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GEOLOGY OF THE NORTHERN BLACK MOUNTAINS, DEATH VALLEY, CALIFORNIA

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with a contribution to radiometric dating

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ABSTRACT

The Black Mountains are an east-dipping tilted fault block of the Basin and Range province, located on the east side of Death Valley, southeastern California. The mountains are underlain principally by Late Tertiary volcanic, plutonic, and sedimentary rocks, with locally exposed Proterozoic and Paleozoic basement. They are the location of two important controversial features, the Amargosa chaos and the turtlebacks, and an important key to the possibility of large-magnitude extensional faulting.

A new geologic map of the north part of the range utilizes a stratigraphy made up principally of the well-known Artist Drive, Furnace Creek and Greenwater Formations and one new informal unit, sedimentary rocks and tuff of Ryan area.

The Artist Drive Formation is divided into 61 units. Some of these are in stratigraphic order and some are lateral variants. The maximum thickness, at a section in the north part of the area, is about 5820'. The Artist Drive Formation includes epiclastic and volcaniclastic sedimentary rocks, air-fall and ash-flow tuffs, and flows of basalt, andesite, dacite and rhyolite. Radiometric ages for the Artist Drive Formation are 8.4 Ma for a unit low in the section and 6.6 Ma for a unit in the middle of the section; the age range from base to top is probably <10 Ma to 6 Ma.

The lower units of the Furnace Creek formation include sedimentary rocks, basalt, and palagonite tuff totalling >980'. The overlying Greenwater Formation consists of rhyolite, vitrophere, and tuff with minor basalt and has a maximum thickness of 3450'. The units of the Furnace Creek Formation which overly the Greenwater consist of basalt with minor sedimentary rocks and have a maximum thickness of 1590'. Another part of the Furnace Creek Formation, of uncertain stratigraphic position, consists of siltstone, shale, and nodular limestone with minor basalt. The age of the lower part of the Furnace Creek formation is about 6.0 Ma, of the Greenwater Formation 5.4 Ma, and of the upper part of the Furnace Creek Formation 5.0 Ma. Also of uncertain stratigraphic position are the sedimentary rocks and tuff of the Ryan area, which consist mostly of sandstone, siltstone, and conglomerate with interlayered tuff. Maximum thickness of these rocks is as much as 4070', and they range in age from 13.7 Ma to 6.4 Ma.

Overlying the flanks of the northern Black Mountains are Quaternary and Quaternary-Tertiary deposits of unconsolidated sand, gravel and larger clasts with some volcanic rocks, divided into 14 units. Underlying the Tertiary section, with either fault or stratigraphic contact, are minor occurrences of Paleozoic and Proterozoic sedimentary rocks and the gneiss, pegmatite, marble and schist of the Badwater turtleback footwall.

The volcanic rocks in the northern Black Mountains are mostly a bimodal basalt-rhyolite association. They are of small to moderate volume and appear to be locally erupted. Analyses of a suite of volcanic rocks representing several units are difficult to interpret

owing to the altered nature of many of the rocks. The analyses show that the rocks are somewhat alkaline, being richer in alkalis than suites from continental margin volcanic arcs but comparable to others from the Great Basin. The plots on Harker diagrams show considerable scatter, but merge with those for the central Death Valley volcanic field. The chemical data fail to show any derivative relationships between the units, but do show that Furnace Creek basalts Tfb2, Tfb3, and Tfb4 become more mafic with time.

The northern Black Mountains are bounded by major faults on the southwest and northeast sides. The principal branch of the Black Mountains fault system on the southwest side is buried under alluvium in Death Valley, but has an apparent displacement of 4000' in the north part of the area increasing to 6000' in the south part. Displacement on the other branch, the Artist Drive fault, similarly increases from 0 in the north part to 4800' in the south part. The right-lateral Grandview fault on the northeast side of the range has unknown strike-slip and possibly 1-2000' of dip-slip.

The Badwater turtleback fault in the south part of the area is a detachment fault with gentle to steep westerly dip. It is a continuous feature which exposes mid-crustal rocks in its footwall, suggesting large displacement. Other prominent low-angle normal faults in the range, including one at Buff Canyon, have Tertiary rocks in both hanging and footwalls. A set of cross faults in the central part of the range are interpreted as normal faults related to a left-lateral shear couple which was operative after 5 Ma. The northern Black Mountains anticline is interpreted as a flexure formed preceding faulting on the Black Mountains fault system.

Local deformation, including crustal extension and normal faulting, probably took place between 5.0 and 4.0 Ma. If large magnitude extensional faulting, such as the tectonic removal of the entire Panamint Range, has taken place, it must have started at least as long as 11.6 Ma and possibly 14 Ma ago.

The northern Black Mountains sedimentary basin initially received epiclastic sediments from adjacent highlands, followed by voluminous volcanic rocks. If the source of clasts of sedimentary rocks now present in conglomerates was the adjacent Funeral Mountains and the source of granitic clasts was plutons lying to the south in the Black and Greenwater Mountains, the clasts traveled considerable distances in different directions and commingled. If the source was the retreating Panamint range, the two types of clasts traveled shorter distances in the same direction. In the latter case, large magnitude extensional faulting is required.

Principal borate deposits in the Death Valley region are in a belt extending from Death Valley up Furnace Creek wash and across the Greenwater Range to Amargosa Valley. The borates occur as both lenticular bedded deposits and as veins in various units of the Furnace Creek Formation. Principal borate minerals are colemanite, ulexite, and proberite. I suggest that hot springs related to the volcanism that produced the silicic volcanic rocks of the Greenwater Formation were the source of boron-rich solutions. The Billie Mine was the only active borate producer in 1995.

INTRODUCTION

The Death Valley region has fascinated geologists for over a century. A part of the Basin and Range Province of western North America, it shares with other parts of that province the characteristic elongate mountain ranges separated by desert valleys, but here on an especially grand scale. Death Valley is 190 miles long by 5 to 20 miles wide, has a central depression reaching 282' below sea level, and is bordered by mountains as high as 11,049'.

The dominant orientation of basins and adjacent ranges in this region is north-south, but parts of some ranges and all of others trend northwest-southeast.

Bordering Death Valley to the west is the Panamint Range (fig. 1) including Tucki Mountain in its central part and the Cottonwood Mountains in its north part. On the northeast side of the north part of Death Valley lie the Grapevine and Funeral Mountains, and on the east side of the central and south parts are the Black Mountains, focus of the present report. The Greenwater and other, smaller, ranges lie to the east of the Black Mountains.

The geology of the Basin and Range Province, and in particular that of its largest segment, the Great Basin, is dominated by tilted fault blocks composed of Precambrian through Cenozoic rocks separated by valleys underlain by unconsolidated sedimentary deposits. The internal structure of the fault blocks is in most cases complex. Rocks underlying the ranges adjacent Death Valley are predominantly Proterozoic sedimentary rocks and gneiss, Paleozoic sedimentary rocks, and Tertiary through Quaternary volcanic and continental sedimentary rocks. Mesozoic and Tertiary plutonic rocks are also locally present.

Certain special, perhaps unique, features have contributed especially to the interest that geologists have had in the Death Valley region, and to the voluminous literature that has resulted. These are: 1) the Amargosa chaos, 2) the turtlebacks, and 3) the possibility of large-magnitude extensional faulting. The Amargosa chaos is a complex mosaic of blocks of both hanging and footwall rocks associated with low-angle faulting, found in the Virgin Spring and nearby areas in the central and southern Black Mountains. The turtlebacks are exhumed fault surfaces exposing footwall

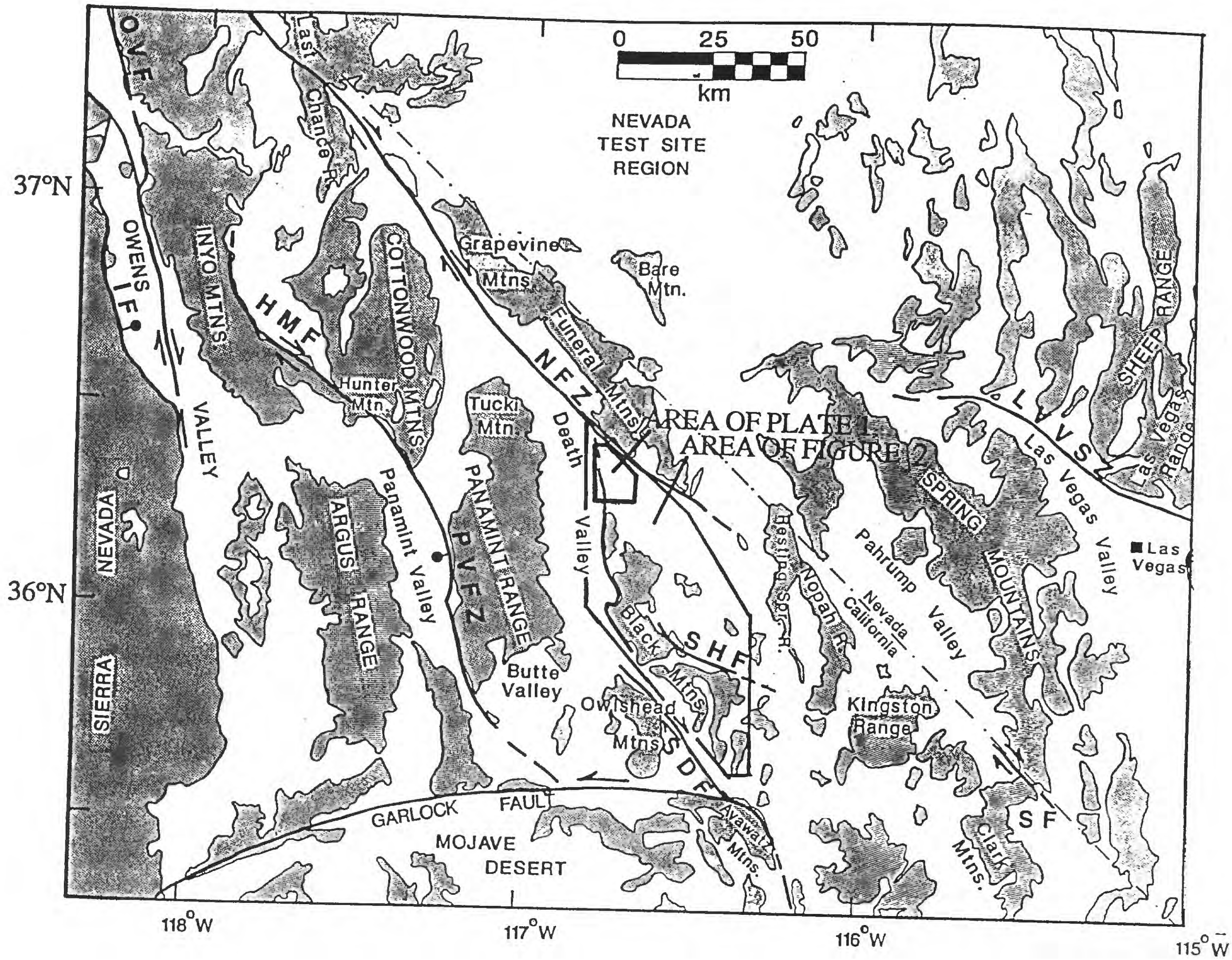

FIGURE 1-- Index map to part of the Basin and Range province in California and Nevada, showing mountain ranges and major fault zones. After Wernicke and others, 1988, fig. 4.

rocks as old as Proterozoic which have undergone intense deformation, possibly at mid-crustal levels. One of the three, the Badwater turtleback, is partially in the area mapped. The possibility of large-magnitude extensional faulting has been debated by many geologists, starting with Stewart (1983), who first proposed it. The rocks in the Black Mountains, and the structures found therein, are key factors in reconstructing the various possibilities.

SCOPE OF THIS REPORT

New work for this report consisted of geologic mapping in the northern Black Mountains, thin section study, chemical analyses of some volcanic rocks, and one new radiometric age. Limited testing for borate occurrences was also done. The geologic map which has resulted (pl.1) covers the area north of lat. 36°15' between Death Valley and Furnace Creek Wash, with the exception that mapping ends at the contact between the Artist Drive and Furnace Creek Formations north of Monte Blanco. McAllister's (1970) map of the Furnace Creek borate area overlaps in part with pl.1, and covers the excepted area.. His mapping focuses on the Furnace Creek basin lying between the Funeral and Black Mountains but extends a little into the Black Mountains. South of lat. 36°15', the geologic mapping is by Drewes (1963), supplemented by additional unpublished work by Wright and his associates (oral comm. 1994) and by reconnaissance by the writer.

The quality of the geologic map (pl. 1) is limited by the accessibility of the terrain which it covers. Strike and dip symbols on the map show where traverses were made across units which contain bedded sedimentary rocks. Many areas, for instance those underlain by the Greenwater Formation and by Furnace Creek units Tfb2 through Tfb4, were easily mapped by observation from a ridge crest in the vicinity and extension of contacts on aerial photographs. A more problematic area is that which extends south from the headwaters of the north branch of Blind Canyon along the exceedingly steep escarpment facing Death Valley. Although the ridge capped by the two peaks each of which is marked 2310' (pl. 1) is accessible, the next ridge to the east is not, and this area, marked by many faults and unit pinchouts, is only poorly understood.

THE AMARGOSA THRUST AND AMARGOSA CHAOS

In a classic paper on structure in the Death Valley region, Noble (1941) describes the unusual structures found in the Virgin Spring area, near Jubilee Pass in the south part of the Black Mountains (fig. 2). He discovered and named an extensive fault, the Amargosa thrust, and described the complexly deformed rocks of the overthrust plate which he named the Amargosa chaos.

Because of the widespread attention which the Amargosa chaos has received, a summary of Nobles' description is in order. The chaos consists of blocks mostly 200' (60 m) to 1/4 mile (0.4 km) in maximum dimension, tightly packed but in a confused and disordered arrangement. The blocks are of lozenge, fish-tail, or other odd shapes, and are minutely fractured, although bedding or layering are commonly discernable. Each block may be considered to be a fault block, and the rocks therein are of various ages.

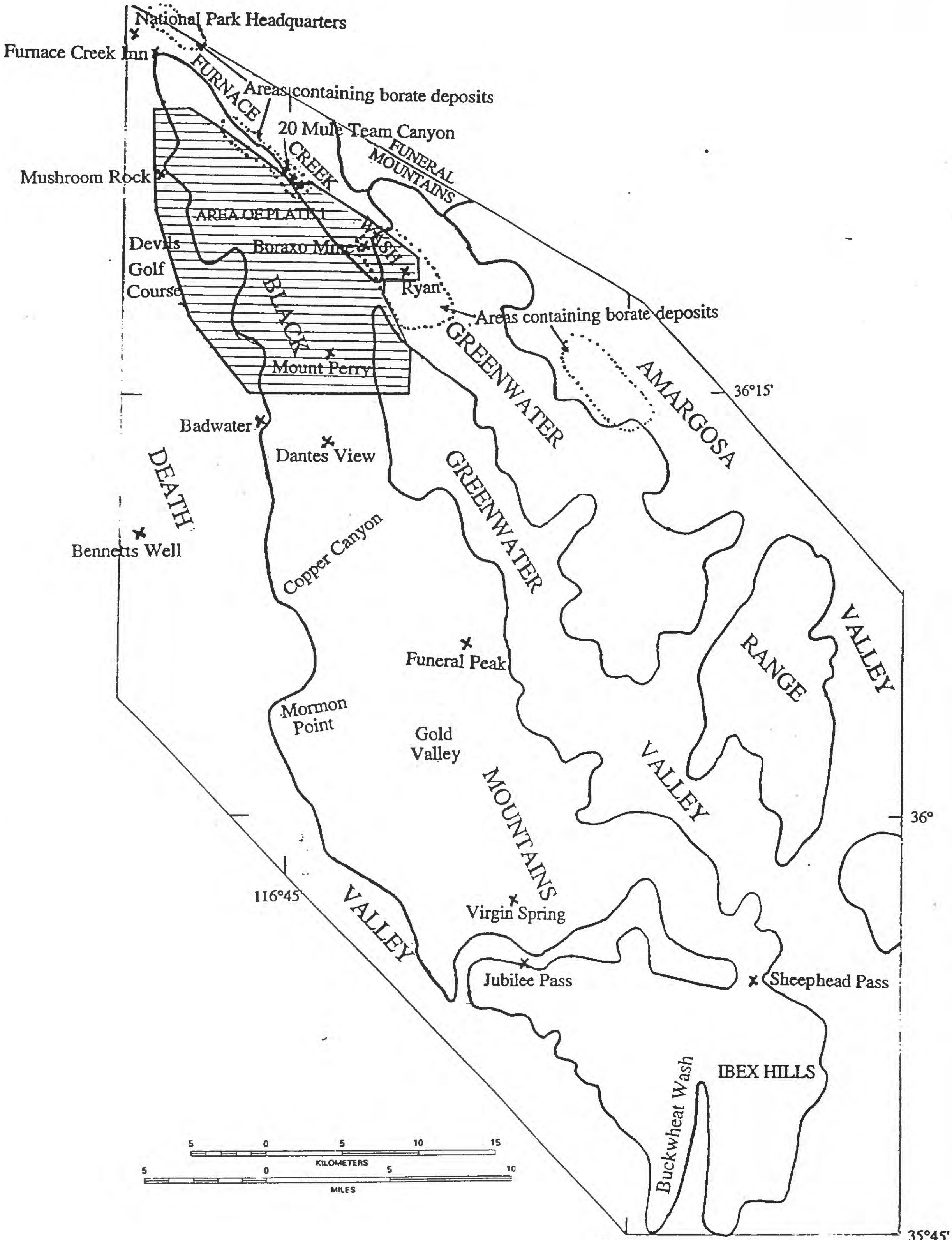

FIGURE 2.-- Index map to the Black Mountains and Greenwater Range, showing geographic features.

The chaos is divided into three phases, principally on the lithology and ages of the constituent blocks. The Virgin Springs phase consists of blocks mostly derived from the Pahrump Group, other Proterozoic, Lower and Middle Cambrian formations and consisting of dolomite, limestone, sandstone, shale, marble, quartzite, and slate. Precambrian gneiss and Tertiary rhyolite are also locally present. The Calico phase locally overlies the Virgin Springs phase and consists almost entirely of Tertiary volcanic rocks. The prevalent mixture of dark and light-colored rock types has given rise to the name Calico Peaks and thus to the phase name. The Jubilee phase also locally overlies the Virgin Springs phase and contains a larger proportion of more thoroughly broken-up material. Granite and Tertiary conglomerate are the predominant rock types, but the entire range of rock types in the Virgin Spring phase plus Tertiary volcanic rocks are locally present.

According to Wright and others (1991), most of the occurrences of the Virgin Spring chaos and the associated Amargosa fault are located in a belt extending from Sheephead Pass through Virgin Spring to Gold Valley, a locality at the crest of the Black Mountains 13 mi (21 km) south of Dantes View (fig 2). North of Gold Valley, the chaos is buried beneath the Shoshone volcanics.

A map and report by Hunt and Mabey (1966) summarizes the stratigraphy and structure of Death Valley and the adjacent parts of the Panamint, Funeral and Black Mountains from latitudes 36° (Mormon Point, fig. 2) to 36°45' (north end of Funeral Mountains, fig. 1). They extend the concept of the Amargosa thrust of Noble (1941) to include other low-angle faults in the Death Valley region and introduce the term Amargosa thrust system. They recognize, however, that these are normal faults in the sense that younger rocks overlie older ones. The Amargosa thrust is mapped in the lower slopes of the Panamint Range between Starvation Canyon and Blackwater Wash (Their pl. 1; for locations see also USGS 7.5' quadrangle maps Galena Canyon, Hanaupah Canyon, Devils Speedway, and Tucki Wash.). This area lies across Death Valley west of that part of the northern Black Mountains between the Artist Drive Block and Copper Canyon (pl. 1, fig. 1). The central part of this portion of the Amargosa thrust is structurally arched and rocks of the Amargosa thrust complex are exposed between Hanaupah Canyon and Trail Canyon. In this area, the complex consists principally of Precambrian gneiss and other metamorphic rocks but also contains Tertiary granitic rocks and felsite dike swarms.

Hunt and Mabey believe that the Amargosa thrust is continuous from the Virgin Spring area (Noble, 1941) northward through the Mormon Point, Copper Canyon, and Badwater turtlebacks (fig.2) and westward under Death Valley to its exposure in the Panamint Range, broken only by normal faults which downdrop it on the east side of the valley. By this interpretation, most of the Black Mountains is in the upper plate of the thrust, and the turtlebacks and the Virgin Spring area are fensters. Several additional low-angle (normal) faults whose traces lie upslope west of the Amargosa thrust in the Panamint Range are interpreted to bound a stack of fault slices which are part of the Amargosa thrust system (Hunt and Mabey, pl. 1).

THE TURTLEBACKS, INTRODUCTION

The term "turtleback"was apparently first introduced by Curry (1938). Curry (1954) described the three turtlebacks in the Black Mountains and named them, from north to south, the Badwater, Copper Canyon, and Mormon Point (figs. 2, 5). Each is an exposed fault surface underlain mostly by Precambrian gneiss, schist and marble, locally intruded by Tertiary dike swarms. (Later, (Wright and others 1991) much "Precambrian" gneiss was re-interpreted as the Willow Springs Diorite of Tertiary age (fig. 5).) The fault surfaces are overlain at their edges by fault gouge and breccia composed of both Precambrian rocks and of Tertiary volcanic and sedimentary rocks.

Curry (1954) believes that the turtlebacks are the sole of a single large overthrust plate. The fault surface and enclosing rocks have subsequently been folded, producing the curved surfaces now seen. The principal fold axis of each turtleback plunges to the northwest at angles of 20 to 25°.

According to Wright and others (1991) the turtleback faults define antiformal surfaces of brittle deformation separating complexes consisting of quartzofeldspathic gneiss and carbonate-bearing metasedimentary rocks from an upper plate of Cenozoic igneous and sedimentary rocks. They are believed to have normal displacement parallel to the axes of pre-existing folds and guided by the relative weakness of carbonate layers in the footwall. They are not part of the Amargosa thrust, but are parts of the set of brittle normal faults that define the western edge of much of the Black Mountains. The Copper Canyon and Mormon Point turtlebacks are believed to have undergone two phases of ductile deformation, the earlier one producing layer-parallel foliation and isoclinal folds and the later one open, northwest-plunging folds. The Badwater turtleback shows similar deformation, including northwest plunging folds, suggesting that the northern Black Mountain block has been coherent since the formation of the turtleback folds. The Badwater turtleback differs from the others, particularly in that the marbles are complexly interlayered with the gneiss. Further details on the Badwater turtleback are given by Miller (1992),and discussed in a later section of this report.

THE BLACK MOUNTAINS

The Black Mountains border the east side of Death Valley and extend about 55 miles (88 km) southeast from Furnace Creek Inn to Buckwheat Wash, where they merge with the Ibex Hills (fig. 2). They are a fault block tilted to the east and are underlain principally by Late Tertiary and Quaternary volcanic and continental sedimentary rocks and Late Tertiary plutonic rocks. The Black Mountains are the site of the three turtlebacks, whose footwalls expose Proterozoic gneiss and other metamorphic rocks, and of the Amargosa chaos. Exposures of Proterozoic and Paleozoic sedimentary rocks are extremely limited in the Black Mountains, in strong contrast to their abundance in the Panamint, Funeral and Grapevine Mountains.

GENERAL GEOLOGY

The geology of the central part of the Black Mountains is shown on the map of the Funeral Peak quadrangle (Drewes, 1963) which extends to the edge of the area of pl.1. Dantes View, at the crest of the range, and Badwater, on the valley floor, are both near the northwest corner of this quadrangle. The crest and escarpment parts of the Black Mountains in most of this quadrangle are underlain by plutonic rocks, in part granitic and in part diorite. The latter has more recently been identified as the Willow Spring Gabbro or Diorite of Tertiary age (Wright and others, 1991) Most of the dip slope is underlain by Late Tertiary volcanic rocks. A portion of the Greenwater Range is also in this quadrangle, and vitrophere and tuff-breccia members of the Greenwater Volcanics are mapped there. Small patches of these units are also shown near Dantes View; reconnaissance by the writer discovered more extensive occurrences of the Greenwater in this area.

Drewes (1963) proposes a master fault system for the Death Valley region which is related to the left-lateral Garlock Fault to the south at the edge of the Mojave Desert (fig. 3).

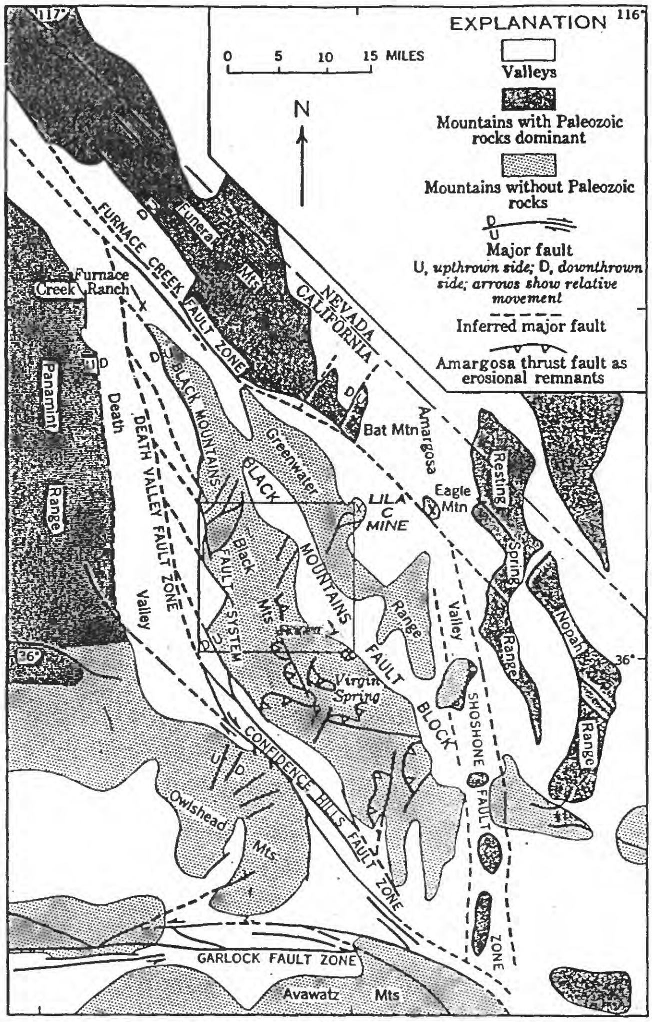

FIGURE 3-- Generalized geologic map of Black Mountains fault block and vicinity, after Drewes, 1963, fig 2.

The right-lateral Confidence Hills fault zone branches from the Garlock fault and extends northwest to the south part of Death Valley, where it joins the Death Valley fault zone. The Shoshone fault zone also branches from the Garlock Fault and joins the Furnace Creek fault zone in the Amargosa Valley. These faults are all believed to have undergone a complex combination of strike-slip and dip-slip movement. They define a diamond-shaped area which he names the Black Mountains fault block.

Drewes names a system of normal faults which define the front of the Black Mountains at the edge of Death Valley the Black Mountain fault system. This is separate from the inferred Death Valley fault zone which lies to the west in the middle of the valley. The Black Mountain faults have truncated spurs leaving prominent triangular facets. Minimum vertical displacement is believed to be 4,000' (1200 m).

Wright and others (1991) provide a more recent synthesis of the structural and magmatic history of the Black Mountains block, an area including the Black Mountains, Greenwater Range and adjacent smaller ranges, essentially the same as Drewes (1963) Black Mountains fault block (fig.3). The right-lateral Sheephead and Furnace Creek fault zones bound this area on the south and north, respectively, and the Black Mountain frontal faults and a normal fault continuous with the Furnace Creek fault bound it on west and east, respectively (fig. 4). Thus defined, this area is one of exceptionally large crustal extension and the central part has been the locus of extensive plutonic and volcanic activity, beginning with the intrusion of the 11.6 Ma Willow Spring Gabbro and followed by intrusion of silicic plutonic rocks and the eruption of mafic and silicic volcanic rocks, including the extensive 8.5 to 7.5 Ma Shoshone volcanics. This igneous activity is fundamental to the history of the Black Mountains block. Although the bulk of it took place south of the area of the present report, the younger Greenwater Volcanics and Funeral Formation lavas are continuous between the two areas.

An isotopic study of the 11.6+-0.2 Ma Willow Spring Diorite is provided by Asmerom and others (1990) (figs.4, 5). The data suggest that the batholith (?) represents a view of mid-crustal magma mixing between mantle-derived and crustal material. The Black Mountains may expose a cross-section of a continental rift magmatic system, from partially contaminated mafic to intermediate intrusive rock in the deep crust to their volcanic equivalents. Such additions of mantle-derived material may be a significant part of crustal growth, and help reconcile the large crustal pull-

apart with the fact that the crust has a normal thickness of 30-35 km. An interpretive map by Holm and Wernicke (1990) (fig. 5) shows a mid- to late-Miocene fault system accomplishing tectonic denudation in the east part of the range but also including the north part of the Badwater turtleback fault. A Pliocene to Quaternary fault system accomplishes tectonic denudation in the west part of the range and includes the Copper Canyon and Mormon Point turtleback faults. The oldest Tertiary strata (pre 10 Ma) pre-date intense phases of extension and lie on unmetamorphosed strata of Paleozoic to late Precambrian age. Foliation, ductile shear, and mylonitic lineation in the Willow Spring Diorite require a paleodepth of 10-20 km. The Black Mountains may be one of the youngest and possibly deepest exposed examples of Cordilleran metamorphic core complexes.

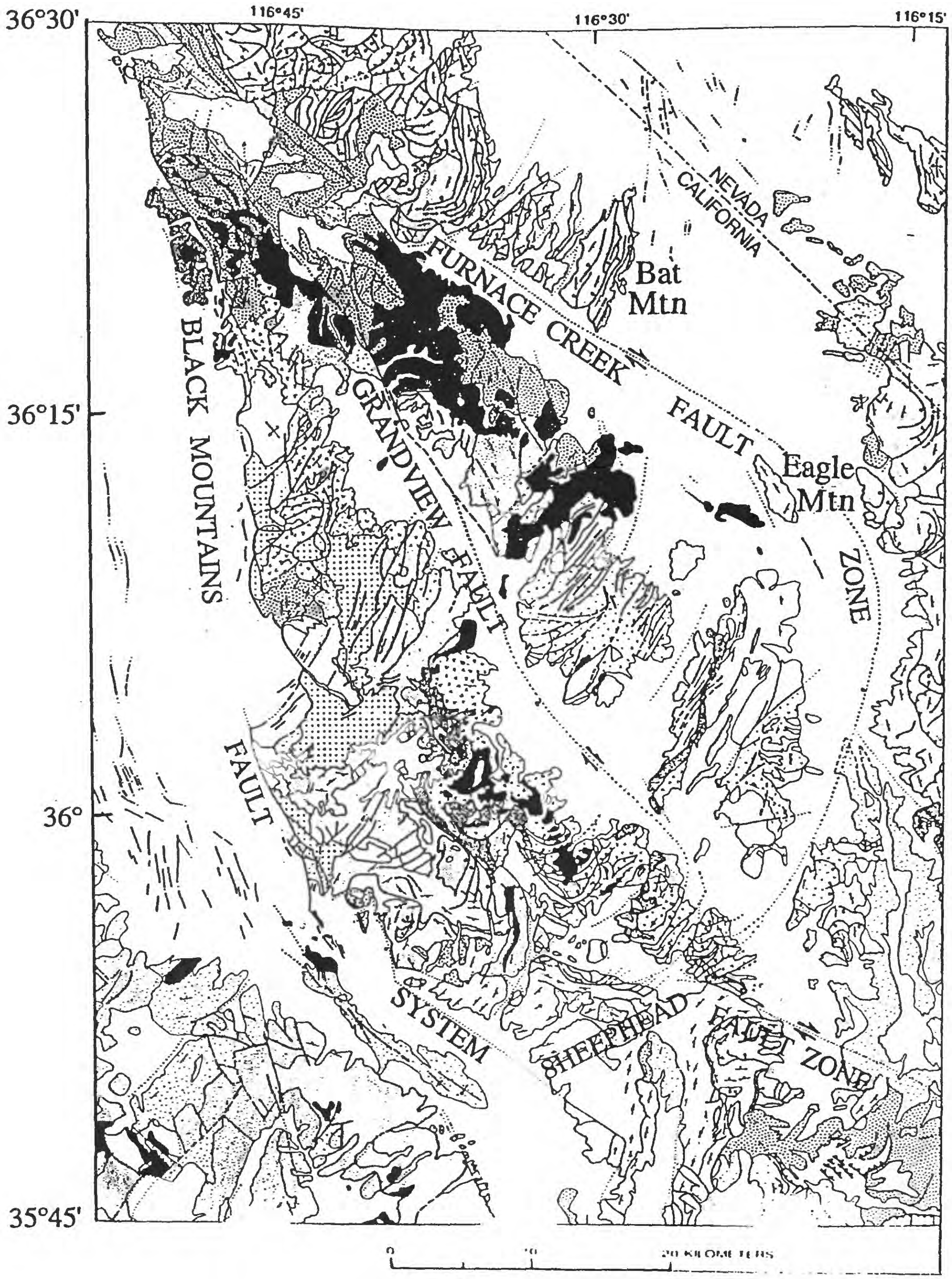

FIGURE 4-- Part of a geologic map compiled by Wright and appearing as fig. 2 in Wright and others, 1991. Area shown is essentially same as that in fig. 2 of this report, see fig. 2 for names of mountain ranges and other geographic features. Black areas are basalt and andesite, dense random-dot pattern shows sedimentary and interlayered volcanic rocks, v's are Shoshone volcanic rocks, includes Greenwater in part, spread dots in square pattern shows Willow Spring gabbro. For further details , see Wright and others (1991).

Holm and others (1992) discuss the intrusive and unroofing history of the Black Mountains, based on 30 Ar-Ar age determinations from 18 localities on a traverse from the Badwater turtleback 55 km (35 mi) to the south (fig.5). The Black Mountains are a "Miocene mid-crustal magmatic system (intermediate-mafic to silicic) intruded into Proterozoic basement". Ages on Tertiary intrusive rocks reported by Armstrong (1970) are 7.5+-0.3 Ma on diorite and 6.3+-0.4 Ma on granite porphyry. Data from Badwater turtleback mylonitized Precambrian rocks show it cooled through 350° at about 24 Ma and through 300° at about 13 Ma. Fine grained dioritic dikes cross-cutting foliation are 6.3+-0.2 Ma. A granite pluton in the Greenwater Range gives an age of 9.76+-0.25 Ma (Ar-Ar), believed to be 1 Ma too old. The Smith Mountain Granite in the central Black Mountains has a hornblende Ar-Ar age of 8.7 Ma, showing a major silicic intrusive event coeval with volcanism in the Greenwater Range.

Mica cooling ages from the Badwater turtleback are older than those from the Mormon Point and Copper Canyon turtlebacks, suggesting that the latter are at a deeper crustal level, the deepest in the Black Mountains.

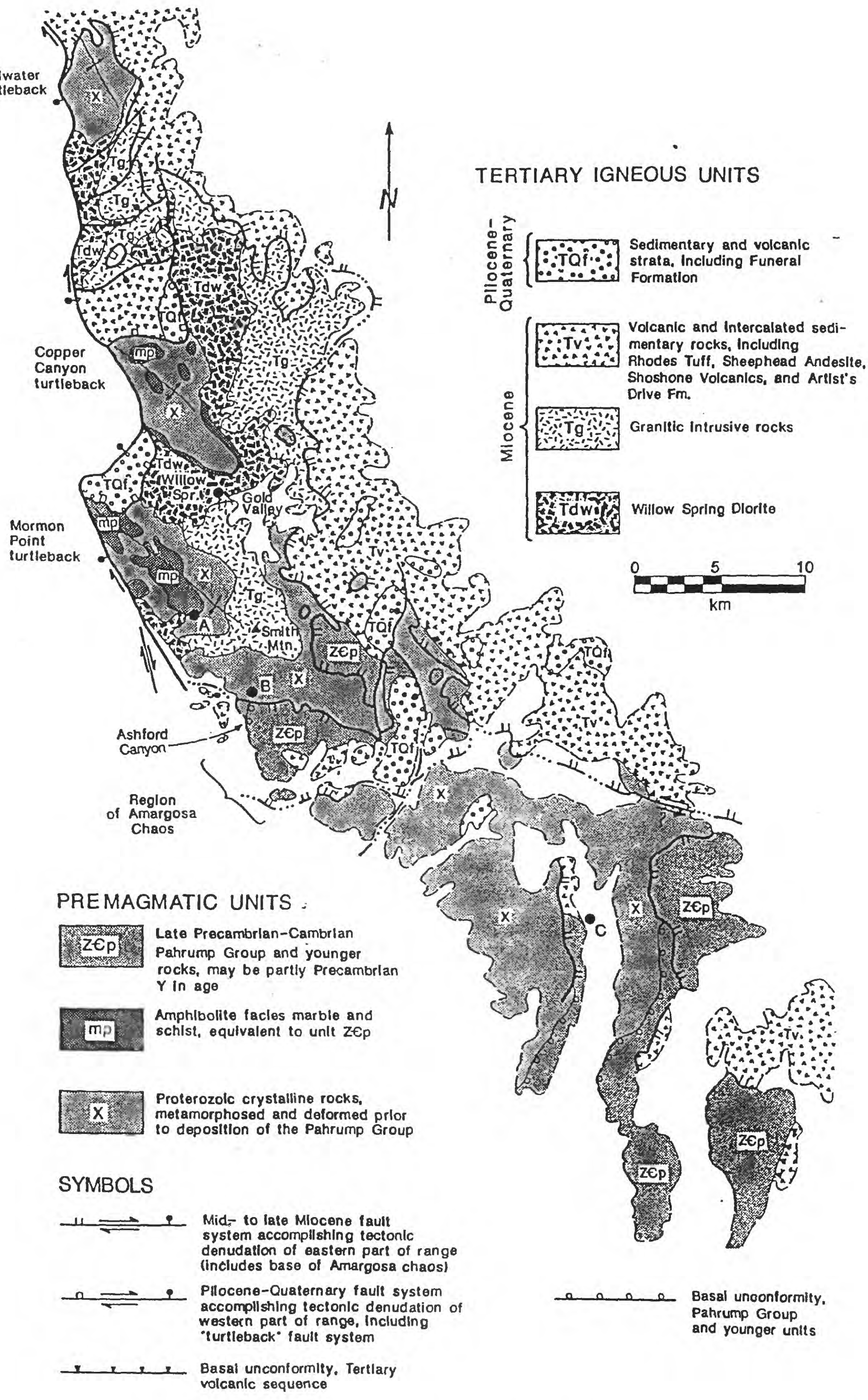

FIGURE 5-- Interpretive geologic map of the Black Mountains, after Holm and Wernicke, 1990, fig. 2. Compare with fig. 2 of this report; region of Amargosa Chaos includes Virgin Spring and Jubilee Pass; south boundary of plate 1 is in Badwater turtleback.

STRATIGRAPHY OF THE NORTHERN BLACK MOUNTAINS AND FURNACE CREEK WASH

The northern Black Mountains are underlain principally by a sequence of volcanic and sedimentary rocks of Late Tertiary age. Latest Tertiary to Quaternary surficial deposits overlap the margins, and Proterozoic and Paleozoic basement is locally exposed. The principal units present are the Artist Drive, Furnace Creek, Greenwater, and Funeral Formations.

The earliest known summary of this stratigraphy is provided by Noble (1941), who quotes unpublished work by T.P. Thayer giving descriptions and thicknesses of major units in the northern Black Mountains. The section is, from the base up: Artist Drive Formation, 5000' (1500 m); Furnace Creek Formation, 2500' (750 m); Greenwater Volcanics 2500' (750 m); Funeral Fanglomerate 3000' (900 m). The Artist Drive Formation is tentatively correlated with the Oligocene Titus Canyon Formation (Stock and Bode, 1935) but may be in part Miocene. The Furnace Creek Formation is dated as probably Early Pliocene on the basis of plant fossils collected in Furnace Creek wash (northern Black Mountains) (Axlerod, 1940). Mammalian tracks in probably correlative rocks in Copper Canyon (central Black Mountains) also suggest an Early Pliocene age for the Furnace Creek Formation (personal communication from H.D. Curry to Noble). The Furnace Creek and Funeral Formations are given Pliocene(?) ages.

Hunt and Mabey (1966, pg. A119, fig. 88) believe that the Artist Drive Formation is about 6000' (1800 m) thick in the northern Black Mountains and thins by offlap to the northeast under the Texas Spring syncline in the valley of Furnace Creek wash, where gravity data suggest that there are only 5000' (1500 m) of combined Tertiary and Quaternary sedimentary rocks.

The principal groundwork on the stratigraphy of the northern Black Mountains is provided by McAllister's (1970) map of the valley occupied by Furnace Creek Wash from Death Valley to Ryan (fig. 2). The major units mapped are the Artist Drive, Furnace Creek, and Funeral Formations, with Paleozoic and Proterozoic units in the lower slopes of the Funeral Mountains on the northeast side of the valley. McAllister divided the Artist Drive Formation into five stratigraphically ordered units and two lithologies that recur at various stratigraphic levels. My mapping has re-interpreted in greater detail most of the Artist Drive mapped by McAllister, creating 62 units designated Ta1 through Ta30A.

McAllister (1970) also divides the Furnace Creek Formation into five stratigraphically ordered units, in this case with four additional recurring lithologies. The ordered units appear in a continuous section in the vicinity of Zabriskie Point (McAllister, 1970, also near the north edge of pl. 1). The recurring lithologies include a large thickness of basalt and interlayered tuff lying between Corkscrew Canyon and the area south of the Boraxo Mine, which I have placed in Furnace Creek units Tfb2, Tft2, Tfb3, Tft3, Tfb4, and the Greenwater Formation.

Evidence for the age of the Furnace Creek Formation comes from collections of diatoms (written communications from K.A. Lohman to McAllister, 1961, 1967). In terms of North American mammalian chronology, the uppermost part is clearly middle Pliocene (Hemphillian) and the lower part less definitely early Pliocene.

The Funeral Formation (McAllister, 1970) is principally basalt capping the Greenwater Range and conglomerate in the central part of the valley of Furnace Creek wash. I interpret a small area of his Funeral Formation southwest of Ryan as Furnace Creek Formation (pl. 1, units Tfb4 and Tfs4).

A later map by McAllister (1973) includes a portion of the Greenwater Range and Amargosa Valley, extending the 1970 map to the southeast. This map includes the northernmost exposures of the Greenwater Volcanics in the Greenwater Range, here shown to overlie the Furnace Creek and underlie the Funeral Formation. K-Ar ages of 4.14±.12 Ma for basalt from the Funeral Formation and of 5.32±.15 and 6.04±.20 for vitrophere from the Greenwater Formation are given.

A detailed history of volcanism, sedimentation, and faulting by Cemen and others' (1985) is dependent on the assignment by McAllister (1970) of a number of isolated blocks of sedimentary and volcanic rocks in the southeast part of the Furnace Creek basin, particularly the large block lying directly north of Ryan (pl. 1), to members of the Artist Drive Formation as defined in the Black Mountains to the west. In my view, however, these rocks do not correlate with the Artist Drive Formation and this history needs revision (Greene, 1995).

Cemen and Wright (1988) discuss the stratigraphy and chronology of the Artist Drive Formation. This work is based on the mapping of McAllister (1970), in which the Artist Drive is divided into five members and the exposures in the hills north of Ryan (pl. 1) are placed in the Artist Drive Formation. Cemen measured a section north of Ryan, starting at the top of the exposure of the Cambrian Bonanza King Formation and described 20 units of sedimentary rocks with sparse intercalated tuff beds for a total of 1780 ' (541 m) of strata. The bulk of the section is sandstone and siltstone, calcareous in the lower part, with minor limestone. The principal conglomerate unit is 240' (73 m) thick; its base lies 210' (64 m) above the base of the section. Clasts in the conglomerate include limestone, sandstone and quartzite attributable to several Cambrian and Late Proterozoic formations. Also present are Tertiary sandstone and granite clasts. This section is identified as the lower sedimentary member of the Artist Drive Formation on McAllisters' (1970) map; on pl. 1 it is unit Trs1 of the Sedimentary rocks and tuff of the Ryan area. Two tuff beds low in the section yielded K-Ar ages of 13.7±0.7 Ma and 12.7±0.3 Ma (Cemen and others, 1985).

Strata overlying the measured section in the Ryan area were identified as the lower pyroclastic member, the middle sedimentary member, and the upper pyroclastic member, respectively, of the Artist Drive formation, following the usage of McAllister (1970). On pl.1 these are units Trt2, Trs3, and Trt4, respectively, of the sedimentary rocks and tuff of the Ryan area. The pyroclastic members are principally greenish tuff breccias, and the sedimentary member is mudstone, sandstone, and conglomerate. A tuff sample from the lower pyroclastic member yielded a K-Ar age of 8.7±0.3 Ma.

Cemen also made observations of the section of the Artist Drive Formation near Desolation Canyon, and extended McAllister's (1970) mapping down the scarp as much as .5 mile for a strike length of about 2.5 miles, showing the outcrop of the Bonanza King Formation in what I have named Buff Canyon (pl. 1). No section was measured, but the lower sedimentary member (unit Ta1 of my map) was estimated to be about 1200' (365 m) thick, mostly sandstone and siltstone, but including 10 ' (3 m) of conglomerate containing a clast assemblage similar to that in the lower member at Ryan. The lower pyroclastic, middle sedimentary, upper pyroclastic, and upper sedimentary members, as mapped by McAllister (1970), are also mentioned; the first three are believed to correlate with similarly named units north of Ryan. The units in the Buff Canyon area appear on my map as Artist Drive Formation units Ta1, 2, 2H, 6, 7, 10, 11, 20, 21, 21A, and 22 through 30.

Cemen and Wright conclude that the Artist Drive Formation was deposited in the interval 14 to 7.5 Ma ago, and that the Furnace Creek basin began to form about 14 Ma ago. The radiometric ages, however, all come from the Ryan area (Sedimentary rocks and tuff of the Ryan area of my usage, see also Greene, 1995). They also conclude that the conglomerates in the Black Mountains and Ryan areas had a southerly source, the granite fragments may have come from a Tertiary pluton now exposed farther south, and the fragments of Late Proterozoic and Paleozoic formations came from exposures in the Black Mountains and Greenwater Ranges where they are now absent.

Radiometric ages of some important units in the Funeral Peak quadrangle have been supplied by Fleck (1970) and Holm, Fleck and Lux (1994). "Older volcanics" on the Black Mountains dipslope near Hidden Spring have ages of $8.42\pm.16$, $7.81\pm.30$, $7.98\pm.15$, and $8.24\pm.16$ Ma (ages corrected for new decay constants as per Dalrymple, 1979). These ages average 8.11 Ma and are the same as part of the Artist Drive Formation. The Copper Canyon Formation, a unit of sedimentary rocks, tuff and basalt lying low on the scarp adjacent Death Valley, has ages ranging from $4.9\pm.1$ to 5.9 ± 1 Ma. Thus the Copper Canyon is the same age as the Greenwater and parts of the Furnace Creek Formation.

Wright and others (1991) report that the Greenwater Volcanics consist principally of dacite lava flows and domes, but also contain smaller amounts of basalt, andesite, and rhyolite lava flows and ash-flow tuffs. The base of the section in the southern Greenwater Range consists of basalt and andesite interbedded with thin non-welded ash-flow tuffs and tuffaceous sedimentary rocks. These are overlain by massive, vitric, dacite lava flows and flow-breccias. These rocks contain phenocrysts of plagioclase, biotite, and hornblende, and are identical to those mapped as rhyolite vitrophere (unit Tgv) by the present writer. Basalt and andesite of the overlying Funeral formation have been dated by K-Ar at 4.0 to 4.8 Ma. These volcanic rocks are thickest near Ryan and are believed to be vented along faults penetrating deep in the crust.

A REVISED STRATIGRAPHY OF THE NORTHERN BLACK MOUNTAINS

The following descriptions, along with the single unit of intrusive rocks, include all 104 rock units shown on the geologic map, pl. 1. Descriptive material which is additional to that given in the Description of Map Units (pl. 2), is included for approximately three-fourths of the units. An outline map (fig. 5A) locates the geographic areas which appear in the Correlation of Map Units (pl. 2). This is intended to be an aid in finding the rock units on the geologic map (pl. 1).

The principal formations, Artist Drive, Furnace Creek, and Greenwater, have each been divided into a number of units. Nearly all of these units are lenticular within the area mapped. Therefore, each formation, particularly the Artist Drive, contains a different sequence of units in any given exposed section. A study of pls. 1 and 3 will clarify this. Maximum thicknesses of the more important units are given in table 1. It must be emphasized, however, that the sum of these thicknesses would be meaningless, since many units are in lateral position to others, particularly in the Artist Drive Formation. Therefore, some more realistic total thicknesses are also given in table 1.

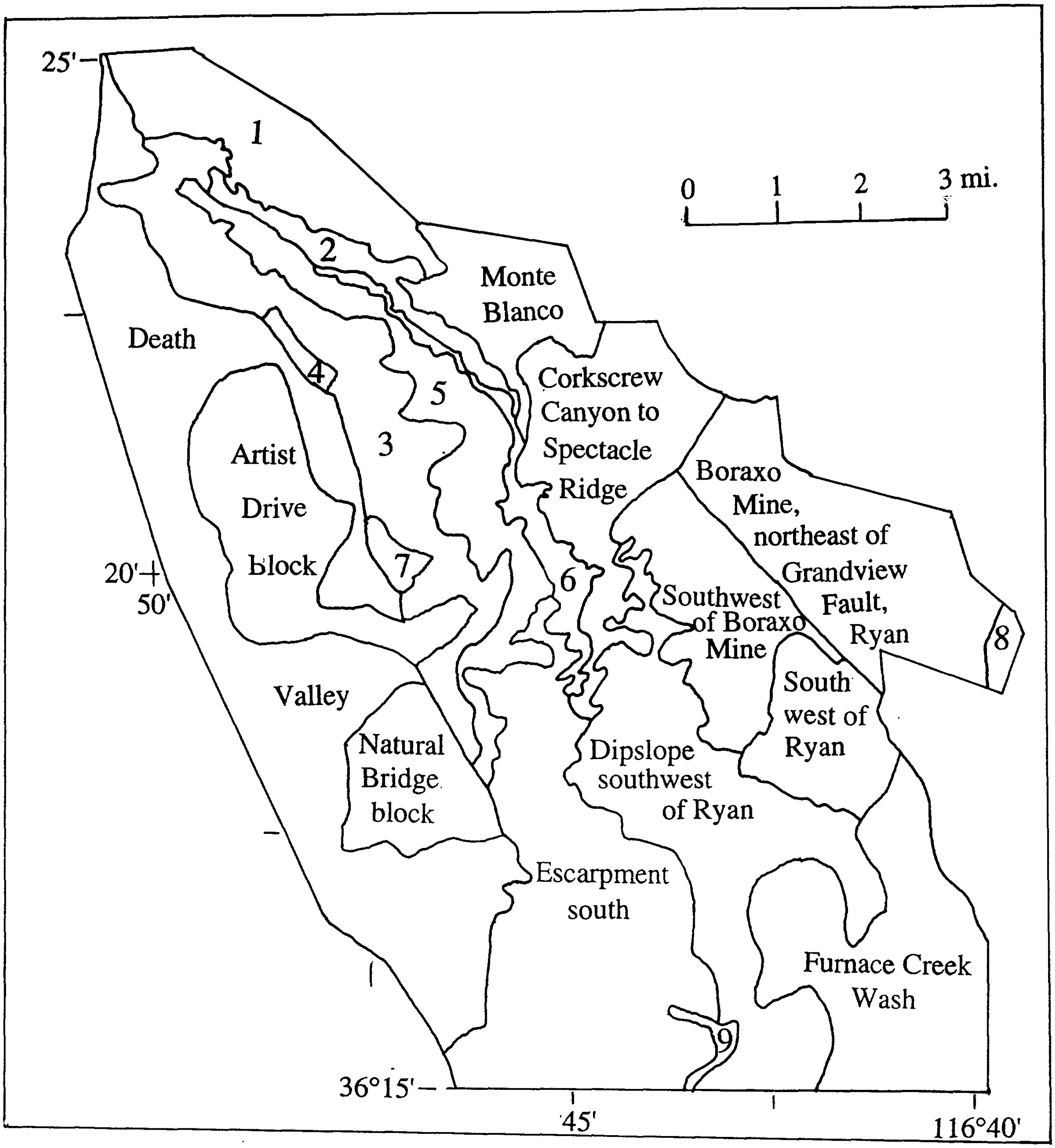

FIGURE 5A -- Outline map of northern Black Mountains showing areas referred to in Correlation of Map Units, plate 2. Key to numbered areas: 1) Dipslope, northeast part, southwest of Zabriskie Point, 2) Dipslope and crest, north and central, 3) Artist Drive block and escarpment, north, 4) Artist Palette, 5) Escarpment, north and central, 6) Escarpment, central, 7) Escarpment, south-central 8) Greenwater Range, 9) Mt Perry

TABLE 1 -- *Unit and Section Thicknesses*

Unit	Rock Type	Thickness, ft	m	Unit	Rock Type	Thickness, ft	m
Ta1	siltstone,shale	1600	490	24	sandstone, basalt	120	37
1A	basalt	100	30	24A	siltst, basalt, tuff	300	92
2	tuff	780	240	24B	basalt	180	55
2A	basalt	100	30	25	sandstone, basalt	190	58
2B	tuff, lavas	225	68	26	tuff	220	67
2C	shale, siltst, lmst	50	15	27	sandstone, congl,	420	128
2D	tuff	100	30		limestone, basalt		
2E	tuff, lavas	1380	420	28	siltstone, shale	300	92
2F	tuff, lavas	140	43	29	tuff	60	18
2G	tuff, lavas	80	24	30	conglom, sandst	600	180
2H	conglomerate	150	46	30A	basalt	300	92
3	siltstone, sandstn	100	30				
4	basalt	920	280	Tf1	siltst, basalt, palg	500	150
5	rhyolite	240	73	Tf2	basalt, tuff	450	137
6	sandstn, siltst, shl	800	240	Tg	rhyolite, vitr,tuff	3450	1052
7	tuff	980	300	Tf3	basalt, tuff	980	280
8	sandst, siltst, bslt	240	73	Tf4	basalt, tuff	610	185
9	basalt	300	92				
10	basalt, andesite	210	64	Trs1	sandst, siltst, cng	3350	1022
11	rhyolite	170	52	Trt2	tuff	415	127
11A	dacite, rhyolite	480	145	Trs3	sandst, siltst, cng	305	94
12	tuff, basalt	290	88				
13	rhyolite	2850	870				
13A	basalt	400	120				
13B	tuff	200	60				
14	tuff	280	85				
15	basalt	350	105				
16	sandstn, siltst, shl	200	60				
17	tuff	200	60				
18	basalt	350	105				
19	sandstn, siltst, shl	350	105				
20	conglom, sandst	200	60				
21	sandstn, siltst	300	92				
22	tuff	450	137				
23	sandstn, siltst	200	60				
23A	basalt	550	168				

TABLE 1 --*Unit and Section Thicknesses* -- continued

Section	Units included	Thickness ft	m
West of Buff Canyon, section BB'	Ta1, 2, 6,7,10, 19, 20, 21A, 21, 22, 23, 24, 24B, 26, 27, 29, 30	5820	1775
Artist Drive Block, section at C	Ta1, 2E, 2F	3000	915
Artist Drive to Corkscrew Canyon, section EE'	Ta1, 2, 4, 6, 7, 8, 9A, 10, 11, 16, 18	5680	1730
Corkscrew Canyon to south of Ryan	Tf1, 2, 3, 4	2480	755
Scarp above south part Artist Drive, section FF'	Ta2, 4, 6, 7, 8, 11A, 12, 14, 15, 17	4740	1445
Scarp above Natural Bridge, section HH'	Ta13, Tgr+Tgs	3400	1040
Ryan	Trs1, t2, s3	4070	1240

Note: Metric equivalents are given to the same number of significant figures, increased by one and rounded off where appropriate.

BASEMENT ROCKS

FOOTWALL ROCKS OF THE BADWATER TURTLEBACK PzPtl

Footwall rocks of the Badwater Turtleback have been described by Miller (1992) and structural features considered in detail. I made only a single traverse onto the turtleback from the valley floor. Therefore, the following description is taken mostly from Miller.

The rocks consist principally of mylonitic gneiss, mylonitic marble, and mylonitic pegmatite with sparse pelitic schist. North of "Nose Canyon" (near south boundary of plate 1), the proportions are approximately gneiss 40%, marble 30%, pegmatite 30%, and schist 1%. South of "Nose Canyon", gneiss is more abundant and schist absent.

The gneiss consists of "widely variable amounts of quartz, plagioclase and orthoclase feldspar, muscovite and biotite with minor amounts of chlorite, epidote and garnet". The gneiss occurs in tabular bodies which locally pinch out into marble, or join where marble pinches out into them.

Marble occurs in both calcitic and dolomitic varieties, locally in sharp contact and locally interlayered forming gradational contacts. These easily deformed rocks show abrupt large thickness changes. The calcite marble is mostly fine-grained and strongly foliated. It locally contains centimeter-scale chert and quartzite layers. The calcite marble commonly also contains white mica, or locally, actinolite, diopside, quartz, and plagioclase, mostly in fragmented form. The dolomite marble is generally weakly foliated and apparently mostly free of other mineral grains.

The pegmatite consists mostly of albitic plagioclase, quartz, microcline, and muscovite. The pegmatite forms boudins in the marbles and boudinaged sills and dikes in the gneiss. It shows a complete range of fabrics from weakly to penetratively foliated.

The pelitic schist consists principally of kyanite, garnet, and quartz with zincian ilmenite.

Miller (1992, pg.14) reports a discordant U-Pb age of 1.7 GA on the gneiss of this unit. He believes (pg. 17) that the marbles are most likely derived from the Late Proterozoic Crystal Spring Formation. L.A. Wright (oral comm., 1995) however, believes that the carbonate, quartzose, and pelitic rocks represent a mantle of Late Proterozoic Noonday Dolomite and Johnnie Formation on a core of gneiss.

A small part of the footwall directly south of Mt. Perry and above elevation 4000' (1220 m) is shown on the map of Miller (1992, pg. 13) in part as quartz monzonite and in part as a quartz latite dike swarm, both of Tertiary age. These rocks have not been studied in detail. I collected two samples of altered and partly mylonitized tonalite (appendix 1) from the place where footwall rocks reach the range crest (pl. 1). It is uncertain in what unit these rocks properly belong.

OTHER OCCURRENCES OF PRE-TERTIARY AND PRE-TERTIARY ROCKS PzPt2

In a gully directly south of Mushroom Rock (1.4 mi. (2.3 km) southwest of Buff Canyon) there are exposures of dark-gray brecciated dolomite with silty matrix forming a well consolidated rock; where locally weathered it is contrasting pinkish-brown. At one locality, white brecciated quartzite overlies the dolomite. The quartzite is mentioned by Hunt and Mabey (1966, p. A25, A63), who believe it is part of the Early Cambrian Zabriskie Quartzite. Lauren Wright, Bennie Troxel, and their associates believe the quartzite is part of the Ordovician Eureka Quartzite (oral comm. from Lauren Wright, 1995). The affiliation of the dolomite is unknown, but it is most likely part of the Cambrian Bonanza King Formation.

At the mouth of Gower Gulch (1.0 mi (1.6 km) northwest of Buff Canyon) and at the mouth of an unnamed wash (.75 mi (1.2 km) northwest of Buff Canyon) there are exposures of light-gray limestone, in part brecciated and in part only mildly fractured. These were mapped as Amargosa Chaos by Hunt and Mabey (1966, pl. 1). According to Bennie Troxel (oral comm., 1995), these rocks are part of either the Late Proterozoic and Cambrian Wood Canyon or the Cambrian Carrera Formation. L.A. Wright and I. Cemen believe these rocks are part of the Tertiary section (oral comm. from Wright, 1996).

BONANZA KING FORMATION (LATE CAMBRIAN) Cbk

Medium-dark-gray limestone forming a distinct block at the front of the range at the mouth of Buff Canyon has been tentatively assigned to the Bonanza King Formation (L.A. Wright, oral commun., 1994). The rock weathers dark-gray and has massive, indistinct bedding. Much of the contact with clastic sedimentary rocks of the overlying unit Ta1 is clearly depositional, as angular fragments of the limestone are locally caught up in the clastic rocks, forming a basal sedimentary breccia.

Dark-gray dolomite with pervasive breccia texture also outcrops 1500' (450 m) south of the Billie mine shaft near Ryan. This occurrence has also been assigned to the Bonanza King Formation (Cemen and others, 1985).

ARTIST DRIVE FORMATION

The Artist Drive Formation was first described by Noble (1941), who credits the name to T.P. Thayer. The type area is the west face of the Black Mountains near Artist Drive, in the area of the present report. Noble estimates the thickness to be 5000' (1500 m). A review of several authors' treatment of the Artist Drive has been given in preceding pages.

I have divided the Artist Drive Formation into 61 lithologic units, designated Ta1 to Ta30A on the geologic map (pl. 1). No attempt was made to indicate the lithology of the units in these designations. Some of the units are sequential and some are lateral variants. Descriptions of these units follow; some are moderately detailed and others are sketchy, owing mostly to the poor accessibility of the exposures.

Units are numbered in ascending stratigraphic order. Lateral variants are given the same number modified by a letter, however, in the case of Ta2, some lettered variants are superposed. It should be pointed out that there is some uncertainty about the position of the package formed by units Ta19 through Ta30. Their position is determined by the assumption that Ta19 overlies Ta16 and Ta18 where they meet directly west of Monte Blanco. However, this contact could be a fault; in that case the package Ta19 through Ta30 might instead be positioned between Ta11 and Ta16 (pl. 1), and units above Ta11 would require different numbers.

THICKNESS AND AGE

Approximate maximum thicknesses of most of the units in the Artist Drive Formation are given in table 1. In addition, some composite thicknesses are given, showing the "real" full thickness of the formation at several localities. The maximum thickness is 5820' (1770 m), near Buff Canyon.

The age of the Artist Drive presents a difficult problem, particularly because a correlation, which I believe is in error, has been made between the Artist Drive Formation and the sedimentary rocks and tuff of Ryan (see below). This correlation first appeared in the map of McAllister (1970), and a number of later workers (Cemen and others, 1985; Cemen and Wright, 1988; Snow and Lux, 1996) have accepted it.

Robert J. Fleck has provided a new $^{40}Ar/^{39}Ar$ age for tuff from Ta2, a unit low in the Artist Drive section. The method used and results obtained are discussed in appendix 2. The data indicate a <u>maximum</u> age of 8.4 ± 0.4 Ma for the unit. This is younger than previously suspected and there is little reason to argue that the unit is any younger than this figure; therefore I will accept 8.4±0.4 Ma as the age of the unit.

Thus we now have an age for the lower part of the Artist Drive Formation in the type area. Neglecting the error bars, this age is 2.4 Ma younger than that of Ryan unit Trt2, with which it has been correlated (McAllister, 1970). No new constraint on the age of the underlying unit Ta1 has been provided, but an age of <10 Ma for this unit seems most likely. This is 3-4 Ma younger than the ages reported for Ryan unit Trs1, with which it has been correlated (Cemen and others, 1985; McAllister, 1970).

Moving up in the section, I correlate rhyolite at Dantes View with Artist Drive unit Ta13. K-Ar ages of this rhyolite are 6.49±.13, 6.51±.13, and 6.67±.13 Ma as reported by Fleck (1970, ages corrected for new decay constants as per Dalrymple, 1979). Therefore, if the correlation is correct, the age of Ta13 is quite firm at 6.6 Ma, only 1.1 Ma older than the Greenwater Formation (see below). Again neglecting the error bars, this leaves only 1.8 Ma for the deposition and eruption of Artist Drive units Ta2 through Ta13. Taking 9 to 10 Ma as a likely age for the base of the Artist Drive formation and 6 Ma as a likely age for the top, the time for eruption and deposition of the entire formation is only 3 to 4 Ma.

UNIT Ta1

Unit Ta1 consists principally of interbedded shale, siltstone, and sandstone. The rocks are characteristically "buff" or "tan" (pale to moderate yellowish brown according to the Rock Color Chart, Geological Society of America, 1948). Older weathered surfaces are dark yellowish brown. The rocks have distinctive, even, planar bedding. Siltstone and shale commonly alternate in beds a few cm to a few 10's of cm thick, but some intervals of shale or silty shale are thicker. Sandstone may be fine, medium, or coarse grained and is locally interlayered in beds a few cm thick. Locally, unusual rock types including limestone, limestone pebble conglomerate and greenish tuffaceous sandstone, are found in layers <1 m thick.

Thin section study reveals that the normal sandstone and siltstone of this unit are epiclastic, containing no volcanic rock fragments. Four thin sections are described in appendix 1.

Rocks of this unit outcrop prominently in an east-trending canyon directly east of the mouth of Desolation Canyon, which I have named Buff Canyon. They attain their maximum thickness of about 1700' (520 m) there and unconformably overlie an outcrop of Cambrian Bonanza King Formation. They also outcrop in roadcuts in the northernmost part of Artist Drive where the road descends toward the highway near Mushroom Rock.

UNIT Ta1A

Rocks of unit Ta1A are basalt and andesite, dark gray to black where fresh but in most outcrops weathered to yellowish brown, or to light gray fluffy soil. The rock is mostly breccia and agglomerate but is locally solid. Some of the rock is aphyric but some contains small to large plagioclase phenocrysts. Calcite veins are abundant. The rock studied in thin section (appendix 1) is an altered andesite containing 30% plagioclase phenocrysts.

Rocks of this unit outcrop on a low ridge directly east of Desolation Canyon and elsewhere short distances south and east.

As I interpret the structure, these rocks are the lateral equivalent of some of the uppermost sedimentary beds of unit Ta1.

UNIT Ta2

Unit Ta2 consists of varied tuffs and tuffaceous sedimentary rocks, the latter mostly fine conglomerate. Greenish and pinkish hues are characteristic of these rocks, and older weathered surfaces are brownish- black.

Conglomerate is commonly basal or nearly so and consists of mostly subangular fragments, generally 2 mm to 1 cm, locally to 3 cm, in medium to light-greenish-gray tuffaceous matrix. Composition of the fragments varies widely; sedimentary rocks include limestone, micaceous sandstone, quartzite, and argillite; volcanic rocks include andesite, pumice, and other silicic rocks; granitic rocks and mineral grains of apparent plutonic origin are also present. Matrix consists of broken devitrified shards and fine rock fragments.

Tuff overlying and interlayered with the conglomerate is light-greenish-gray to grayish-yellow-green, locally grayish pink. It is in part of even, granular appearance and in part contains abundant flattened pumice lumps and fragments of other rock types. The pumice lumps are dusky-yellow-green to grayish-green and make the rock strikingly colorful. Thin sections (appendix 1) show that the pumice lumps are replaced by quartz, chlorite, and white mica. The matrix contains sparse phenocrysts of plagioclase and biotite, broken devitrified shards, and fine rock fragments.

The pumice-rich rocks are ash-flow tuffs; the others are probable air-falls, possibly reworked, and the conglomerates are likely fluviatile deposits.

In the northernmost part of the Artist Drive block and the adjacent main scarp, rocks of unit Ta2 are tuff and conglomerate of greenish hues as described above, however in the central part of Artist Drive south of Artist Palette the rocks contain less conglomerate and are mostly pinkish; colors range from pale red to moderate orange pink. Thin sections (appendix 1) reveal quartz and hornblende phenocrysts as well as plagioclase and biotite. Rocks at the scarp face are brecciated, probably by fault movement, and are locally silicified.

UNIT Ta2A

Unit Ta2A is the lowest in a sequence that includes, in ascending order, Ta2B and Ta4A and forms the section at Artist Palette and the ridge a short distance northwest of there.

Unit Ta2A consists of basalt, black where fresh but mostly seen in olive-brown to yellowish-brown rounded, deeply weathered outcrops. The thin section (appendix 1) shows traces of plagioclase and olivine phenocrysts and rock fragments.

UNIT Ta2B

This heterogeneous unit contains basalt, andesite, dacite, rhyolite and tuffs including ash-flow tuff. A section exposed in the north-facing scarp of the ridge northwest of Artist Palette has the following sequence: At the base is olive-brown weathering basalt of unit Ta2A; above are 1) brown dacite breccia, with admixed sedimentary rock at base; 2) basalt, in part agglomerate, some admixed sedimentary rock; 3) greenish tuff containing angular brown rhyolite fragments, similar to some in unit Ta2; 4) pinkish-brown rhyodacite welded tuff, with basal breccia.

At Artist Palette, the following rock types occur, in approximate stratigraphic order: 1) basal weathered basalt of unit Ta2A, 2) rhyolite and dacite, various pinkish and brownish colors, flow banded and breccia, 3) basalt and andesite, 4) tuff, greenish, pinkish, gray or light-brownish-gray, some contains angular rhyolite fragments; sparse local gray and brown aphyric vitrophere.

At Desolation Canyon the sequence is 1) weathered basalt of Ta2A at base, 2) greenish and pinkish tuffs, 3) rhyolite, brownish, platy, flow-banded and breccia.

Fourteen thin sections of volcanic rocks from unit Ta2B are described in appendix 1.

UNITS Ta2C AND Ta2D

Another sequence forming a minor variant of unit 2 occurs at the base of the main scarp 0 to 0.6 mi (0 to 1 km) southeast of the point where Artist Drive turns north along the scarp. It consists of 1) olive-brown spheroidally weathered basalt of Ta2A at the base, 2) thin bedded shale, siltstone and limestone, unit Ta2C, and 3) ash-flow tuff and tuffaceous conglomerate, greenish gray and similar to much in unit 2 but containing thin interlayered basalt, unit Ta2D.

UNITS Ta2E, Ta2F, AND Ta2G

These units underlie a major portion of the Artist Drive block and part of the main scarp 1 to 2 mi (1.5 to 3 km) to the southeast. They are characterized by the presence of greenish-gray tuff similar to that in unit Ta2 but also contain abundant interlayered volcanic flow rocks.

Unit Ta2E is well exposed in the west-facing scarp of the central part of the Artist Drive block, visible from the main highway. This exposure is characterized by alternating sub-units of greenish-gray tuff and lava flows, principally dacite and rhyolite, but varying to andesite and basalt. Sub-units are a few m to about 30 m thick and form a distinctive striped pattern. Dacite and rhyolite are dark- to light-brownish- or pinkish-gray and flow banded or flow breccia. Andesite and basalt are light-gray to reddish-brown, in part vessicular to amygdaloidal flows and in part agglomerate. The tuffs have varied contents of pumice and other volcanic rock fragments and are mostly greenish-gray; however, light-gray to white tuffs and poorly bedded sedimentary rocks are present locally, as is conglomerate similar to that in unit Ta2. The part of unit Ta2E which lies at the north end between unit Ta2F and the cover of gravel unit QTg2 is especially heterogeneous.

Similar rocks make up this unit elsewhere in the Artist Drive block and in the main scarp to the southeast.

Rocks of unit Ta2F overlie those of Ta2E in the central part of the Artist Drive block. They consist of the same rock types, however flow rocks predominate and tuffs are sparse.

Rocks of unit Ta2G overlie those of Ta2F. They are similar in types and proportion to unit Ta2E; a prominent greenish gray tuff defines the base.

Twenty-four thin sections of volcanic rocks from units Ta2E and Ta2F are described in appendix 1.

UNIT Ta2H

Unit Ta2H consists of a distinctive microdiorite conglomerate. It is present in fault blocks and is locally clearly interlayered with unit 2, in the main scarp from 0.6 to 2.5 mi (1 to 4 km) south of Artist Palette. The conglomerate consists of angular fragments grading to well-rounded pebbles, locally cobbles to 20 cm, of microdiorite in matrix of coarse sand. The microdiorite is a fine grained rock consisting of plagioclase, hornblende, opaque mineral and cryptofelsite groundmass (appendix 1). This distinctive rock type occurs only in this conglomerate, and imparts to it a brownish-black weathering stain, darker than adjacent rocks.

There is an additional exposure of microdiorite conglomerate at the end of the ridge directly south of Buff Canyon. It is included with unit Ta2H because of the distinctiveness of this lithology, however there is no adequate structural explanation for its presence at that locality.

UNIT Ta2I

Unit Ta2I is a distinctive grayish-pink to light-brownish-gray rhyolite exposed in the lower part of the main scarp opposite the south part of the Artist Drive block. The rhyolite contains sparse microphenocrysts of plagioclase, K-feldspar, biotite, and opaque mineral. It is mostly flow-banded and weathers to angular fragments and blocks, stained medium brown on older surfaces. Two thin sections of rhyolite from this unit are described in appendix 1.

UNIT Ta3

Unit Ta3 consists of thin-bedded fine to very-coarse sandstone and siltstone. This unit is mostly only 5 to 15 ft. (1.5 to 4.5 m) thick but is generally present lying between greenish tuff at the top of unit Ta2 and basalt of unit Ta4, in the area 0 to 1 mi. (0 to 1.6 km) southeast of Artist Palette. For much of this length, the outcrop width is insufficient to show on the geologic map.

UNIT Ta3A

Unit 3A consists of light gray tuffaceous sedimentary rocks and interlayered basalt flows and possible sills. It is exposed on a ridge directly north of Blind Canyon, where basalt may be as much as 25% of the section, and on the scarp face south of this canyon, where the proportion of basalt is small.

UNIT Ta4

Unit Ta4 is a thick sequence of basalt, basaltic andesite, and andesite flows which underlie much of the main scarp east of the north and central parts of the Artist Drive block. Colors are medium- to dark-gray and brownish-gray; some are amygdaloidal but most are solid. Agglomerate and cinder agglutinate are conspicuously absent.

Basaltic andesite flows containing abundant plagioclase phenocrysts 2-5 mm long are the most conspicuous and probably the most abundant rock type present. Other rocks contain larger phenocrysts and some, none. Calcite veins are locally abundant and leave fragments in the surface debris. These rocks are commonly altered, probably deutericly, and badly weathered.

Eight thin sections of basalt and andesite from unit Ta4 are described in the appendix 1.

UNIT Ta4A

Unit Ta4A forms the top unit in the "Artist Palette sequence", occurring at Artist Palette and north to Desolation Canyon. The lower units, Ta2A and Ta2B are described in previous sections.

The unit consists mostly of basalt with less abundant andesite and minor tuffaceous sedimentary rocks. These rocks are conspicuously exposed where Artist Drive follows a narrow canyon through the ridge underlain by this unit 1.2 mi (2.0 km) northwest of Artist Palette. The basalt is in part solid but agglomerate, cinder agglutinate, and conglomerate of basalt clasts are also common. Most is dark-gray but color varies to reddish-brown in fresh rocks and greenish-gray in altered ones. Most contains sparse plagioclase microphenocrysts. Andesite is dark-brownish-gray, aphyric and platy-weathering. Interlayered tuffaceous sedimentary rocks are light-gray to pinkish; some contain rhyolite fragments.

Eight thin sections of basalt and andesite from unit Ta4A are described in appendix 1.

UNIT Ta4B

This thin unit of tan tuffaceous sedimentary rocks overlies basalt of unit 4 in the area immediately south of Artist Palette. Thin sections of two rocks from this unit are described in appendix 1.

UNIT Ta5

Rocks of unit Ta5 appear in two lenticular bodies in the main scarp, opposite the north and south parts of the Artist drive block. They are principally pale-brown aphyric rhyolite with distinctive flow banding. Some of the rhyolite is flow-breccia, lighter in color. A basal vitrophere, dark-gray and brownish-gray, aphyric and brecciated, is commonly present.

UNIT Ta6

Unit Ta6 outcrops continuously in the main scarp from Buff Canyon nearly to Blind Canyon. It consists of conspicuously well-bedded sedimentary rocks, generally medium- to light-gray and weathering very-light-gray, locally brown. Sandstone is dominant near the base, with siltstone and minor limestone interbedded. Siltstone and shale are dominant in the middle part; interbedded sandstone increases in proportion upward and is again dominant in the upper part.

This sedimentary unit appears to be mostly epiclastic, although some volcanic grains are present in the thin section of the limy sandstone which was studied (appendix 1). Ripple-mark and mudcrack were locally observed in these rocks.

UNIT Ta6A

Unit Ta6A is basalt, and is present at one locality near the end of the scarp directly south of Buff Canyon.

UNIT Ta7

Unit Ta7 appears in the main scarp overlying Ta6 and extending somewhat further to the south. The rocks are ash-flow tuff and tuffaceous sedimentary rocks and are in part similar to those in unit Ta2. Porous light- brownish-gray tuff with greenish-gray pumice is typical, these rocks grade into denser, greener tuff. Locally, they are pinkish. A striped effect observed from a distance in cliff exposures suggests multiple flow units merged into one cooling unit. Much of the tuff contains angular volcanic rock fragments to 1 cm, and some tuffaceous conglomerate with rounded pebbles to 2 cm, is present. Clasts of sedimentry rocks are sparse, and of granitic rocks, absent. Two thin sections of tuffs from this unit are described in appendix 1.

UNIT Ta7A

Unit Ta7A is a small lens of rhyolite located up the scarp from Artist Palette. Rhyolite is mostly light-brownish-gray and flow banded, some is vitrophere. Part is a flow breccia containing pinkish-gray, very-pale- orange, and white angular fragments.

UNIT Ta8

Unit Ta8 overlies the south part of unit Ta7 in the main scarp. It consists of well bedded sandstone, siltstone and shale of epiclastic origin with a few interlayered basalt flows. A lens of silicified tuff is present at one locality.

UNIT Ta9

Unit Ta9 is a thin unit of basalt, locally overlying unit Ta8.

UNIT Ta9A

Unit Ta9A is a thin unit of pink and greenish tuffaceous sedimentary rocks, locally overlying unit 9.

UNIT Ta10

Unit Ta10 is present near the top of the main scarp from Buff Canyon south to the headwaters of Corkscrew Canyon. The unit consists principally of basalt and andesite, dark gray and olive gray. The appearance of the scarp exposure suggests 3 to 6 relatively thick flows. Most of the rock is solid, but some is breccia or agglomerate, particularly at the base.

The typical rocks contain abundant microphenocrysts of plagioclase in aphanitic groundmass. Three thin sections are described in appendix 1.

In the north part of the exposure, thin lenticular layers of sedimentary rocks are present in the basal portion of the unit. Typically, a basal basalt flow 2m thick is overlain by about 1 m of sandstone or cobble conglomerate, locally containing cobbles of inflated basalt. The main basalt section overlies.

UNIT Ta11

Unit Tall consists of rhyolite which caps the crest of the Black Mountains from a little south of Buff Canyon to the headwaters of Corkscrew Canyon. The rhyolite is brownish- to light-brownish -gray and pale-red and distinctly flow banded and streaked. The sample studied (appendix 1) contains traces of minute plagioclase and hornblende(?) phenocrysts.

Presence of flow-banding typical of rhyolite flows indicates an extrusive origin for rocks of this unit rather than an intrusive origin as suggested by McAllister (1970).

UNIT Ta11A

Unit Ta11A outcrops prominently on the main scarp south of Corkscrew Canyon, and south of the pinchout of unit Ta11. It consists of rhyolite and dacite of varied color and texture. Some of the rock is black aphyric vitrophere with incipient spherulitic crystallization; this rock has prominent small-scale columnar joints in outcrop. Other rock is light-brownish-gray, somewhat porous, and breccia-textured; still other is medium-light-gray and flow-banded with sparse feldspar phenocrysts and quartz filled amygdules.

UNIT Ta12

Unit Ta12 outcrops on the main scarp from south of Corkscrew Canyon to Blind Canyon. It consists of interlayered light-gray tuff, well-bedded sedimentary rocks, and basalt. Tuff and bedded sedimentary rocks with thin interlayered basalt predominate in the north part of the units outcrop area. Farther south adjacent Blind Canyon there is a thick section consisting of basalt flows with thin interlayered tuff in the upper part and thick layers of tuff with thin basalt flows and possible sills in the lower part.

At the dryfall which gives Blind Canyon its name, steeply dipping well-bedded medium-gray siltstone and shale at the apparent base of the section are overlain by two coherent slabs of pinkish tuff, apparently on low-angle faults. The exposures are of insufficient extent to map another unit. This structure is enigmatic; it could be a window into another turtleback somewhat analogous to Buff Canyon.

UNIT Ta13

Unit Ta13 consists mostly of rhyolite. It enters the section near Blind Canyon (opposite the south end of the Artist Drive block) and thickens southward over a short distance, becoming the predominant unit in the main scarp overlooking the Natural Bridge block and the north part of the Badwater Turtleback. Most of the rhyolite is light-brownish-gray and weathers dark-brown. Some is flow-banded and some is breccia. It is mostly in massive layers; locally thinner layers are present with minor tuff or shale interlayered. Five thin-sections of rhyolite from this unit are described in appendix 1.

This unit is faulted out where the Badwater Turtleback extends to the top of the range directly south of Mt. Perry. It re-enters the section after a break of about 3 mi. (5 km) and continues at least as far as Dantes View, where it underlies the crest of the range (south of the area of pl. 1).

UNIT Ta13A

Unit Ta13A is a lenticular body of basalt, interlayered with rhyolite of unit Ta13, present in the main scarp east of the north part of the Natural Bridge block.

UNIT Ta13B

This unit consists of tuff, in several lenticular bodies interlayered with rhyolite of unit Ta13 and in part overlying basalt of Ta13A. It is light-gray and greenish-gray and contains rhyolite fragments in at least the basal part.

UNIT Ta14

Unit Ta14, the "Lower maroon and gray tuff" is found on the west slope of the main range overlying unit Ta12 and the north end of Ta13. The unit consists of alternating sub-units of pink- to reddish-brown tuff and light-gray non-bedded tuff; a full sequence is pink/gray/pink/gray. A lens of basalt is present at one locality. This strikingly colorful unit shows well from a distance in cliff exposures underlying basalt of unit 15.

UNIT Ta15

Unit Ta15 is present in steep slopes and cliffs directly west of the main ridge crest from opposite the south part of the Artist Drive block to Blind Canyon. It consists of basalt and andesite flows, each 1 to 6 m thick, in a stack of even appearance.

UNIT Ta16

Unit Ta16 mostly overlies rhyolite of unit Ta11 on the dip slope near the crest of the range, but appears in the escarpment slope also overlying unit Ta15 for a short distance near Corkscrew Canyon. It consists of massive greenish-gray tuffaceous sandstone and siltstone and yellowish-gray well-bedded sedimentary rocks in alternating sub-units. The well-bedded sedimentary rocks are thin-bedded fine-grained sandstone, siltstone, and shale, with local sandy limestone, in part silicified. Interlayered basalt flows were also observed in the thickest section of this unit, near the headwaters of Corkscrew Canyon.

UNIT Ta16A

This unit is in lateral position to Ta16 and overlies Ta11 for a short distance on the dipslope near the crest of the range west of Twenty Mule Team Canyon. It consists of thin alternating subunits of rhyolite, basalt, and very light gray to brownish gray sedimentary rocks, including minor limestone.

Some strata exposed in the headwaters portion of Twenty Mule Team Canyon directly east of Monte Blanco are tentatively assigned to this unit. They consist of, from the top down, conglomerate and breccia composed principally of rhyolite fragments, basalt, and coarse grained sandstone.

UNIT Ta16B

Rocks of unit Ta16B are present in small lenticular bodies at the crest of the range overlying rhyolite of unit Ta11. They are cobble conglomerate containing clasts of limestone, quartzite, and volcanic rocks.

UNIT Ta17

Unit Ta17, the "Upper maroon and gray tuff", generally overlies basalt of unit Ta15 and is found slightly higher up the escarpment slope from Corkscrew Canyon headwaters south to near Blind Canyon. In addition to pinkish-gray, light gray, and reddish-brown tuffs, the unit locally contains green tuff, in part conglomeratic, with enclosed pebbles of volcanic rocks to 2 cm and local cobbles of vitrophere. Rhyolite, pinkish-gray and part flow banded, part lithophysal is also locally present. The section near Corkscrew Canyon headwaters contains basalt flows as well. A thin section of rhyolite and one of tuff from this unit are described in appendix 1.

UNIT Ta18

Unit Ta18 underlies a long dipslope and locally lies at the crest of the range, in the area directly northwest of Corkscrew Canyon. The unit consists of a stack of basalt flows, 1 to 6 m thick each, locally well exposed in a small west facing escarpment A partial section consisting of 5 flows with no intervening sedimentary rocks was observed; along with a baked zone in the topmost tuff of the underlying unit 16. Thin interlayered tuff beds are locally present in upper part of the unit, exposed in the dipslope. This unit was assigned to the Furnace Creek Formation by McAllister (1970), probably because it is mostly overlain by sedimentary rocks of the Furnace Creek. However, as I interpret the structure, it is overlain by unit Ta19 near its northwest end and properly belongs in the Artist Drive sequence.

UNITS Ta19 TO Ta30A

INTRODUCTION

Units Ta19 through Ta30A underlie dipslopes and secondary ridges in the northernmost part of the area mapped, north and east of Buff Canyon. Ta19 overlies units Ta10, 11, 16A, and 16B, and apparently overlies Ta16 and Ta18. The top units of this sequence, Ta30 and Ta30A, underlie sedimentary rocks and basalt of the Furnace Creek Formation, which extend from this contact north and east to Furnace Creek Wash, Zabriskie Point, and Furnace Creek Inn (McAllister, 1970).

UNIT Ta19

Rocks of unit Ta19 underlie ridge crests for a short distance directly south of Buff Canyon, then continue as a long dipslope extending southeast to Monte Blanco. They consist of epiclastic shale, siltstone, sandstone and conglomerate, typically thin to medium bedded. Most of the unit consists of thinly interbedded siltstone and shale with minor sandstone, outcropping well on dipslopes and the edges of flatirons. Colors are yellowish-gray to pale-yellowish-brown and grayish-orange, rarely greenish-gray, weathering the same or somewhat darker. Bedding is mostly planar and the outcrops shed chips and slabs. Ridge crests and the tops of flatirons are commonly underlain by beds of very-coarse sandstone and pebble conglomerate. Conglomerate contains clasts of limestone, quartzite, basalt, and granitic rocks, angular to 1 cm and rounded to 7 cm, a few beds contain cobbles to 20 cm.

In the last 0.5 mi (0.8 km) near the southeast end of the outcrop band of this unit, the strata consist mostly of siltstone, shale, and fine grained sandstone; coarse-grained sandstone and conglomerate have lensed out. Thus the rocks are similar to the adjacent Furnace Creek Formation unit Tfs1 and the position of the fault separating the two is uncertain. However, the fault is placed in nearly identical positions on plate 1 and on the map of McAllister (1970).

UNIT Ta20

Unit Ta20 outcrops in large dip plates on northeast side of the ridge directly south of Buff Canyon. It is in part overlying and in part in lateral position to strata of unit Ta19. The rocks are mostly conglomerate and coarse granule sandstone. Colors are yellowish-gray and light-greenish-gray. Conglomerates generally contain unsupported well-rounded limestone pebbles and cobbles to 15 cm in coarse sandstone matrix.

UNIT Ta21

Unit Ta21 consists of well-bedded greenish- and pinkish-gray sandstone and siltstone, probably tuffaceous.

UNIT Ta21A

This unit is similar to unit Ta21 but contains also interlayered basalt.

UNIT Ta22

Unit Ta 22 is a prominent cliff-forming unit overlying unit Ta21A in the upper part of Buff Canyon and in fault contact with unit Ta1 in the main part of this canyon. Its resemblance to unit Ta2 can be a cause for confusion. Unit Ta22 consists of tuff, mostly greenish and weathering brown, but locally pinkish. Much contains angular rhyolite fragments.

UNIT Ta23

Unit Ta23 consists mostly of tuffaceous siltstone and sandstone, greenish and brownish gray. Local variants include rhyolite vitrophere and conglomerate with well rounded pebbles of limestone, quartzite, and granitic rock. A thin basalt layer appears locally at the top.

UNIT Ta23A

Unit Ta23A is basalt.

UNIT Ta23B

Unit Ta23B is pinkish- and greenish-gray tuffaceous siltstone.

UNIT Ta23C

Unit Ta23C is sandstone, mostly very-coarse-grained, with interlayered basalt.

UNIT Ta24

Unit Ta24 consists of sandstone with lenticular interlayered basalt. The sandstone is mostly greenish-gray, coarse- to very-coarse-grained and probably tuffaceous. It caps a prominent ridge crest directly east of Buff Canyon, accessible with difficulty from Furnace Creek Wash.

UNIT Ta24A

Unit Ta24A consists of tan well-bedded tuffaceous siltstone in the lower part, locally containing interlayered thin basalt flows. The upper part is pinkish- and greenish-gray tuff, much containing rhyolite fragments.

UNIT Ta24B

Unit Ta24B is basalt.

UNIT Ta25

Unit Ta25 consists principally of coarse-grained greenish-gray sandstone with interlayered basalt. These rocks outcrop prominently on dipslopes and the crests of minor ridges north of Buff Canyon. The sandstone is massive to flaggy-bedded and

characteristically weathers dark-brownish-gray. Conglomerate, limestone, and sandy limestone are locally interbedded. Interlayered basalt is in part flows and in part agglomerate.
Basalt is the dominant rock in the westernmost exposures of this unit.

UNIT Ta26

The main part of unit Ta26, lying east of Buff Canyon, is ash-flow tuff, typically pinkish-gray with a characteristic brown-weathering, resistant, upper part. Color varies locally to greenish- or yellowish-gray. The tuff contains abundant rhyolite fragments. Locally, gray vitrophere and white pumiceous sedimentary rocks are present overlying the ash-flow tuff.

Where the outcrop narrows north of Buff Canyon, the brown-weathering ash-flow tuff pinches out and a non-resistant pinkish and greenish tuff continues to the east, characteristically outcropping in small reverse scarps on the dipslope. A thin section is described in appendix 1.

UNIT Ta26A

Unit Ta26A is a heterogeneous mixture including very light gray and greenish-gray tuffs, siltstone, limy sandstone, palagonite tuff, and minor altered basalt. It is readily seen in the lowermost part of Gower Gulch at the edge of Death Valley. It is shown in lateral position to unit Ta26, but the relationship is uncertain.

UNIT Ta27

Unit Ta27 is the thickest and most continuous dipslope-forming unit in the north part of the map area, extending from the edge of Death Valley to the headwaters of Twenty Mule Team Canyon. It consists principally of interlayered sandstone, conglomerate, limestone, and basalt. Sandstone is typically medium- to very-coarse-grained and greenish-gray to medium-gray and weathering dark-brown. Conglomerates form prominent dip plates and typically contain unsupported, well-rounded pebbles and cobbles of limestone, granitic rock, and volcanic rocks. Cobbles range to as much as 20 cm in diameter. Other dip plates and flatirons are capped by limestone and limy sandstone with interbedded yellowish- and pinkish-gray siltstone and shale. Basalt flows are interlayered with the sedimentary rocks, seemingly in haphazard fashion.

Conglomerate and basalt lens out in the area between 0.8 and 0.5 mi (1.3 and .8 km) from the southeast end of this units occurrence and sandstone and siltstone predominate from there to the southeast end.

UNIT Ta27A

Unit Ta27A is basalt. It is separated from Ta27 where lenticular masses of this rock type are large enough to show on the map.

UNIT Ta27B

Unit Ta27B consists of local, lenticular masses of pinkish-, greenish-, and yellowish-gray tuff.

UNIT Ta28

Unit Ta28 is mostly poorly bedded yellowish-gray siltstone and shale, weathering grayish-orange . Locally, greenish-gray sandstone and siltstone overlies or is in lateral position to part of the siltstone and shale. Sandstone and siltstone are predominant near the pinchout of the unit in the headwaters of Twenty Mule Team Canyon.

UNIT Ta29

Unit Ta29 is a thin unit of pinkish- and greenish-gray sedimentary rocks that forms a marker bed separating unit Ta27 from Ta30. The rocks are tuffaceous sandstone and siltstone, mostly non-bedded, which outcrop well in small scarps facing up the dipslope.

UNIT Ta30

Unit Ta30 is the topmost in the dipslope sequence in the north part of the map area, being overlain by fine-grained sedimentary rocks of the Furnace Creek Formation. This unit was mapped as basal conglomerate of the Furnace Creek Formation (unit Tfc) by McAllister (1970) but is here assigned to the Artist Drive Formation, principally because of its lithologic similarity to unit Ta27 and others lower in the section.

This unit consists mostly of conglomerate with interbedded sandstone. Basalt is confined to separately mappable units shown as Ta30A. Conglomerate is mostly composed of unsupported pebbles, cobbles and boulders in coarse sandstone matrix, typically greenish-gray. Limestone is the most abundant clast type, basalt, rhyolite, and tuff are also common, and granitic rocks rare. Many beds contain cobbles as large as 25 cm, some have boulders to 1.5 m. Interlayered sandstone is fine- to very-coarse-grained and also typically greenish-gray; minor siltstone and limestone are also present.

UNIT Ta30A

Unit Ta30A is a stack of many thin flows of basalt, containing no interbedded sedimentary rocks. It locally forms the top of the Artist Drive formation and locally forms mappable lenses in unit Ta30.

SEDIMENTARY ROCKS AND TUFF OF RYAN AREA

INTRODUCTION

The name "Ryan Formation" was introduced by Axelrod (1940, p. 528) for some beds in Furnace Creek Wash which overlie the Furnace Creek Formation. The name is credited to H.D. Curry; no description nor precise location are given. These strata are most likely ones assigned by McAllister (1970) to the Funeral formation or possibly the uppermost Furnace Creek formation. In any case the name "Ryan Formation" has not been further used. Therefore, I am considering it to be abandoned and am re-introducing it informally for some strata near Ryan which underlie the Furnace Creek Formation.

Unit symbols (pls. 1, 2) for Sedimentary rocks and tuff of Ryan area include a number designating the stratigraphic order and a letter suggestive of the principal lithology.

UNIT Trsl

Sedimentary rocks of unit Trs1 outcrop prominently in the hills directly east of the Billie Mine and extend to Ryan. These hills are foothills of the Greenwater Range, which is mostly a flat-topped plateau capped with basalt of the Funeral Formation (pl. 1, figs. 2, 4).

The unit consists of a heterogeneous assemblage of calcareous clastic rocks and limestone. The clastic rocks include fine to coarse grained sandstone, conglomerate, siltstone, and shale; all grade into limestone by increase in carbonate content. Finer grained rocks are well-bedded, coarser sandstones are thickly bedded but may be finely laminated. Fresh rocks are light-gray to very-light-brownish-gray but all weather to a distinctive yellowish-brown by which the hills underlying them can be easily distinguished from a distance.

Conglomerate constitutes only a few percent of the section but is distinctive and is a cliff-former in the scarp directly east of the Billie Mine and elsewhere. Conglomerate contains rounded clasts, commonly to 10 cm., consisting mostly of pre-Tertiary limestone, but also of quartzite and volcanic rocks. Clasts are in matrix of coarse sandstone and are commonly unsupported. Thus the conglomerate resembles that in Artist Drive Formation unit Ta30 and other conglomerates lower in the section.

Rock descriptions and strike and dip acquired during traverses enable a sketch section of this unit to be erected which extends from the nose of the ridge 1000' (300 m) north of the Billie Mine main shaft to the Old RR Grade 1000' (300 m) northeast of Ryan. The section is approximately 3350' (1020 m) thick and consists of the rock types described above. Conglomerate is mostly confined to the lower 2/3 of the section. The base is not exposed; although rocks identified as limestone of the Cambrian Bonanza King Formation are exposed in the scarp 1500' (450 m) south of the shaft, local structure suggests that these are a basement high. The top of the section is at the contact with greenish tuff of unit Trt2. A section partly identical to the one above outlined was measured in detail by Cemen and Wright (1988), and discussed in a previous section.

On the north side of the hill adjacent to the Boraxo pit, sandstone and conglomerate of this unit also crop out, but here they are strongly cemented with silica into extremely brittle rocks having a characteristic medium- to dark-brown color. Some bedded chert and chert breccia are also present. They in part underlie and in part have fault contacts with rocks of unit Trt2.

McAllister (1970) correlated this unit with the Artist Drive Formation. He placed both the section east of the Billie Mine and some rocks in the Black Mountains at the western edge of his map in his Artist Drive Formation unit Tal. Support for such a correlation is found in the fact that the strata in both localities are overlain by greenish-gray tuff, my units Trt2 at Ryan (see below) and Ta2 in the the Black Mountains; McAllisters' unit Tapl in both places. However, the correlation of the tuff units now appears to be in error, since their radiometric ages differ by 2.2 Ma (see below for age of Trt2). As to the underlying sedimentary units, Trs1 (Ryan) and Ta1 (Buff Canyon) are both thick sections of mostly clastic sedimentary rocks, but clastic rocks in Trs1 are calcareous in the lower part and limestone and conglomerate are interbedded. Tal, by contrast, is non-calcareous, contains very sparse conglomerate and little or no limestone.

UNIT Trt2

Unit Trt2 is exposed in two small residual hills lying northwest of the Boraxo Mine, in larger hills lying adjacent the Boraxo Mine to the north and east, and, most significantly for the understanding of the stratigraphy, overlying the above-described section of unit Trs1 at Ryan. The unit consists mostly of massive tuff, probably mostly of ash-flow origin. Pumice is abundant and phenocrysts of feldspars or dark minerals sparse in this rock. Its characteristic greenish-gray color makes this rock distinctive in the field but colors locally vary to light-gray or pinkish. The greenish-gray tuff in this unit closely resembles that in Artist Drive Formation units Ta2 and Ta7.

At the hill adjacent the Boraxo Mine, some of this unit consists of tuffaceous conglomerate. Unsupported pebbles of volcanic rocks are mostly 0.5 to 1 cm in diameter. Clasts of sedimentary or granitic rocks were not observed. This gray to slightly greenish rock weathers to spotty brown.

Lenses of yellow-brown clastic rocks resembling those of unit Trs1 occur low in the well-exposed section of this unit directly north of Ryan. Also, in the prominent east-trending ridge directly east of Ryan, tuff and clastic sedimentary rocks are interlayered at the base of this unit.

UNIT Trs3

Unit Trs3 is found principally in the hill directly north of the Boraxo Mine and in the scarp directly north of Ryan. Directly adjacent the Boraxo pit, it consists of conglomerate and coarse sandstone. The conglomerate contains unsupported well-rounded pebbles and cobbles, commonly to 5 cm, locally to 10 cm. These clasts are in part limestone, and less commonly quartzite, derived from pre-Tertiary formations, and in part volcanic rocks. The sandstone and conglomerate clearly overlie greenish-gray tuff of unit Trt2. Small outcrops of these rocks also occur in the hills lying to the northwest.

In the section at Ryan, this unit consists of yellow-brown weathering sandstone and siltstone similar to that in unit Trs1, but clearly overlying tuff of Trt2. Conglomerate was not observed. There is a brownish-black mineralized zone at the base of this unit, and lenses of greenish-gray tuff are interlayered in the lower part. Where this unit is directly overlain by capping basalt of the Funeral Formation, there is a reddish baked zone which is visible for many miles. McAllister (1970) mapped these strata as Artist Drive unit Tam.

UNIT Trt4

This unit outcrops at Ryan overlying unit Trs3. It consists of greenish-gray, locally pinkish, tuff similar to that in unit Trt2. McAllister mapped these strata as Artist Drive unit Tapu.

THICKNESS AND AGE

Maximum thickness of the lower three units of the sedimentary rocks and tuff of Ryan are as follows (table 1): Trs1, 3350' (1020 m); Trt2, 415' (127 m); and Trs3, 305' (93 m). K-Ar ages reported by Cemen and others (1985) are as follows: tuff beds low in Trs1, 13.7±.4 Ma and 12.7±.4 Ma; tuff low in Trt2, 10.6±.2 Ma, tuff low in Trt4, 6.4±.3 Ma.

FURNACE CREEK FORMATION

INTRODUCTION

The Furnace Creek Formation has been mapped by McAllister (1970) in a band as much as 5 mi (8 km) wide extending from Death Valley southeast up the valley containing Furnace Creek Wash. He divided the formation into several units, including the main lacustrine mudstone unit, conglomerates, basalt, altered basalt, and rhyolitic tuff. McAllister includes in the Furnace Creek Formation large thicknesses of basalt and tuff (my units Tfb2, Tft2, Tfb3, and Tft3) which are in the dipslope on the southwest side of Furnace Creek Wash. Since basalt of unit Tfb2 clearly overlies sedimentary rocks typical of the Furnace Creek in the east wall of Corkscrew Canyon, my interpretation of the content of the formation is in general agreement with that of McAllister. However, I have placed the conglomerate unit (Ta30) in the Artist Drive Formation. Further work on the Furnace Creek Formation appears in McAllister (1973) and Cemen and others (1985).

In the north part, my mapping stops at the contact between Artist Drive unit Ta30 and the lacustrine mudstone unit of the Furnace Creek Formation, as mapped by McAllister (1970). However, in the east-central and southeast parts (southeast of Corkscrew Canyon), I have mapped and interpreted the Furnace Creek rocks.

I have divided the Furnace Creek Formation into 5 informal members, as indicated by unit symbols with the subscripts 1 through 5. The unit symbols also include a letter suggestive of the lithology. Member 1, mostly sedimentary rocks, outcrops mostly north of Corkscrew Canyon and has been mapped by McAllister (1970). Member 2, mostly basalt and tuff, outcrops from Corkscrew Canyon to Spectacle Ridge and is overlain by rocks of the Greenwater Formation. Member 3, also mostly basalt and tuff, continues the section to the east, overlying the Greenwater Formation. Member 4 continues the section east to Furnace Creek Wash south of Ryan, and has typical Furnace Creek sedimentary rocks interlayered with basalt. Member 5, lying mostly north of the Grandview Fault near Ryan, is mostly sedimentary rocks including nodular limestone. Though given a higher number, the stratigraphic position of member 5 relative to the others is uncertain.

LOWER UNITS

UNIT Tfs1

This unit consists principally of thinly interbedded siltstone, shale and fine sandstone, characteristically light-gray to "tan" and weathering to grayish-orange. Coarser sandstone and pebble conglomerate are present locally, as are beds of borate minerals. Bedding is generally planar but may be irregular and ripple mark is locally present. Areas underlain by this unit, notably between Zabriskie Point and the contact with unit Ta30 to the southwest, have characteristic "badlands" topography. These rocks are mapped as the main lacustrine mudstone unit by McAllister (1970).

UNIT Tfp1

Rocks of this unit underlie a hill directly north of part of Corkscrew Canyon. This hill is identified as Monte Blanco on the map of McAllister (1970), who placed these rocks in a fragmented altered basalt unit (palagonite tuff of my terminology) of the Furnace Creek Formation. They consist of altered bits of basalt with matrix of clays and calcite, and contain sparse basalt pebbles to 5 cm and very sparse blocks to 20 cm. The contact with well-bedded siltstone of unit Tfp1 is in part conformable and in part unconformable.

UNIT Tfb1

Unit Tfb1 consists of basalt, locally interlayered with sedimentary rocks in the lower part of the Furnace Creek Formation.

UNIT Tfb2

Units Tfb2 and Tft2 are a thick package of basalt and sedimentary rocks that cap the range from Corkscrew Canyon south to Spectacle Ridge . South of Spectacle Ridge basalt of this unit underlies the upper part of the west facing escarpment for a short distance.

Unit Tfb2 consists mainly of basalt. It is exposed mostly in dip slopes but is locally seen in escarpments and cliffs as a pile of thin (1-5 m) flows. Thin (<1 m) beds of light-gray tuff separate some of the flows. The basalt is dark-gray to dark-brownish-gray, most contains plagioclase phenocrysts in trace amounts, however, some flows contain as much as 20% plagioclase phenocrysts. Eight thin sections of basalt of unit Tfb2 are described in appendix 1.

UNIT Tft2

Unit Tft2 consists of sedimentary rocks, mostly poorly bedded tuffaceous gritstone but locally containing finer-grained,well bedded, sandstone, interlayered in mappable units with basalt of unit Tfb2. The sedimentary rocks are gray to tan, locally greenish or pinkish, and commonly outcrop well on steep dip and escarpment slopes.

UNIT Tfc2

Unit Tfc2 outcrops on the east slope of the range directly north of Spectacle Ridge. It is a large mass of red cinder agglutinate and must mark a vent locality, probably one of several for unit Tfb2 basalt.

UNIT Tfp2

Unit Tfp2 outcrops low on the east slope of the range 2 km north of unit Tfc2. It consists of palagonite tuff and may mark another vent area.

THICKNESS AND AGE

The thickest section of units Tfs1, Tfb1, and Tfp1 in the area of plate 1 is at Monte Blanco and is about 440' (134 m, table 1). Tfb2 and the units associated with it are about 450' (137 m) thick. The only K-Ar age reported (Cemen and others, 1985) on the Furnace Creek Formation is one of 5.87+-1.5 Ma on a basalt flow, believed to be about 2200' (670 m) above the base of the formation. Because of the large analytical error range, and the lack of a location for this sample, this age is of doubtful significance.

GREENWATER FORMATION

UNITS Tgr, Tgv, Tgs, AND Tgb

The Greenwater Formation is divided into units that consist principally of rhyolite (Tgr), vitrophere (Tgv), tuffaceous sedimentary rocks (Tgs), and basalt (Tgb). Within the map area these rocks outcrop at the crest of the range and on the dipslope from the latitude of the Boraxo Mine south, and in the Artist Drive and Natural Bridge blocks on the edge of Death Valley. These rocks continue to the south at least as far as the road leading to Dantes View, and are also present in the Greenwater Range, where they have been mapped by Drewes (1963).

The Greenwater Formation forms an important key to the structure and stratigraphy of the area. It separates the basalt and sedimentary rock package formed by units Tfb2 and Tft2 from the similar package formed by units Tfb3 and Tft3. Its appearance in the Natural Bridge block suggests a vertical displacement of as much as 6000 ' (2000 m) on the fault separating this block from the main part of the range.

The characterizing rock type in the Greenwater is rhyolite, mostly light-brownish-gray to pale-red, in part flow banded and in part flow breccia. Sparse to common microphenocrysts of plagioclase and sparse microphenocrysts of biotite and hornblende are characteristic of most of the rock. The rhyolite forms layers tens of meters thick, but bases and tops are locally seen. Vitrophere zones are commonly present adjacent, especially basal to, the rhyolite masses, and partially devitrified rhyolite is also common. Some interlayered sedimentary rock may also be present, but where rhyolite is the predominant rock, unit Tgr is mapped.

Vitrophere without adjacent rhyolite underlies large areas, and is mapped as unit Tgv. The vitrophere is mostly medium- to light-gray with uniform groundmass of glass, locally weakly flow-banded, especially where partially devitrified. It commonly occurs as a breccia of large (ca. 20-70 cm) blocks, locally these blocks are rounded, giving the appearance of conglomerate. The vitrophere, like the rhyolite, generally contains sparse to common microphenocrysts of plagioclase and sparse microphenocrysts of biotite and hornblende. As is commonly the case in silicic volcanic rocks, the biotite and hornblende are fresh in the vitrophere and altered in the rhyolite.

Tuffaceous sedimentary rocks are interlayered with the rhyolite and vitrophere, where they are the predominant rock type they are mapped as unit Tgs. The sedimentary rocks are tan to light gray, locally pinkish, rarely greenish. They are composed mostly of coarse, angular fragments, locally including pebbles. Sparse crystal fragments of plagioclase and dark minerals are present along with abundant volcanic rock fragments including shards, pumice and angular bits of rhyolite. These rocks are generally in massive layers, but bedding may locally be seen.

Layers of basalt (Tgb) are locally interlayered with the rhyolite, vitrophere, and tuff of the Greenwater Formation between Spectacle Ridge and Mount Perry. They may be related to the basalt of the underlying unit Tfb2.

Thin sections of 44 samples of rhyolite, vitrophere, tuff, and basalt from the Greenwater Formation are described in appendix 1.

THICKNESS AND AGE

Maximum thickness of the Greenwater formation in the area of plate 1 is about 3400' (1035 m, table 1). K-Ar ages on the Greenwater Formation reported by McAllister (1973) are 5.32±.15 Ma and 6.04±.20 Ma. and those reported by Fleck (1970) are 5.46±.16 and 5.62±.11. Each of these ages has been corrected to new decay constants according to the table in Dalrymple (1978). Therefore, the age of the Greenwater may be considered well established at close to 5.5 Ma.

FURNACE CREEK FORMATION, UPPER UNITS

UNITS Tfb3 AND Tft3

The upper basalt and sedimentary rock package underlying the east slope of the Black Mountains in the area directly east and south of the Boraxo Mine are assigned to units Tfb3 and Tft3 of the Furnace Creek Formation. The rocks dip to the northeast, overlying those of the Greenwater Formation and underlying Furnace Creek units Tfb4 and Tfs4

Basalt of unit Tfb3 is similar to that in unit Tfb2, and to that in Artist Drive Formation unit Ta18. A thin section is described in table 1. Stacks of flows 1 to 5 m thick each are characteristic, and are exposed in escarpment slopes. As is common with rather thin flows, much of the basalt is vesicular and some is cinder agglutinate. Rock that is solid or nearly so is confined to the central portions of flows. While most rocks are dark-gray, some more inflated ones are grayish-red. Thin layers of tuffaceous sedimentary rocks are locally present between basalt flows, and are separately mapped as unit Tft3 where thick enough to show.

Sedimentary rocks of unit Tft3 include tuffaceous types similar to those in units Tft2 and Tgs. They are mostly yellowish-gray to light-gray, and are locally of substantial thickness. A thin section is described in appendix 1.

UNITS Tfb3A AND Tft3A

Units Tfb3A and Tft3A outcrop in the central part of the Artist Drive block and in the main scarp a few miles to the southeast. They consist of interlayered basalt (Tfb3A) and tuffaceous sedimentary rocks (Tft3A). These units form a distinctive and visually striking outcrop area when viewed from the Artist Drive road, as the basalt is less weathered and blacker than most area basalts and the sedimentary rocks are a contrasting light tan. They unconformably overlie Artist Drive Formation units Ta2E, Ta2F, and Ta2G, which are mostly rhyolite, dacite and greenish tuff. They also overlie rhyolite and vitrophere of Greenwater Formation units Tgr and Tgv. Units Tfb3A and Tft3A are analogous to, and may correlate with, units Tfb3 and Tft3 of the area west and south of the Boraxo Mine, described above.

Basalt layers consist of one or more flows, each only a few meters thick. Some is solid but much is amygdaloidal and some is agglomerate or cinder agglutinate. Fresh colors are dark-gray to brownish-gray. Most contains small quantities of plagioclase and olivine microphenocrysts. Seven thin sections are described in appendix 1.

Interlayered sedimentary rocks are mostly tan tuffaceous poorly sorted sandstones. These rocks are mostly porous and are crumbly where even slightly weathered, shedding talus of bits and grit. A thin section is described in table 1. Greenish or pinkish rocks are conspicuously absent. Much of the sandstone contains altered pumice fragments, and some contains angular rhyolite fragments to 1 cm. Pebbly layers with rounded clasts of volcanic rocks to 7 cm are locally present, as are conglomerate layers containing volcanic clasts to 15 cm.

UNITS Tfb4 AND Tfs4

Furnace Creek basalt (unit Tfb4) forms two distinct stacks of thin flows, separated by sedimentary rocks, in the area south of the Boraxo Mine. The basalt is dark-gray to black, aphanitic to fine-grained and much contains altered olivine phenocrysts. Two thin sections are described in the appendix 1. Reddish cinder agglutinate is locally interlayered, and blocky agglomerate common at the bases of flows. An unusual agglomerate of angular to sub-rounded blocks as much as 20 cm in diameter in a layer as much as 8 m thick and containing some reddish cinder was mapped by McAllister (1970) as a vent.

Thinly interbedded siltstone, shale and fine-grained sandstone (unit Tfs4) similar to strata in unit Tfs1 outcrop in a north-flowing wash directly south of the Boraxo Mine (plate 1). These rocks define the contact between basalt of unit Tfb3 and that of unit Tfb4. Another band of Furnace Creek sedimentary rocks lies directly to the east, between the two principal stacks of basalt constituting unit Tfb4, and is well exposed in two northeast-flowing washes. Here the thin-bedded siltstone is overlain by an upper sub-unit consisting of coarse sandstone and conglomerate. The contact is transitional in some exposures and mildly unconformable in others. Locally the siltstone grades laterally into light-gray limestone, a rather porous rock which nevertheless is resistant and forms a lag of slabs. McAllister (1970) assigned the rocks in the upper sub-unit to the Funeral Formation.

UNITS Tfs5, Tfls5, AND Tfb5

Outcrops of thinly interbedded siltstone, shale, and sandstone in the mesa directly east of the Boraxo Mine and in parts of the small residual hills lying west of the mine are assigned to unit Tfs5. This is the typical Furnace Creek lithology similar to Tfs1 and Tfs4. Other outcrops between Ryan and Furnace Creek Wash contain coarse-grained sandstone and conglomerate in addition to the typical siltstone and are also assigned to this unit.

Much of the Furnace Creek Formation in member 5 consists of limestone, unit Tfls5, a lithology which is sparse or absent in the other members. This limestone is light to very light gray and nodular and fragmental to oolitic in texture. This distinctive lithology is generally found unmixed with clastic sedimentary rocks and locally forms thick mono-lithologic sections, as in the scarp at Ryan. In the hills west of the Boraxo Mine, mappable units of limestone (Tfls5) are interlayered with clastic rocks (Tfs5). In the mesa east of the Boraxo Mine, the clastic rocks clearly overlie the limestone and the two lithologies are interbedded at the contact. Much limestone has been mapped as conglomerate by McAllister (1973).

Basalt, unit Tfb5, occurs underlying a low knob directly south of the Boraxo Mine, near the Sigma Mine, and west of Ryan. It is interlayered with sedimentary rocks as in member 1. Basalt at the first-named locality contains altered olivine phenocrysts and a speckled groundmass of altered plagioclase and pyroxene.

THICKNESS AND AGE

Thickness of Tfb3 and associated units is about 980' (299 m) and of Tfb4 and associated units about 610' (186 m) (table 1). Estimates of the thickness of Tfs5 and Tfls5 were not attempted, however each may be locally several hundred feet thick. There are no radiometric ages reported for upper Furnace Creek rocks, however their age must lie between 5.5 Ma (Greenwater) and 4.8 Ma if Funeral Formation ages quoted below are correct.

FUNERAL FORMATION

UNIT Tfu

Mapping (plate 1) has been extended for completeness from Ryan up the scarp which forms the southwest flank of the Greenwater Range. The Funeral Formation caps the range in this vicinity and consists of many thin flows of basalt. The basalt is described by McAllister (1970, 1973).
It has been dated at 4.14±.12 Ma (McAllister, 1973; age is corrected for new decay constants as reported by Dalrymple, 1978). Additional radiometric ages as old as 4.8 Ma (Wright, unpub. data) are reported for this unit by Wright and others (1991).

QUATERNARY AND QUATERNARY-TERTIARY UNITS

INTRODUCTION

Quaternary and Quaternary-Tertiary units consist principally of unconsolidated silt, sand, gravel, cobbles and larger rock fragments, although some contain volcanic rocks also. The age of most of these units is quite uncertain, as there are no radiometric ages nor described fossils known to the writer. They are placed in the order given by superposition and geomorphic evidence.

Unit symbols (pls. 1, 2) for Quaternary and Quaternary-Tertiary units include a number designating the inferred stratigraphic order and a letter suggestive of the principal lithology.

UNIT QTg1

This unit consists of silt, sand, and gravel including cobbles and boulders. It underlies a terrace on top of bedrock in the central part of the Artist Drive area. Locally, bedded sand and gravel are present but the unit is mostly a lag of cobbles, blocks and slabs; predominant rock types are volcanics derived from underlying units 2E, 2F, and 2G. It is mapped as part of the Funeral Formation by Hunt and Mabey (1966).

UNIT QTg2

This unit contains interlayered pebble to cobble gravel and coarse sand with abundant angular fragments. It is present in the north and central parts of the Artist Drive area and in four low hills lying west of the Artist Drive Block at the edge of the salt deposits underlying the bottom of Death Valley. Clasts are mostly volcanic rocks with rhyolite and tuff predominant; basalt, limestone and quartzite are also present, with a characteristic lag of cobbles and blocks at the surface. Dips are gentle to moderate. The four hills near the salt deposits have at their surfaces lag boulders of basalt and rhyolite to 50 cm or more; some rhyolite and tuff boulders are seen to be disintegrating in place. This unit constitutes remnants of a terrace formed of older, coalesced alluvial fans. The contact with overlying unit QTbg3 is commonly sharp, locally gradational. It is part of the Funeral Formation of Hunt and Maybe (1966).

UNIT QTbr

Rocks of this unit form the lowest part of the hanging wall of the Badwater Turtleback directly south of Mt. Perry. They consist of breccia of rhyolite fragments, many 0.5 to 2 cm in maximum dimension, others to several tens of cm. The rock is well consolidated but weathers to a hummocky surface with small caves, stained with iron oxides. These features are well exposed at the east end of the mapped band of this unit.

This unit is the hanging wall monolithologic breccia referred to by Miller (1992, pgs. 120, 122, 127). Miller believes that the breccia formed during a period of gravitational reactivation of the turtleback fault system, but the age of this movement is unclear. In my view, it is most logically approximately the same age as unit QTg2.

UNIT QTl3

This unit consists of weakly bedded sandy silt and clay with sparse pebbly beds. It is present in a small area adjacent the upper part of Furnace Creek Wash southwest of Ryan and is well-exposed underlying Qg4 in cliffs adjacent major washes. It is probably lacustrine.

UNIT QTbg3

This unit is cobble and boulder gravel consisting mostly of basalt fragments. It is present in the north part of the Artist Drive area in large remnants overlying QTg2 and in smaller remnants surrounded by Qg5. It is characterized by lag of angular basalt blocks commonly as much as 0.5 m, locally to 2 m. There is a distinctive brownish-black patina on fragments; also, the unit is very dark on air photos. Basalt is of various textures, locally aphyric but mostly porphyritic with sparse to abundant tiny to large plagioclase phenocrysts. Two thin sections are described in appendix 1. Surface blocks are commonly in disintegrating condition. Mushroom Rock is a boulder in this unit. Apparently a remnant of a local volcanic center. It is part of the Funeral Formation of Hunt and Mabey (1966) and includes also their "Lake Manly deposits".

UNIT QTg3

This unit also consists of silt, sand and gravel including cobbles and boulders. It forms an apron of coalescing alluvial fans covering a terrace between Artist Drive and Natural Bridge. It is similar to Qg4 but appears to underlie this unit at the north end of the exposure 1.9 mi (3.0 km) northwest of Natural Bridge. Natural Bridge is in unit QTg3. The unit distinctly underlies Qgv4 near the bridge. Unit QTg3 is part of Qg2 of Hunt and Mabey (1966).

UNIT Qgv4

This unit contains sand, gravel, rhyolitic tuff, and basalt. It is present chiefly on the ridge directly north of Natural Bridge but there are small exposures elsewhere adjacent to Death Valley. It consists of beds of sand and gravel with interlayered 1) light gray rhyolitic tuff-breccia and conglomerate with characteristic orange to dark-red weathering stains and locally silicified, and, 2) basaltic cinder agglutinate and scoriaceous basalt flows, commonly brecciated, commonly stained with hematite, and locally cemented with calcite. There is a surface veneer of rhyolite blocks in the higher parts. This unit records the youngest volcanic activity in the area, and is apparently related to normal faulting. Five thin sections of rocks from this unit are described in appendix 1.

UNIT Qg4

This unit is composed of silt, sand and gravel including cobbles and boulders. It forms an extensive apron of coalesced alluvial fans lying between the upper part of Furnace Creek Wash and the crest of the Black Mountains southwest of Ryan. Remnants extend northwest to the Boraxo Mine. It is mostly coarse sand and pebble to cobble gravel containing volcanic clasts. It is included in the Funeral Formation by McAllister (1970). A remnant of an older alluvial fan lying between Artist Drive and Natural Bridge is also included in this unit. It is similar to Qg5, but more severe weathering and dissection suggest that it is older. It is part of Qg2 of Hunt and Maybe (1966).

UNIT Qbg5

This small unit is formed of gravel consisting of angular fragments of rhyolite derived from adjacent outcrops of unit Ta2B. It is present in a small area near Desolation Canyon. It is well bedded, has substantial dip, and is cemented with caliche. It may be a beach deposit.

UNIT Qg5

This unit consists of silt, sand and gravel including cobbles and boulders. It is present as dissected remnants of older alluvial fans adjacent Death Valley, Artist Drive, and Furnace Creek Wash. It is part of Qg2 of Hunt and Maybe (1966). It is dominantly tuffaceous sand and silt in the north part of the Artist Drive area; elsewhere it is interlayered pebble to cobble gravel and coarse sand with angular fragments. Clasts are largely volcanic rocks. It is commonly bedded, the top beds are parallel to the fan surface but dips are steeper below. The surface is generally a lag of angular to rounded blocks, slabs and cobbles, moderately weathered, and appearing darker than unit Qfa on air photos.

UNIT Qls

This unit is a landslide deposit, present in a canyon directly east of Artist Drive. It formed as a catastrophic rock fall and contains blocks up to automobile-size. Access to the upper part of this canyon and the adjacent ridge is possible over this deposit.

UNIT Qt

This unit is talus fans and cones of angular rock fragments derived by weathering of immediately upslope units. Most occurrences are on the escarpment slope facing Death Valley.

UNIT Qfa

The topmost unit also consists of silt, sand and gravel including cobbles and boulders. It is present as large coalescing alluvial fans at the base of the range encroaching into Death Valley, and as smaller fans adjacent Furnace Creek Wash and elsewhere. The fans are generally in an active state of aggradation though channeled by the principal washes. Alluvium in active stream channels is also included in this unit. Clasts are largely volcanic rocks. The unit includes most of units Qg3 and Qg4 of Hunt and Maybe (1966).

UNIT af

Unit af is artificial fill. As mapped, it consists mostly of mine spoil adjacent to the Boraxo, Billie, Ryan, and Sigma mines. A large spoil pile adjacent to the Boraxo Mine is clearly visible from highway 190 near the junction with the road to Dantes View, though the large open pit constituting the mine is not visible. The pit is not accessible and no attempt to map it was undertaken.

INTRUSIVE ROCKS

UNIT Td

Several dikes, one large enough to be mappable, of pale-brown rhyolitic rock are present near the head of Desolation Canyon. The rock mostly has breccia texture, and contains 1% plagioclase and traces of mafic phenocrysts in cryptofelsite groundmass containing plagioclase microlites. A thin section is described in appendix 1. The age of this rock is unknown but it is very likely a feeder for unit Ta11 or another rhyolite flow unit.

EXTENSION OF FURNACE CREEK AND GREENWATER FORMATIONS TO EAST SIDE OF GREENWATER RANGE ADJACENT AMARGOSA VALLEY

McAllister (1973) and Drewes (1963) both map the Furnace Creek Formation in washes tributary to the Amargosa Valley on the east side of the Greenwater Range, between 3 and 12 mi. (5 and 19 km) southeast of Ryan. McAllister's map also includes areas underlain by Artist Drive formation, and both maps show pumiceous tuff of the Greenwater Formation overlying sedimentary rocks of the Furnace Creek Formation. The following described localities are on USGS 7.5' quadrangles East of Ryan, West of Eagle Mountain, and Greenwater Canyon, provisional editions 1987 and 1988.

Limited investigation by the writer revealed that outcrops in the area of lat. 36°16'20" to 40", long. 116°33'20" to 34' are in part very light gray shale, siltstone, and thinly-bedded limestone in addition to chip-breccia and oolitic limestone identical to that found in Furnace Creek unit Tfls5 at Ryan and vicinity, (pl. 1). At lat. 36°15'40" to 50", long. 116°19'30" to 45" similar rocks are overlain by pumiceous tuff identical to that found in the Greenwater Formation elsewhere, and typical Greenwater vitrophere is exposed .8 mi. (1.3 km) farther southwest. Thus McAllister's mapping of these two units is confirmed. Coarse and very coarse brown-weathering sandstone, locally pebbly and locally limonite-rich, is also found in this area and is mapped (McAllister, 1973) as Artist Drive Formation. However, these rocks also overlie lithologies characteristic of the Furnace Creek Formation, and therefore, in my view, should be included in that formation.

At the Lila C mine (lat. 36°14'10" to 30", long. 116°29'40" to 50") and at outcrops 1 mile (1.6 km) to the south (lat. 36°13'25" to 35", long. 116°29'40" to 55") very light gray shale, siltstone and thinly-bedded limestone are interbedded with pumiceous tuff which is finer grained than the typical Greenwater. These rocks are mapped as Furnace Creek Formation (McAllister, 1973), but show character intermediate between typical

Furnace Creek and Greenwater. A layer of lump-pumice tuff is mapped as Greenwater Formation.

At outcrops 1.3 mi. (2.1 km) farther south (lat. 36°12'15" to 35", long. 116°30'10" to 20"), typical Furnace Creek lithologies including abundant chip-breccia and oolitic limestone are overlain by lump-pumice tuff which includes sparse pebbles of vitrophere, rhyolite and basalt typical of lava flows in the Greenwater Formation (McAllister, 1973, Drewes, 1963).

Another section, mapped as Funeral, Greenwater and Furnace Creek Formations (Drewes, 1963), is located at lat. 36°12'40" to 13'10", long. 116°31'10" to 20", 2.4 mi. (3.8 km) southwest of the Lila C mine. Basalt and conglomerate of the Funeral Formation overlie lump-pumice tuff with vitrophere pebbles similar to that at the last-described section, and the Furnace Creek beds contain coarse- and very-coarse-grained sandstone in addition to more typical lithologies.

INTERPRETATION AND CORRELATIONS BY SNOW AND LUX (1996)

Snow and Lux (1996) propose a division of Tertiary strata in the Cottonwood, Panamint, Grapevine, Funeral and Black Mountains (fig.1) into three time-transgressive tectono-stratigraphic sequences. The early-extensional Grapevine sequence includes the Titus Canyon, Ubeheebe, and Panuga Formations. These rocks are older than the onset of major extension at about 15 Ma. Strata of the syn-extensional Amargosa sequence include the Leadfield, Bat Mountain, Navadu, and Artist Drive Formations, the latter deposited in the Furnace Creek Basin. The late-extensional sequence includes the Furnace Creek, Funeral, and Nova Formations, which overlap syn-extensional strata. These units are allostratigraphic units, i.e., based on their bounding discontinuities, rather than lithostratigraphic units. The record of Amargosa deposition indicates east to west migration of the locus of active extension. Three complete cycles of tilting, erosion, and deposition during Amargosa time are recorded in the Nova basin between the Cottonwood and Panamint Mountains.

During Tertiary extension, the Cottonwood Mountains formed a rollover, or extensional fault-bend fold above a listric detachment (Snow and White, 1990). Several types of measurements at this rollover are used to test the viability of tectonic reconstructions which juxtapose now separated strata.

Snow and Lux (p. 21) summarize data on the Artist Drive Formation, quoting the K-Ar ages which are from the Ryan area. They point out that pebbles of hypabyssal granites could have an origin in the Panamint Mountains and seyenite and quartz monzonite in the Cottonwood Mountains (Hunter Mountain pluton and White Top stock). On the basis of the radiometric ages, the Artist Drive strata are correlated with the Entrance Narrows and Lemoigne Canyon Members of the Navadu Formation.

The Furnace Creek Formation is also summarized, and the age of 5.9 Ma (locality unknown) quoted. Clasts from northeast facing fans (i.e., on the southwest side of the basin) contain fossiliferous Devonian through Permian rocks (McAllister, 1976). Permian rocks are not present in the Funeral Mountains, but are present in Furnace Creek clasts. Permian strata are exposed in the northern Panamint and southern Cottonwood Mountains. On the basis of the one radiometric age, the Furnace Creek is considered equivalent to the middle Lemoigne Canyon Member; it is assigned to the late-extensional sequence.

The reconstruction along the northern Death Valley-Furnace Creek fault zone places the Panamint and Cottonwood Mountains south of the Funeral Mountains, providing a source for the Bat Mountain fan (Cemen, Drake, and Wright, 1982, Bat Mountain is located on figs. 3 and 4) . An offset portion of the Bat Mountain fan is adjacent the Tucki Wash fault in the northern Panamint Mountains. Thus, Precambrian strata may have been within 10 km (6 mi) of Bat Mountain at about 15 Ma.

Snow and Lux (p. 31) interpret the first appearance of conglomerate with granite clasts (unit 5 of Cemen and Wright, 1988) as the beginning of synextensional sedimentation. Locally exposed granitoids in the Panamint Mountains (10.7 Ma, Hodges and others, 1990) and Greenwater Range are similar to the age of 10.6 Ma reported by Cemen and others (1985) for "Artist Drive" tuff near Ryan. Another age, 8.7 Ma, for this tuff bed, reported by Cemen and Wright (1988) and quoted by Snow and Lux, is a misquote of the age reported in the 1985 paper (oral comm. from L. A. Wright, 1996). Snow and Lux believe that these ages indicate coeval intrusion, extrusion and increased sedimentation rate, implying onset of major extension.

Intraclasts of lower Artist Drive rocks are present in middle and upper Artist Drive strata but continuous outcrop and limited faulting mean major extension ceased by 5-6 Ma. (p. 31). Extensional translation of Artist Drive strata at Desolation Canyon from a position near Ryan has occurred. Seyenite, quartz monzonite and Permian limestone clasts in the Artist Drive Formation mean that the Cottonwood Mountains lay to the southwest; before movement on the northern Death Valley-Furnace Creek fault zone . Thirty km (19 mi) of dextral slip realigns markers in the Cottonwood and Funeral Mountains and probably occurred after 10 Ma. Slip was completed prior to deposition of the Furnace Creek Formation at 5-6 Ma across the fault zone.

Snow and Lux make some correlations between tilting events in the Cottonwood Mountains and depositional pulses in the Furnace Creek basin, Bat Mountain, and other places. The middle Artist Drive is interpreted as filling a graben created by separation of the Resting Springs Range from the combined Cottonwood and Funeral Mountains (p. 35).

Progressive east to west migration of the limit of extension is indicated by relative ages of tilting in the Death Valley extended terrane and in the Panamint Valley. This is compatible with the "rolling hinge model" whereby range-sized crustal slivers progressively detach from an allochthon.

While Snow and Lux propose a plausible scenario, conglomerate is sparse in the Artist Drive Formation, particularly in units Ta1 through Ta18, which form the bulk of the formation. Therefore, I feel that there is little evidence that it constitutes a syn-extensional unit.

VOLUME AND SOURCE LOCATION

The section in the northern Black Mountains is largely composed of volcanic rocks, but most of the units appear to be locally erupted ones of small volume compared to many volcanic fields in the Basin and Range (fig. 6). The volcanic suite is largely a bimodal basalt-rhyolite association (figs. 7-16), although some andesite and dacite appear in Artist Drive units 2B, 2E, 2F, 2G, 10, and 11A. I have drawn figure 6 to show the center of mass of each unit as it appears in outcrop and the order-of-magnitude volume. The volume was calculated assuming each unit to be a bipyramidal disk with thickness = 2h and strike length = 2r. Then $v = \pi hr^2$. This method assumes that the point of eruption of each unit is somewhere near the center of mass, though few dikes or obvious vents have been noted in the field.

The pattern of eruption for the Artist Drive Formation appears to be very nearly random in both space and time. A small volume of basalt (1A) is followed by a larger volume of tuff (2) accompanied by a mixed bag of volcanic rocks (2B, 2E, 2F, and 2G). This is followed by relatively large volumes of basalt (4) and tuff (7). Basalt and rhyolite are interlayered up through unit 12. The overlying unit 13 is a large volume of rhyolite. The apparent source for unit 13 near the south edge of the map area and the volume calculated are based on the assumption that rhyolite at Dantes View and extending 5.5 miles (8.8 km) farther south (as shown on the map of Drewes, 1963) correlates with this unit. Alternating units of basalt and tuff, mostly found in the north part of the area, complete the volcanic component of the Artist Drive section.

Overlying units of the Furnace Creek Formation consist of relatively large volumes of basalt with some interlayered tuff. If the sources of these lavas match their centers of mass, they proceed to the southeast as they get younger. Lensing in between the Furnace Creek units at the level Tf2 and the level Tf3 are large volumes of rhyolite and tuff with a small volume of basalt, all parts of the Greenwater Formation. The center of mass of the rhyolite and tuff is in the Greenwater Range and appears in the southeast corner of fig. 6. This position and the volume calculation are based on the maps of Drewes (1963) and McAllister (1973) as well as the area shown in pl. 1. Drewes (1963) and McAllister (1973) both indicate that vitrophere is the predominant rock type in what amounts to the southern half of the Greenwater outcrop, however my local reconnaissance suggested an important component of rhyolite. On the other hand, an area directly east of Mt Perry (pl. 1) is all vitrophere, much of it in boulder-breccia form.

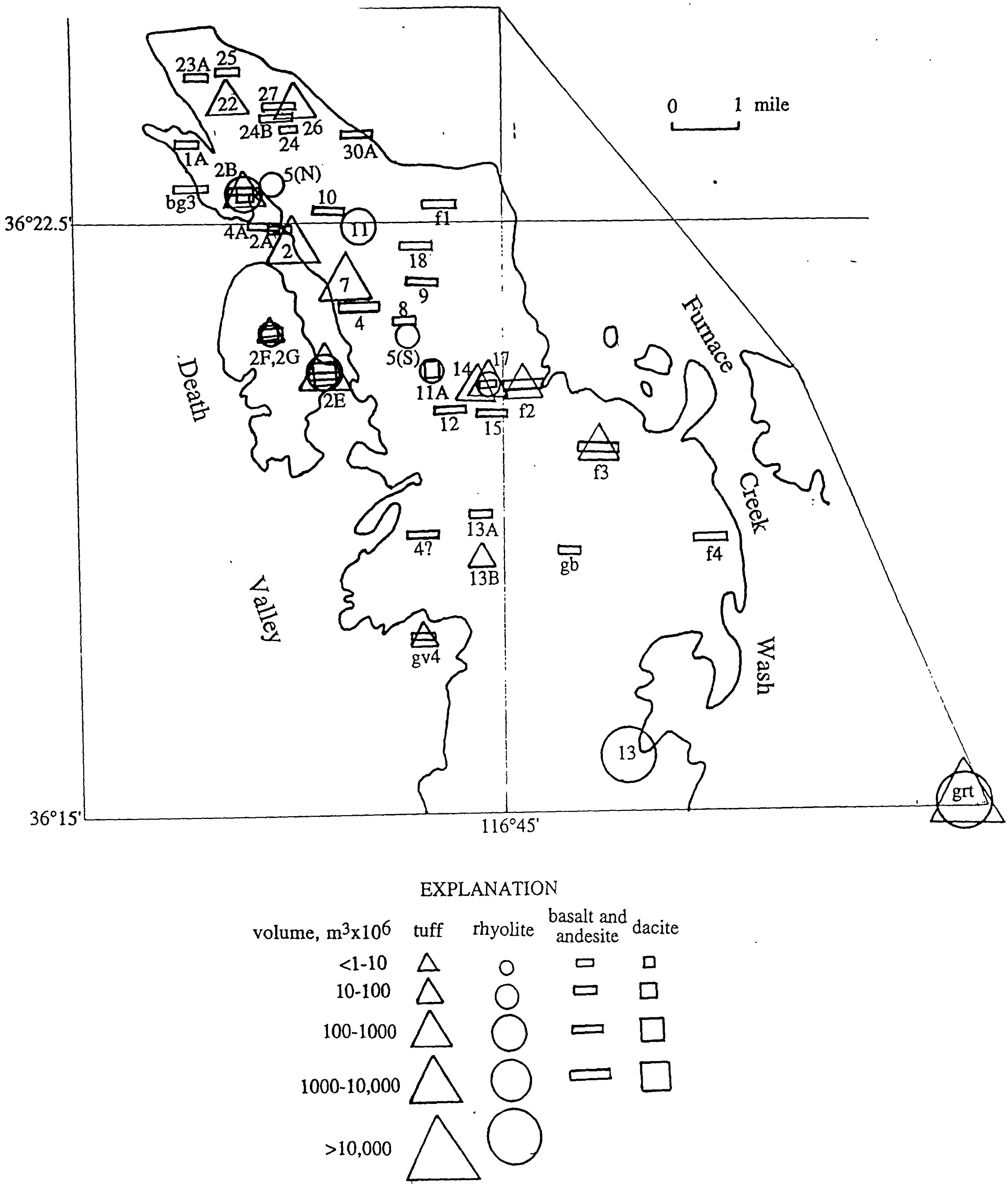

Figure 6. Map showing approximate center of mass and order-of-magnitude volume of volcanic rock units in the northern black Mountains. Unit symbols are simplified from map explanation, plate 2. The order of eruption of these rocks is: Artist Drive units 1A through 30A, Furnace Creek units f1 and f2, Greenwater rhyolite and tuff grt and basalt gb, Furnace Creek units f3 and f4, basalt gravel bg3, and basalt and tuff gv4. The generalized outline of Tertiary rocks appearing on plate 1 is shown for location purposes.

The possibility of a caldera at this locality, although about 12 miles (19 km) west of the center of mass, is suggested.

It is tempting to relate the suggested source localities to faults ancestral to the major range-bounding faults which now offset the units themselves, however, such reasoning may be faulty since the presence of the faults is directly related to the outcrop pattern of the units. However, large volumes of tuff and smaller volumes of other rock types (Artist Drive units 1A, 2A, 2B, 2E, 2F, 2G, 4 and 7) have an apparent source close to the fault separating the Artist Drive block, suggesting a relationship. The validity of this idea is dependent on the assumption that the range is rooted in its present position.

CHEMISTRY OF BLACK MOUNTAINS VOLCANIC ROCKS

Major-element analyses by X-ray spectrographic methods were made for 34 samples of volcanic rocks from the northern Black Mountains. Formations sampled include the lower part of the Artist Drive, the Greenwater, the Furnace Creek, and surficial unit QTbg3 (Funeral Formation of Hunt and Mabey (1966). Analytical results for the standard oxides, recalculated to 100% water-free, appear in table 2, along with the loss on ignition (LOI) at 925°C. In the table, the samples are ordered by increasing SiO_2 content.

Samples chosen for analysis were the freshest in appearance that could be found, however, the volcanic rocks in this area are commonly altered and five of the analyses had to be dismissed from further consideration and were not plotted on the diagrams. Samples with order nos. 12, 13A and 16, contain too little Ca and Na and too much K for their SiO_2 content, suggesting replacement of Ca and Na by K. Samples 14A and 19A had reasonable Ca contents but too little Na, and too much K, suggesting replacement of Na by K. Unfortunately, these deletions meant that the sample from tuff unit Ta7 and all samples from the important rhyolite unit Ta13 could not be plotted. Some tuff samples had such high LOI (mostly water) as to render them suspect; however, these samples had reasonable Ca, Na, and K contents and were plotted.

The names given to the rocks are based on SiO_2 content and are those of Carmichael, Turner, and Verhoogen (1974, p. 557). These names generally correspond well to field identifications. They are: $\%SiO_2<52$, basalt; $52<\%SiO_2<55$, basaltic andesite; $55<\%SiO_2<63$, andesite;

TABLE 2. *Major element contents of analyzed samples of volcanic rocks from the Black Mountains*

Field No.	DV-1153	DV-842	DV-688	DV-229	DV-481	DV-1207	DV-1663	DV-1377
Unit	Tfb4	Tfb4	Tfb3a	Ta4A	Tfb2	Tfb2	Ta4	Ta2F
rock type	basalt	basalt	basalt	basalt	basalt	basalt	ba-andesite	ba-andesite
order	1	1A	2	3	4	5	6	6A
SiO_2	46.08	48.21	48.48	50.14	50.26	50.49	52.95	53.87
Al_2O_3	16.25	15.55	18.64	19.52	18.36	19.00	18.37	17.92
$FetO_3$ [1]	14.19	13.60	10.29	8.49	8.77	8.33	8.83	7.41
MgO	6.39	5.10	5.98	5.46	5.94	5.36	3.44	4.75
CaO	8.10	8.91	9.27	9.58	9.83	9.85	6.36	8.31
Na_2O	3.41	2.97	3.94	3.69	3.37	3.37	5.15	3.90
K_2O	1.81	1.96	1.02	1.03	1.35	1.47	2.31	2.11
TiO_2	2.96	2.47	1.76	1.49	1.48	1.52	1.79	1.19
P_2O_5	.64	1.06	.47	.44	.50	.51	.69	0.40
MnO	.16	0.18	.16	.16	.13	.12	.11	0.12
LOI	2.21	2.24	1.11	2.08	1.71	1.99	2.15	1.74
Le Bass rock name	trachy-basalt	basalt	basalt	basalt	basalt	basalt	basaltic trachy-andesite	basaltic trachy-andesite

1. $FetO_3$ is total iron expressed as Fe_2O_3

Field No.	DV-1835	DV-462	DV-1892	DV-562-2	DV-83-2	DV-1508	DV-1318	DV-2044
Unit	Ta4	Tfb2	Ta2E	QTbg3	QTbg3	Ta10	Ta2B	Ta13
rock type	basaltic andesite	andesite	andesite	andesite	andesite	andesite	andesite (silicic	dacite
order	7	8	8A	9	9A	10	11	12
SiO_2	53.99	55.05	55.09	55.73	56.55	59.51	62.9	66.28
Al_2O_3	16.12	18.01	15.86	17.53	16.62	17.99	17.11	17.32
$FetO_3$	10.61	7.41	8.49	7.91	8.65	5.68	4.71	2.27
MgO	2.98	4.88	6.57	3.67	2.09	2.42	1.16	.50
CaO	6.76	7.6	8.33	7.24	6.00	6.16	4.20	2.12
Na_2O	3.83	3.23	2.95	3.82	4.11	3.92	4.56	2.90
K_2O	2.43	2.25	1.63	2.15	3.24	2.87	4.00	8.00
TiO_2	2.29	1.12	0.84	1.35	1.82	1.06	.95	.43
P_2O_5	.86	.33	0.12	.48	0.78	.34	.30	.15
MnO	.14	.12	0.13	.12	0.13	.07	.12	.04
LOI	1.00	1.05	1.31	.49	0.44	1.50	1.34	2.33
Le Bass rock name	basaltic trachy-andesite	basaltic andesite	basaltic andesite	basaltic trachy-andesite	trachy-andesite	trachy-andesite	trachy-dacite	

TABLE 2. *Major element contents of analyzed samples of volcanic rocks from the Black Mountains*

Field No.	DV-1041	DV-2206	DV-1034	DV-675	DV-1195	DV-1502	DV-500	DV-181
Unit	Tgs	Ta13	Tgr	Ta2E	Tgr	Ta7	Tgv	Ta11
rock type	dacite tuff	dacite	dacite	rhyolite	rhyolite	rhyolite tuff	rhyolite vitro-phere	rhyolite
order	13	13A	14	14A	15	16	17	18
SiO_2	66.84	67.10	67.77	68.15	69.02	69.13	69.31	69.60
Al_2O_3	16.38	15.55	16.42	14.17	16.67	15.07	16.94	17.14
$FetO_3$	3.46	2.93	3.15	3.09	2.49	1.89	2.45	1.89
MgO	1.32	0.44	1.20	0.36	.53	1.01	.78	.30
CaO	3.45	1.83	3.67	3.02	2.65	1.43	2.05	1.29
Na_2O	3.20	1.87	3.29	1.94	3.52	2.18	3.87	3.20
K_2O	4.57	9.58	3.81	8.59	4.51	8.94	4.05	6.09
TiO_2	.55	0.47	.47	0.44	.38	.27	.36	.37
P_2O_5	.19	0.16	.17	0.11	.19	.06	.14	.10
MnO	.04	0.07	.05	0.11	.04	.02	.06	.02
LOI	8.14	1.23	3.20	2.13	1.14	3.53	2.88	.98
Le Bass rock name	trachy-dacite		dacite		rhyolite		rhyolite	

Field No.	DV-498	DV-2002	DV-1331	DV-34	DV-206-2	DV-1979	DV-1862	DV-266
Unit	Tgr	Ta13	Ta2F	Ta2B	Ta2B	Ta11	Ta11	Ta2
rock type	rhyolite	rhyolite	rhyolite	rhyolite	rhyolite	rhyolite	rhyolite	rhyolite tuff
order	19	19A	20	21	22	22A	22B	23
SiO_2	69.84	69.87	70.04	70.10	70.25	70.99	71.01	71.29
Al_2O_3	16.29	14.18	15.52	16.03	15.70	14.60	14.88	13.37
$FetO_3$	2.38	2.05	2.42	2.20	2.16	2.30	2.19	2.09
MgO	.61	0.43	.39	.30	.43	0.34	0.62	1.12
CaO	2.11	1.82	2.23	1.86	2.02	1.85	1.69	3.38
Na_2O	4.10	2.34	4.22	4.13	3.92	3.74	3.92	4.21
K_2O	4.13	8.82	4.61	4.85	5.02	5.63	5.16	4.04
TiO_2	.36	0.35	.42	.38	.37	0.38	0.39	.34
P_2O_5	.13	0.10	.12	.10	.11	0.12	0.11	.12
MnO	.05	0.04	.04	.05	.03	0.04	0.03	.03
LOI	.74	1.65	1.13	.61	1.18	0.66	1.05	5.12
Le Bass rock name	rhyolite		rhyolite	rhyolite	rhyolite	rhyolite	rhyolite	rhyolite

TABLE 2. *Major element contents of analyzed samples of volcanic rocks from the Black Mountains*

Field No.	DV-486	DV-677
Unit	Tgs	Ta2E
rock type	rhyolite tuff	rhyolite vitro-phere
order	24	24A
SiO_2	71.87	75.20
Al_2O_3	15.23	13.61
$FetO_3$	2.16	1.45
MgO	.44	0.31
CaO	1.57	1.05
Na_2O	4.76	4.59
K_2O	3.55	3.46
TiO_2	.32	0.22
P_2O_5	.06	0.06
MnO	.04	0.04
LOI	6.08	4.83
Le Bass rock name	rhyolite	rhyolite

63<%SiO_2<68, dacite, and, %SiO_2>68, rhyolite. Also shown in the table are the names of the IUGS classification (Le Bass and others, 1986). This classification is based on SiO_2 and alkali contents.

A set of Harker diagrams (figs. 7 to 16) plot the major oxides vs SiO_2 content. These diagrams show considerable scatter, not surprising in view of the fact that the samples come from several formations constituting a thick section of volcanic rocks in which units of silicic, intermediate, and mafic composition are interlayered in no particular order.

Rocks from some of the Black Mountains units show special characteristics, such as high K_2O in the samples from Artist Drive unit Ta11 (fig. 7, order nos. 18, 22A and 22B) and high MgO in Furnace Creek unit Tfb2 (fig. 10, nos. 4, 5, and 8) and no. 8A from Artist Drive unit Ta2E; however, these are of doubtful significance. The two samples (1 and 1A) of basalt from Furnace Creek unit Tfb4 are distinctly high in K_2O (fig. 7), high in $FetO_3$ (fig. 11), and, most notably, low in Al_2O_3 (fig. 12), for their SiO_2 contents.

The chemistry of volcanic rock suites is commonly best compared by the plot of Na_2O+K_2O vs SiO_2 (figs . 14 and 16). On fig. 14 the boundary between alkaline and subalkaline fields of Irvine and Barager (1971) and boundaries between alkali, high-alumina, and tholeiite fields of Kuno (1966) are all shown. Also plotted are the trends for a suite from Mt Jefferson in the Cascade Range of Oregon (Greene, 1968) and for some Andes-Cascades averages (Miyashiro, 1974). It is readily seen that most of the rocks fall in Kuno's (1966) alkali field but fewer fall in Irvine and Barager's (1971) alkaline field. All the rocks plotted are richer in alkalis than those of the Mount Jefferson suite or the Andes-Cascades averages. These are, however, from continental margin magmatic arcs. Suites from the Great Basin are commonly higher in alkalis, for example, the Indian Peak volcanic field (Best and others, 1989) and the central Death Valley field, discussed below.

The petrologic affinity of certain units is clearly shown by the Na_2O+K_2O vs SiO_2 diagram (fig. 14); others are borderline or ambiguous. Furnace Creek basalt units Tfb3A and Tfb4 are clearly alkaline, falling well above-left of Irvine and Barager's (1971) line. The Greenwater volcanics all plot close to Kuno's (1966) alkali-high alumina dividing line.

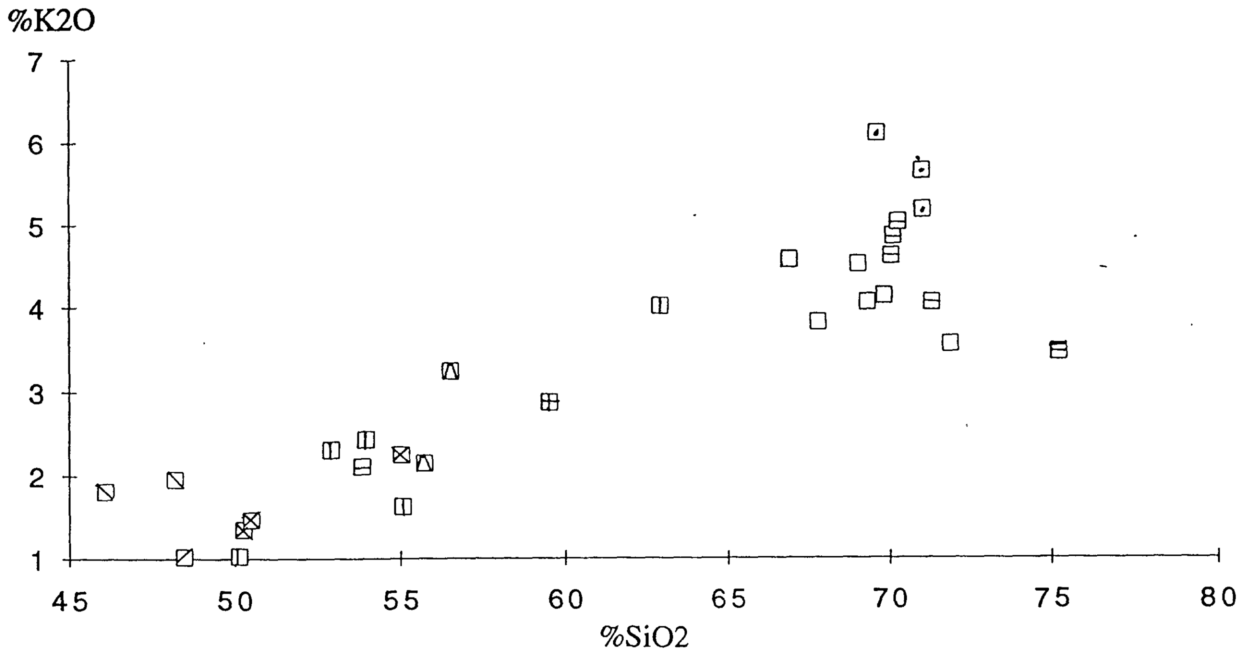

FIGURE 7.-- Harker diagram showing percent SiO2 vs percent K2O for analyzed rocks from the northern Black Mountains.

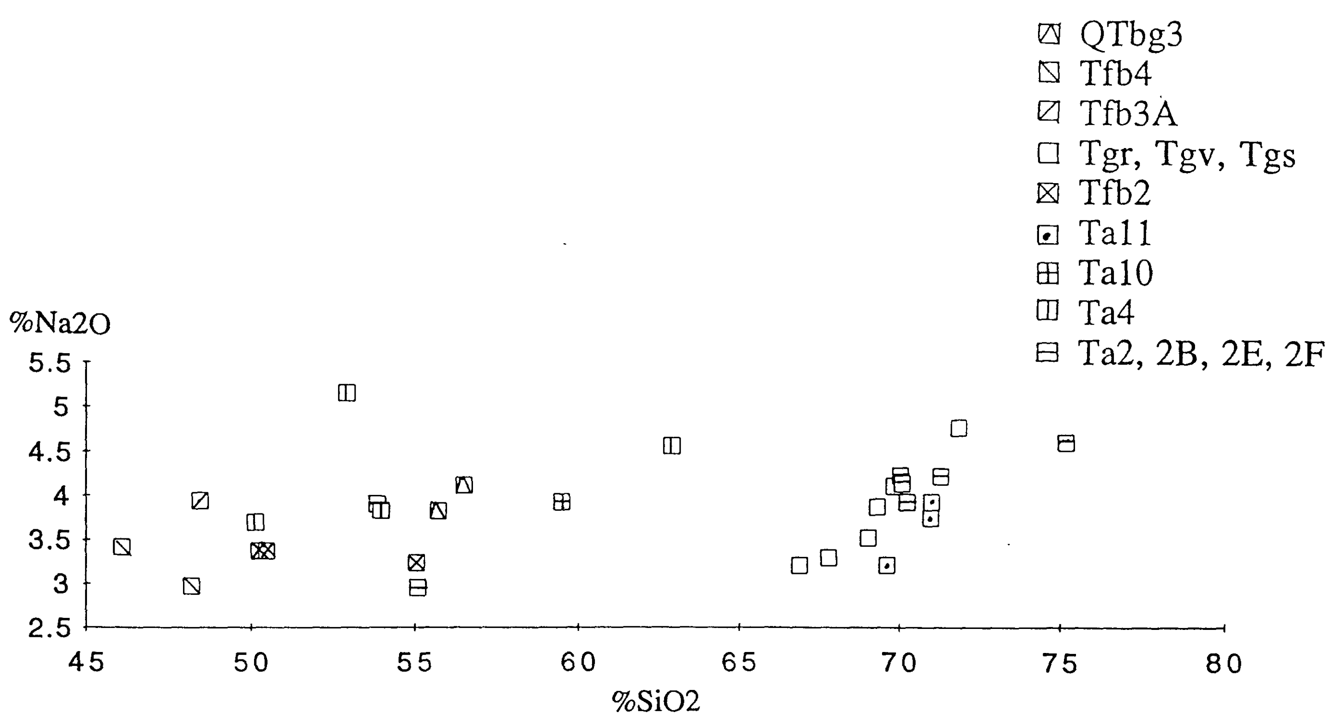

FIGURE 8.-- Harker diagram showing percent SiO2 vs percent Na2O for analyzed rocks from the northern Black Mountains.

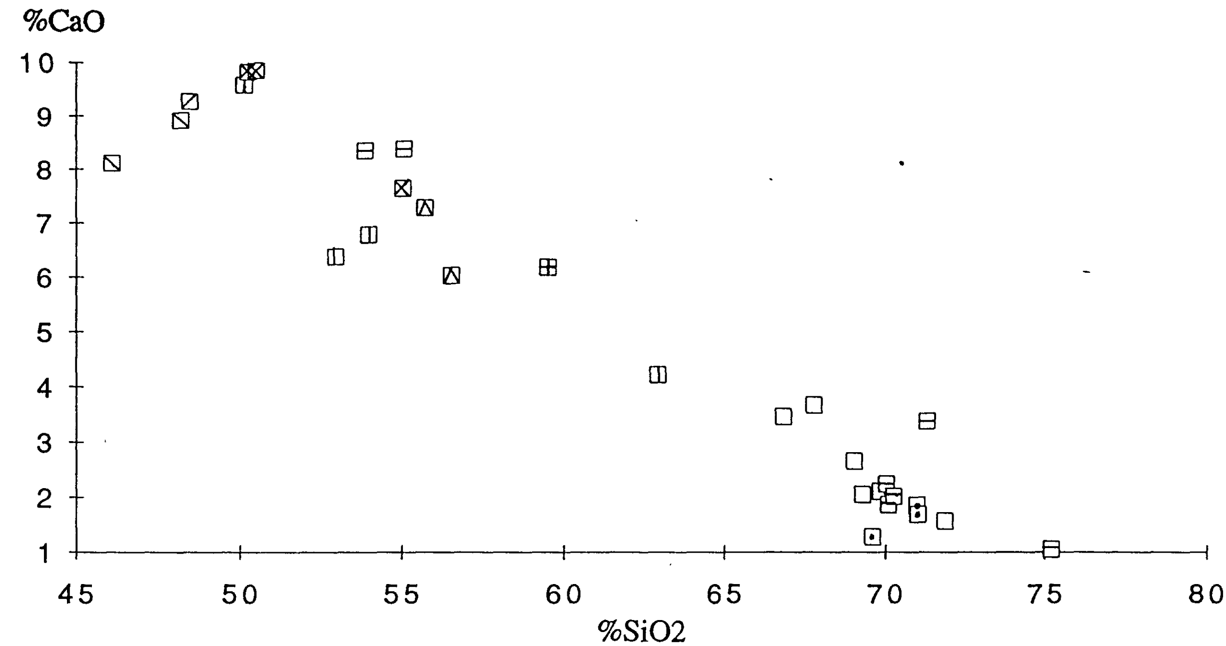

FIGURE 9.-- Harker diagram showing percent SiO2 vs percent CaO for analyzed rocks from the northern Black Mountains.

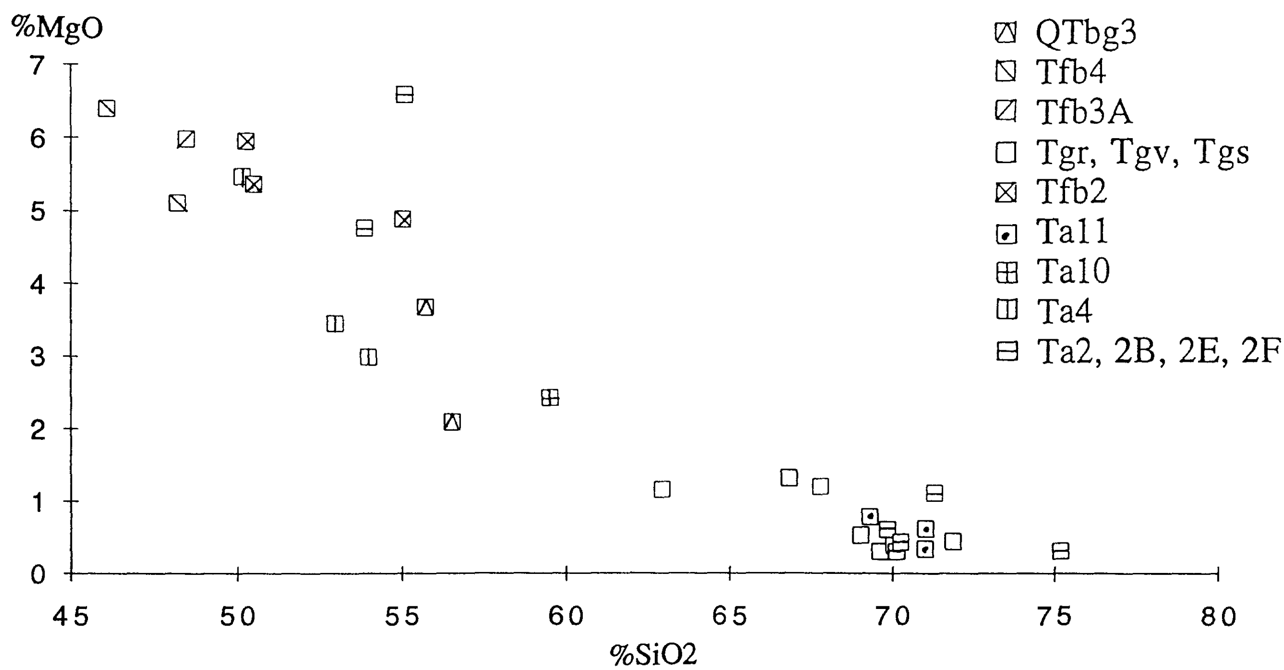

FIGURE 10.-- Harker diagram showing percent SiO2 vs percent MgO for analyzed rocks from the northern Black Mountains.

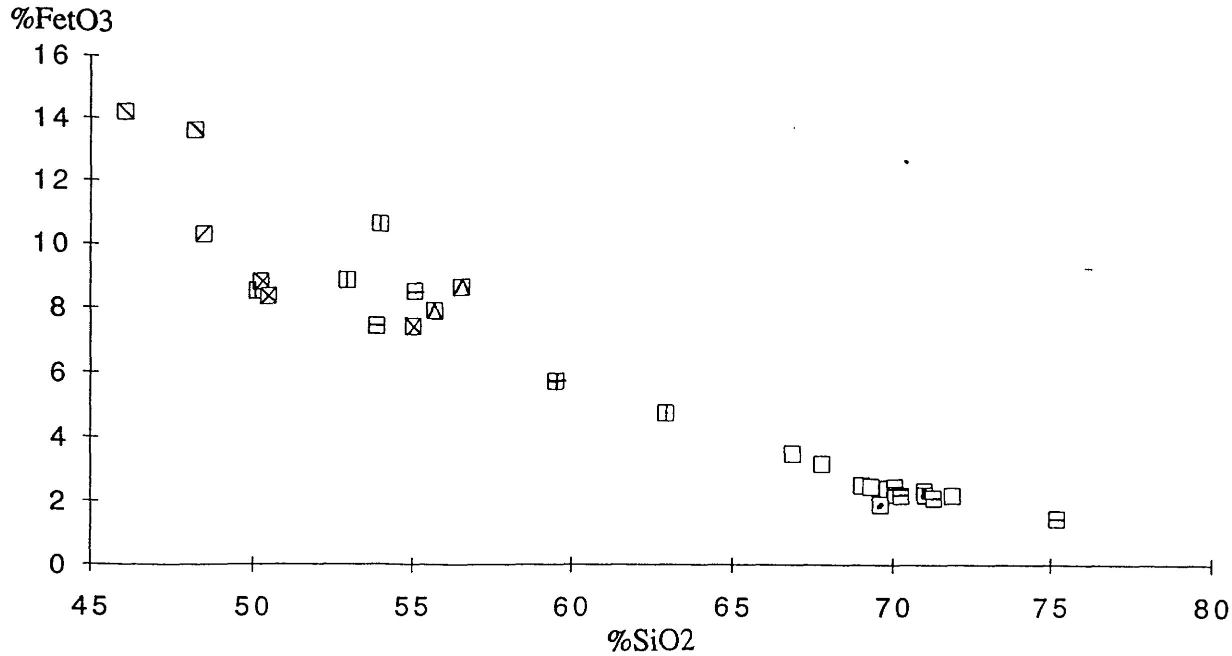

FIGURE 11.-- Harker diagram showing percent SiO2 vs percent FetO3 for analyzed rocks from the northern Black Mountains.

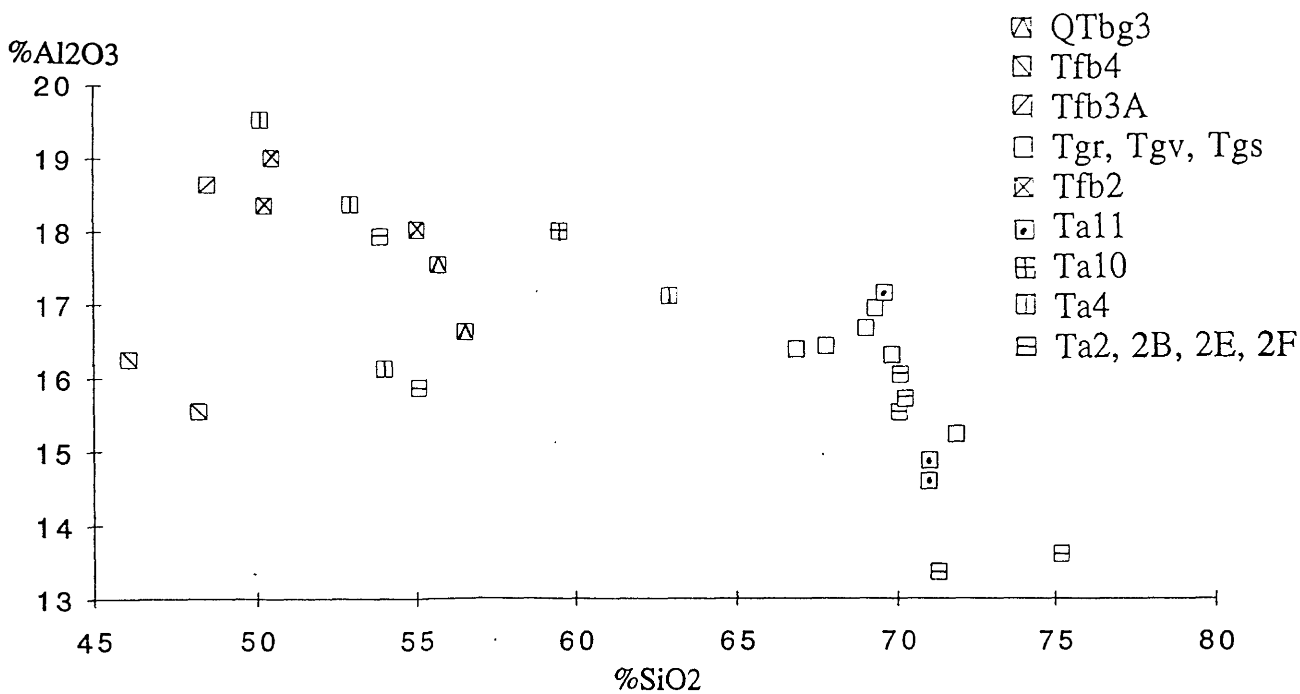

FIGURE 12.-- Harker diagram showing percent SiO2 vs percent Al2O3 for analyzed rocks from the northern Black Mountains.

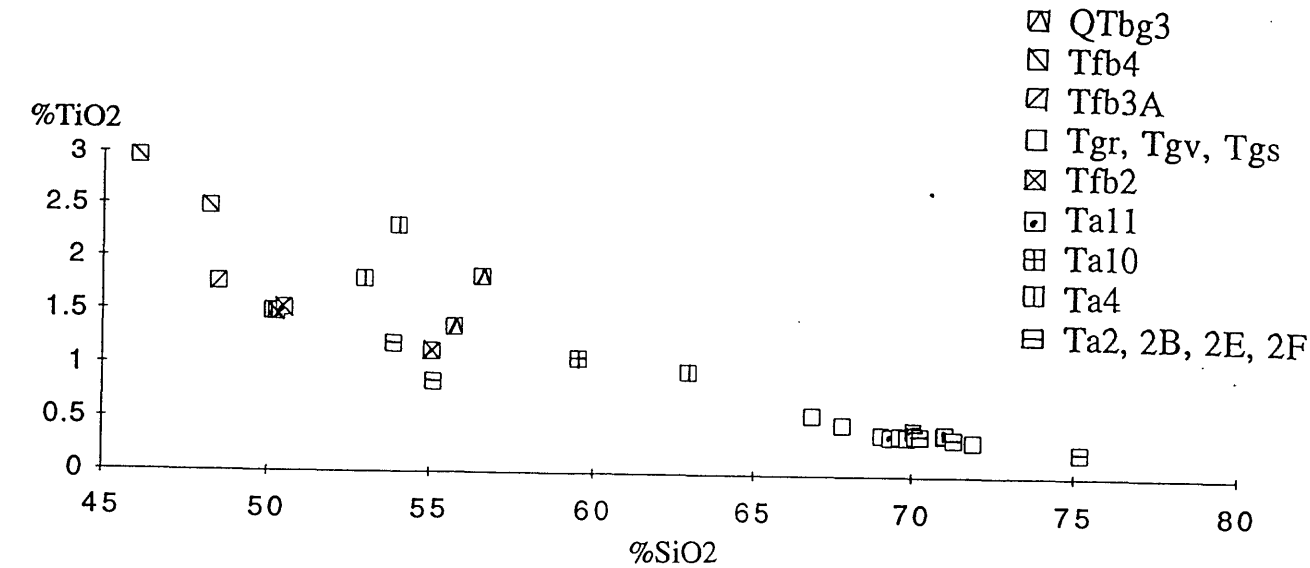

FIGURE 13.-- Harker diagram showing percent SiO2 vs percent TiO2 for analyzed rocks from the northern Black Mountains.

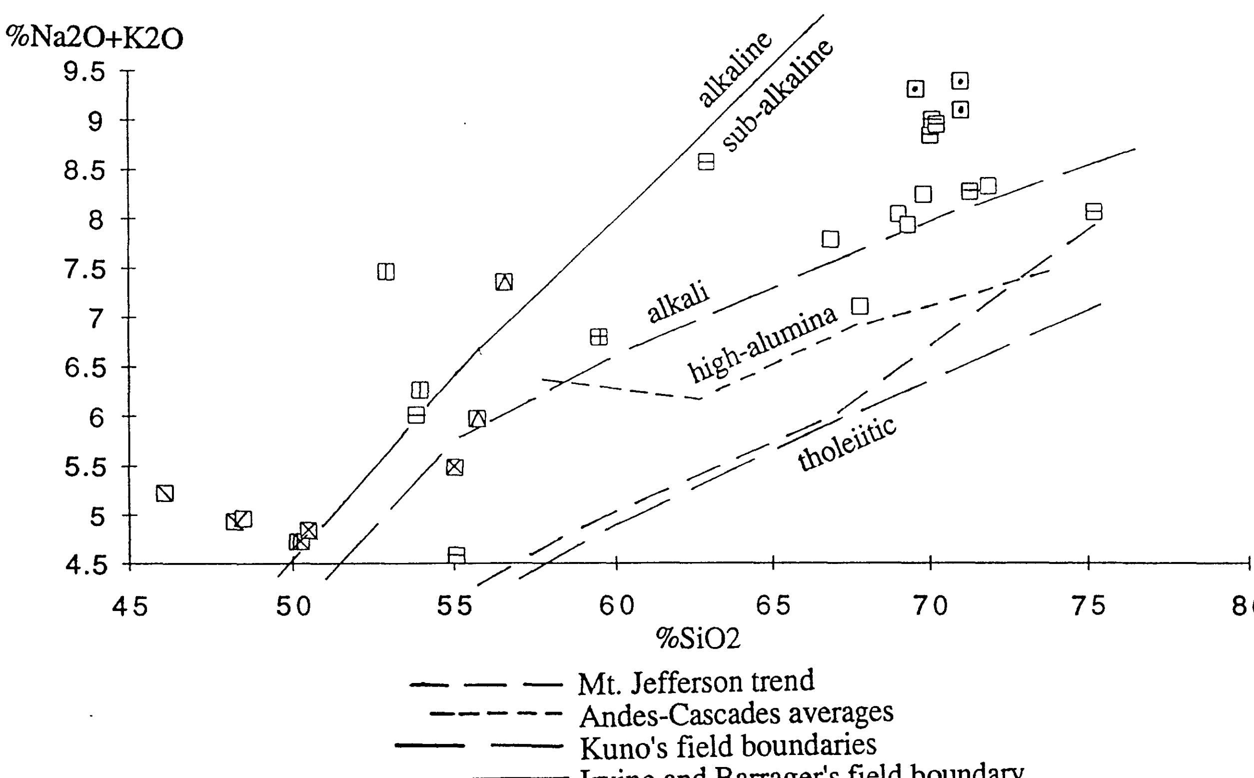

FIGURE 14.-- Harker diagram showing percent SiO2 vs percent Na2O+K2O for analyzed rocks from the northern Black Mountains, with field boundaries after Kuno (1966) and Irvine and Barrager (1971).

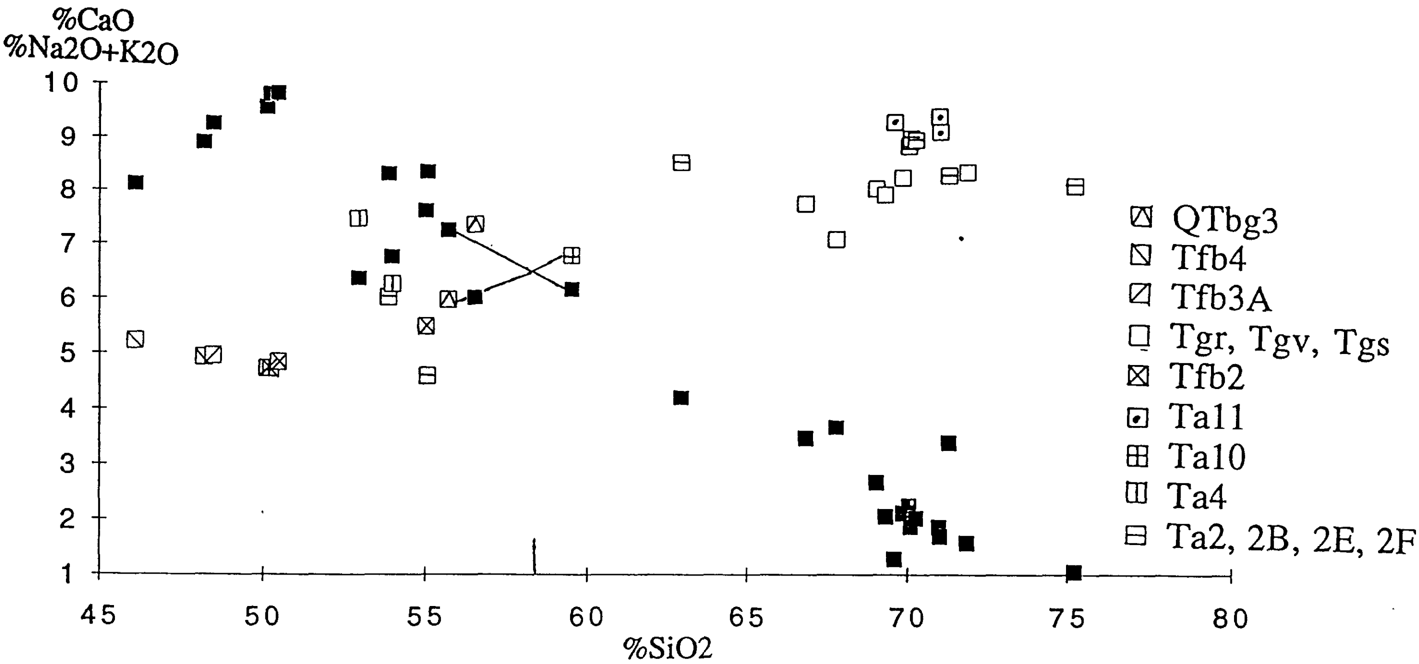

FIGURE 15.-- Harker diagram showing percent SiO2 vs percent Na2O+K2O and vs CaO for analyzed rocks from the northern Black Mountains.

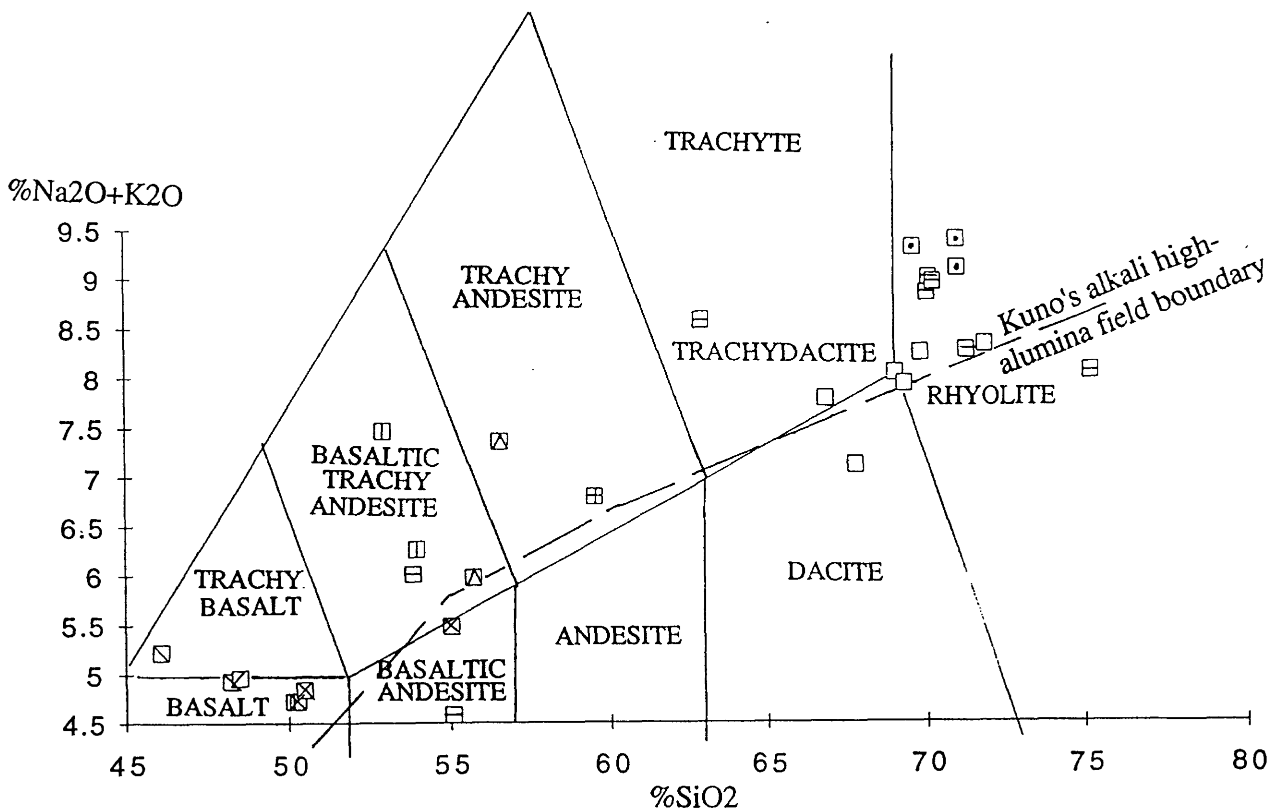

FIGURE 16.-- Harker diagram showing percent SiO2 vs percent Na2O+K2O for analyzed rocks from the northern Black Mountains, with field boundaries for rock names after Le Bass and others (1986) and Kuno's (1966) alkali high-alumina boundary.

A rhyolite tuff (order no. 23) from unit Ta2 low in the Artist Drive Formation is similar to the Greenwater, while three samples (no.s 20, 21, and 22) from lateral variants Ta2A and Ta2F have virtually identical, slightly more alkalic compositions. The range-capping rhyolite unit Ta11 is infinitesimally more alkaline. The basalt from Furnace Creek unit Tfb2 (order nos. 4 and 5) is slightly alkaline, while the basaltic andesite (no. 7) is less so. Basalt and basaltic andesite (nos. 3, 6 and 7) from Artist Drive unit are all apparently alkaline, and a basaltic andesite (no. 8A) alkali-deficient, but, see below.

That some of the scatter in this diagram may be due to alteration is shown by comparing it to the one for CaO vs SiO_2 (fig. 15), which is very close to its mirror image. Samples with order nos. 6 and 9A look suspicious, because they have low CaO content and high alkalis for their SiO_2 content. Conversely, sample no. 8A is low in alkalis and high in CaO. This suggests that these samples are somewhat altered, but not so much so that the analyses should be discarded. If lines are drawn through the values for seemingly unaltered samples nos. 4, 5, 9, and 10, the lines intersect at 58.3, giving a Peacock (1931) alkali-lime index of 58.3 and placing the rocks in Peacocks (1931, p. 64) calc-alkalic suite.

Wright and others (1991, pg.105) plot Harker diagrams for analyzed samples from the central Death Valley volcanic field, which lies adjacent to the area of the present report. Two units which are part of this field, the Greenwater Volcanics and the Funeral Formation, extend into the area of pl.1.. Other units plotted include the older pre-Shoshone and Shoshone Volcanics and the younger valley basalts. Points plotted on Wright and others (1991) diagrams for SiO_2 vs MgO, Fe_2O_3, TiO, Na_2O, and K_2O show scatter over the same fields as those for my plots (figs.10, 11, 13, 8, and 7). Thus the diagrams would merge if combined, indicating the two suites have very similar chemistry and suggesting a similar origin.

Wright and others (1991) plot of the SiO_2 vs Na_2O+K_2O diagram, shows, as expected, points scattered over the same field as in my plot (fig. 14). Dacite and rhyolite from Wright and others (1991) Greenwater Volcanics fall in the same position as mine. Wright and others (1991) point out that rhyolite and dacite from the older Shoshone Formation have noticeably higher alkalis than Greenwater rocks of similar SiO_2 content. Basalts of the Funeral Formation plotted by the same authors fall in the alkaline field of Irvine and Barager (1991) and have similar composition to those of the Furnace Creek units Tfb3A and Tfb4 plotted in fig. 14.

The SiO_2 vs Na_2O+K_2O diagram for northern Black Mountains rocks is also plotted with the rock names of the IUGS classification (LeBass and others, 1986) superposed (fig.16). These names are listed in table 2 but are not further used in this report because they are applicable only to analyzed rocks. It should be noted that a field boundary in this classification lies in virtually the same position as the alkali- high-alumina boundary in Kuno's (1966) diagram, thus all basalts, basaltic andesites, and andesites plotting above this line are trachybasalts, basaltic trachyandesites, and trachyandesites, respectively.

Two additional plots, figs. 17 and 18, illustrate the compositional variations of these rocks. The plot of Mg# (MgOx100/MgO+$FetO_3$) vs SiO_2 (fig. 17) shows much scatter; Mg#s range from 24 to 77 in mafic rocks and from 14 to 38 (one exception) in silicic rocks. Rocks of the Greenwater Formation are generally high in Mg# for their SiO_2 content, suggesting that biotite and hornblende in these rocks are richer in Mg (or that magnetite is sparser) than is commonly the case for rocks of this type.

The triangular FMA diagram (fig. 18) shows a calc-alkaline trend for these rocks, but with substantial scatter including a few points in the tholeiitic field (Irvine and Barager, 1971). Wright and others (1991, pg. 106) also plot an FMA diagram for their samples. As is the case for the for the other diagrams, it is virtually identical to the one for my samples.

The foregoing chemical data do not clearly point to any derivative relationships between the units. Many of them are so local that further detailed study may not be justified, however others are more widespread and deserve further work. Furnace Creek units become more mafic, especially, richer in iron, from Tfb2 to Tfb3A to Tfb4 (figs. 11, 14, 17, 18), suggesting possible derivation from successively deeper crustal levels. The younger unit QTbg3, however, is more silicic. The Greenwater Formation, which lies between Furnace Creek units Tfb2 and Tfb3, shows little chemical relationship to either; however, it extends at least 17 mi farther to the southeast and its eruptive center most likely to lies to the southeast (See above).

Geophysical work with the Consortium for Continental Reflection Profiling (COCORP) reported by Serpa and others (1988) and deVoogd and others (1988) has established the probable presence of a basaltic magma body underlying the central part of Death Valley at a depth of about 15 km. A normal fault inferred to be a magma conduit leads to a 690 Ka old cinder cone, located in the middle of the valley 8 mi. (13 km) south of Mormon Point (fig. 2). This suggests that older basalt, such as that present in the Artist Drive and Furnace Creek Formations, may have been derived from similarly great depths, and that normal faults may have served as conduits. Unfortunately, this data sheds no light on the origin of the silicic rocks.

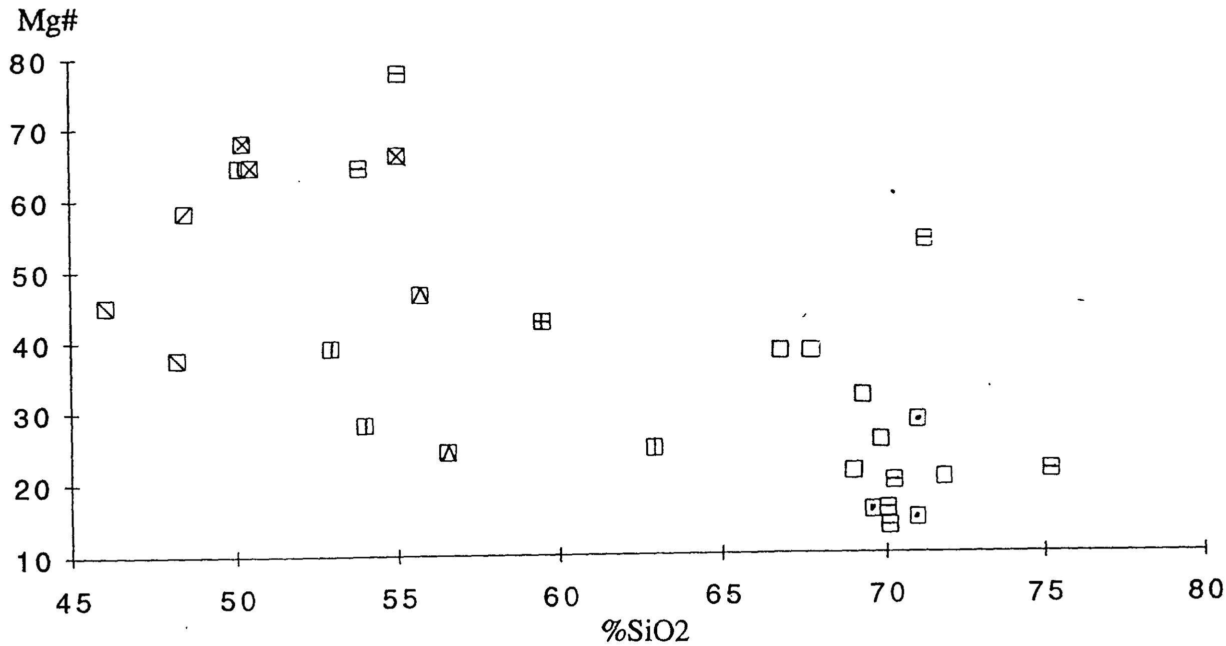

FIGURE 17.-- Diagram showing percent SiO2 vs Mg# for analyzed rocks from the northern Black Mountains. Mg#= percent MgOX100/ percent MgO+FetO3.

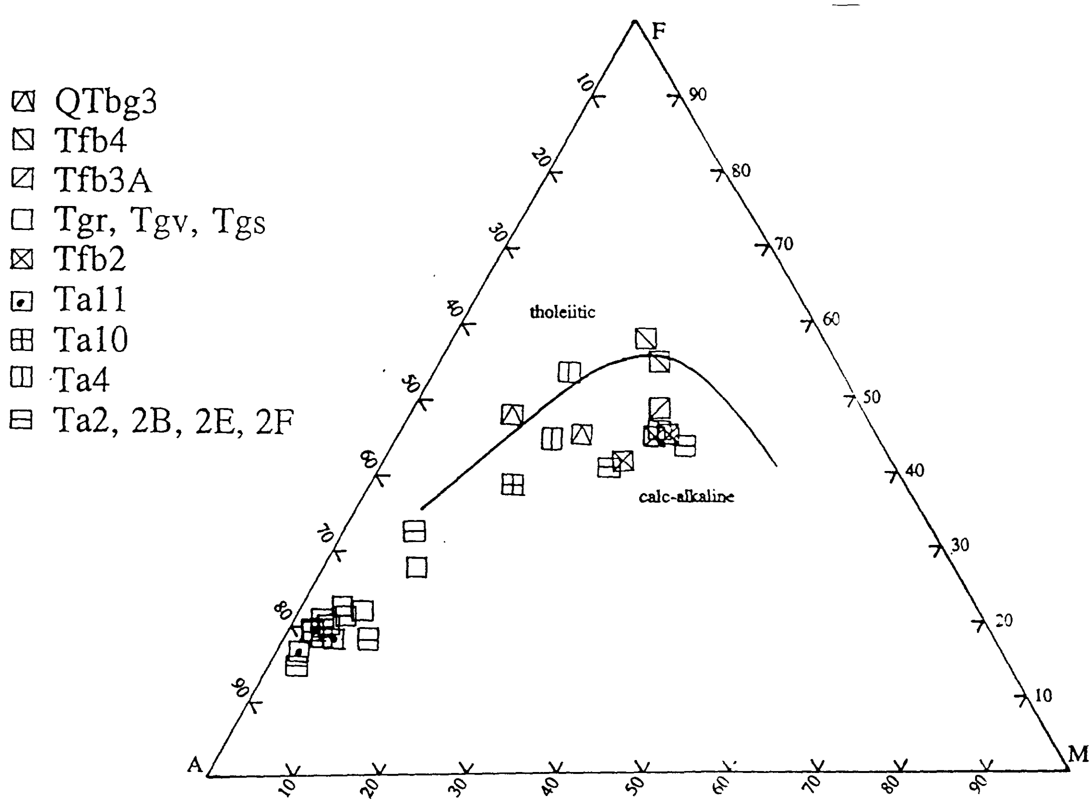

FIGURE 18.-- Triangular FMA diagram, showing field boundary after Irvine and Barrager (1971). F= percent FetO3, M= percent MgO, A= percent Na2O+K2O.

STRUCTURE

INTRODUCTION

Mountain ranges adjacent Death Valley are typical tilted fault-blocks of the Basin and Range province, but contain complex internal structures which have been the subject of much controversy. In particular, in the Black Mountains these structures include 1) detachment faults, 2) the Amargosa chaos, and 3) the turtleback faults.

DETACHMENT FAULTS AND THE AMARGOSA CHAOS

Wright and his associates (Wright and others 1983, 1984, 1987) believe that extensional faulting of substantial magnitude is mostly confined to the Black Mountain structural block, i.e., the Black Mountains and Greenwater Range (figs., 2, 3, 4). In this area are found 1) shallow, listric normal faults, 2) low-angle normal faults that penetrate the basement and 3) late Cenozoic plutons and volcanic bodies (Wright and others 1983). Severe Cenozoic extension in the southern Great Basin has migrated westward. In the Black Mountains and Greenwater Range, volcanic and sedimentary units 8-9 Ma old dip 60°, while basalt 4-5 Ma old (Funeral Formation) is horizontal (Wright and others, 1984). The Amargosa chaos is formed where an upper plate has "collapsed" (moved relatively more to the northwest) above a northwest-moving lower plate (Wright and others, 1987).

Stewart (1983) was the first to introduce the concept that detachment faults of large displacement have affected the entire Death Valley region. He proposed that the Panamint Range structural block has been transported 80 km (50 mi) northwest from a position on top of the Black Mountains block (fig. 19). Principal evidence is the matching of thicknesses of Zabriskie Quartzite (plotted) and other Proterozoic to Mesozoic units in the restored position of the blocks. Movement is bounded on the northeast and south by the Furnace Creek fault zone and the Garlock fault, respectively. The sole of movement was a low-angle detachment fault which is essentially the same as the Amargosa thrust of Noble (1941). This is believed to be a deeply rooted low-angle normal fault. The three principal turtleback surfaces are considered to be part of the detachment fault, as is the Amargosa chaos. By this concept, the Garlock fault is an intracontinental transform involving greater extension

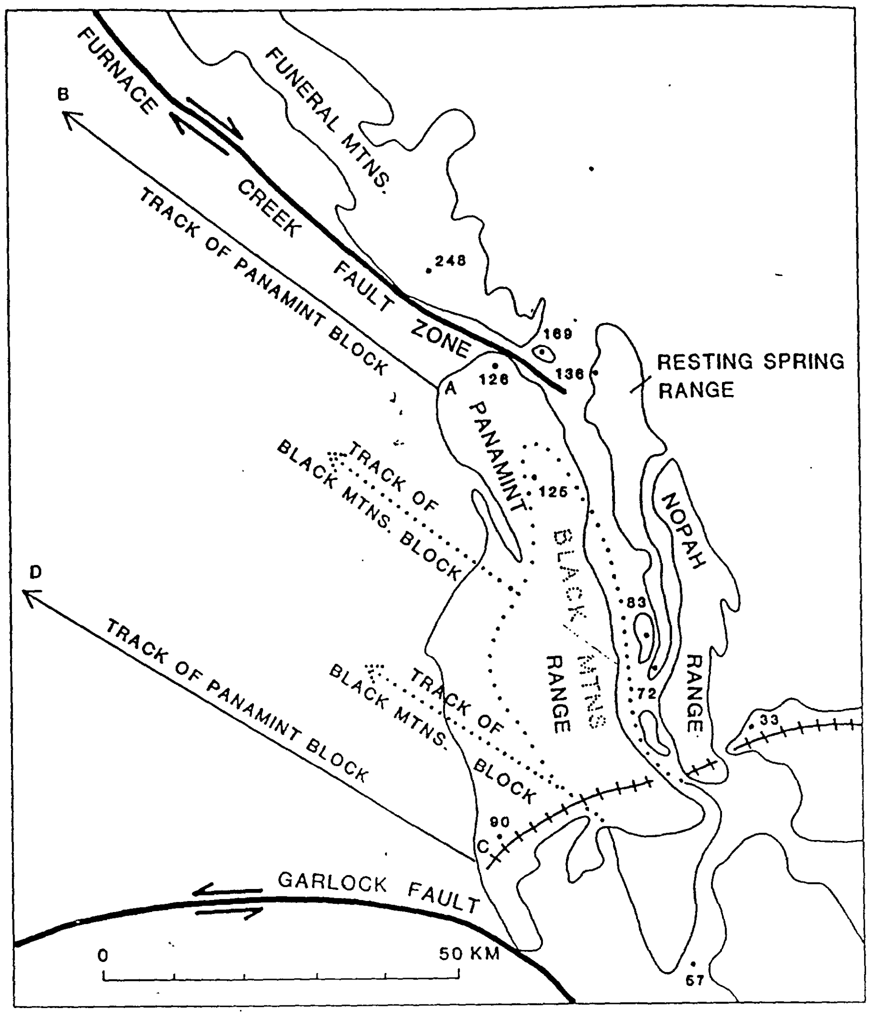

FIGURE 19.-- Reconstruction of Death Valley area prior to detachment faulting, after Stewart, 1983, fig. 3. Dotted pattern indicates pre-faulting position of Black Mountains block below Panamint Range block. B and D indicate present positions of areas that were at A and C, respectively, prior to detachment faulting.

on its north than its south side. Because it and the Furnace Creek fault zone diverge, there must also be extension at right angles to them.

Wernicke and his associates have further refined the concept of large-magnitude extension in the southern Great Basin. Wernicke, Axen, and Snow (1988) match the Panamint thrust on Tucki Mountain with the Chicago Pass thrust in the Nopah Range (fig.1). This fit is confirmed by correlation of structurally higher thrusts in the two ranges, and by the similarity of other geologic features. The restoration requires movement of Tucki Mountain, Death Valley, and adjacent areas 125 +-7 km N65+-7°W. Further extension is required to restore Tucki Mountain relative to the Cottonwood Mountains, and to restore the Cottonwoods relative to the Sierra Nevada. The total extension between the Colorado Plateau and the Sierra Nevada is 247+-56 km N73°+-12°W. Snow and Wernicke (1989) show that the correlation of three Mesozoic structures across the northern Death Valley-Furnace Creek fault zone (fig. 20) gives 68+-4 km N48W+-6° of dextral offset between the Cottonwood and Funeral Mountains, in agreement with previous observations but with more precision.

Hamilton (1988a, b) adds further details to the structural picture in the Death Valley region, consistent with the assumption that large-magnitude extension has occurred. Upper crust fault blocks of rocks of both pre- and syn- extensional strata dip east and the faults separating them dip west; all end downward at detachment faults. He believes that the mountain ranges surrounding Death Valley were stranded atop flattened eastern sectors of detachment faults while slip continued on west-dipping western sectors.

THE TURTLEBACK FAULTS

Miller (1992) examines the structures in the Badwater turtleback, and relates them to the regional geology. The turtleback faults are especially relevant to the question of extension because they separate rocks deformed in mid-crust from those deformed in the upper crust. The structural features of the mylonites in the footwall include stretching lineation, asymmetric folds, boudinage, evidence of ductile flow and zones of melange. He believes brittle faults in the footwall started during ductile deformation and continued under fully brittle conditions. Brittle faults are of two types: decollement style subparallel to mylonitic foliation, and faults which cut foliation at high angles .

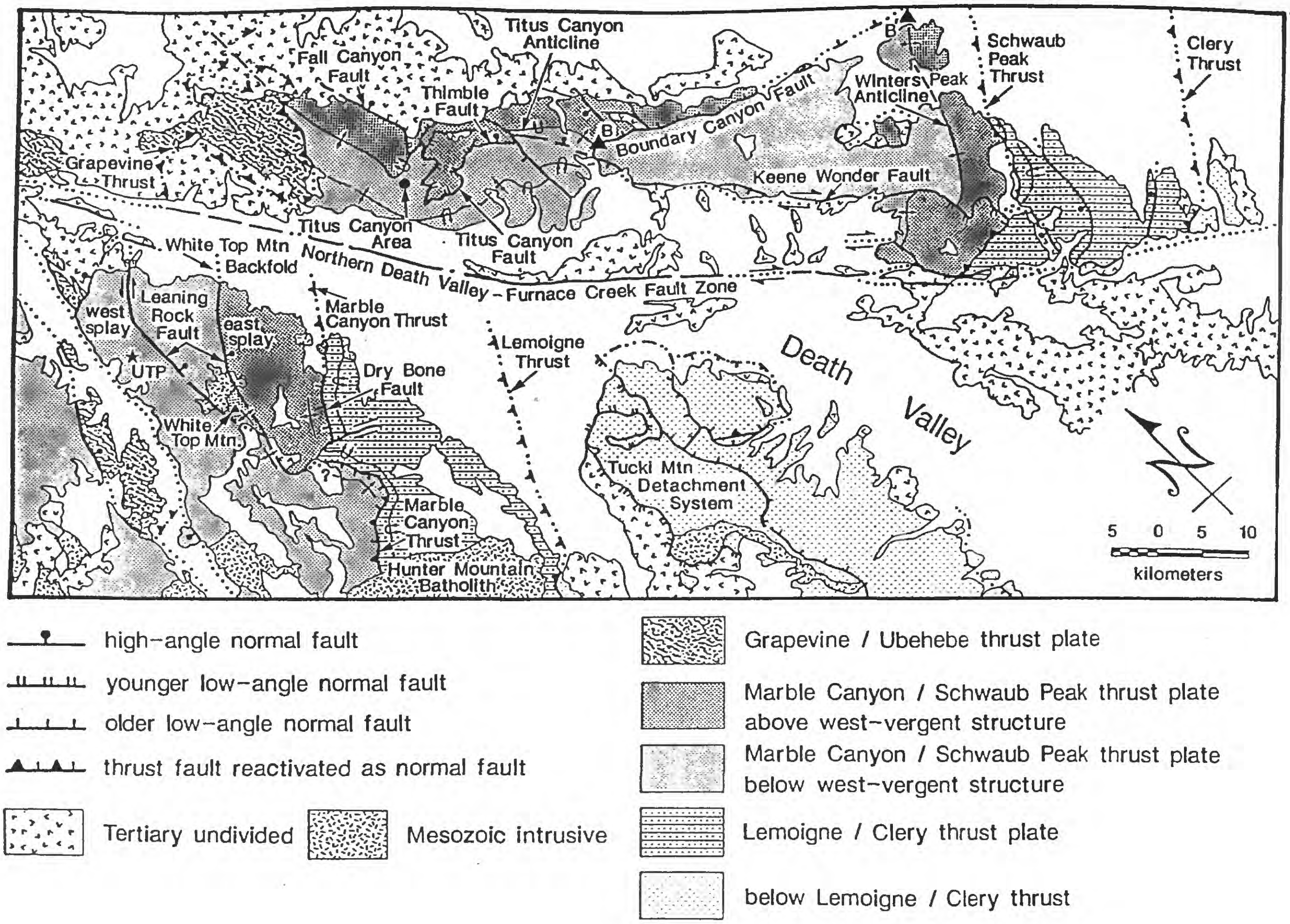

FIGURE 20.-- Interpretive tectonic map of Mesozoic thrust plates in the northern Death Valley area, after Snow and Wernicke, 1989, fig. 2. Northeast of the Northern Death Valley-Furnace Creek Fault Zone structures shown are in, from northwest to southeast, the Grapevine and Funeral Mountains; southwest of the fault zone they are in the Cottonwood Mountains and Tucki Mountain. The Black Mountains and Greenwater Range lie across Death Valley to the southeast, and are shown as Tertiary undivided.

Miller believes that the turtleback fault system consists of three west dipping faults which decrease in age and increase in dip to the west. Fault #1 (oldest) is at east side of the turtleback, #2 is the main fault of the west side, #3 is the frontal fault on the west side; it is only a small segment but displaces alluvium.

In contrast to most interpretations, (Hamilton, 1988, Holm et al 1992), Miller believes that parts of the east and south boundaries of the turtleback are not faults, seeing part of the east edge as depositionally overlain by 6.3 Ma volcanic rocks continuous with those at Dantes View. I disagree, the footwall rocks are overlain by fault breccia composed of rhyolite of the 5.4 Ma Greenwater Formation, making faults #1 and 2 continuous.

Miller describes striations and mesoscopic folds which show oblique slip of the hanging wall to the northwest followed by normal slip to the west, for fault #2.

The shape of the Badwater turtleback is due to the presence of progressively steeper fault segments to the west, and to the Badwater turtleback antiform, which trends N20E, perpendicular to the direction of transport during ductile deformation. Other turtlebacks, according to Miller, also have antiformal axes at N20E., though they are shown with northwest trending axes in other papers, including Wright et al (1991) and Drewes (1963).

STRUCTURE OF THE NORTHERN BLACK MOUNTAINS

The northern Black Mountains comprise the northern one-third of a large fault block tilted to the northeast, a type of structure typical of the basin and range province of the western United States. The Black Mountains fault system separating the range from Death Valley to the west has large down-to-the-west dip-slip displacement and some probable right-lateral strike-slip. Downdropped Holocene alluvial fans and historic seismic activity show the fault system to be active up to the present (Hunt and Mabey, p. A110). The Grandview fault on the northeast side of the range separates it from the Furnace Creek basin and in part from the Greenwater Range. This fault is dominantly right-lateral strike-slip, but has an apparent dip-slip component down to the southwest (pl. 1, McAllister, 1970). Within the Black Mountains are the turtleback faults and the Amargosa chaos. Half of the Badwater turtleback, the northernmost one of three in the Black Mountains, is in the area mapped. Additional faults and folds add complexity to the structure.

The structure of the northern Black Mountains is illustrated by a series of cross-sections (pl. 3, secs AA' to CC' and EE' to II', locations on pl. 1) and one longitudinal section (DD", in the Artist Drive block). The sections are generally extended to basement rocks, but it is to be emphasized that their lower portions are interpretive. Each unit was extended in the subsurface approximately as far as one-half of the strike length, i.e., it is assumed to be a disk with lens-shaped cross-section. This approach is consistent with that used in the section "Volume and source location" in this report.

BLACK MOUNTAINS FAULT SYSTEM

The Black Mountains fault system has two main branches. The westernmost, or principal branch is shown as a dotted line on plate 1. Its position, taken from Hunt and Mabey (1966), is an approximate one, yet it cannot be too far off. Hunt and Mabey (p. A72) state that gravity and magnetic data suggest that the thickness of valley fill opposite Artist Drive is about 4000' (1200 m) and is about 9000' (2700 m) near Bennetts Well, about 15 mi. (25 km) to the south (fig. 2). Some warping of beds may decrease the fault displacement, nevertheless these figures suggest that the displacement on the principal fault branch is about 4000' (1200 m) down-to-the-west in the north part of the map area and increases southward to about 6000' (1800 m, pls. 1, 3).

The other branch of this system, the Artist Drive fault, runs along the base of the scarp separating the main part of the range from the Artist Drive and Natural Bridge blocks (pl. 1). Its position is generally well-established, though it has been locally necessary to connect segments with concealed portions. Locally, there is more than one splay, and segments are offset by cross-faults. This fault has small displacement near its north end, just south of Buff Canyon, where Artist Drive units Ta1 and Ta2 crop out in both the hanging wall and footwall. In the south part of the Artist Drive block, the top of unit Ta2E is at about 800' (244 m) elevation while in the hanging wall to the east it rises to 2300' (700 m). This 1500' (356 m) difference is in part fault displacement and in part tilting of the beds. In the Natural Bridge block, exposures of the Greenwater formation as low as 180' (55 m) below sea level are opposite lowermost Greenwater beds in the hanging wall at 4600' (1402 m), suggesting a displacement of as much as 4800' (1460 m, pls. 1, 3). Thus the Artist Drive and Natural Bridge blocks form a flap on the Death Valley side of the Black Mountains, tilted to the south relative to the main part of the range. The cumulative displacement where the two faults join between Natural Bridge and Badwater appears to be as much as 10,800' (3290 m).

GRANDVIEW FAULT

The right-lateral Grandview fault is shown on plate 1 in the same position as mapped by McAllister (1970) from south of the Boraxo mine to Furnace Creek Wash near the Sigma Mine. To the northeast, it has been extended as a concealed fault much as shown by Cemen and others (1985, fig.8) to join the Cross-valley fault and other faults mapped by McAllister. From the group of "islands" in the alluvial apron near the Boraxo mine southeast through Ryan, the rock package lying on the northeast side of the Grandview fault is distinctly different from that lying on the southwest side. The new radiometric date (See stratigraphy section) indicates that Artist Drive unit Ta1 and Ryan unit Trs1 are not correlative, however, cross-sections EE', FF', and GG' are drawn consistent with either correlation or non-correlation. The Grandview Fault appears to have approximately 3 mi.(5 km.) of right-lateral displacement in this area. Up-throw on the northeast side of the Grandview fault near the Boraxo Mine is indicated whether Trs1 correlates with Ta1 or not. The interpretations shown on sections EE' and FF' suggest 1000-2000' (300-600 m) of dip-slip.

An open syncline, defined by the wraparound of unit Tfb3, lies adjacent the Grandview fault directly west of the Sigma mine. This structure tightens to the southeast and continues at Furnace Creek wash beyond the area shown on plate 1 , where steep, erratic dips have been mapped by McAllister (1970) in fanglomerate of the Funeral Formation (Qg4 of plate 1). I have mapped the uppermost stack of basalt flows in this area as Furnace Creek unit Tfb4, although McAllister (1970) correlated this package with the Funeral Formation on the northwest side of the Grandview fault (See stratigraphy section). In my view, therefore, the Grandview fault has insignificant dip-slip in this area, instead of the substantial amount required by McAllister's correlation.

Northwest of the Boraxo mine, the projected trace of the Grandview fault in the vicinity of Monte Blanco separates similar rocks, all mapped as Furnace Creek unit Tfs1. These rocks also appear on both sides of the fault farther on to the northwest, according to the map of McAllister (1970), thus accommodating lateral displacement with little dip-slip.

TURTLEBACK AND RELATED FAULTS

Three turtleback surfaces with overlying turtleback faults have been mapped in the Black Mountains, and have been the subject of much interest (Curry, 1938, 1954, Noble and Wright, 1954, Drewes, 1963, Hunt and Mabey, 1966, Stewart, 1983, Hamilton, 1988a, Miller, 1992, Holm and others, 1994, and others). The turtleback faults are gently to moderately dipping normal faults, commonly called detachment faults. Parts of the turtleback surfaces are the actual fault surfaces, i.e., exposures of the footwall with the hangingwall striped away.

The north part of the Badwater turtleback, northernmost of the three, is in the mapped area. The structure of the turtleback is described in detail by Miller (1992), who sees evidence of several episodes of ductile and brittle deformation in the footwall rocks. Miller believes that the turtleback fault is discontinuous in the area at the top of the range south of Mt. Perry, so that volcanic rocks overlie footwall plutonic rocks with depositional contact for 1 mile (1.6 km). Part of this distance is on plate 1 and part beyond the south margin on the Dantes View 7.5' quadrangle. I disagree with Miller, having found abundant brecciated rhyolite along this contact (unit Tbr), and see the turtleback fault as a continuous feature. This interpretation is consistent with, but does not prove, large displacement on the turtleback fault. Dip on the turtleback fault is small to moderate and varied in the upper part of the turtleback, but steep, as much as 30°, in the lower part. It merges with the range-bounding fault near Natural Bridge.

I interpret a similar detachment to be present beneath the Black Mountains at least as far north as section HH' (pl.3). Sections GG', FF', and EE' also show the possibility of a detachment at the base of the Tertiary section.

At the north end of the area, there is a low-angle detachment fault exposed in the walls of Buff Canyon. It also steepens and merges with the range bounding fault to the west. Though similar in style to the turtleback faults, this one involves the Tertiary section in the footwall. I have interpreted the detachment to be continuous as far south as section CC'. This raises the intriguing possibility that this detachment is continuous with the turtleback fault.

The strike of bedding shifts from north-south in the area south of Corkscrew Canyon to northwest on the north side, and eventually to east-west north of Buff Canyon. The detachment fault may provide a surface on which the upper units have slid to the west, the displacement being greater to the north so that they wrap around.

There are other low-angle normal faults in the northern Black Mountains. One is spectacularly exposed on the south side of peak el. 4980, 1.2 mi (1.9 km) due south of Spectacle Ridge. Steeply dipping basalt and rhyolite layers of the Greenwater Formation show westerly movement of about 200' (60 m) on a gently tilted fault surface. An enigmatic structure at the principal dryfall in Blind Canyon (too small to show on pl. 1) also appears to be a west-dipping detachment, with Tertiary rocks in both hanging and footwalls.

CROSS FAULTS

Minor faults cutting across the strike are abundant in the mapped area. A family of cross-faults in the central part of the area between Blind Canyon and Monte Blanco have apparent left-lateral displacement, as shown by the offset of Artist Drive unit Ta7 and other units (pl. 1). However, normal fault movement with the north side downdropped produces the same map pattern. Normal, or oblique, movement seems more likely than strike-slip.

A fault at the north edge of unit Ta4 north of Artist Palette belongs to this family, though part of it follows the strike of units Ta4 and Ta6. Good exposures show that much of this fault is vertical. This appears to be a normal fault with the north side downdropped. The pinchout of the basalt of unit Ta4 has become the locus of the northernmost segment of the fault.

Cross-faults on the east side of the range between the pinchout of the Greenwater Formation west of the Boraxo Mine and the limit of Furnace Creek unit Tfb4 near Lemonade Spring also are normal, north-side-down. Three such faults juxtapose Furnace Creek units Tfb3 and Tft3 on the north side against Greenwater Formation on the south side. The southernmost fault in this group is over 2 mi (3.3 km) long and has substantial north-side-down displacement.

To produce the cross-faults and the strike shift noted above, a shear couple striking northwest and with a left-lateral sense must have at one time been operating in the block between the Artist Drive and Grandview faults (fig. 21). Such a couple is consistent with north-south tension resulting in east-west oriented normal faults, and could also produce the wraparound to east-west strike at the north end of the area. It is not consistent, however, with the shear sense of the right-lateral Grandview and other faults of the northern Death Valley-Furnace Creek fault system. The proposed left-lateral couple may be related to the latest movement on the detachment faults.

NORTHERN BLACK MOUNTAINS ANTICLINE

A persistent structure which appears in sections AA' through II' (pl. 3) is the anticline whose axis underlies the escarpment slope. The axis plunges gently to the north as the structure of the range rises to the south. The detachment faults at the Badwater turtleback and at Buff Canyon are also arched by this structure, and the intervening suggested detachments are similarly interpreted. Anticlines in the hanging wall adjacent to major normal faults are found elsewhere in the Basin and Range province and have been attributed to isostatic adjustment following normal faulting, i.e. lower crustal and mantle material flows in under the upthrown side (Wernicke and Axen, 1988). However, the facts that the uplift is long and narrow and has its axis away from the fault casts doubt, in my view, on the applicability of this idea to the northern Black Mountains. I propose, instead, that this is a drag fold, involving a continuum of deformation with the beds being bent downward preceding breaking at the fault.

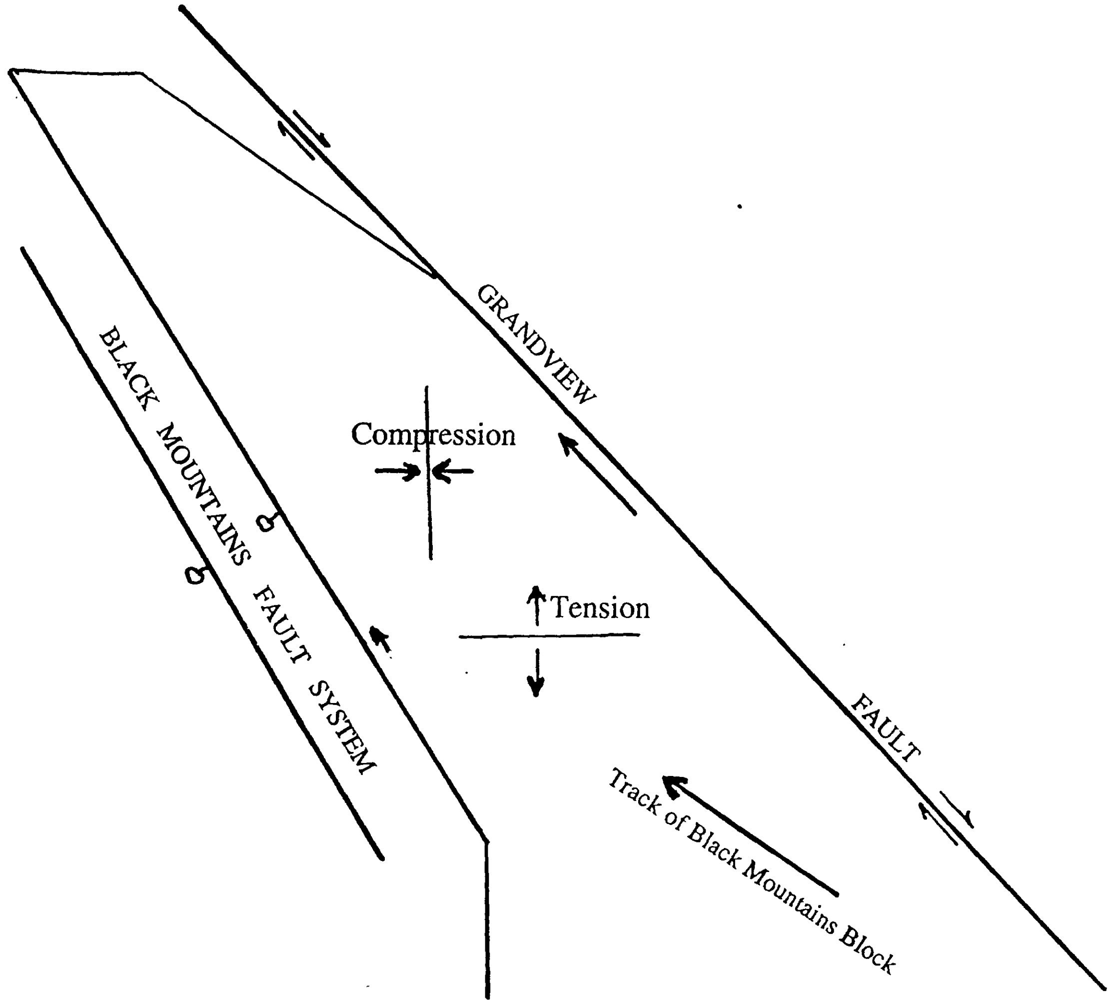

FIGURE 21.-- Schematic diagram showing suggested post-5.0 Ma stress system in the northern Black Mountains. Black Mountains are moving approximately N54°W on one or more detachment faults as suggested by Stewart (1983). Right-lateral Grandview fault bounds block on northeast side. Left-lateral stress set up in block by greater drag on south side, resulting in north-south tension within block and tendency of uppermost plate to wrap around towards east-west strike.

INTERPRETATION

STRUCTURE OF THE NORTHERN BLACK MOUNTAINS

The structure of the northern Black Mountains supports the idea of extension on low-angle normal faults within the block formed by the Black Mountains and Greenwater Range (Cemen and others, 1985; Wright and others, 1991). Evidence is found in the Badwater turtleback fault, the low angle normal fault at Buff Canyon, and other low-angle faults as described above. The faults north of the Badwater turtleback contain Late Tertiary volcanic rocks in both their hanging walls and footwalls. Rocks as young as the Greenwater Formation (5.5 Ma) are involved in the low-angle faulting, as shown at the Badwater turtleback fault. The upper part of the Furnace Creek Formation, probably about 5.0 Ma, is cut by in east-west oriented normal faults, while the overlying Funeral Formation (4.1-4.8 Ma) is not.

These facts indicate that major local deformation, including crustal extension and normal faulting took place after 5.5 Ma. The time to accomplish this deformation is squeezed into a rather short interval if the age suggested above for the topmost Furnace Creek beds (5.0 Ma) and the oldest age for the Funeral Formation (4.8 Ma) are correct. In any case, during this period, a left-lateral shear couple, antithetic to the older right-lateral strike slip movements, appears to have developed in the northern Black Mountains. Movement on the major range-bounding normal faults began earlier and has proceeded intermittently.

LARGE-MAGNITUDE EXTENSION

Evidence for large-magnitude extension is provided by the apparent offset of sections of Proterozoic and Paleozoic rocks and associated structures, and comes from the Panamint, Cottonwood, Funeral and other ranges (Stewart, 1983, Wernicke and others, 1988, Snow and Wernicke, 1989). In the northern Black Mountains, the only supporting evidence is the presence of mid-crustal rocks in the footwall of the Badwater turtleback, suggesting substantial tectonic denudation. There is no evidence for the amount of extension or whether or not the turtleback faults are all part of a single extensional fault.

The presence of the lowermost beds of Artist Drive Formation unit Ta1 in depositional contact on Cambrian Bonanza King Formation in Buff Canyon indicates that the Artist Drive and overlying Late Tertiary formations are locally rooted on Paleozoic and older rocks, even if broken above by low-angle normal faults of moderate displacement. A large pluton in the central Black Mountains, the Willow Springs Diorite (11.6 Ma), is also locally rooted and intrudes footwall rocks (Holm and Wernicke, 1990, Drewes 1963). Holm and Wernicke (1990) believe this batholith crystallized at the same time as the onset of major crustal extension. Voluminous volcanic rocks of the central Death Valley volcanic field are as old as 8.5 Ma (Wright and others, 1991) and also appear to be locally rooted. I have similarly interpreted the volcanic rocks present in the northern Black Mountains (fig. 6).

Therefore, if extensional faulting with accompanying tectonic denudation removed a large section of rocks, such as the entire Panamint Range, as suggested by Stewart (1983), from the roots of what are now the Black Mountains, this event must have happened before the deposition of the lowermost Artist Drive beds (<10 Ma). Unless part of the Willow Springs Diorite is present in a range lying to the west, it too, must be younger than (possibly contemporary with) tectonic removal of an overlying section. The timing of tectonic denudation may also be limited by the age of unit Trs1 at Ryan, 13.7 Ma. The Ryan area, too, is part of the Black Mountains block though north of the Grandview fault. However, the brecciated nature of the contact between the Bonanza King Formation and overlying unit Trs1 suggests a detachment fault, and means that this isolated block is not necessarily locally rooted. This leaves the Willow Spring Diorite at 11.6 Ma as a firmer minimum age for the onset of extensional faulting.

A NORTHERN BLACK MOUNTAINS SEDIMENTARY BASIN

Whether the roots of the Black Mountains were exposed by tectonic denudation or normal erosion, a basin formed on top of Proterozoic and Paleozoic rocks which received epiclastic sediments derived from adjacent outcrops of these formations. The sediments formed Artist Drive unit Ta1. Deposition of voluminous lavas and tuffs followed (units Ta2, 4, 7, 10, etc.), with intervals of epiclastic sedimentation (units Ta6, 8, 19). Only six units (Ta2, 19, 20, 23, 27 and 30) contain conglomerate, clasts in these consist at least in part of limestone and quartzite pebbles derived from Proterozoic and Paleozoic formations. Units Ta2, 19, 23, 27 and 30 also contain clasts of granitic rocks.

The epiclastic rocks of unit Ta1, including limestone and quartzite clasts, could have been derived from the Funeral Mountains, assuming the relative positions of the two ranges to be nearly the same as at present. However, the granitic clasts in overlying units present a problem. Basal conglomerate of unit Ta2 contains angular fragments of limestone, quartzite, and argillite apparently derived from Paleozoic and Proterozoic formations, along with fragments of granitic rocks. Where is the source of the granitic rocks? If they are from the central Black Mountains or southern Greenwater Range, they would have to travel 12 to 25 mi (20 to 42 km) northwest to comingle with clasts of sedimentary rocks traveling 5 to 10 mi (8 to 17 km) southwest from the Funeral Mountains. An age of 10 Ma on granite from the Greenwater Range (Wright and others, 1991) is the oldest reported from the Black Mountains block and limits the oldest part of unit Ta2 to <10 Ma if this scenario is correct. This interpretation does not require large-magnitude extensional translation, nor does it preclude it.

A different scenario would have the retreating Panamint Range be the principal source of sediments. In this case Paleozoic and Proterozoic formations in that range would supply the clasts of sedimentary rocks. A 10.7 Ma granite (Hodges and others, 1990), presumably the granite at Skidoo of Hunt and Mabey (1966), would supply the granitic clasts. In this case, the travel path of the sedimentary clasts would be any short distance to the east and that of the granitic clasts about 8 mi (13 km) farther, if the outcrop pattern in the Panamints were similar to what it is now. This interpretation has an advantage in that a common, nearby, source for the sedimentary and granitic clasts is postulated. However, large-magnitude extensional translation is required to move the Panamints away from the Black Mountains to their present position.

Both granitic and sedimentary clasts also occur in conglomerates in Artist Drive units Ta19, 23, 27, and 30. Essentially the same arguments apply to the matter of designating their source area. However, if the source is the retreating Panamints, that block must necessarily get farther away with the passage of time. The presence of rounder clasts attests to this possibility (See unit descriptions). The ages of these upper units are not known by direct evidence, but if the stratigraphic order which I have shown is correct, then they are all <6.6 Ma, the age of unit Ta13. This is similar to the scheme of Snow and Lux (1996), who propose that slip was completed prior to 5-6 Ma, the apparent age of the Furnace Creek Formation, which directly overlies Ta30. A problem remains in transporting cobbles of both granitic and sedimentary rock from as far away as the Panamints to units as young as Ta27 and Ta30.

Clearly, further work is needed, particularly a detailed study of granitic clasts in the Artist Drive Formation by petrography and chemical or isotopic signature to compare them with possible sources. The enigmatic microdiorite conglomerate must also have a source in a small pluton; possibly a remnant may be discovered. Sedimentologic studies to determine current and source directions for the clastic rocks are also in order.

BORATE DEPOSITS

Borates in the Death Valley region were first extracted from the salt flats in the late 1800's, but the principal deposits are in a belt extending from the East Coleman Hills (near the National Park headquarters) up Furnace Creek Wash and across the Greenwater Range to Amargosa Valley (fig.2). Several hundred prospects and mines are shown on the maps of McAllister (1970, 1973). All are in various units of the Furnace Creek Formation, as subdivided by McAllister. They are principally in the main part of the formation below the gypsiferous member, in the gypsiferous member, and in the altered fragmented basalt unit (Tfs1 and Tfp1 of my usage). In an area near Gower Gulch, deposits are in the lower conglomerate member (Artist Drive unit Ta30 of my usage). Near Ryan and in the Amargosa Valley, deposits are in rocks mapped as or resembling my Furnace Creek units Tfs5 (siltstone and shale) and Tfls5 (nodular limestone). As previously mentioned, however, these rocks may not be younger than Furnace Creek units Tfb4 and Tfs4.

The borates occur as both lenticular bedded deposits and veins (McAllister, 1970, pg. 8). The principal borate minerals are colemanite, $Ca_2B_6O_{11}.5H_2O$, ulexite, $NaCaB_5O_9.8H_2O$, and probertite, $NaCaB_5O_9.5H_2O$. Zoning is well developed in some deposits, with probertite in the core, ulexite next, and colemanite in the outermost zone. Lenticular deposits are as much as 200' (60 m) thick, but mudstone and other rocks are interlayered with the borates. Veins as much as a foot (0.3 m) thick contain combinations of the principal minerals and a number of other Na, Ca, and Mg borate minerals. Minerals found at weathered outcrops and in weathered basaltic debris contain these and yet other borate minerals, some unique to this area. The list of local borate minerals known to McAllister (1970, pg. 9) includes 26 species.

Limited chemical testing for borate minerals was done in the field in the process of geologic mapping. White efflorescent minerals apparently formed by evaporation of ground water leaking from cracks in outcrops were tested. Positive borate anomalies outside the areas of known borate occurrences were found in a few places only, all of them in or near the Artist Drive block (pl. 1). Some were directly adjacent the Artist Drive fault, others farther to the west; none were in Furnace Creek units Tfb3 or Tft3. These anomalies suggest only that ground water circulation in the area has moved some dissolved borate from the Furnace Creek Wash occurrences to the localities of the anomalies.

The borates apparently formed as evaporite deposits in the lake in which the clastic rocks of the Furnace Creek Formation were deposited. Since weathering in the drainage basin is likely to release an insignificant amount of boron, volcanic-related hot springs venting boron-rich solutions from depth are required. I suggest that such solutions are related to the volcanism that produced the abundant rhyolite, vitrophere and tuff of the Greenwater Formation, possibly from the site of a proposed caldera lying directly east of Mt. Perry (see Volume and source location). According to the stratigraphy shown on plate 1, Furnace Creek units Tfs1, Tfb2, and their lateral variants predate the Greenwater, while Tfb3, Tfb4 and their variants postdate it, and Tfs5 and equivalents are of uncertain position. The fact that no borate deposits are found at the Tfb3 and Tfb4 level is consistent with a Greenwater-related source, while the existence of deposits at the Tfs5 level suggests that those rocks may be lateral to Tfs1.

In 1995, the American Borate Company's Billie Mine, 1.5 mi. (2.4 km) north of Ryan, was the only operating borate mine in the Death Valley region. This mine is located just outside the Death Valley National Monument boundary but inside the newly created National Park. Mining, however, has continued. American Borate also leases the Boraxo Mine, a large open-cut 1 mile (1.6 km) west of the Billie Mine. Production had ceased at this mine by 1991 but maintenance work has continued. U.S. Borax Company owns the property at Ryan, including several large mines, now shut down, and the area to the south and east in the Greenwater Range. They also control some property in Corkscrew Canyon, where there is an underground mine with substantial past production. In 1994, U.S. Borax was doing maintenance and cleanup work at Ryan, and exploration drilling in the Greenwater Range.

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APPENDIX 1
PETROGRAPHIC CHARACTERISTICS OF ROCKS FROM NORTHERN BLACK MOUNTAINS

Sample Number	Unit	Rock Type	Variety	Color	Other Characteristics
673-3	PzPt1 (?)	gneiss	diorite	very light gray & brownish black	
911	PzPt1 (?)	gneiss	tonalite	very light gray & dark greenish gray	medium grained
912	PzPt1 (?)	gneiss	tonalite	light gray, fine brown mottle	fine to medium grained
105	Ta1	sandstone	very fine grained	very pale yellowish brown	non-volcanogenic
243-2	Ta1	siltstone		brownish gray	
253	Ta1	limestone		medium dark gray	
1321	Ta1	sandstone & siltstone	non-volcanogenic	pale yellowish brown (sandst), light olive gray (siltst)	cross-bedded set
72	Ta 1A	andesite		medium gray	
106	Ta2	conglomerate	tuffaceous	matrix greenish gray, fragments medium brown	porous, weak
124-3	Ta2	tuff	ash-flow(?)	grayish orange pink	fragments medium gray, red
129	Ta2	conglomerate	tuffaceous	light grayish-grayish green	fragments medium gray, brownish gray
214-1	Ta2	tuff, ash-flow(?)	rhyodacite	yelllowish gray	pumice frag-ments yellow-green, other fragments brown
241	Ta2	conglomerate	tuffaceous	pale yellowish brown	fragments darker browns & grays
242	Ta2	tuff	ash-flow(?)	light brown	fragmants light gray, to 12 mm
261	Ta2	tuff	ash-flow	very light brownish-pinkish gray	mottle light gray
266	Ta2	tuff	ash-flow(?)	greenish- light greenish gray	fragments darker greens and grays, to 8 mm

% Phenocrysts

#	Pla	Bi	Hb	Op	Cl	Ol	Qt	Rks	Phenocryst alteration	Groundmass composition
673-3										plagioclase 95, hornblende 5, opaque 1, apatite tr, calcite
911										plagioclase 75, quartz 20, biotite tr, chlorite 5, apatite tr, calcite
912										plagioclase 70, quartz 20, apatite tr, opaque 5, calcite
105										non-volcanogenic
243-2										non-volcanogenic
253										X
1321										X
72	30				tr	tr			olivine to clays & opaque rims	plagioclase, clinopyroxine, opaque, clays
106										X
124-3	5	m		tr				sed, volc	biotite to hematite	broken shards, murky matrix
129										X
214-1	tr	tr	tr					pum, and, rhyo		sparse broken shards, murky isotropic matrix
241	40	10	10	tr			tr			shard, cryptofelsite
242	tr				tr			and, rhyo		faint shard, patchy coarser replacement
261	10	m		tr	tr				plagioclase saussuritized	cryptofelsite, granular, radial replacement
266	m	tr	tr				tr	dac		murky shards and pumice

537	Ta2	tuff	ash-flow, reworked	grayish pink, reddish veins and streaks	fragments light gray
1266	Ta2	tuff		grayish yellow-green	
1267	Ta2	conglomerate	tuffaceous	grayish green & lighter greens	fragments greenish-gray and brown
1467	Ta2	tuff		light greenish gray	fragments yellowish-green and brown
1429	Ta 2A	basalt	altered	medium dark gray, brownish	altered part medium yellowish brown
34	Ta 2B	rhyolite		grayish red	lighter streak
98	Ta 2B	andesite	silicic	medium gray	lighter mottle
206-2	Ta 2B	dacite		grayish red	
207	Ta 2B	rhyodacite	ash-flow tuff	grayish to pale red	light gray mottle & splotch
212	Ta 2B	basaltic andesite		medium dark gray	amygdules white mineral
1228	Ta 2B	andesite	silicic	brownish gray	
1230	Ta 2B	andesite		dark gray	olive gray mottle
1231 -1	Ta 2B	basalt		medium olive gray	
1296	Ta 2B	rhyolite tuff	ash-flow(?)	pale red	darker and lighter mottle
1302	Ta 2B	dacite(?) breccia		brownish gray, light gray, pale red, moderate orange-pink	
1303 -2	Ta 2B	basalt		brownish gray	lighter mottle
1305	Ta 2B	tuff	ash flow(?)	grayish & pale red	streak & mottle
1318	Ta 2B	andesite		grayish red	
1431	Ta 2B	rhyolite	vessicular	light gray & grayish orange pink	streak & mottle

537	tr	tr					tr	sed, volc		shard, pumice, granular matrix
1226	tr	tr								shard, pumice, cryptofelsite
1267								and, dac, sed		shard, cryptofelsite, calcite
1467	tr	tr	tr		tr		tr	volc, sed		shard, pumice, granular matrix
	Pla	Bi	Hb	Op	Cl	Ol	Qt	Rks		
1429	tr				m			pxite ba	olivine to clays, opaque rims	plagioclase, clinopyroxine, altered glass, clays
34	12			tr	tr			and	clinopyroxine to actinolite and calcite	plagioclase, opaque, calcite, devitrified glass
98	25			1	m	5?			olivine to clays & opaque rim	plagioclase, opaque, altered glass, quartz(?)
206-2	tr									cryptofelsite with plagioclase microlites
207	20			tr	tr			and, rhyo		shard and pum-ice, dark "dust"
212	5					1			olivine to opaque & clay, plagio-clase slight	plagioclase, clinopyroxine, opaque, calcite
1228	10		tr	tr	tr			and	hornblende to clays	cryptomafite, calcite
1230	10		tr	tr	tr	tr			olivine to clays	cryptomafite & glass, clays, calcite
1231 -1	20			tr	tr	tr		ba	olivine to clays	cryptomafite & glass
1296	10			tr	tr			and		pumice & shard, part recrystall-ized, part spherulitic
1302	tr							dac		fine dacite(?) fragments
1303 -2	tr					m			olivine to opaque & clays	plagioclase, clinopyroxine, opaque, clays, calcite
1305	10			tr	tr			and, dac		shard & pumice, part recrystal-ized, part spherulitic
1318	15			tr	m	tr			olivine to opaque	cryptomafite
1431	tr	tr	tr?							cryptofelsite, part recrystal-ized, quartz

326-2	Ta 2E	basalt	altered	brownish to olive gray	
328	Ta 2E	siltstone	volcanogenic,	pale reddish brown	light gray layers
330	Ta 2E	andesite	altered	grayish red	amygdaloidal
347	Ta 2E	dacite		pale red	light gray streak
675	Ta 2E	dacite(?)		pale to grayish red	streaked and mottled
677	Ta 2E	vitrophere	rhyolite	lustrous black	light gray pheno-crysts common
678	Ta 2E	rhyolite		light brownish gray	medium dark gray mottle
1338	Ta 2E	tuff(?)	rhyolite	pale red	
1342	Ta 2E	tuff breccia		grayish yellow green	fragments lighter and darker
1345	Ta 2E	dacite		brownish and light brownish gray	streaked and mottled
1352	Ta 2E	dacite		light brownish gray	darker and lighter streak and mottle
1358	Ta 2E	andesite	altered	medium olive gray	
1364	Ta 2E	vitrophere breccia	dacite(?)	dark gray	light brownish gray streak
1367	Ta 2E	rhyolite(?)		pale red	light gray streak
1423	Ta 2E	andesite		brownish gray	lighter and darker spotting
1566	Ta 2E	dacite		medium grayish red	light gray streak
1592	Ta 2E	dacite(?)		brownish gray	banded pale yellowish brown
1619	Ta 2E	breccia	dacite- andesite	pale red	brownish gray streak, fragments light gray

326-2	tr				tr	tr		ba, rhyo	plagioclase & clinopyroxine to calcite, olivine to clays, opaque	plagioclase, clinopyroxine, opaque, altered glass
328								rhyo		X
330	20				m	tr			plagioclase sauss-uritized, olivine to clays, opaque	plagioclase, clinopyroxine, tachylitic glass
347	m	m						and	slight, to calcite, opaque	cryptofelsite, quartz, calcite
675	1	tr	tr					and	plagioclase to calcite, biotite & hornblende mostly opaque	murky cryptofelsite, lighter bands & patches
677	7	m		tr	tr					glass, perlitic cracks, patchy devitrification
678	5 Kfs m	tr		tr						cryptofelsite, recrystallized; quartz, calcite
1338	tr	tr								cryptofelsite, recrystallized, spherulitic
1342	tr Kfstr							dac, and		cryptofelsite, some shards, recrystallized
1345	tr	tr		tr	tr			ba	biotite to opaque	murky crypto-felsite with plag-ioclase microlites
1352	3	tr		tr					plagioclase to calcite	cryptofelsite, quartz
	Pla	Bi	Hb	Op	Cl	Ol	Qt	Rks		
1358	3			tr	1?			fels	plagioclase sauss-uritized, clino-pyroxine to ox-ides, carbonates	plagioclase, alt-ered glass & dark minerals, opaque
1364	tr	tr		tr	tr					glass, perlitic cracks, streaky devitrification
1367	tr	tr	tr	tr				and	plagioclase to calcite, biotite to opaque	cryptofelsite, recrystallized; quartz, calcite
1423	10		tr	tr	tr	tr			plagioclase, olivine & opaque to clays; quartz	cryptomafite, plagioclase microlites
1566	tr	tr				tr		and	plagioclase to calcite, biotite to opaque, carbon-ate, olivine to opaque, clay	cryptofelsite, quartz, carbonate olivine is in rock fragments and zenocrysts
1592	tr			tr						cryptofelsite, banded & breccia with quartz fill
1619	tr	tr				tr?		fels, and	plagioclase to calcite, olivine to opaque rim, cal-cite, clay center	calcite, ankerite, opaque

1892	Ta 2E	basaltic andesite		dark gray	
62	Ta 2F	rhyolite		light brownish gray	darker streak & mottle, crack texture
334	Ta 2F	dacite		grayish red	faint flow banding
519	Ta 2F	andesite		grayish red	
1329	Ta 2F	basalt		brownish gray	
1331	Ta 2F	dacite		grayish red	lighter flecks
1377	Ta 2F	basalt		medium to dark grayish red	streak and mottle
1477	Ta 2F	basaltic(?) andesite		medium olive gray	lighter & darker spots
1496	Ta 2F	basalt		dark gray	
2637	Ta 2F	basaltic andesite		brownish to olive gray	
1537	Ta 2H	conglomerate	microdiorite	pale yellowish brown	medium gray fragments
1562	Ta2I	rhyolite	aphanitic	light brownish gray	lighter streaking
1604	Ta2I	rhyolite	aphanitic	grayish pink	
81-2	Ta4	andesite	aphyric	medium dark gray	white amygdules, brown speckle
147	Ta4	andesite		olive black	

1892						2		and	olivine to opaque	plagioclase, clinopyroxine, glass, opaque, clays
	Pla	Bi	Hb	Op	Cl	Ol	Qt	Rks		
62	m	tr		tr				and, dac	plagioclase partly resorbed	cryptofelsite, local plagioclase microlites
334						tr?			plagioclase part highly altered, olivine(?) opaque	cryptofelsite & opaque, epidote, quartz
519	15			tr	tr?				plagioclase slight olivine to opaque rim, clay center	plagioclase, glass, opaque, clinopyroxine (?), clays, calcite, zeolites
1329										murky plagioclase, clinopyroxine, olivine, opaque, calcite amygdules
1331	20			tr	tr			and	clinopyroxine to calcite, mica	murky cryptofelsite
1377	20			tr	m	m			plagioclase part saussuritized, olivine to opaque rims, clay center	plagioclase, clinopyroxine, opaque, altered glass, clays
1477	5			tr	m				olivine to clays & calcite	cryptomafite, plagioclase microlites, clays, calcite
1496						tr			olivine to clays	plagioclase, clinopyroxine, opaque, clays
2637	m				tr	tr			plagioclase slight olivine to opaque & clays	plagioclase, clinopyroxine, opaque, olivine, altered glass, clays
1537								dio		
1562	m Kfs tr	tr		tr				tr	plagioclase to calcite, biotite to opaque	cryptofelsite
1604	m	m							biotite to opaque	cryptofelsite
81-2						tr?			olivine to opaque	plagioclase, clinopyroxine, opaque, clays, calcite
147	25			tr	1	tr			plagioclase saussuritized, olivine to opaque & clays	plagioclase, clinopyroxine, opaque, glass

260	Ta4	basalt(?)		brownish gray	
539	Ta4	basalt		dark gray	
546	Ta4	basalt		medium dark gray, brownish	
1663	Ta4	andesite		medium dark gray	abundant light gray phenocrysts
1834	Ta4	andesite		brownish gray	
1835	Ta4	andesite		dark gray, brownish	
55	Ta 4A	basalt		brownish gray	lighter speckle & streak
59	Ta 4A	basalt	aphyric, altered	brownish gray	
96-1	Ta 4A	basaltic andesite	clast in conglomerate	brownish gray	
205	Ta 4A	basalt			
229	Ta 4A	basalt		brownish black	
1298	Ta 4A	basalt		brownish gray	mottled
1314	Ta 4A	andesite		medium grayish brown	
1426	Ta 4A	basalt		brownish gray	
145	Ta 4B	conglomerate	andesite fragments	grayish orange pink	lighter fragments

260	22				tr	tr			plagioclase slight, olivine to opaque & clays	plagioclase, clinopyroxine, tachylitic glass, clays, epidote
539	20				m	tr			plagioclase highly altered	plagioclase, clinopyroxine, olivine, opaque
546	20				tr	tr?			olivine to opaque & clays	plagioclase, clinopyroxine, opaque, altered glass, clays, calcite
1663	25				tr	tr			plagioclase slight, olivine to opaque & clays	plagioclase, opaque, altered tachylitic glass
1834	20			tr	tr				plagioclase slight	plagioclase, clinopyroxine, opaque, glass, clays
1835	tr		tr		tr				hornblende to micas	plagioclase, clinopyroxine, opaque, glass, clays

	Pla	Bi	Hb	Op	Cl	Ol	Qt	Rks		
55	20					5?			olivine to opaque	plagioclase, opaque, altered glass, calcite
59	tr								plagioclase centers altered	plagioclase, opaque, altered glass, calcite
96-1	20					tr			olivine to opaque & clays	plagioclase, clinopyroxine, opaque, altered glass,
205	m					tr			plagioclase slight	plagioclase, clinopyroxine, olivine, opaque, glass
229	10			tr		5			olivine to opaque & clays	plagioclase, clinopyroxine, opaque, clays
1298	1	m							olivine to opaque & clays	plagioclase, clinopyroxine, opaque, glass, calcite
1314	1	tr				m		ba	olivine to opaque & clays	plagioclase, clinopyroxine, olivine(?), opaque
1426									plagioclase slight, olivine to opaque	plagioclase, clinopyroxine, opaque, calcite
145										X

150	Ta 4B	sandstone	fragments	medium gray to light brownish gray	fragments sedimentary, vol-canic, plunonic
768-1	Ta6	sandstone	calcareous	yellowish gray	volcanic and plutonic grains
551	Ta7	ash-flow tuff	breccia	grayish yellow green	fragments to 1 cm, darker & greener
1502	Ta7	tuff		pinkish gray	pumice lumps pale yellow green
184	Ta 10	andesite		medium gray	
201	Ta 10	andesite	breccia	brownish gray-grayish red	angular fragments murky andesite to 3 cm
1508	Ta 10	andesite		dark gray	mottle & blotch olive gray
181	Ta 11	rhyolite		grayish- dark grayish red	darker streak
141	Td	rhyodacite		pale brown	weak flow banding
410	Ta 13	rhyolite		medium dark to medium light gray, brownish	streak & mottle
412	Ta 13	rhyolite		grayish to dark grayish red	streak & mottle
822	Ta 13	rhyolite		pale red	streak & mottle lighter & darker
829	Ta 13	rhyolite		brownish gray	
2044	Ta 13	rhyolite		pale red	streak hematite red
465	Ta 17	tuff	ash flow(?)	pale red	fragments light gray & dark red-dish brown, to 1 cm

150										X
768-1										X
551	tr	tr	tr					rhyo	plagioclase slight	rock fragments, shards, pumice
1502	tr	tr	tr?	tr			tr	siltst		vitric, local shard & pumice, local spherulitic crystalization
184	25			tr	m	1?			olivine to clays	plagioclase, opaque, glass
201	20					1		and		quartz & carbonate
1508	20		m?	tr	m	tr?			olivine to opaque, clays; hornblende to mica, calcite	micromafite with plagioclase microlites
181	m		m					and	plagioclase slight, hornblende to opaque, clays	cryptofelsite granophyric, opaque, quartz veins
141	1		tr?						hornblende(?) to calcite	murky crypto-felsite, plagio-clase microlites
410	10	tr	tr	tr					plagioclase saussuritized, biotite & hornblende to opaque	cryptofelsite, calcite replacement
412	10	tr	1	tr					plagioclase saussuritized, biotite & hornblende to opaque	cryptofelsite, crack texture
822	15 Kfstr	m	tr	tr			5		plagioclase saussuritized, biotite & hornblende to opaque	cryptofelsite
829	10	m	tr	tr					plagioclase saussuritized, biotite & hornblende to opaque	cryptofelsite
2044	20	m		m					plagioclase saussuritized	cryptofelsite
465	15			tr	tr			rhyo, and		shard, matrix near-opaque, clays(?), calcite(?)

474	Ta 17	rhyolite	flow breccia	grayish red & very pale red	
1526	Ta 19	sandstone	coarse, medium & fine layers	grayish- very pale orange	
2573	Ta 26	tuff, rhyolitic	ash flow(?)	grayish pink	brown & gray fragments
462	Tfb2	basaltic andesite		dark gray	yellowish gray mottle
464	Tfb2	basalt		medium dark gray, brownish	
481	Tfb2	basalt		brownish gray	
482	Tfb2	basalt		brownish gray	
645	Tfb2	basalt		dark brownish gray	
1137	Tfb2	basalt	altered	dusky yellowish brown	light gray spots
1207	Tfb2	basalt		brownish gray	
1966	Tfb2	basalt		dark gray	
362	Tgr	vitrophere	rhyolite	medium- med-uim dark gray	
366	Tgr	rhyolite		pale red	
372	Tgr	rhyolite		medium light- light gray	patchy
375	Tgr	rhyolite		brown	faint flow banding
483-2	Tgr	vitrophere	rhyolite	dark gray	
484	Tgr	rhyolite		grayish red, streak & mottle pale red	abundant crystal-lined vessicles

474	m	tr?	tr	tr					hornblende to opaque & clays, biotite altered	fragments of dark cryptofels-ite, quartz
	Pla	Bi	Hb	Op	Cl	Ol	Qt	Rks		
1526										fragments lime-stone, andesite, felsite
2573	2	tr			tr			rhyo, sndst qtzt		rock fragments, shards, pumice
462	15			tr	1 op 1	1			olivine to opaque & clays, ortho-pyroxine to micas	plagioclase, clinopyroxine, glass, opaque
464	5				2	tr		ba	plagioclase slight, olivine to opaque & clays	cryptomafite, nearly opaque, clays
481	tr				tr	tr			plagioclase slight in centers, olivine to opaque	plagioclase, olivine, clinopyroxine, glass, opaque
482	tr				tr	1			plagioclase slight, olivine to opaque & clays	plagioclase, olivine, altered glass, opaque, clinopyroxine(?),
645	1					m			olivine to opaque & clays	plagioclase, olivine, glass, clinopyroxine, opaque, calcite
1137	20			tr	tr	10			plagioclase to calcite, olivine to opaque	plagioclase, tacylitic glass, opaque, clays, calcite
1207	tr				tr	15			olivine to opaque & clays	plagioclase, clinopyroxine, opaque
1966	tr					tr			plagioclase in centers, olivine to clays	plagioclase, clinopyroxine, olivine, altered glass, opaque, clays, zeolite
362	10	1	m	tr				dio		glass, perlitic fracture
366	10	1	1	tr			tr?		biotite & hornblende to opaque	cryptofelsite, patchy light & dark, calcite
372	10	1	1	tr					biotite & hornblende to opaque	glass, incipient devitrification
375	5	tr	m	tr	tr					glass, partial devitrification
483-2	7	1	m	tr						glass, perlitic fracture
484	10	m	tr	tr					biotite & hornblende to opaque rims	cryptofelsite, quartz, calcite

485-3	Tgr	rhyolite		pale red	
498	Tgr	rhyolite		pale brown	vessicular, lighter streak
511	Tgr	rhyolite		grayish red	
621-1	Tgr	rhyolite		grayish red	lighter banding
626-2	Tgr	vitrophere	rhyolite	medium light gray	
738	Tgr	rhyolite		light brownish gray	
772	Tgr	rhyolite		pale red	streaked grayish red
800	Tgr	vitrophere	rhyolite	medium light & light gray	slightly brownish
835	Tgr	rhyolite		light- medium brownish gray	streak and mottle
889	Tgr	rhyolite		pale- grayish red	mottled
909	Tgr	rhyolite	vessicular	grayish red	
916-3	Tgr	rhyolite		light brownish gray	
918-1	Tgr	rhyolite		very pale red	
918-2	Tgr	rhyolite	tuff(?)	pale red	faint grayer banding
928	Tgr	rhyolite		light brownish gray	
1034	Tgr	rhyolite		pale- very pale red	banded
1145	Tgr	vitrophere	rhyolite	medium light gray	mottle pinkish gray
1174	Tgr	vitrophere	rhyodacite	light gray, slightly greenish	
1178	Tgr	rhyolite		light brownish gray	streaks light gray
1185	Tgr	rhyolite		pale red	fragments grayish red

485-3	10	m		tr				cryptofelsite, granular & spherulitic
498	10	m	m	tr				cryptofelsite, granular & spherulitic
511	1	m	tr?	tr		ba		cryptofelsite
621-1	5	tr	m	tr			plagioclase in centers or zones, biotite & horn-blende to opaque	cryptofelsite, banded
626-2	10	m	m	tr		and	biotite & hornblende to opaque	glass, perlitic fracture
738	7	m	tr				biotite & hornblende to opaque	cryptofelsite, patchy replace-ment, vessicular
772	20	5	5	tr			plagioclase to calcite, biotite & hornblende to opaque	cryptofelsite, murky
800	10	m	tr					glass, feldspar microlites, patchy devitrification
835	20	m	tr	tr			plagioclase in zones	cryptofelsite, light & murky
889	10	m		tr			plagioclase to calcite	cryptofelsite, part recrystallized, quartz, calcite
909	10	m		tr				cryptofelsite, murky
916-3	10	m	m	tr			plagioclase sauss-uritized, horn-blende to carbon-ate & opaque	cryptofelsite, recryatallized to granophyric
918-1	m	tr	tr	tr			plagioclase to calcite, horn-blende to carbon-ate & opaque	cryptofelsite, part recrystall-ized, quartz
918-2	5	m	tr	m			plagioclase to calcite, biotite & hornblende to opaque	cryptofelsite, murky, streaked, part recrystallized
928	7	1	tr				plagioclase to calcite, biotite & hornblende to opaque	cryptofelsite, murky, quartz veins
1034	20	1	m	tr				cryptofelsite, plagioclase microlites
1145	10	m	m	tr				glass, partial devitrification
1174	5	tr	m	tr	tr			glass, incipient devirtification
1178	5	tr	m	tr				cryptofelsite, calcite
1185	7	tr	m	tr				cryptofelsite, plagioclase microlites, opaque, clays

1195	Tgr	rhyolite		grayish & pale red	streak & mottle
1210	Tgr	rhyolite		pale red	darker mottle
1576	Tgr	rhyolite		grayish red	lighter streak
754	Tgr	rhyolite	dike	dark moderate red	
431	Tgv	vitrophere	rhyolite	light gray, brownish gray & grayish red	lenticular layering
488	Tgv	vitrophere	rhyolite	medium gray	lighter mottle
500	Tgv	vitrophere	rhyolite	medium light gray	lighter mottle
766	Tgv	vitrophere	rhyolite	pale red	very light gray speckle
1402	Tgv	vitrophere	rhyolite	medium light gray, pinkish gray, yellowish gray	mottled
1662	Tgv	vitrophere	rhyolite	medium gray	
1690	Tgv	rhyolite(?)		banded grayish & pale red	spots light gray
486	Tgs	tuff	ash flow(?)	very pale yellowish brown	darker mottle
756	Tgs	tuff	airfall(?)	mild pink	light & dark fragments
793	Tgs	tuff		very light gray	locally faint yellowish or pinkish
855	Tgs	tuff	pumice	pinkish- light yellowish gray	varied fragments
1041	Tgs	tuff		light greenish-yellowish gray	
1042	Tgs	rhyolite		grayish red	
1087	Tgs	tuff	punky	pinkish gray	spots grayish yellow
492-1	Tgb	basalt		dark gray, slightly brownish	
492-3	Tgb	basalt		brownish gray	

1195	10	m	m	tr						cryptofelsite, streaked, vessicular
1210	3	tr	tr	tr						cryptofelsite, part recrystall-ized, quartz
1576	10	tr	m	tr					plagioclase to calcite	glass, incipient devirtification, part spherulitic
754	15	1	1						biotite & hornblende to opaque	cryptofelsite, murky
431	15	1	1	tr						glass, local devitrification
488	10	m	tr	tr			m			glass, perlitic fracture
500	7	m	m	tr						glass, perlitic fracture
766	5	m	tr	tr						glass, local tubular vessicles
1402	10	m	tr	tr			tr			glass, perlitic fracture, devitri-fied on shears
1662	7	1	tr	tr						glass, perlitic fracture
1690	5	tr?	m	tr						cryptofelsite, part recrystallized
486	5	m	tr?	tr					plagioclase slight, horn-blende to opaque	cryptofelsite, shard, part recrystallized
756	10	1	tr							cryptofelsite, pumice, shard
793	10	m	tr	tr			tr?	fels		rock fragments, shards, pumice
855	m	tr					m	rhyo		rock fragments, pumice
1041	15	m	m	tr						pumice, shard, part recrystallized
1042	tr	tr	tr						hornblende to opaque	dark crypto-felsite, plagio-clase microlites, local spherulitic
1087	10	tr	tr	tr				pum, rhyo		shard, rock fragments
	Pla	Bi	Hb	Op	Cl	Ol	Q	Rks		
492-1	5					m			olivine to opaque & clays	plagioclase, opaque, clino-pyroxine, altered glass
492-3	5					m			olivine to opaque & clays	plagioclase, opaque, clino-pyroxine, altered glass, calcite

2354 -2	Tfb3	basalt		brownish gray	white speckle
617	Tft3	gritstone	volcanogenic	grayish orange pink	
503	Tfb3 A	basalt		dark gray	sparse white amygdules
527	Tfb3 A	basaltic andesite		brownish gray	light gray streak & mottle
685	Tfb3 A	basaltic(?) andesite		brownish black	
688	Tfb3 A	basalt		dark gray	
1572	Tfb3 A	basaltic(?) andesite		brownish gray	
1584	Tfb3 A	basalt	altered	medium dark gray, slightly brownish	
1935	Tfb3 A	basalt		medium dark gray, slightly brownish	light & dark spots
689	Tft3A	sandstone	tuffaceous	pinkish gray	darker fragments
842	Tfb4	basalt		dark gray	
1153	Tfb4	basalt		dark gray, slightly brownish	
562-2	QT bg3	basaltic andesite		dark gray	
770	QT bg3	andesite		medium dark gray	
407	Qgv4	rhyolite		light brownish gray & medium light gray	streak & mottle
408	Qgv4	gritstone	volcanic arenite	brownish to light brownish gray	

2354-2	35					2			olivine to opaque	plagioclase, altered glass, opaque, calcite
617										X
503	5					tr			olivine to opaque	plagioclase, opaque, clino-pyroxine, altered glass
527	10			tr	5	5			plagioclase slight, olivine to opaque & clays	plagioclase, opaque, clino-pyroxine, altered glass, clays
685	7				3	1			olivine to clays	plagioclase, clinopyroxine, glass; amygdules clays & zeolite(?)
688	5					1			olivine to opaque & clays	plagioclase, opaque, clino-pyroxine
1572				tr	tr	m				plagioclase, opaque, clino-pyroxine, tachy-litic glass, clays
1584	tr					tr			olivine to opaque	plagioclase, opaque, clino-pyroxine, tachy-litic glass, calcite
1935	20	tr	m						plagioclase to calcite, biotite & hornblende to opaque	plagioclase, opaque, altered glass, amygdules calcite & clays
689										X
842				tr	tr	tr			olivine to trans-lucent brown	plagioclase, clinopyroxine, olivine, opaque, calcite
1153						m			olivine to murky or opaque	plagioclase microlites, murky dark minerals
562-2	25				5	tr			plagioclase in centers or zones	glass, plagioclase, clinopyroxine
770	40				1	1				plagioclase, clinopyroxine, opaque
407	10	m	tr	tr			tr	and	plagioclase saussuritized, biotite and horn-blende to opaque	cryptofelsite, quartz, calcite
408										X

422	Qgv4	gritstone & conglomerate	tuffaceous	grayish pink	brown & gray fragments
425	Qgv4	rhyolite	breccia, flow or tuff	brownish gray	lighter mottle
1720	Qgv4	tuff	rhyolite	light to very light brownish gray	streak and mottle hematite red

422					X
425	1	tr?	dac, rhyo	plagioclase slight, hornblende to opaque, clays	rock fragments, cryptofelsite, locally spherulitic
1720	2			plagioclase part saussuritized	cryptofelsite, quartz, hematite

Footnotes: 1. Mineral names are abreviated in the headings of the % Phenocrysts column. Abreviations are as follows: Pla = plagioclase, Bi = biotite, Hb = hornblende, Op = opaque minerals, Cl = clinopyroxine, Ol = olivine, Qt = quartz, Rks = rock fragments. Other phenocrysts which are locally inserted in the table include Kfs = K-feldspar.

2. In the % Phenocrysts columns, m= present in minor amount, generally 0.1 to 1%, tr= present in trace amount, generally <0.1%.

3. Mineral names are generally spelled out in the Phenocryst alteration and Groundmass composition columns, however rock names are abreviated in the column where rock fragments are identified. Abbreviations are as follows: rhyo = rhyolite, dac = dacite, and = andesite, ba = basalt, fels = felsite, pum = pumice, volc = volcanic, dio = diorite, pxite = pyroxenite, sed = sedimentary, sndst = sandstone, siltst = siltstone, qtzt = quartzite. Calcite is generally a secondary mineral.

4. The colors of most rocks are given names from the Rock Color Chart (Geological Society of America, 1948). This chart systemizes colors according to the Munsell system, utilizing hue, value, and chroma to assign each color a specific number-letter designation and a name. The assignment of names is generally systematic but has some flaws, particularly in rocks of low chroma, i.e. slightly tinted grays, where the modifiers "light" and "dark" are unevenly applied. Reference to the rock color chart will aid the reader in visualizing these rocks.

5. A X in the last column indicates no entry for that rock in 2nd page columns.

APPENDIX 2
A NEW ^{40}AR/^{39}AR AGE DETERMINATION, BY ROBERT J. FLECK

AGE OF THE SAMPLE

A sample of greenish-gray ash-flow tuff (DV- 3898) was collected from near the base of Artist Drive Formation unit Ta2 near the north end of the Artist Drive block.

Biotite was separated from sample DV-3898 and analyzed by $^{40}Ar/^{39}Ar$ laser fusion in groups of 6 to 12 grains. The sample is a biotite-bearing pyroclastic rock with angular, biotite-bearing clasts. These clasts exhibit little or no transport and may represent accidental fragments from an explosive eruption. Alternately, these clasts might have been entrained in an ash-flow that traversed a steep, immature volcanic surface. Apparent ages of the biotites range from 9.8 to 8.3 Ma with a reasonably tight grouping at 9.54 ± 0.16 Ma. Younger ages are scattered, suggesting a mixture of ages, with the youngest of these (about 8.4 ± 0.4 Ma) representing a maximum age for the unit. The older grouping of ages may approach the age of underlying units, but cannot be interpreted with any confidence. We suggest, however, that this part of the Artist Drive sequence is younger than about 9.5 Ma and, perhaps, younger than 8.4 Ma. Ages of more reliable, uncontaminated samples will be necessary to obtain a more precise determination.

ANALYTICAL TECHNIQUES

The $^{40}Ar/^{39}Ar$ dating technique was first utilized by Merrihue and Turner (1966) as a means of improving the precision of conventional K-Ar age dating by permitting simultaneous measurement of both the radioactive parent (^{40}K) and its decay product (^{40}Ar). York and others (1981) utilized a continuous laser as a fusion device to date extremely small amounts of material. This approach, laser-fusion $^{40}Ar/^{39}Ar$ dating, has evolved to dating of single or small numbers of mineral grains to detect and overcome the effects of xenocrystic contamination (LoBello and others, 1987; Dalrymple and Duffield, 1988; Fleck and Carr, 1990). $^{40}Ar/^{39}Ar$ results reported here suggest significant contamination by older material. The laser-fusion techniques used in this study follow procedures described by Dalrymple and Duffield (1988), Dalrymple (1989), and Fleck and Carr (1990). Samples used in $^{40}Ar/^{39}Ar$ dating were irradiated in the U.S. Geological Survey TRIGA Reactor Facility in Denver, Colorado. An intralaboratory standard sanidine, 85G003, (Taylor Creek Rhyolite, 27.92 Ma) was used for calculation of the neutron flux. The age of this monitor mineral is as reported by Duffield and Dalrymple (1990), standardized to an average age of 513.9 Ma measured in the Menlo Park laboratory for interlaboratory standard hornblende, MMhb1 (Samson and Alexander, 1987) and our intralaboratory standard biotite, SB-3. Decay and abundance constants for all ages reported are those recommended by Steiger and Jager (1977).