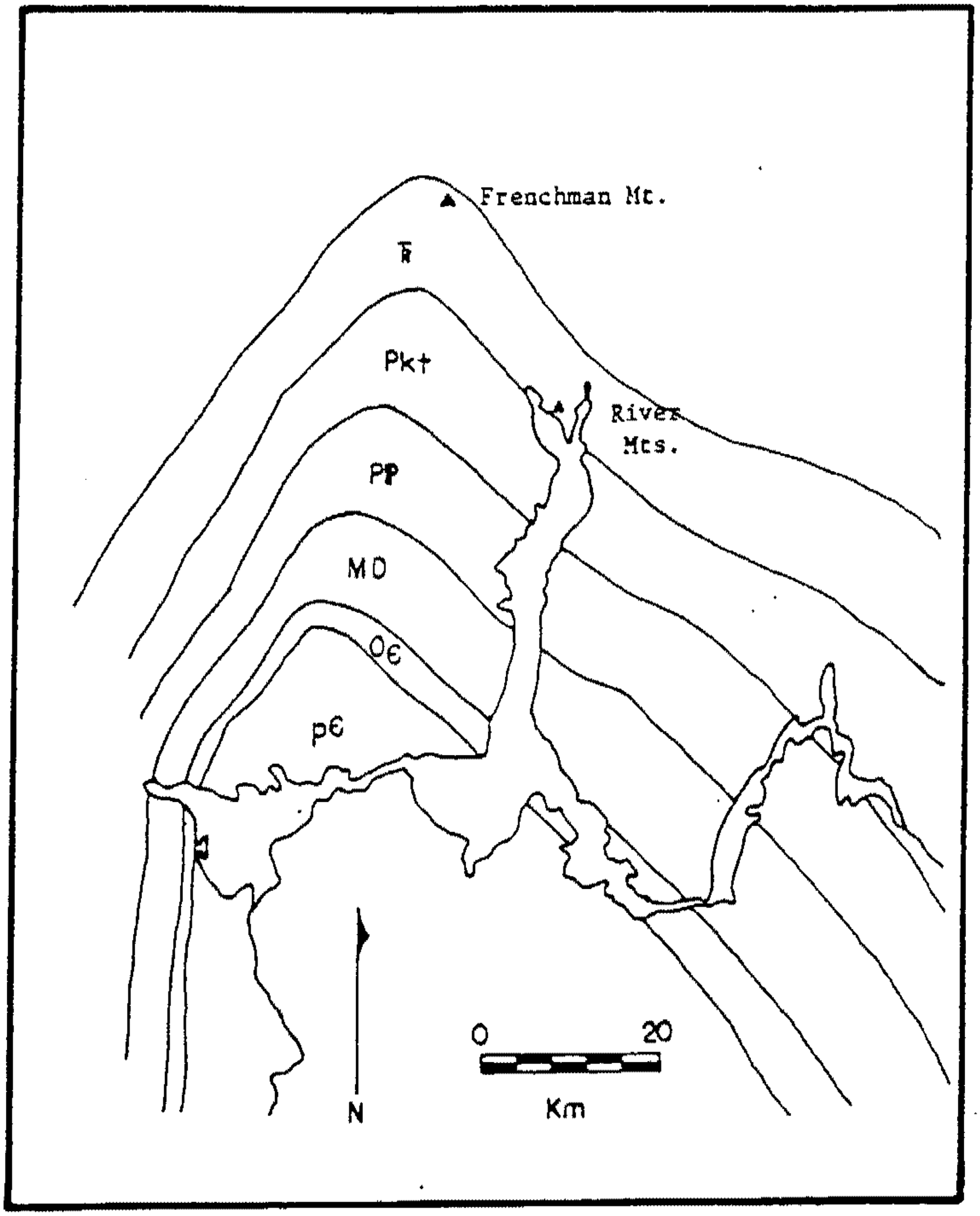

Figure 25. Location of north-striking arch that formed during the late Cretaceous to early Tertiary (modified by Timm, 1985, after Bohannon, 1984).

The presence of Paleozoic rocks in the Arch Mountain area suggests that the Paleozoic - Mesozoic section that originally *was* deposited above Arch Mountain and a large region south of Lake Mead was not entirely removed by erosion. The absence of significant Paleozoic and Mesozoic rocks in the Arch Mountain area and the presence of detachment faults at Arch Mountain, Petroglyph Wash, and Saddle Island suggest that the Phanerozoic section that was deposited in the region around Arch Mountain became detached during the Tertiary and was transported to the west, adjacent to the Las Vegas Valley shear zone and above a west-dipping, regionally extensive detachment fault complex, possibly the Arch Mountain-Saddle Island detachment system. In this model the Frenchman Mountain block, the Spring Mountains, Sheep Mountain, and Paleozoic rocks in Petroglyph Wash *are* the detached remanents of the Paleozoic and Mesozoic strata that were deposited in the region south of Lake Mead.

Restoring the Paleozoic and Mesozoic Strata

Spring Mountains and Frenchman Mountain Block

The Paleozoic strata exposed in the Frenchman Mountain block are clearly representative of the foreland east of the Sevier orogenic belt (Longwell, 1974). The orogenic belt is exposed in the Spring Mountains and in the Muddy Mountains. Approximately 65 km of east-southeast translation of the Spring Mountains and the Frenchman Mountain block is required to restore the Keystone and Muddy Mountain thrust plates along the axis of the Las Vegas Valley shear zone, yet maintaining the foreland position of the Frenchman Mountain block. Restoring the Spring Mountains and the Frenchman Mountain block along the Las Vegas shear zone places them south of Lake Mead (Figure 26). The Spring Mountain block is interpreted as a large block that did not experience significant rotation. Instead, it remained a "stable," coherent block as it rode passively to the west above a proposed detachment zone (Wernicke et al., 1984). In contrast, the geometry of the north-striking, high-angle normal faults that cut the Frenchman Mountain block indicate that the Frenchman Mountain block broke into a series of strike ridges that rotated eastward as the block moved to the west in the upper plate of the regional detachment fault system. The geometry of the eastward-tilted strata of the Horse Spring Formation east of Frenchman Mountain indicates that the strata were deposited synchronous with detachment faulting. Older units of the Horse Spring Formation east of Frenchman Mountain dip to the east at a higher angle than the younger units (Bohannon, 1984). It is common for strata that are deposited synchronously with

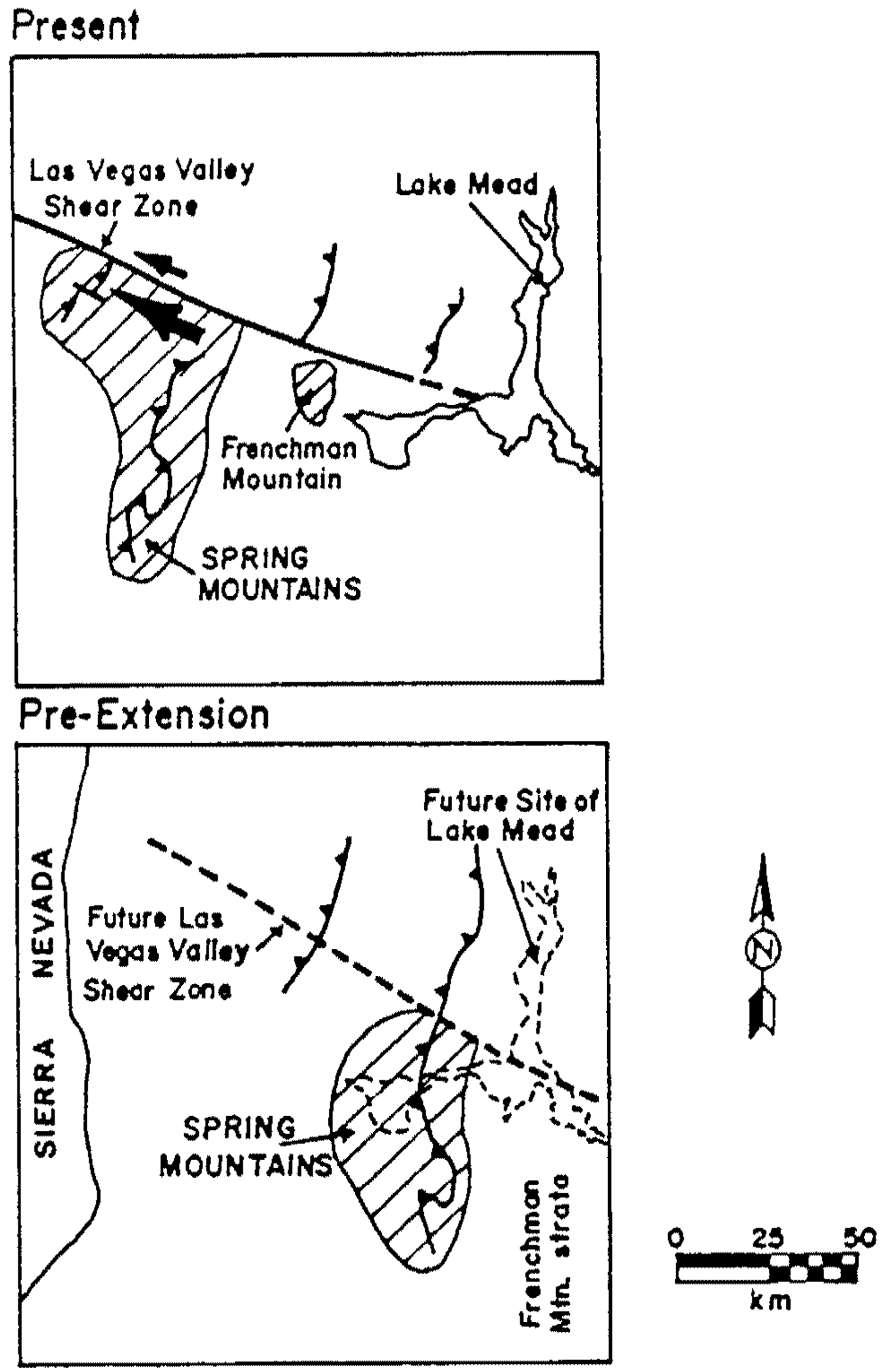

Figure 26. Present geology (dark arrows represent relative displacement vectors) and reconstruction of offset Mesozoic thrust faults (heavy solid lines with teeth). Restoring the Spring Mountains and the Frenchman Mountain block along the Las Vegas shear zone places them south of Lake Mead.

detachment faults to exhibit greater dip angles in the older strata than in the younger strata. This is because the older strata are subject to a longer episode of stratal rotation during tectonic transport (Davis, 1983).

Sewall and Smith (1988) correlated the Rainbow Gardens and Thumb members of the Horse Spring Formation exposed east of Frenchman Mountain with lithologically similar units in the upper plate of the Saddle Island detachment and suggested that detachment faulting, in addition to strike-slip faulting, transported the sections from the Gold Butte area to their present positions. This evidence suggests that either the Arch Mountain detachment was involved in the transport of the sections from the Gold Butte area, or that the transport was accommodated by a detachment that is structurally higher than the Arch Mountain detachment. If there was a structurally higher detachment, it must lie in the upper plate of the Arch Mountian detachment and, unfortunately, it has since been eroded from the klippe exposed at Arch Mountain. In the Cohenour Mine area, however, sediments that are lithologically similar to Horse Spring Formation are interpreted to be in the upper plate of the Arch Mountain detachment. The presence of these sediments may be additional evidence to suggest that the Frenchman Mountain block was transported to the west in the upper plate of the Arch Mountain detachment as well as the Saddle Island detachment.

Sheep Mountain

The Paleozoic strata of the Sheep Mountain block may be concisely tied to the Frenchman Mountain block by the stratigraphic correlation of the lithologically distinct middle Devonian C member of the Mountain Springs Formation; Zilinsky and Miller (1984) suggested that the lithologic features and thickness of the member C at Sheep Mountain and Frenchman Mountain indicate that the successions formed paleogeographically near Arch Mountain, between the Muddy Mountains and the South Virgin Mountains. The strike-slip models do not explain the displacement of the Sheep Mountain block.

Conclusions

Restoring the Spring Mountains, the Frenchman Mountain block, and Sheep Mountain to their pre-extension paleogeographic position requires that they lie in the upper plate of the Arch Mountain and Saddle Island detachments. The evidence presented above supports the interpretation that many of the Phanerozoic strata that were deposited in the Arch Mountain area, and in the area to the south of the Las Vegas Valley shear zone, were structurally denuded and that the structural denudation accounts for a large percentage of the missing Paleozoic-Mesozoic strata south of Lake Mead. If the Las Vegas Valley shear zone displacement is removed, and the Spring Mountains, Frenchman Mountain and Sheep Mountain blocks are restored to to their pre-faulting position adjacent to the Muddy Mountains and the Colorado Plateau (Figure 27a), then one can see that the Black Mountains, including Arch Mountain, are part of the basement that once existed beneath those blocks (Figure 27b).

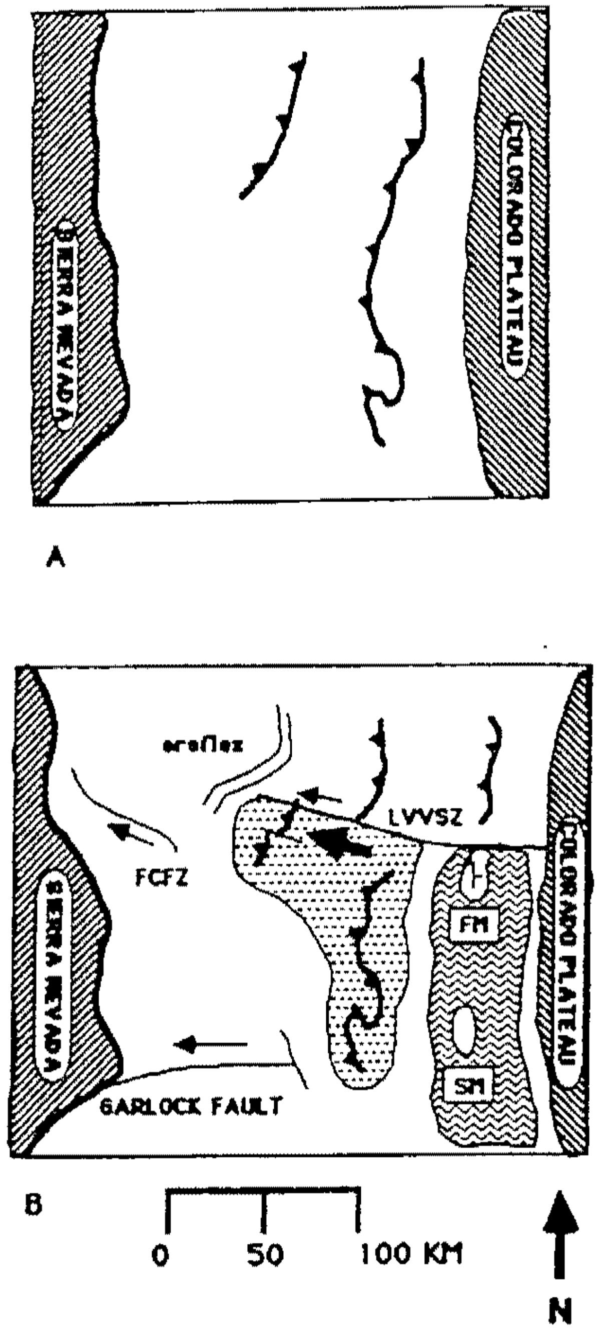

Figure 27. Idealized map view showing A) prior to detachment and strike-slip faulting, the Sevier thrust (heavy line with teeth on upper plate) was a continuous, north-trending belt and B) present position of thrust faults separated by Las Vegas Valley shear zone (LVVSZ); Spring Mountains block is shown by stipled pattern; FM = Frenchman Mountain block; SM = Sheep Mountain block; FCFZ = Furnace Creek fault zone; wavey pattern represents exposed basement terrain structurally denuded of cover; arrows represent displacement vectors (modified after Wernicke et al., 1982).

It is apparent, however, that two pieces of evidence remain enigmatic: (A) the trace of the Las Vegas Valley shear zone south of Frenchman Mountain is difficult to locate, and (B) the nature of the relationship between the Las Vegas shear zone and the Lake Mead fault system is not clear. These problems are addressed below.

2. Significance of Regional Structural Features

The Saddle Island Detachment Fault

The Saddle Island detachment is exposed within the north-striking horst at Saddle Island, southeast of Frenchman Mountain. The upper plate of the Saddle Island detachment contains rocks that range from Precambrian basement to Paleozoic and Tertiary sediments and intrusives (Sewall, 1988). The lower plate exposes Precambrian amphibolite and gniess that exhibits penetrative mylonitic fabric that indicates top to the west displacement (Duebendorfer et al., 1988). The Saddle Island exposure contains all the characteristic elements of a metamorphic core complex, including lower plate mylonites, a detachment marked by chlorite schist and a microbreccia zone, and a brittlely deformed upper plate. Displacement associated with an evolving, crustal scale shear can explain the structural and lithological relationships at Saddle Island (Smith, 1982; Sewall, 1988; Duebendorfer et al., 1988).

The Arch Mountain Detachment Fault

The Arch Mountain detachment lies approximately 25 km east of Saddle Island and it may represent the eastward extension of the Saddle Island detachment. Mylonites, however, are not present in the lower plate of the Arch Mountain detachment; instead the lower plate is intensely brecciated and brittlely deformed by numerous low-angle faults that display top-to-the-west offset. The transition from ductile mylonites in the lower plate of the Saddle Island detachment to brittle deformation in the lower plate of the Arch Mountain detachment likely indicates that the detachment system shallows to the east. This geometry suggests that the breakaway zone lies to the east of Arch Mountain, possibly along the Grand Wash Cliffs. The Arch Mountain detachment constrains the geometry of a regional detachment structure that extends from the Grand Wash Cliffs or South Virgin Mountains area to at least as far west as Saddle Island. West of Saddle Island the detachment might extend beneath the Spring Mountains.

The Las Vegas Valley shear zone

The relationship, between the northwest-trending Las Vegas Valley shear zone and the northeast-trending Lake Mead fault system has never been fully understood. This is because the Las Vegas Valley shear zone is difficult to trace southeast of the Frenchman Mountain block in the area of the Lake Mead fault system, although the Las Vegas Valley shear zone must project eastward from Frenchman Mountain and pass south of the Muddy Mountains (Anderson, 1973). Bohannon (1984) indicated two possible exposures of the Las Vegas Valley shear zone to the south of Frenchman Mountain, one to the north of the Gale Hills and one to the south.

To the southeast of the Gale Hills, Longwell et al. (1965) and Joan Fryxell (personnal communication, 1988) suggested right-lateral sense offset along the Gold Butte fault. Perhaps the Las Vegas Valley shear zone projects southeast of Frenchman Mountain, adjacent to the Gale Hills, and intersects the Colorado Plateau along (or south of) the Gold Butte fault. If this is correct, then north of the Gold Butte fault the Grand Wash fault forms the north-striking breakaway zone (the Beaver Dam breakaway of Wernicke et al., 1984) for the northern detached terrain, and south of the Gold Butte fault the Grand Wash fault is the south-striking breakaway (the Grand Wash breakaway of Wernicke et al., 1984) for the southern detached terrain. Thus, the Gold Butte fault (southeast extension of the Las Vegas Valley shear zone ?) may act as a transfer fault between the northern and southern extended terranes.

Anderson (1973) stated that if the Las Vegas Valley shear zone does extend southeast of Frenchman Mountain for any considerable distance then it is either concealed beneath Tertiary volcanic and sedimentary rocks or is offset by displacements on the Lake Mead fault system. He concluded, however, that neither interpretation is tenable because "the (Tertiary) volcanic and sedimentary rocks are intricately and intensely involved in the strike-slip displacements on the (Lake Mead fault system)." He also concluded that if the Las Vegas Valley shear zone is displaced by the Lake Mead fault system it must pass through Boulder Canyon, but "remarkable structural continuity from south to north across the (canyon) precludes (the presence of the Las Vegas Valley shear zone)."

My mapping at Arch Mountain agrees with Anderson's (1973) interpretation that the Las Vegas Valley shear zone does not disrupt structural continuity north and south of Boulder Canyon, and it confirms that the shear zone does not cut the Black Mountains Block south of Boulder Canyon. I cannot, however, discount the possibility that the fault did at one time pass south of Boulder Canyon, in the upper plate of the Arch Mountain detachment or in a structurally higher detachment.

If the Las Vegas shear zone acted as a transfer fault in the upper plate of the Arch Mountain detachment, then the trace of the shear zone might be difficult to recognize. Mostly Precambrian foliated rocks are exposed in the klippe at Arch Mountain, and these rocks are fairly homogeneous so offset would not be obvious; however no evidence of east-west-trending zone of brecciation or lineaments was observed in the Arch Mountain klippe that might be interpreted as remnents of the shear zone. The Precambrian rocks in the upper plate of the Arch Mountain detachment are only about 200 m thick at present. Erosion may have long ago removed all traces of the shear zone if the shear zone was confined in the upper plate of a detachment fault that cut Precambrian rock structurally higher than the rocks exposed in the klippe at Arch Mountain.

Placing the Las Vegas Valley shear zone in the upper plate of the Arch Mountain detachment intrinsically implies that the shear zone formed before the uplift of the Arch Mountain horst and the Black Mountains block, and Anderson (1973) concluded that the uplift of the Black Mountains block occurred synchronously with displacement on the Hamblin Bay fault between 12 and 10.6 Ma.

This "synchronous interplay of vertical and horizontal tectonics at the northern boundary of the Black Mountains" is an excellent additional example of the "close genetic tie between late Cenozoic normal and strike-slip faulting" (Anderson, 1973), but it also suggests at least two stages of structural development: an early stage involving detachment faulting and the development of the Las Vegas Valley shear zone in the upper plate of the Arch Mountain, detachment and a later stage involving the cogenetic uplift of the Black Mountains block and the development of the Lake Mead fault system. The Las Vegas Valley shear zone is difficult to locate south of Frenchman Mountain, possibly, because it is covered by Tertiary volcanics and is overprinted by younger offset along the Lake Mead fault system which developed synchronously with normal faulting and horst and graben formation south of Lake Mead.

Lake Mead Fault System

The Lake Mead fault system is exposed to the north of Arch Mountain (see Figure 19) where the Hamblin Bay fault system truncates the Black Mountain and Detrital Valley (Virgin basin) structural blocks (Anderson, 1973; Naumann, 1987). Approximately 20 km of left-lateral offset along the fault system separated the Hamblin-Cleopatra volcano between 12.7 and 11.1 m.y. ago (Anderson,1973). Anderson (1973) outlined a model explaining the relationship between the Hamblin Bay fault and the high-angle normal faults to the south (see Figure 24). Naumann (1987, Figure 3) showed how the uplifting of the Black Mountains block and the down-dropping of the Detrital Valley block along the Boulder Wash and Hamblin Bay faults produced left-lateral dip-slip offset. Combining the geometries shown by Anderson (1973) with that shown by Naumann (1987) and Smith et al. (1987a) leads me to the conclusion that the Hamblin-Cleopatra volcano may have been distended as the Northern Black Mountains uplifted concurrently with the down-dropping of the Boulder basin and the Virgin basin (Detrital Valley Block). Thus, the high-angle normal faults that cut the Black Mountains may be part of a coordinated system of faults intimately related to the Lake Mead fault system (Figure 28). This interpretation is rudimentary and needs development. If further research confirms this interpretation, however, it may imply that much of the movement on the Hamblin Bay and related oblique-slip faults is transformed from large-scale, high-angle normal faults south of the Hamblin Bay fault; namely, the Boulder Wash, Ransome, Emery, Indian Canyon, Fortification Hill, and Mead Slope faults (Longwell, 1963, Anderson, 1973). Isostatic rebound is a mechanism that may explain this type of offset such that after most of the Paleozoic, Mesozoic, and Tertiary volcanic cover was removed from the region south of Lake Mead, high-angle normal faulting became the primary active process accommodating crustal deformation south of the Lake Mead fault system and that the strike-slip/oblique-slip faulting is a passive response to crustal extension related to large-magnitude vertical uplift of the Black Mountains structural block.

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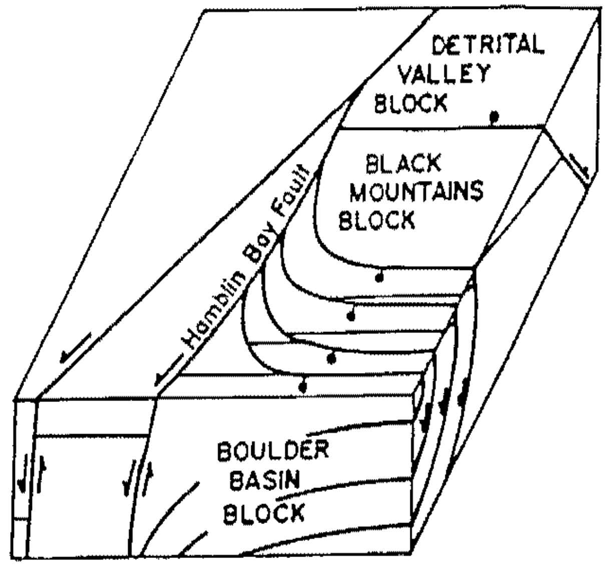

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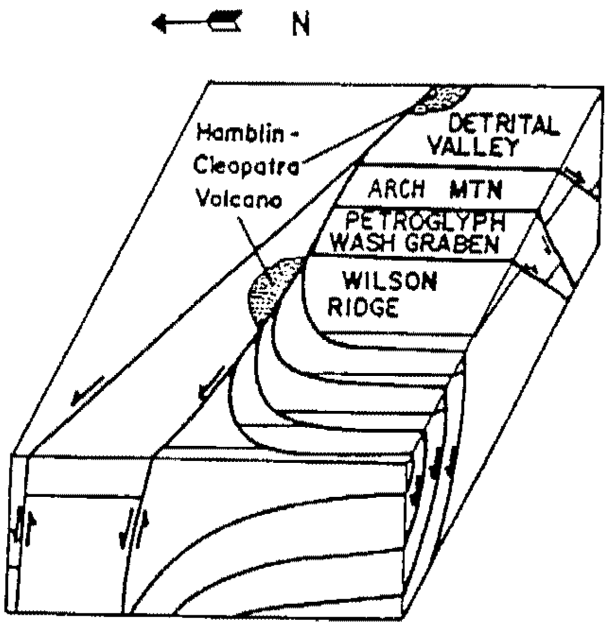

B

Figure 28. A) Simplified block diagram showing how the sinistral offset of the Hamblin-Cleopatra volcano may be the result of major high-angle normal fault formation south of the Hamblin Bay fault (modified from Anderson, 1973). B) The Hamblin-Cleopatra volcano may have been distended as the Northern Black Mountains uplifted concurrently with the down-dropping of the Boulder basin and the Detrital Valley Block (modified from Anderson, 1973, and Smith et al., 1987a). Thus the sinistral offset of the Hamblin-Cleopatra volcano may be the result of important vertical offsets adjacent the Hamblin Bay fault.

This interpretation is in concurrence with Anderson's (1973) conclusion that the area south of the Hamblin Bay fault provides critical data to assess the relationship between large-scale normal and strike-slip faulting, but it contradicts the conclusions of Ron et al., (1986) that strike-slip faulting is the primary process accommodating crustal deformation along the Lake Mead fault system.

I suggest that Ron et al., (1986) erroneously concluded that strike-slip faulting is the primary process accomodating crustal deformation along the Lake Mead fault system, because in their localized study of faults in the Hamblin-Cleopatra volcano area they neglected to consider the effects of the large-scale, north-striking, high-angle normal faults south of the Hamblin Bay fault. They based their conclusion, in part on (1) the assumption that block rotation about a vertical axis should accompany normal faulting, based on a tilted fault block model and (2) paleomagnetic data indicate that the faulted rocks in the area have not been significantly affected by structural tilt; therefore, they concluded that normal faulting is secondary in importance to strike-slip faulting. The geometry of the high-angle normal faults at Arch Mountain indicates that a horst and graben model is more appropriate than the tilted fault block model. Guth and Smith (1987) indicated that Ron et al. (1986) also ignored the implications of regional detachment faulting.

WORKING HYPOTHESIS

Introduction

In this section I will incorporate the diverse lines of evidence discussed earlier and present a conceptual model that can be tested by future research.

Conceptual Model of Regional Development

The region south of Lake Mead was apparently bowed into a north-trending arch during late Cretaceous to early Tertiary time. During the early to mid-Tertiary, the Precambrian and Phanerozoic rocks south of the Las Vegas Valley shear zone broke away from the Colorado Plateau, perhaps along the Grand Wash fault, and rode to the west in the upper plate of the Arch Mountain detachment fault or in a structurally higher detachment. Detachment faulting in the region south of the Las Vegas Valley shear zone was severe, thus Precambrian basement was denuded and exposed to erosion before the deposition of the Patsy Mine volcanics were deposited about 20 to 18 Ma (Anderson et al., 1972). Westward displacement of the upper plate rocks above a regional detachment fault system is indicated by mylonites in the lower plate of the Saddle Island core complex (Duebendorfer et al., 1988). Westward displacement of the upper plate rocks south of the Las Vegas Valley shear zone is further indicated by: (1) thrust faults (the Keystone thrust complex) in the Spring Mountain block that are offset from correlative thrust faults (Muddy Mountain thrust complex) in the Muddy Mountains; (2) right-lateral-sense drag folds in the ranges north of the Las Vegas Valley shear zone, and (3) apparent drag folding of the Sunrise Mountain part of the Frenchman Mountain block south of and adjacent to the Las Vegas Valley shear zone.

The Spring Mountain block is interpreted as a large block that remained "stable" (coherent) as it rode passively to the west approximately 65 km, above the detachment zone (Wernicke et al., 1984). The Frenchman Mountain block did not remain coherent, rather it broke into a series of eastward tilted strike ridges as it moved westward above a regional detachment fault system. Portions of the detachment system may be exposed at Saddle Island and at Arch Mountain (Figure 29). The megabreccia blocks of Precambrian rapakivi granite and gneiss that are now exposed in the Horse Spring formation east of Frenchman Mountain were likely calved, perhaps seismically, from a structurally exposed headwall in the South Virgin Mountains and were deposited into a proximal episutural basin (Parolini, 1986) before large magnitude tectonic transport of the Frenchman Mountain block. Continuous westward transport, synchronous basinal sedimentation, and eastward tectonic rotation produced greater dip angles in older members of the Horse Spring Formation and lesser dips in younger sediments.

The Paleozoic strata at Sheep Mountain are lithologically similar to the Frenchman Mountain section; therefore, before detachment faulting they also occupied a paleogeographic position east of the Sevier thrust belt, near the edge of the Colorado Plateau. It is apparent that the Black Mountains, including Arch Mountain, are part of the exposed basement that once existed beneath those blocks.

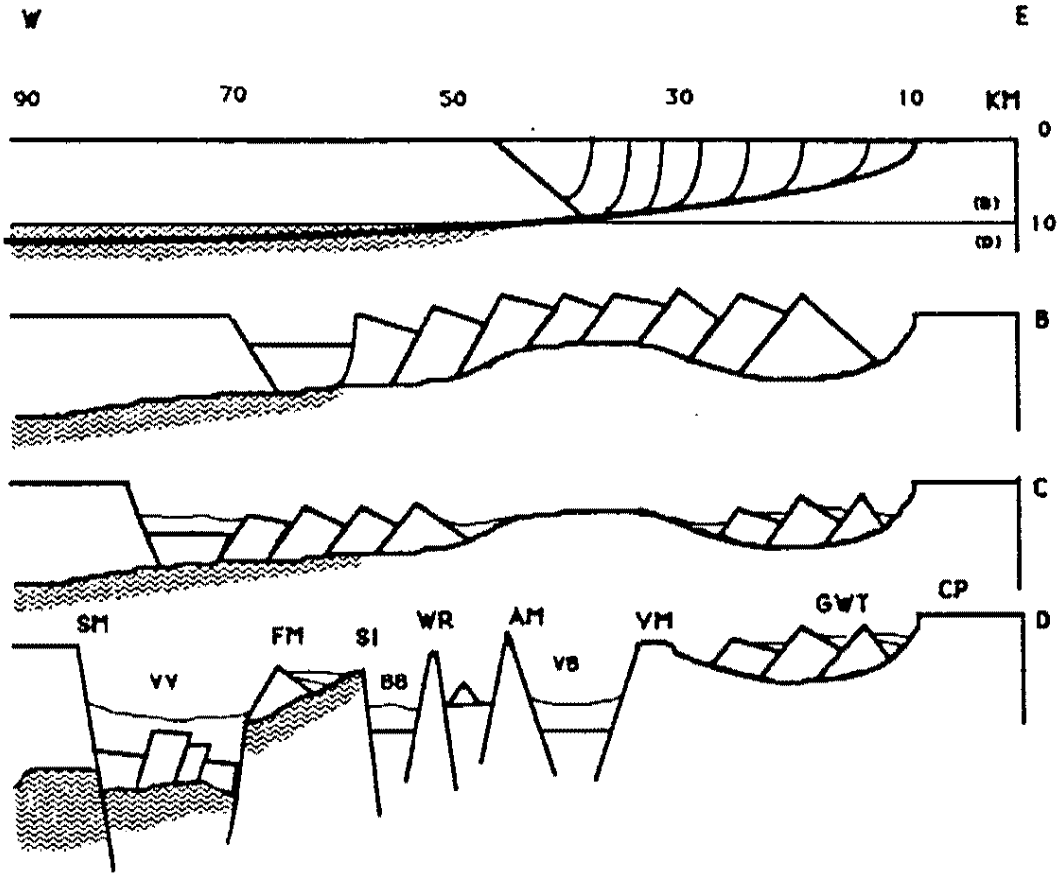

Figure 29. Conceptual model for structural development of Lake Mead area (modified from Spencer, 1984). A) Inception of master detachment and listric normal faults in the upper plate, mylonitic fabrics (wavy pattern) develop within the brittle (B) - ductile (D) transition approximately 10 km beneath the crust. B) East-west extension results in stable and tilted blocks. Tectonic denudation of upper plate results in antiformal warp in lower plate. C) Continued tectonic denudation has resulted in uplift and initial exposure of lower plate to erosion. D) Present structural geometry includes high-angle normal faults. CP = Colorado Plateau; GWT = Grandwash Trough; VM = Virgin Mountains; VB = Virgin Basin; AM = Arch Mountain; WR = Wilson Ridge; BB = Boulder Basin; SI = Saddle Island; FM= Frenchman Mountain; VV = Vegas Valley; SM = Spring Mountains.

I suggest that this evidence supports the interpretation that a large percentage of the Phanerozoic strata deposited in the Arch Mountain area, and in the area to the south of the Las Vegas Valley shear zone, was structurally denuded and that the structural denudation accounts for much of the missing Paleozoic-Mesozoic strata south of the Lake Mead area.

Extension North of Lake Mead

Extension north of the Las Vegas Valley shear zone did not expose lower plate basement terrain. North of the Las Vegas Valley shear zone, an upper plate of Paleozoic and Mesozoic rocks, and probably the Precambrian basement, broke away from the Colorado Plateau along the Grand Wash Cliffs, in the upper plate of a detachment fault system (Guth, 1981; Wernicke et al., 1984; Axen, 1987, Smith et al., 1987a) that is possibly correlative with the Arch Mountain-Saddle Island detachment fault system, or the structurally higher detachment system discussed above. This interpretation seems plausible because the minimum areal extent of the basal fault associated with crustal scale extensional shear zones is typically measured in thousands of square kilometers (Wernicke, 1981).

The upper plate rocks north of the Las Vegas Valley shear zone were disrupted by a series of en echelon, west-dipping, listric normal faults that created a series of tilted domino-style fault blocks (Figure 30) including, from east to west, the Beaver and the Mormon Mountains, the Arrow Canyon, Las Vegas, Sheep, East Desert, Pintwater, and Spotted Ranges (Longwell, 1945; Guth, 1981, 1984, 1987; Wernicke et al., 1984).

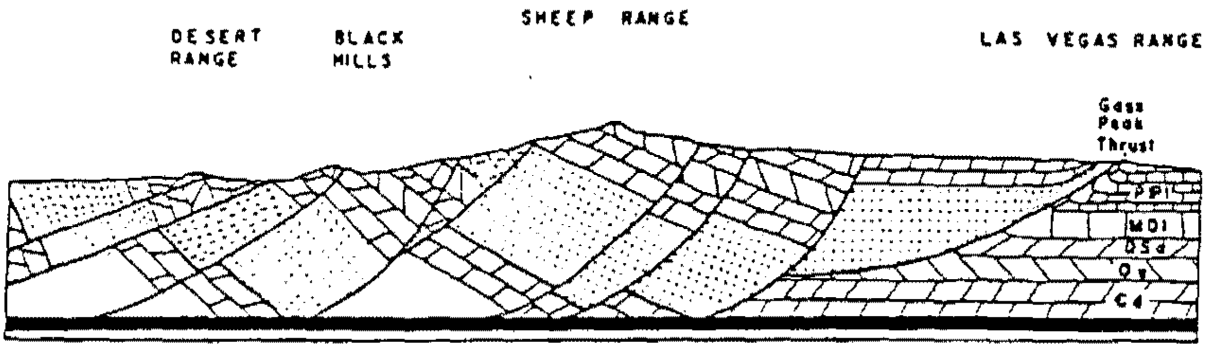

Figure 30. Schematic model for development of the extensional terrane north of the Las Vegas Valley shear zone, in the Sheep and Desert Ranges. Heavy black horizontal line at base of ranges represents the Sheep Range detachment (from Guth, 1981).

The transport of these blocks adjacent to the Las Vegas Valley shear zone is indicated by the right-lateral-sense dragging of the ranges (Longwell, 1974). The transfer fault nature of the Las Vegas Valley shear zone is indicated by markers that are differentially displaced to the east and west of the shear zone axis (Wernicke et al., 1982). Episutural basins formed in the topographic lows between some fault blocks; the basins filled with sediments temporally equivalent to the Horse Spring Formation (Deibert, 1988). Exposures of detachment faults in the Mormon and East Mormon Mountains, Tule Springs Hills and Beaver Dam Mountains indicate approximately 60 km of WSW directed extension (Axen, 1987). West of the spotted Range, the detachment zone projects westward beneath the Nevada Test site (Guth, 1984). Active fault scarps in the northern detached terrain indicate detachment faulting may still be active in that region (Wernicke et al, 1984).

SUMMARY

Arch mountain is a north-trending horst bounded on the west by the Petroglyph Wash graben and on the east by the Virgin Basin. The Arch Mountain detachment fault is exposed for 6 km along strike just below the ridge crest of Arch Mountain and it is typified by a 2 to 20-cm thick zone of hematite-impregnated breccia and cataclasite. The detachment fault places an allochthon of Precambrian gneiss, Paleozoic quartzite, shale and dolomite, Tertiary intrusive rock, and sedimentary rock on a lower plate composed of quartz monzonite that is chemically correlative to the quartz monzonite of the Wilson Ridge pluton.

The western margin of the horst is cut by en echelon, west-dipping, high-angle normal faults that step the detachment fault to the west and rotate it to the east. The Ransome (normal) fault forms the western boundary of the horst and separates Arch Mountain from Precambrian gneiss and Tertiary volcanics. The eastern margin of the horst is cut by en echelon, east-dipping, high-angle normal faults that step the detachment fault to the east and rotate it to the west. The Boulder Wash (normal) fault forms the eastern boundary of the horst and separates Arch Mountain from Tertiary Muddy Creek sediments in the Virgin Basin-Detrital Wash area.

The Ransome and Boulder Wash faults are genetically related to and were formed synchronously with the left-lateral Lake Mead fault system at approximately 12 Ma. The Arch Mountain detachment fault is cut by the high-angle normal faults; therefore, the Arch Mountain detachment fault is older than the Lake Mead fault system. The Arch Mountain detachment fault is possibly related to the development of the Las Vegas Valley shear zone, and it is interpreted to be correlative with the Saddle Island detachment fault.

I propose that the Arch mountain detachment fault represents the brittlely deformed, upper-crustal part of a regional detachment fault system that has a breakaway zone adjacent to the Grand Wash Cliffs. The detachment fault and lower plate mylonites at Saddle Island are interpreted as the plastically deformed, deep level-part of the regional detachment fault system that became exposed by progressive structural denudation, isostatic uplift, and erosion.

The fault history of the regional detachment system is complicated and poorly constrained, but the following scenario is suggested:

1. Regional uplift and arch formation south of Lake Mead during the late-Cretaceous to early Tertiary

2. Early to mid -Tertiary pluton emplacement, detachment faulting, development of the Las Vegas Valley shear zone and westward transport of the Paleozoic and Mesozoic rocks represented at Petroglyph Wash, Boulder Canyon, and the Frenchman Mountain, Sheep Mountain, and Spring Mountains structural blocks

3. Continued detachment faulting and westward transport of the River Mountains volcanics

4. The development of the Lake Mead fault system synchronous with the development of the high-angle normal faults that bound the Black Mountains block.

FUTURE WORK

The following research is suggested for further studies of the Arch Mountian area:

1. Detailed mapping and petrographic analysis of the Precambrian gneiss in the upper plate of the Arch Mountain detachment and the Cohenour Mine area will help to constrain the structural history of the area

2. Detailed petrography, geochemistry, and age dating of the Wilson Ridge plutonic assemblage will help to constrain the evolution of the Wilson Ridge pluton and the age of detachment faulting

3. Detailed petrography, geochemistry, and age dating of the undifferentiated volcanics of the James Bay area plutonic assemblage will help to constrain the volcanic history of the area

4. Sedimentological study of the Wishing Well Cove breccia to determine the environment of deposition and mode of emplacement may provide important evidence for the erosional history of the Petroglyph graben

5. Detailed mapping and sedimentological study of the Muddy Creek Formation exposed along the east flank of the Arch Mountain horst will help to constrain the erosional history of the east flank of Arch Mountain and the nature of Muddy Creek age sediments in the Virgin basin area

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---- APPENDIX A ----

PETROGRAPHY

APPENDIX A

Rock name: Quartz Monzonite

Sample number: D/1/21

Description: Coarse-grained mass of interlocking anhedral crystals; poikolitic plagioclase contains inclusions of quartz; feldspars commonly altered to sausserite; plagioclase is zoned; biotite occurs as slender laths.

Modal Mineralogy: Quartz 25% (anhedral 0.8 mm); plagioclase 45% (subhedral 0.3 mm); orthoclase 20% (anhedral 0.9-1.2 mm); biotite 8% (anhedral 0.5 mm); opaque 2%.

Rock name: Quartz monzonite

Sample number: A/3/7

Description: Coarse-grained mass of interlocking anhedral crystals; poikolitic plagioclase contains inclusions of quartz, feldspars commonly altered to sausserite; plagioclase is zoned.

Modal Mineralogy: Quartz 35% (anhedral 0.5 mm); plagioclase 35% (subhedral 0.4 mm); orthoclase 15% (anhedral 0.9-1.2 mm); biotite 13% (anhedral 0.5 mm); opaque 2%.

Rock name: Quartz Monzonite

Sample number: D/1/7

Description: Coarse-grained mass of interlocking anhedral crystals; poikolitic plagioclase contains inclusions of quartz; feldspars commonly altered to sausserite; plagioclase is zoned.

Modal Mineralogy: Quartz 25% (anhedral 0.5 mm); plagioclase 40% (subhedral 0.4 mm); orthoclase 25% (anhedral 0.9-1.2 mm); opaque 3%; biotite 5%; trace sphene 2%.

Rock name: Dacite

Sample number: J/1/22

Description: Fine-grained porphyritic; euhedral to subhedral phenocrysts of quartz and anhedral xenocrysts of embayed quartz, zoned plagioclase, and orthoclase in a cryptocrystalline groundmass of quartz.

Modal Mineralogy: Quartz 15% (euhedral to anhedral, 0.5 mm); plagioclase 15 % (euhedral to subhedral, 0.5mm); orthoclase 10% (subhedral to anhedral 0.4 mm); opaque trace; ground mass 60%.

Rock name: Dacite

Sample number: B/3/22

Description: Fine-grained porphyritic; euhedral to subhedral phenocrysts of quartz and xenocrysts of embayed quartz, zoned plagioclase, sanidine, with trace sphene, hornblende and opaques in a cryptocrystalline groundmass of quartz.

Modal Mineralogy: Quartz 20% (euhedral to anhedral, 0.7 mm): plagioclase 20 % (euhedral to subhedral, 0.4 mm); sanidine 10% (subhedral to anhedral 0.4 mm); sphene trace, hornblende trace, opaque trace; ground mass 50%.

Rock name: Andesite porphyry

Sample number: B/3/22

Description: Fine-grained porphyritic; phenocrysts of subhedral zoned plagioclase laths, in a reddish-brown cryptocrystalline groundmass of altered felty plagioclase laths.

Modal Mineralogy: Plagioclase 20% (subhedral, 3-9 mm); opaque 3%; biotite 2%; groundmass 75%.

Rock name: Olivine Basalt

Sample number: B/2/20

Description: Fine-grained porphyritic, phenocrysts of olivine set in a matrix of pilotaxitic plagioclase.

Modal Mineralogy: Plagioclase groundmass 75%; olivine 25% (euhedral to subhedral 0.05-0.3 mm); opaque trace.

Rock name: Lamprophyre

Sample number: D/1/21

Description: Fine-grained porphyritic, phenocrysts of biotite set in a pilotaxitic groundmass of plagioclase.

Modal Mineralogy: Plagioclase groundmass 70%; biotite 20% (euhedral to subhedral, 1-5 mm); opaque 10%.

Rock name: Diorite porphyry

Sample number: A/4/18

Description: Very coarse-grained porphyritic; large blocky pheoncrysts of hornblende set in a ground mass of fine to medium grained plagioclase.

Modal Mineralogy: Plagioclase 25% (subhedral to euhedral, 0.5 mm); hornblende 65% (euhedral-subhedral, 0.3-10 mm); opaque 5%; biotite 3% (subhedral, 0.5 mm); sphene 2% (euhedral, 0.2 mm).

---- APPENDIX B ----

GEOCHEMISTRY

GEOCHEMISTRY

Four granititic rock samples were collected from Arch Mountain for geochemical analysis of major elements for the purpose of a preliminary comparison to similar analyses of samples collected by Feuerbach (1986) and Mills (1984) from the Wilson Ridge pluton and the Boulder City pluton.

The four grab samples that were collected in the field were handled with cotton gloves and were placed into airtight plastic bags to prevent contamination. The samples were transported to the lab and were broken with a rock hammer to remove weathered rock that could be a source of error for the geochemical analyses. The freshly broken, nonweathered rock chips were ground to a powder in a clean disk mill and were placed in clean, airtight, plastic bags. The samples were weighed, and 30 g of each sample was sent to Chemex Labs, Ltd., in Sparks, Nevada, for major-element analysis.

The results of the anlayses are in Table 1. The normalized values for sodium, potassium, aluminum, iron, calcium, magnesium, and titanium were plotted against weight percent silica on Harker variation diagrams (Figures 32-35). The data for Arch Mountain are plotted as circles, the data for the Wilson Ridge are plotted as triangles and the boxes represent the Boulder City pluton data. A visual inspection of the graphs shows that the samples from Arch Mountain plot closer to the Wilson Ridge pluton samples than to the Boulder City pluton samples; therefore, the Arch Mountain samples are more chemically similar to the Wilson Ridge samples and less chemically similar to the Boulder City pluton samples. This relationship is particularly obvious in the graph of titanium (Figure

35), and it is also evident in the graphs of aluminum and iron (Figure 33) and of calcium and magnesium (Figure 32). All of the elements except sodium decrease in concentration with increasing silica.

TABLE 1. MAJOR-ELEMENT GEOCHEMISTRY

Sample:	A	B	C	D
Rock Type:	Quartz Monzonite	Quartz Monzonite	Dacite	Quartz Monzonite
SiO2	76.68	69.08	72.38	58.32
Al2O3	12.73	13.70	13.29	18.06
Fe2O3	1.91	4.64	4.47	5.36
CaO	0.23	1.73	0.70	3.98
MgO	0.10	0.75	0.68	1.56
Na2O	6.90	3.82	7.07	4.94
K2O	1.32	4.60	1.12	4.61
TiO2	0.06	0.28	0.23	0.66
MNO	0.02	0.05	0.03	0.10
P2O5	0.07	0.15	0.13	0.31
LOI	0.10	0.24	0.54	0.28
Total	100.15	99.21	100.75	99.3

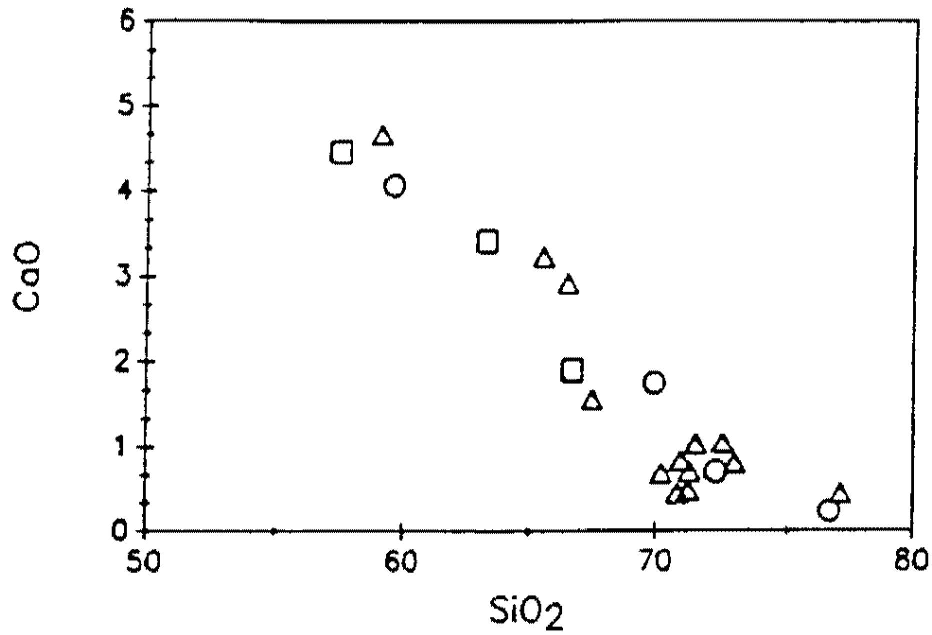
SAMPLE LOCATIONS

A

B

C

D



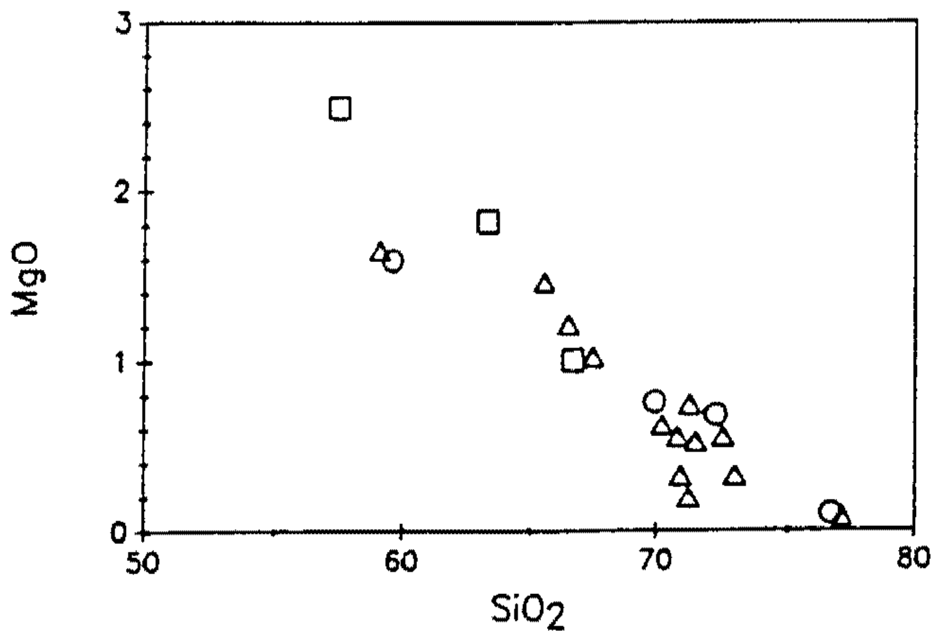


Figure 31. Harker variation diagrams of CaO and MgO versus SiO2. The Arch Mountain data are plotted as circles. The Wilson Ridge pluton data and Boulder City pluton data (from Feuerbach, 1986) are plotted as triangles and squares, respectively.

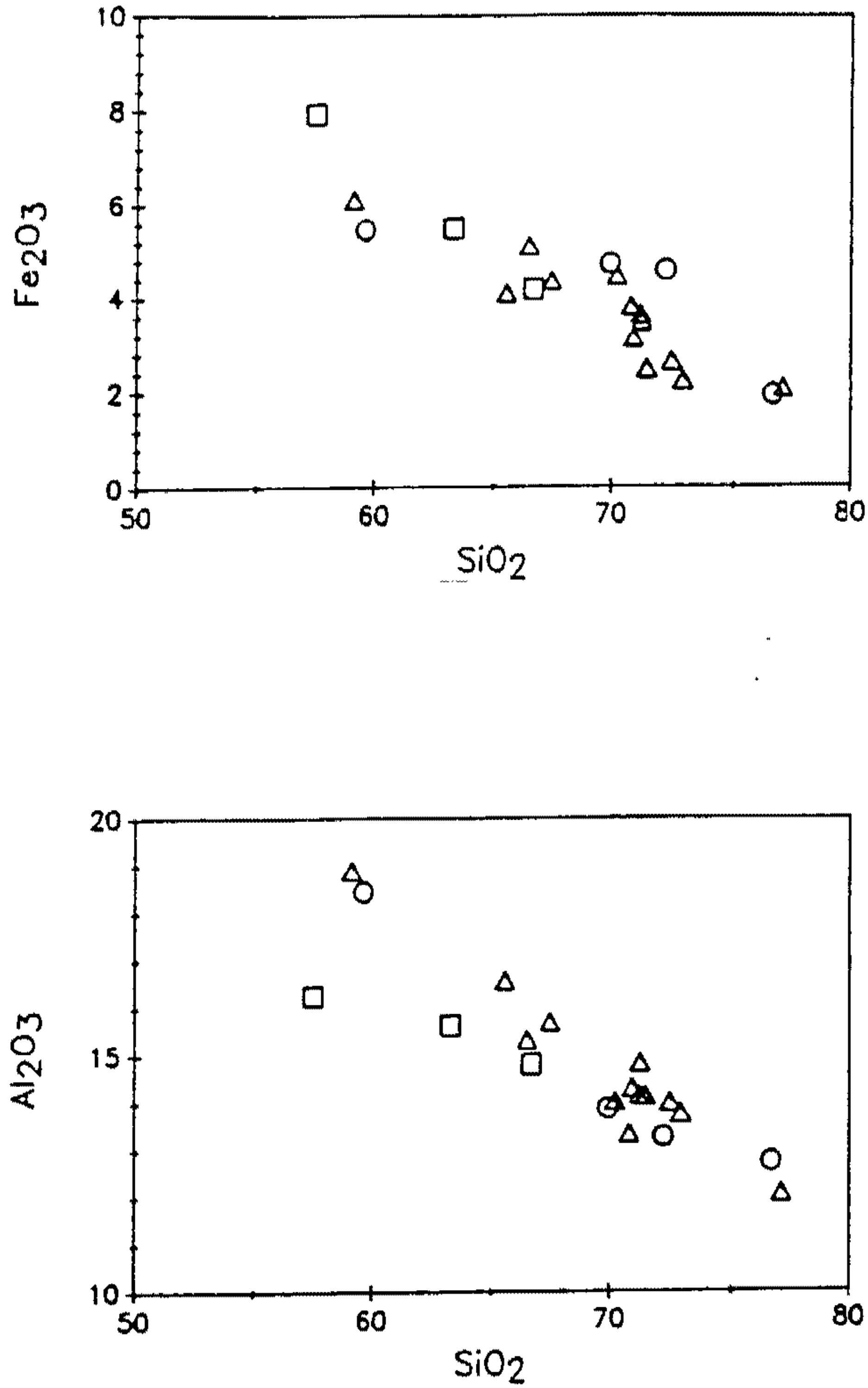
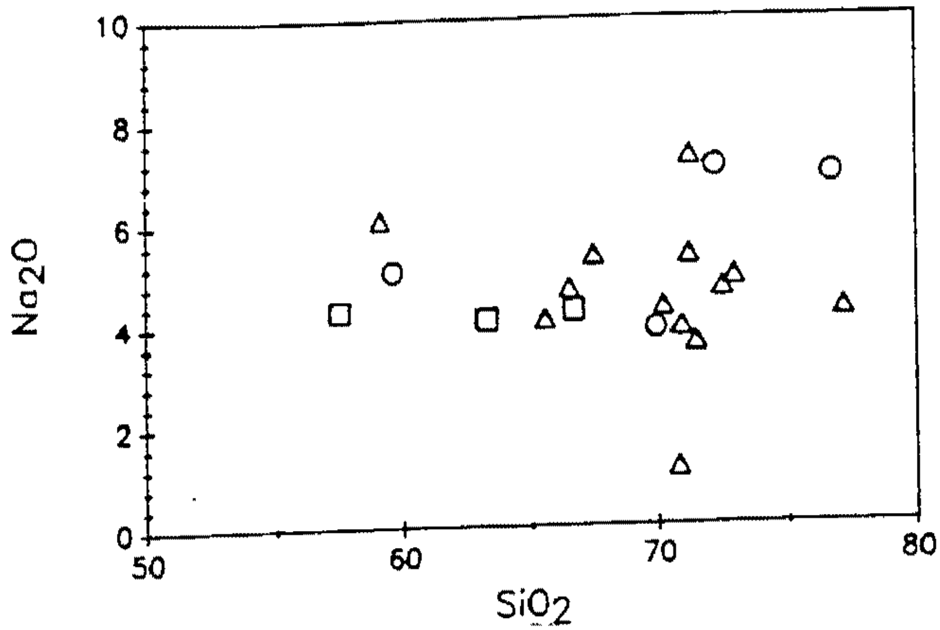


Figure 32. Harker variation diagrams of Fe2O3 and Al2O3 versus SiO2. The Arch Mountain data are plotted as circles. The Wilson Ridge pluton data and Boulder City pluton data (from Feuerbach, 1986) are plotted as triangles and squares, respectively. The Arch Mountain samples are more chemically similar to the Wilson Ridge samples and less chemically similar to the Boulder City pluton samples.



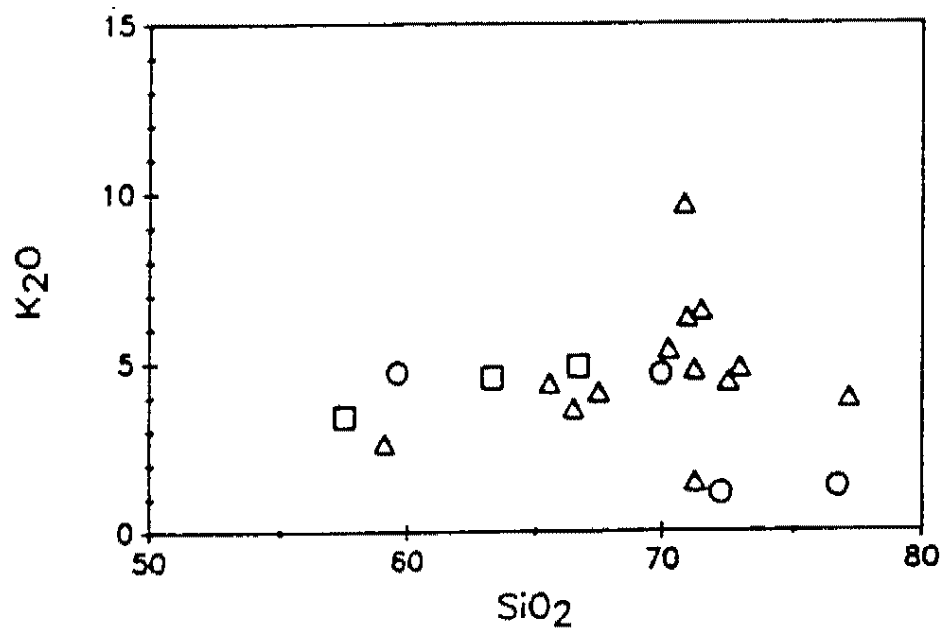


Figure 33. Harker variation diagrams of Na2O and K2O versus SiO2. The Arch Mountain data are plotted as circles. The Wilson Ridge pluton data and Boulder City pluton data (from Feuerbach, 1986) are plotted as triangles and squares, respectively. The Arch Mountain samples are more chemically similar to the Wilson Ridge samples and less chemically similar to the Boulder City pluton samples.

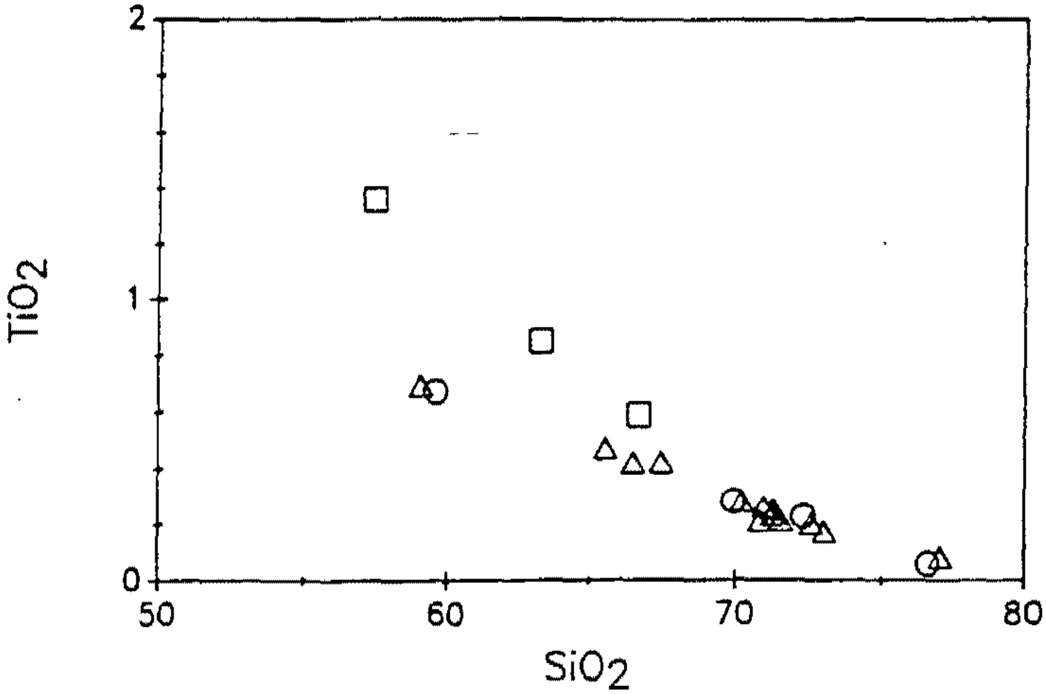


Figure 34. Harker variation diagram of TiO2 versus SiO2. The Arch Mountain data are plotted as circles. The Wilson Ridge pluton data and Boulder City pluton data (from Feuerbach, 1986) are plotted as triangles and squares, respectively. Note the similarity between the Arch Mountain and Wilson Ridge pluton data.