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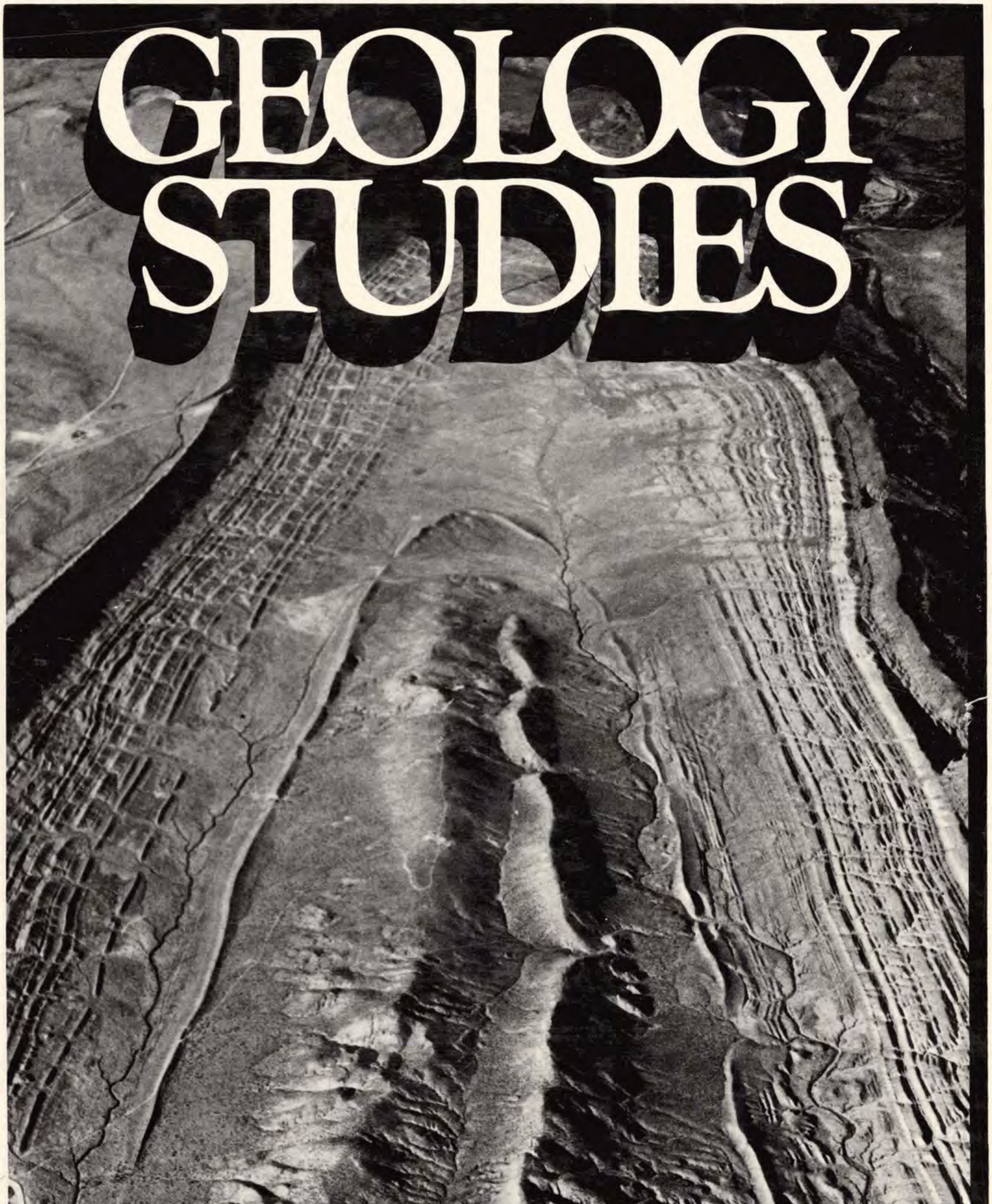

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THE GLORY OF GOD IS INTELLIGENCE

Cover: Virgin anticline near St. George, Washington County, Utah.

Late Cenozoic Volcanic and Tectonic Activity along the Eastern Margin of the Great Basin, in the Proximity of Cove Fort, Utah*

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ABSTRACT.—Extensive recurrent normal faulting and basaltic to intermediate volcanism have occurred in the Cove Fort area, southwest central Utah, for the past one million years and provide important insight into the late Cenozoic dynamics of the region. Volcanic fields cover an area of nearly 518 square kilometers within the Cove Fort graben, which lies along the eastern physiographic margin of the Great Basin. The basaltic flows which range from olivine tholeiites through basaltic andesites, and andesites to latites, have been cut by nearly 300 normal faults. Structurally, the Cove Fort region may be interpreted as a system of small-scale horsts and grabens within the main Cove Fort graben, which appears to reflect the structural pattern of the Great Basin in general.

Within the Cove Fort area, the lava flows have partially preserved the structural features at the surface, thus providing a unique opportunity to observe the dynamics and evolution of a graben. Although throughout the major portion of the Cove Fort area the primary stresses are extensional and form nearly uniform east-west trajectories, several areas show a conjugate shear pattern which indicates some degree of wrench faulting caused by deflections of the primary stresses around the Mineral Mountains granitic intrusive body. Along the E-W primary stress trajectories within the central portion of the Cove Fort area, there have been approximately 7.5 meters per kilometer of horizontal extension within the past one million years.

A microseismic survey of the region indicates that the Cove Fort area is active, but the locus of greatest seismicity does not coincide with the area of most conspicuous faulting within the past million years.

INTRODUCTION

Late Cenozoic deformation within the Great Basin has traditionally been described as normal faulting resulting in the formation of tilted fault blocks and horst-graben structures (Gilbert 1874, Gilluly 1928, Russell 1928, Stewart 1971). Most geologic work within the Great Basin Province has concentrated in the ranges where the rocks and their deformation are well exposed, and many details of fault patterns have been mapped. The structure of the basins in contrast is often considered to be relatively simple, consisting of down-faulted grabens or tilted blocks which have been covered by sediment. Very little is known about the internal deformation within the basins.

In the majority of the grabens within the Great Basin, the structure is not evident because fault scarps produced by recurrent movement in the alluvium of the basins are quickly eroded or buried, leaving little or no trace of even relatively recent deformation. However, in several grabens within the Great Basin where there are young basaltic lava fields, the lavas resistant to erosion have preserved the surface expression of the structural features within the grabens, especially those produced during late Cenozoic time. The Cove Fort and the Black Rock Desert grabens are two basins that have been partially covered by basaltic lavas which have subsequently been cut by many normal faults (fig. 1). Extensional deformation in this area is thus expressed as prominent well-preserved north-south trending normal fault scarps which cut the basaltic lava flows. The Cove Fort area thus provides excellent detail concerning the structural features of a graben within the Great Basin.

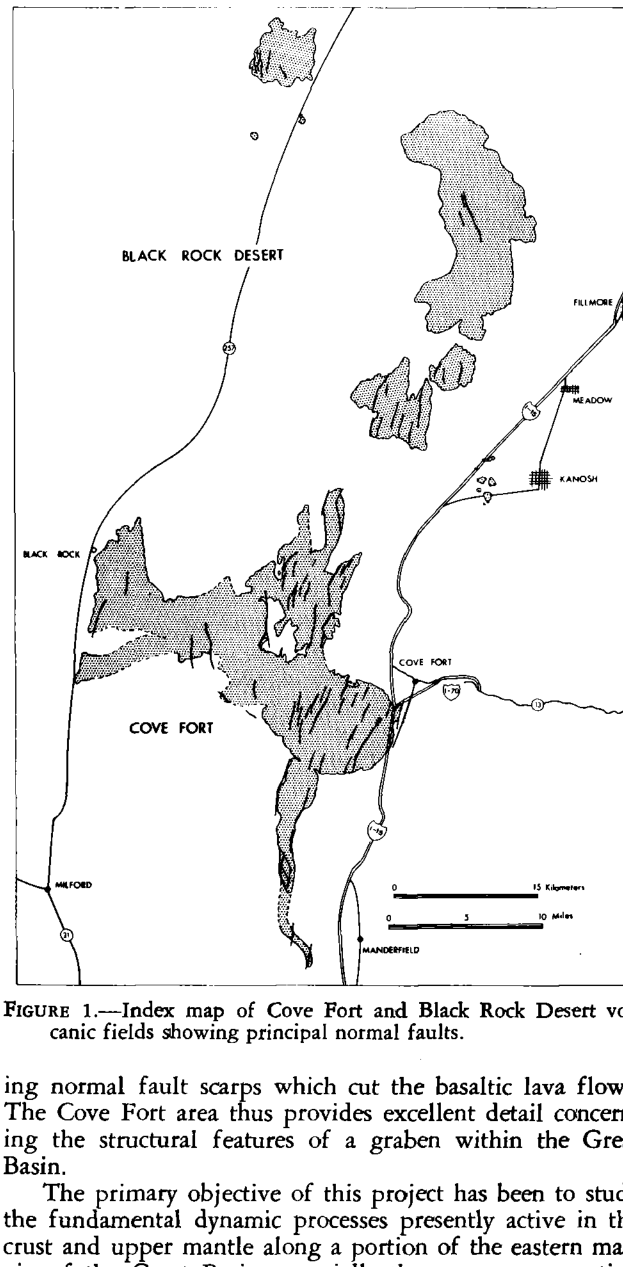

FIGURE 1.—Index map of Cove Fort and Black Rock Desert volcanic fields showing principal normal faults.

The primary objective of this project has been to study the fundamental dynamic processes presently active in the crust and upper mantle along a portion of the eastern margin of the Great Basin, especially the processes operating in the basins marginal to the Colorado Plateau. Clearly, the dynamics of the upper mantle in this region are expressed by the active normal faulting and seismicity and the recent basaltic to intermediate volcanism. The struc-

*A thesis presented to the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree Master of Science, April 1976: W. Kenneth Hamblin, thesis chairman.

tural, physiographic, stratigraphic, and volcanic features of this margin are thus surface manifestations of fundamental dynamic processes.

Study of the recent faulting within the Cove Fort and Black Rock Desert grabens may produce an analysis of the stress distribution and a model of the resultant strain rates and geometry. This model may then be compared to other areas along the western margin and central portions of the Great Basin. A petrographic and petrochemical inventory of the basaltic lavas is made for comparison with other young volcanic fields in and around the margins of the Basin and Range in an effort to better understand the origin of the magmas and their bearing on mantle dynamics.

Previous Work

The general structural setting and the presence of recent volcanic activity along the eastern portion of the Great Basin have been reported by a number of workers. Gilbert (1874) recognized that the north-south trending ranges within the Basin and Range Province are a result of block faulting. Although Gilluly (1928) and Mackin (1960) attribute these structures to tilting of faultblocks and Russell (1928), Thompson (1959), and Cook (1969) describe them as horst and graben structures, Stewart (1971) convincingly demonstrates the existence of both structural types. The recent seismicity of the eastern margin of the Great Basin has been examined by Cook (1969), Sbar et al. (1972), and Smith and Sbar (1974), who interpret the seismic zone along this margin as a boundary between subplates of the North American plate. Best et al. (1966), Condie and Barsky (1972), Lowder (1973), Best and Brimhall (1974), and Hoover (1974) have provided petrographic descriptions and petrochemical analyses of several of the late Cenozoic volcanic fields along the southwestern margin of the Colorado Plateau and the adjacent Basin and Range Province which indicate a relatively large amount of basaltic volcanism during Cenozoic time. Best and Brimhall (1974) and Hamblin and Best (1975) infer that the inception of this volcanism is encroaching upon the Colorado Plateau in a northeast direction.

Although there has been a great deal of work done along the eastern portion of the Great Basin in general, the Cove Fort area has not been studied in detail, and the previous work is limited to either descriptions of a portion of the area or a brief mention of the existence of recent basaltic fields. Gilbert (1890) very accurately described the young volcanic fields in the Black Rock Desert north of the Cove Fort area. He mentioned the volcanic rocks in the northern Cove Fort area but made no attempt to describe or interpret their significance.

In a regional study of the gypsum deposits of Utah, Boutwell (1904) described the Quaternary gypsum sands unit along Cove Creek in the central portion of the area. It was not in the scope of this work to include a description of the deformation and volcanism, but the description of the gypsum beds and their environment of deposition is significant in the study of the evolution of this physiographic margin. In their theses on the geology of the central and northern Mineral Range, Earll (1957) and Liese (1957) mapped contacts with, and mentioned the existence of, the basaltic rocks of the adjacent Cove Fort graben although they made no attempt to extend their studies into the graben. The first attempt at a detailed study of the volcanic rocks in this area was made by Hoover (1974), who confined his efforts to the Black Rock Desert volcanic field. Although he emphasized the petrographic and petrochemical relationships of the basaltic lavas, he also gave an accurate description of the extensional deformation. The significance of this work in respect to the Cove Fort area is that both adjoining grabens that lie along the eastern margin of the Great Basin are partially covered with basaltic lava flows and are highly deformed by extensional faults.

Zimmerman (1961) appears to have been the first to work specifically with a portion of the Cove Fort area and to describe it. His thesis concentrates on the east-central portion of the area with emphasis on the Paleozoic and Cenozoic stratigraphy, but he mapped a portion of the basaltic lava flows, and he gave a general petrographic description of the basaltic rocks. Condie and Barsky (1972) presented a petrographic and petrochemical description of four samples taken along the main east-west road through the north central portion of the area, and from the samples, they extrapolated a general description of the entire Cove Fort area.

Methods of Study

A detailed map of the basaltic lava flows and their subsequent deformation was prepared after several months of field study and from evaluation of high- and low-altitude aerial photographs. These data were compiled on 1:62,500-scale Fairchild aerial photomosaics, and a final map was produced using the photomosaics as a base. The margins of the major subdivided volcanic fields within the Cove Fort area, as well as the major recognizable flow units, are included on the map.

The relative ages of individual flow units and of major fields were mapped using a partially modified system of classifying basaltic flows according to their stages of geomorphic evolution (Hamblin 1963, 1970). This system is based upon three main criteria: (1) the relationship of the flow to the present drainage system, (2) the condition of the margins and surface of the flow, (3) and the amount of tectonic deformation, if any, that has affected the flow. Recent scarps produced by extensional faulting are easily identified in the field and on the high- and low-altitude aerial photographs. Care was taken to map only recent fault scarps cutting either the basaltic lava flows, the alluvium, or the surrounding rocks. Since the oldest basaltic flows within the area are no older than one million years, the faults show deformation that is a representation of at least the minimum strain for the past one million years.

An analysis of the stress distribution and trajectories was made by taking the pattern of the faults and plotting the principle extensional stresses normal to the strike of the faults or normal to the Θ bearing in a conjugate shear pattern. Strain diagrams with the rates and amounts of deformation were produced by the summation of vertical and extensional displacements along the principle extensional stress trajectories.

In an attempt to determine the composition of each individual volcanic field and major variations within the fields, 180 hand samples were taken from the Cove Fort area. From these samples, standard petrographic thin sections were produced, examined, and described. From the petrographic evaluation of the lavas, 21 samples were chosen for major element analysis by x-ray fluorescence spectrometry (Norrish and Hutton 1969). By mechanical displacement of CO_2 gas driven off by a 10 percent solution of hydrochloric acid in a calibrated manometer, CO_2 was analyzed.

K-Ar dates were produced by E. H. McKee of the United States Geological Survey, Menlo Park, California.

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The author is grateful for the assistance and advice of W. K. Hamblin and M. G. Best, without whose support this study could not have been completed. Special thanks are given, too, to H. J. Bissell whose aid and suggestions with the carbonate petrology and stratigraphic procedures were invaluable. The author is also grateful to G. R. Neilson and A. P. Baclawski for their assistance with x-ray fluorescence sample preparation techniques and photocopying. Special thanks are extended to my wife Joanne whose encouragement, support, and aid in typing and proofreading are deeply appreciated.

TECTONIC AND STRUCTURAL SETTING

The Cove Fort graben lies along the physiographic boundary between the Great Basin and the Colorado Plateau and essentially parallels the Wasatch-Las Vegas hinge line (fig. 2). This hinge line formed a structural labium that separated the stable craton from a mobile continental margin from the late Precambrian until at least the early Tertiary (Stewart 1972, Bissell 1974). It represented (1) the eastern margin of the Cordilleran geosyncline from the late Precambrian until the Triassic with the stable craton to the east (Stewart 1972, Bissell 1974, Poole 1974, and Stewart and Poole 1974); (2) the eastern extent of thrusting during the Sevier Orogeny (Stewart 1972); (3) the eastern edge of late Precambrian (Stewart 1972), Ordovician-Devonian (Churkin and McKee 1974), and Pennsylvanian-Permian rifting (Churkin and McKee 1974); and (4) the eastern edge of the Mesocordilleran geanticline (Bissell 1874). This line also seems to be the approximate eastern edge of late Cenozoic block faulting or extension in the Great Basin.

The pre-Tertiary rifting of the Great Basin may have caused an inherited weakness in the crust before the inception of Tertiary extension in the Basin and Range region. The Colorado Plateau and the Sierra Nevada would not have had this inherited weakness since they apparently were not involved with the pre-Tertiary rifting. If the Colorado Plateau and Sierra Nevada were structurally competent bodies relative to the Great Basin prior to the Tertiary extension, the positions of the present boundaries of the southeastern Sierra and western Colorado Plateau may not be coincidental but are, in part, structurally controlled.

Stewart (1971) infers that the greatest portion of deformation in the Great Basin began approximately 17 m.y. ago, culminating in the last 7-11 million years. The amount of total east-west extension in the Great Basin may be estimated by using the "graben rule" (Hansen 1965). This rule states that lateral displacement producing a graben is equal to the ratio of the cross-sectional area of the surface trough of a graben to the depth of faulure. Stewart (1971) estimates that in the thirty grabens along the fortieth parallel, there have been approximately 70 kilometers of east-west extension at a rate of .5 to 1.5 cm/yr.

Hamblin and Best (1975) demonstrated that the inception of basaltic volcanism along the southeastern margin of the Great Basin is encroaching upon the Colorado Plateau in a northeasterly direction at a rate of 1 cm./yr. They infer that the structural margin of the Great Basin is continuing to migrate, certainly not at the same rate as the initial collapse or migration of the structural margins of the Great Basin, but at a significant rate.

The present zone of high seismic activity along the eastern physiographic margin of the Great Basin appears to weaken south of Cove Fort, between Beaver and Cedar City, Utah (Smith and Sbar 1974). This seismic belt bends to the west through Nevada. Along the southwestern margin of the Colorado Plateau there has been a great deal of recent basaltic volcanism even though the present seismicity is low (Best and Brimhall 1974, Hamblin and Best 1970, and Smith and Sbar 1974). In the north central part of Utah along this physiographic margin, where the present seismicity is high, there has been no recent basaltic activity. The Cove Fort and Black Rock Desert areas, however, are the northernmost basaltic fields in central Utah and are included within the zone of high seismicity (fig. 3).

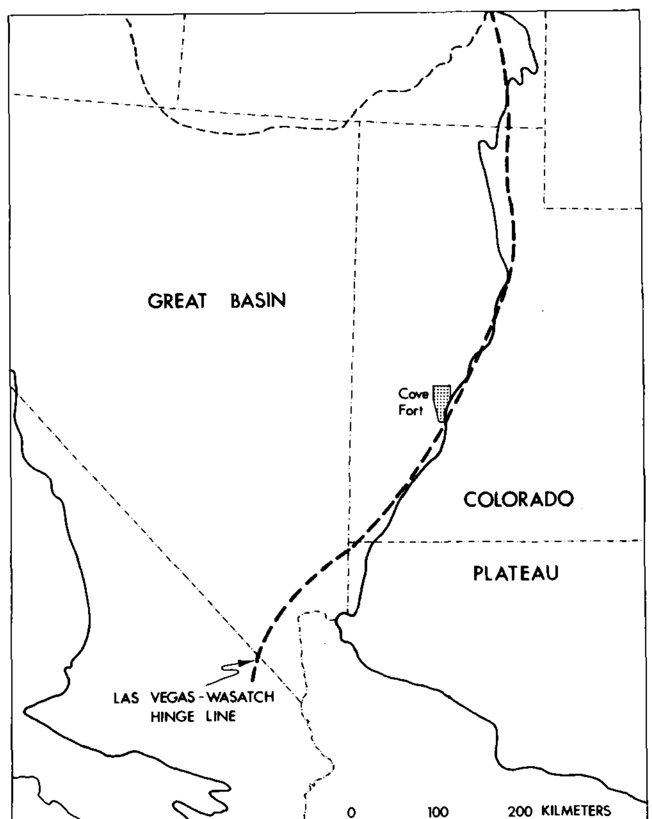


FIGURE 2.—Generalized map showing Las Vegas-Wasatch hinge line and physiographic boundaries of the Great Basin.

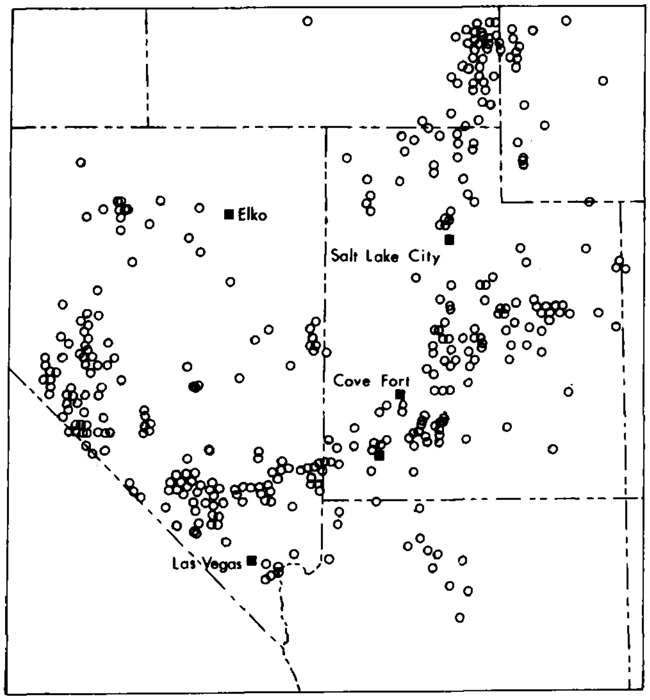


FIGURE 3.—Seismic epicenter plot of the Great Basin-Colorado Plateau area (after Smith and Sbar 1974).

The Cove Fort area is a structural graben, the surface of which lies at approximately 1800 meters above sea level (fig. 4). To the northeast and southeast are the Pavant Range and Tushar Mountains which rise 1200 meters above the Cove Fort graben. In this region the prominent structural features of the western margin of the Colorado Plateau are covered by thick sequences of silicic Tertiary volcanic rocks. There is no major escarpment like the Wasatch or Hurricane faults marking the Great Basin boundary, but there are recent scarps along the western flank of these mountains.

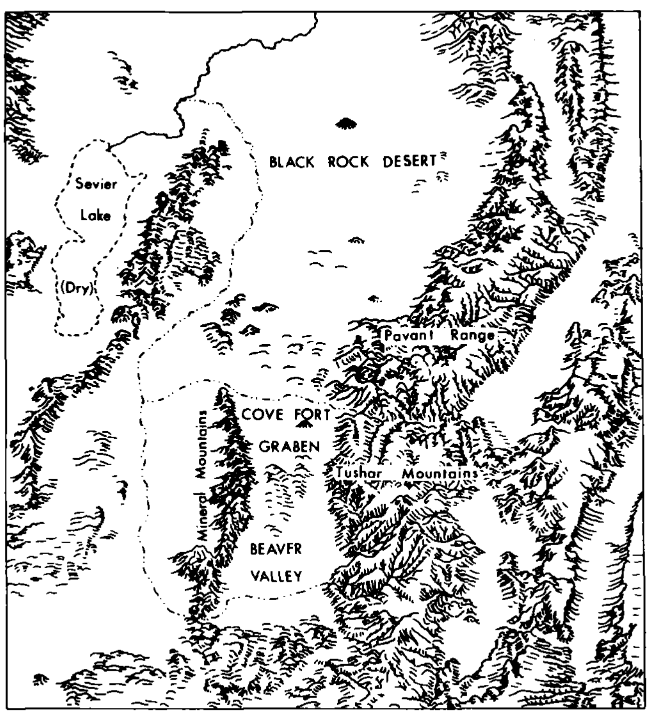


FIGURE 4.—Generalized physiographic map of the Cove Fort region (modified from Ridd 1960).

To the west of Cove Fort graben lie the Mineral Mountains, a north-south trending horst of granitic rocks fault bound on both the eastern and western flanks and rising some 1000 meters above the Cove Fort area.

Cove Creek, the main stream within the Cove Fort area, is ephemeral and flows from the northern Tushar Mountains west across the central portion of the Cove Fort graben and through a low pass along the northern point of the Mineral Mountains, where it joins the Beaver River to flow north to Sevier Lake. Sevier Lake lies at an elevation of 1360 meters and is the base level for this portion of the Great Basin.

QUATERNARY STRATIGRAPHY

Throughout the northern and central portion of the Cove Fort area, there are outcrops of a relatively thick sequence of Pliocene-Pleistocene lacustrine carbonates (figs. 5, 6). Zimmerman (1961) described a measured section and several outcrops of these carbonates, referring to them as Sevier River Formation. His measured section contains 80 meters of marlstones and limestones with subordinate amounts of volcanic and other clastic debris.

The Sevier River Formation was named and described by Callaghan (1937) near the town of Sevier at the south end of Sevier River Valley, south central Utah. The type section is described as consisting of "fanglomerate, conglomerate, sand, and silt derived chiefly from the rhyolitic tuffs and to a lesser extent from the quartz latite flows of the later Tertiary (?) volcanic rocks. The fanglomerate and conglomerate grade eastward into pinkish sand and

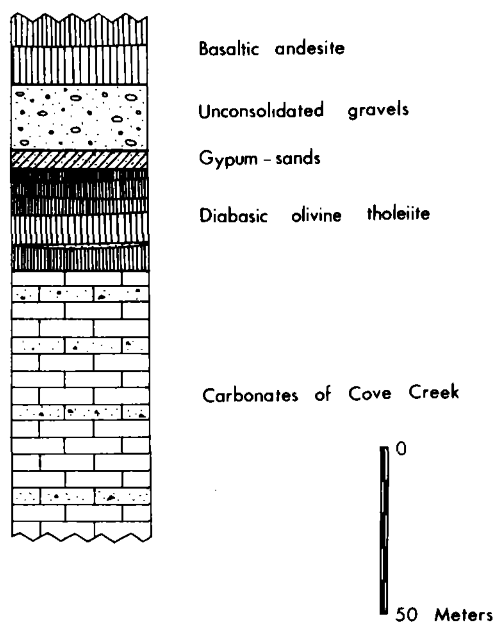


FIGURE 5.—Schematic stratigraphic section of late Cenozoic units.

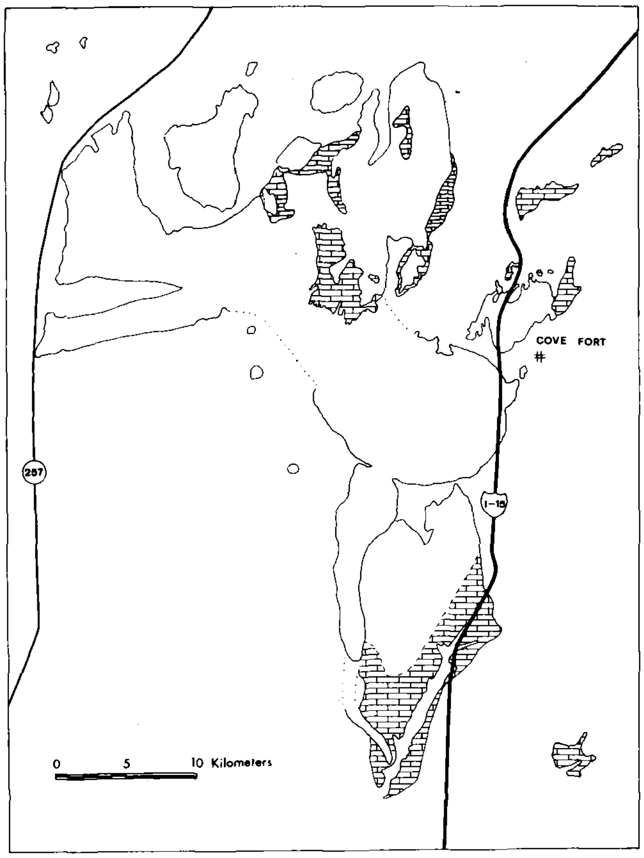


FIGURE 6.—Generalized map showing outcrops of Pliocene-Pleistocene carbonates and other outcrops mapped previously as *Sevier River Formation.*

silt, which in turn grade into white diatomite beds evidently deposited in a lake." Callaghan inferred that the Sevier River Formation is a coarse clastic, alluvial fan to fluvial sequence, deposited within the Sevier River valley along the flanks of the Pavant and Antelope ranges.

Maxey (1946), Thomas (1946), and Gregory (1950) have described similar Pliocene-Pleistocene coarse clastic units as being correlative with the Sevier River Formation. Even though these localities are found 73 kilometers to the south and nearly 48 kilometers to the north, their close lithologic and faunal similarities indicate that they are indeed Sevier River Formation.

The Pliocene-Pleistocene carbonate sequence found in the Cove Fort volcanic area does not fit Callaghan's (1937) description of the type section of the Sevier River Formation. These fresh water marlstones and limestones, in fact, closely resemble many other Tertiary lacustrine carbonate rocks throughout the Great Basin (Bissell, pers. comm.). Nowhere in the description of the type section of the Sevier River Formation did Callaghan (1937) mention limestones or marlstones. Zimmerman (1961), however, quoted Callaghan as saying "variable in composition, consisting of fanglomerates, consisting of sands, silts, and *white lacustrine diatomaceous marls*" (italics added). Callaghan (1937) inferred that there was a lateral change in facies, but the term *marls* was not used, nor was it inferred that the Sevier River Formation is a carbonate sequence.

Even though Zimmerman (1961) found fossils providing a Pliocene-Pleistocene age for the carbonate rocks at Cove Fort, this finding alone does not show correlation to the Sevier River Formation. A rock stratigraphic unit such as the Sevier River Formation must be lithologically correlative. "A unit distinguishable only by its fossils is not a rock stratigraphic unit but is properly classified as a biostratigraphic unit" (American Commission on Stratigraphic Nomenclature, 1970).

Each graben within the Basin and Range very likely contains lacustrine carbonates, possibly even Pliocene-Pleistocene carbonates. There are also Pliocene-Pleistocene fanglomerates and coarse clastic units containing volcanic debris in most of these grabens, but to refer them all to the Sevier River Formation would be unwise stratigraphic procedure. The informal "carbonates of Cove Creek" will be used for convenience only in the text of this paper.

Overlying the lacustrine carbonates of Cove Creek are several broad thin sheets of diabasic olivine tholeites which have been dated at .97 m.y. (Condie and Barsky 1972). These flows cover much of the central, northwest, and northeast portions of the area and extend northward into the Black Rock Desert. The diabasic flows range in thickness from single flow units of 5 meters to multiple flows of over 30 meters and are exposed over an area of at least 250 square kilometers. They may in fact be much more extensive, but they are partially covered by alluvium and subsequent lava flows.

In much of the central portion of the area, the diabasic lavas are partially covered by a series of poorly consolidated gypsiferous sand units which are approximately 4.5 meters thick (Zimmerman 1961). The gypsiferous units are overlain by 12-18 meters of a poorly consolidated conglomerate and gravel sequence which are characteristically poorly sorted and contain rhyolitic and andesitic clasts ranging from silt size to 25 centimeters in diameter. The clasts appear to be similar to the rhyolitic and andesitic lavas to the east in the Tushar Mountains and the Pavant Range.

The gypsiferous and coarse-grained clastic units are overlain in the central Cove Fort area by younger volcanic flows ranging from basaltic andesites to latites.

CLASSIFICATION OF LAVA FLOWS

The relative ages of the lava flows within the Cove Fort area have been determined on the basis of stratigraphic relationships and stage of geomorphic evolution. Colton (1937) and Koons (1945) described a system of classifying basaltic flows in the uplifted plateaus of Utah and Arizona according to relative age. Hamblin (1963, 1970) modified this classification in the study of basaltic flows in the St. George Basin and the northwestern Grand Canyon region. His system separates volcanic lavas into four stages (fig. 7) and is based upon two main criteria: (1) The relationship between the surface upon which the lava was deposited and the present drainage system adjacent to the lava flow, and (2) the degree to which the margins and surface are modified. Hamblin's classification is effective in correlating flows of widely different ages within the Colorado Plateau where erosion has been dominant process. Where uplift and erosion are not the dominant processes, the classification developed by Hamblin encounters difficulties and must be modified.

UNITS	BASIC CRITERION	SUBDIVISIONS	SUBORDINATE CRITERIA		
	Character of surface upon which lavas were deposited		Geomorphic relations	Nature of margins	Nature of surface features
STAGE IV		STAGE IV		Original margins well preserved.	Remarkably fresh surfaces without visible signs of erosion. Lava tops in place.
STAGE III	Lavas deposited on surface developed by present cycle of erosion. Associated cinder cones preserved. Many flows can be traced to source.	STAGE III b		Original margins partly preserved.	Spatter cones and pressure ridges common and well preserved. Present surface rough, but lava tops broken down and cannot be recognized.
		STAGE III a		Original margins partly preserved.	Most original surface features destroyed or covered by alluvium. Spatter cones and pressure ridges not visible.
STAGE II	Lavas deposited on surface developed by earlier cycles of erosion. Ancient drainage systems demonstrated to be ancestral to that of the present.	STAGE II c	Caps lowest terrace developed by ancestral drainage.	Original margins eroded.	Original surface features destroyed.
		STAGE II b	Caps intermediate terraces developed by ancestral drainage.	Original margins eroded.	Original surface features destroyed.
		STAGE II a	Caps highest terraces developed by ancestral drainage.	Original margins eroded.	Original surface features destroyed.
STAGE I	Lavas deposited on ancient erosional surface which exhibits no apparent relation to present drainage.	No subdivision recognized in St. George basin.	Caps highest mesas and buttes.	Original margins eroded.	Original surface features destroyed.

FIGURE 7.—Geomorphic classification of lava flows (after Hamblin 1970).

Within the Cove Fort area, the Cove Creek flows appear as highly faulted, scattered remnants with relatively high topographic relief. The flows are discontinuous with little relationship to the present drainage, and their margins and surfaces are weathered and modified by erosion. The Black Rock flows to the south of the Cove Creek flows appear relatively young, not modified by a great amount of extensional deformation or erosion. They have, in fact, been partially covered by a thin veneer of alluvium. Although the Cove Creek lavas appear to be much older than the Black Rock flows, they are approximately the same age. The difference between the two lava flows is the degree to which the Cove Creek flows have been deformed and uplifted and the Black Rock flows have been preserved from erosion by the alluvial cover. The Cove Fort and Black Rock Desert grabens are in a different geomorphic, structural, and tectonic setting from the high plateaus of Utah and Arizona. In these areas of low topographic relief, progressively older volcanic flows may be covered and partially preserved by subsequent sedimentation instead of being eroded. There are, however, in the same grabens, areas of uplift and active erosion, which may cause the flows to be exhumed or may continue to change the flow margins and surfaces by erosion. A modification of Hamblin's (1970) classification must then be made in an attempt to classify the flows according to their relative age and stage of geomorphic development.

Classification of lava flows within a graben or basin is then based on three criteria: (1) The relationship between the surface upon which the lava was deposited and the present drainage system adjacent to the lava flow, (2) the degree to which the margins and surface are modified by erosion or sedimentation, and (3) the degree to which the lava flow and the surrounding area have been tectonically deformed.

Stage I

Stage I flows are those lavas which have been deposited on a surface which shows no apparent relationship to the present drainage. The surface features and margins have been modified either by erosion (as indicated by the Hamblin [1970] classification) or by subsequent sedimentation. In either case, the direction of flow and the source of the lava would be difficult to determine because surface features would be obliterated by erosion and weathering.

No stage I flows occur in the Cove Fort area, but examples in other areas are the northernmost basaltic lavas in the Pine Valley Mountains, southwestern Utah, and the high flows or remnants in southeastern Nevada.

Stage II

Stage II flows are lavas which have been extruded onto a surface directly related to that produced by the present drainage. Generally, they are located on the older surfaces of the basin, now modified by (1) erosion, (2) later deposition of lava, or (3) sedimentation. The flow margins have been partially eroded (as shown in fig. 7) or have been covered with sediments.

Within the Cove Fort area, the topography upon which the stage II flows were deposited has either been covered by as much as 35 meters of sediment or inverted over 100 meters by erosion. Examples of stage II flows are seen 5 kilometers northeast of Black Rock on Utah Highway 257 at the northwestern terminus of the Black Rock flows and 5 kilometers west of Manderfield, Utah, at the southern portion of the Crater Knoll Field.

Stage III

Stage III flows are lavas deposited on a topographic surface developed by the present system of erosion. Generally they are too young to have been greatly deformed or covered by an appreciable thickness of sediment.

An example of stage IIIa flows is located on the low bluffs south of the Black Rock Road, in the NW $\frac{1}{4}$, section 25, T. 25 S, R. 8 W, in the northern portion of the Cove Fort Field. Stage IIIb flows are found along Interstate 15 in sections 35 and 26, T. 25 S, R. 7 W in the northeastern portion of the Cove Fort Field. Stage IIIc flows are found associated with each of the prominent cinder cones within the Cove Fort area but are best exemplified by the recent flows surrounding the Crater Knoll cinder cone, section 15, T. 27 S, R. 8 W.

Stage IV

Stage IV flows are young and have not been appreciably modified by erosion. The margins are well pressured, and original surface features are essentially unaltered by weathering or erosion.

No stage IV flows are found in the Cove Fort area, but the Ice Springs Field in the Black Rock Desert to the north is a good example within this region (Hoover 1974).

VOLCANIC FIELDS

The Quaternary lava flows in the Cove Fort area may be divided into four individual fields, each with its own distinctive geomorphic,, chronologic, petrographic, and petrochemical characteristics. Within these fields major flows consisting of a series of flow units with close genetic relationships can be recognized and mapped (fig. 8).

Black Rock Field

The Black Rock Field consists of a series of stage II flows which lie in the northern portions of the Cove Fort area. These flows, dated at 0.92 and 0.97 m.y.(Condie and Barsky 1972, Hoover 1974), appear to be the oldest basaltic lava flows exposed in the Cove Fort area. Petrographically they consist of diabasic olivine tholeiite and appear in outcrop as thin flow units, approximately 5 meters thick. Single flows or floods of these lavas extend up to 30 kilometers in length and are commonly 5 kilometers wide. Few flow structures are preserved on the surfaces of the uppermost diabasic flows because of their relative old age. On a macroscale, flow marks are seen, but little detail is apparent. There are, however, several locations where the basal and upper surfaces of lower flow units may be observed. These surfaces are not clinkery or blocky but are undulating, billowy, or ropy. This variety of pahoehoe flow has been described as "elephanthide" by Wentworth and MacDonald (1953). At all localities, the diabasic tholeiites contain well-developed columnar joints with diameters of from 1-2 meters. All other lavas within the Cove Fort Province have relatively poorly developed columnar jointing.

The diabasic lavas have SiO_2 weight percentages from 48 to 49 and are phaneritic with diktytaxitic, ophitic fabrics. Few phenocrysts are seen in thin section, and there is generally less than 10 percent glass.

Microflow structure is not apparent in thin section, hand sample, or outcrop. A more detailed description of these lavas is given below under Petrography and Petrochemistry (q.v.). In general, the texture of the diabasic tholeiites may be described as a "crystalline mush" with an open fabric. Intuitively, it would appear that thin basaltic flows would tend to have a finer-grained texture, and that coarse-grained volcanic lavas would be associated with relatively thick flow units whether most of the "crystalline mush" crystallized prior to eruption or afterward. However, geometry of these thin flows indicates that upon extrusion the lavas had an extremely low viscosity.

In Newtonian flow, low viscosity may be a result of either (1) a low Si-Al/O ratio, (2) a high temperature of the magma, or (3) a high concentration of volatiles, i.e., H_2O, F, or Cl. Any combination of these variables may change the viscosity (Carmichael et al. 1974).

The Si-Al/O ratio of the diabasic lavas of the Cove Fort area and other localities throughout the Colorado Plateau and southeastern Great Basin appears to be no lower than other basalts that were more viscous upon extrusion. In addition, there is little water contained in the diabasic lavas analyzed in this study and in other localities (Hoover 1974, Best and Brimhall 1974).

The apatite in the diabasic olivine tholeiites may contain some F, but there does not appear to be sufficient apatite in the modal or normative compositions of these lavas to cause a significant decrease in viscosity.

There is the possibility that the void spaces within the diktytaxitic fabric represent entrapped volatiles which have since escaped. The volatiles may have lowered the viscosity and in turn increased diffusivity and crystallization rate. A large thin section was prepared of the upper portion of a flow surface that has been partially preserved by a subsequent flow. The surface of the flow appears to have been quenched, containing nearly euhedral and "H-shaped" plagioclase phenocrysts and considerably more groundmass crystals and glass than the central portion of the flow. A quenched zone thus may have capped the volatiles that were trapped in the pore spaces in the diktytaxitic fabric.

Since there is not a significantly lower Si + Al/O ratio or direct evidence of a high concentration of volatiles within the magma, a high temperature of the magma is a viscosity which in turn is expected to contain a relatively high diffusion rate and may be associated with a high rate of crystal growth and/or nucleation rate (Carmichael et al. 1974). The crystallization rate thus may have been great enough to produce the coarse fabric seen in the diabasic lavas, but the presence of euhedral phenocrysts along the quenched surface would cast doubt upon the possibility of a superheated magma.

The possibility of extrusion of the lavas as crystalline mush can be discounted because it would indicate that the flow behaved in a non-Newtonian manner. The mere addition of a few percent crystals to a silicate melt increases viscosity several orders of magnitude (Bottinga and Weill 1972). Also if a magma contained an appreciable number of crystals upon extrusion, it might be expected to contain flow structure in thin section or in hand sample. However, the crystals in the diabasic lavas in the Cove Fort Province do not show evidence of significant flow after crystallization.

Black Rock Flows.—Black Rock flows consist of stage II diabasic olivine tholeiite lavas which cover most of the central and northwestern portions of the Cove Fort area (fig. 8). They have been dated at 0.97 m.y. (Condie and Barsky 1972) and are stratigraphically below all other basaltic flows that crop out within the study area. Three dissected cinder cones along the northeastern flank of the Mineral Mountains appear to be vents associated with at least several of the diabasic flows. The lavas were thus extruded in the central portion of the area and flowed around the northern point of the Mineral Mountains following the ancestral Cove Creek to the Beaver River, some 32 kilometers in length. They apparently covered much of the flat Cove Fort graben floor and were subsequently partially covered by gypsum sands and then by basaltic to intermediate flows.

Black Point Flows.—The Black Point flows lie in the northeastern corner of the Cove Fort area (fig. 8) and consist of stage II diabasic olivine tholeiite lavas which appear to be petrographically and petrochemically identical to those of the Black Rock flows. Although no K-Ar dates have been obtained from the Black Point lavas, geomorphically they appear older than the Black Rock flows. Within them there seems to be no relationship between the present drainage and the surface upon which the flows were extruded. En echelon normal faults have intensively macerated these flows, physically breaking up segments and exposing tilted blocks to weathering and erosive processes (fig. 9). The flow margins are thus obscured and are in a much poorer condition than the Black Rock flows even though their absolute ages are approximately the same.

No cones or vent areas have been located within the Black Point area. However, it is quite possible that these flows are in actuality a northern extension of the Black Rock lavas. At Beaver Ridge, 19 kilometers north of Black Point, Hoover (1974) describes a series of diabasic basalt flows which are petrochemically and petrographically similar to those of the Black Rock Field and have been dated at 0.97 m.y. At Lava Ridge, the northern extension of the Burnt Mountain Field (q.v.), the younger basaltic andesite lavas are resting upon diabasic lavas (figs. 8 and 10). In addition, there are several other isolated outcrops of similar lavas between the Black Point area and Beaver Ridge. It appears that the diabasic flood basalts flowed a considerable distance into the Black Rock Desert as well as covering much of the Cove Fort area. These broad thin flows form a convenient structural datum for the monitoring of subsequent deformation within the area.

Burnt Mountain Field

The Burnt Mountain Field consists of a series of stage II and stage III andesite and basaltic andesite flows that lie in the northern portion of the Cove Fort area (fig. 8). This field covers an area of approximately 130 square kilometers and has been subdivided into three series of flows: (1) Burnt Mountain flows, (2) Cove Creek flows, and (3) Twin Peaks flows.

Burnt Mountain Flows.—The Burnt Mountain flows consist of a series of basaltic andesite lavas in the central portion of the field (fig. 8). No potassium argon dates are available for them; with respect to the other lavas within this field, however, they appear to be stratigraphically and geomorphically younger. The flows adjacent to the Burnt Mountain cinder cone are late stage III lavas and may be as young as 50,000 years. To the north, at Lava Ridge, the basaltic andesite lavas appear as late stage II to early stage III flows.

Generally, the flow units within the Burnt Mountain area appear to radiate from the Burnt Mountain cinder cone and form an inflorescent mound of flows referred to by Cloos (1962) as "table-shield volcanoes" or a shield-like volcanic platform. Basaltic mounds are a dominant pattern of flows, each containing a cinder cone at the apex.

Throughout the Cove Fort area, the basaltic andesite lavas appear as *αα* type flows, with a rough and clinkery surface. The flow units are generally 10-20 meters thick and commonly contain tumuli and collapsed lava tubes. A special type of jointing is commonly found in the basaltic andesite lavas, generally within the core of the flow, and have been described by Green and Short (1971) as dehydration joints. These joints appear as horizontal lens-shaped cracks and may in fact be related to a late pulse of lava after the cooling of the margins as there appears to have been little H_2O in the magma.

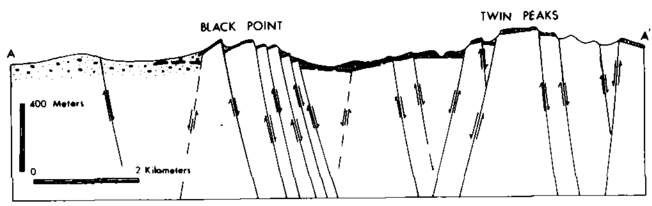


FIGURE 9.—East-west cross section through Black Point.

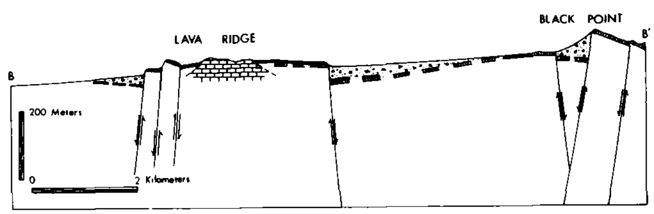
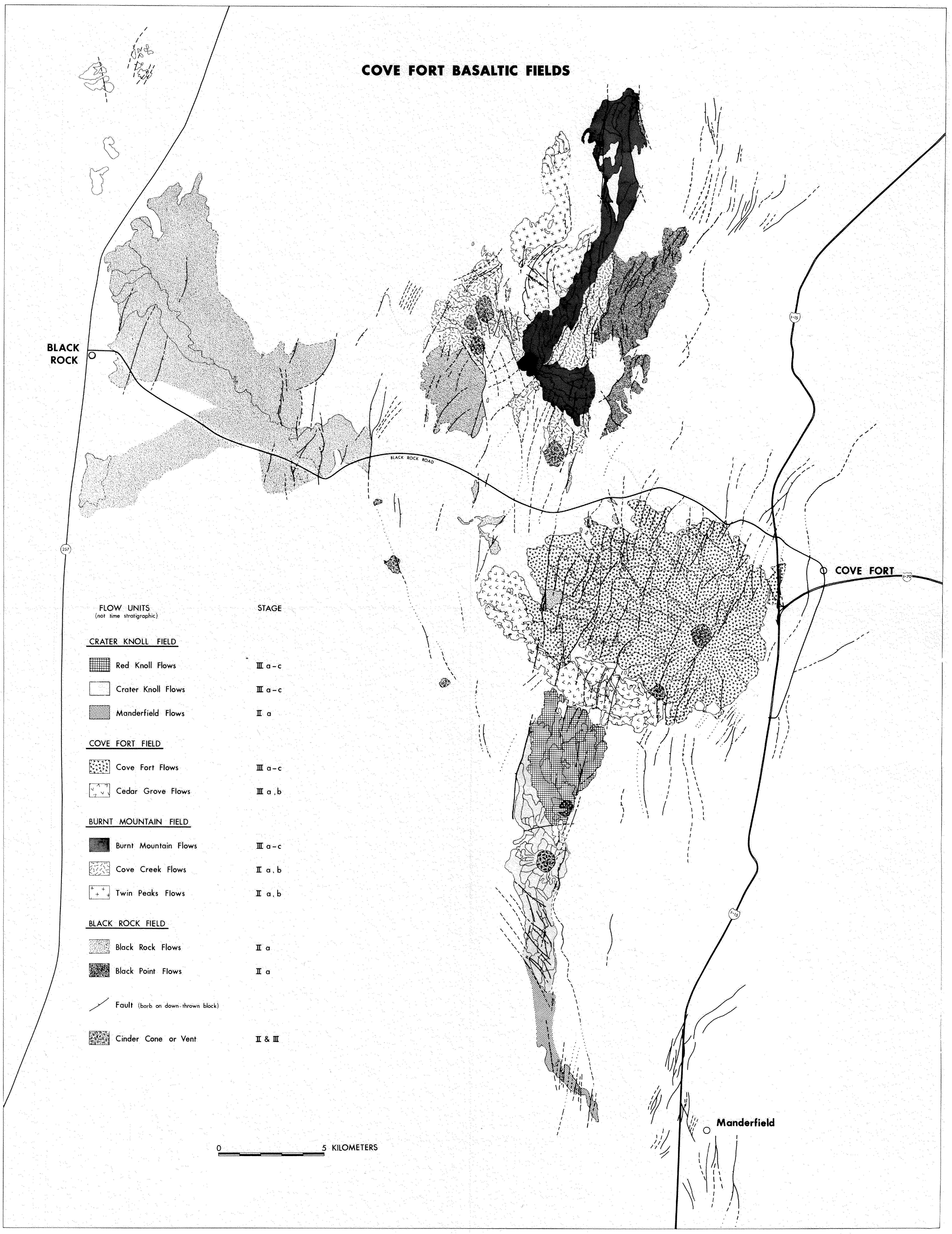


FIGURE 10.—East-west cross section through Lava Ridge.


COVE FORT BASALTIC FIELDS
BLACK ROCK
COVE FORT
Manderfield
BLACK ROCK ROAD
FLOW UNITS
(not time stratigraphic)
STAGE
CRATER KNOLL FIELD
Red Knoll Flows III a–c
Crater Knoll Flows III a–c
Manderfield Flows II a
COVE FORT FIELD
Cove Fort Flows III a–c
Cedar Grove Flows III a, b
BURNT MOUNTAIN FIELD
Burnt Mountain Flows III a–c
Cove Creek Flows II a, b
Twin Peaks Flows II a, b
BLACK ROCK FIELD
Black Rock Flows II a
Black Point Flows II a
Fault (barb on down-thrown block)
Cinder Cone or Vent II & III
0 5 KILOMETERS

Cove Creek Flows.—The Cove Creek flows consist of distinctive aphyric andesite lavas which lie in the north central portion of the Cove Fort area. Two major centers of extrusion occur, one in the northern and one in the southern area, each containing its own eroded cinder cones and their associated flows. The two areas are divided by a series of upfaulted blocks of the Pliocene-Pleistocene carbonate sequence and are partially covered by the younger Burnt Mountain flows (fig. 8).

In the northern portion of the Cove Creek area, the flows have been cut by normal and wrench faults leaving many isolated lava-capped buttes with no apparent relationship to the present drainage system. Several of these faulted blocks rise over 250 meters above the level of Cove Creek.

Three kilometers northwest of the main body of the northern portion of the Cove Creek flows is found a remnant of the aphyric andesite lavas on the southern flank of the southern Twin Peaks (fig. 8). The remnant is approximately 120 meters above the valley which now separates this flow from the main body of the Cove Creek flows. The interjacent valley has no evidence of a great amount of faulting on the southeast side, but the northwest side has been faulted at least 120 meters, forming a small asymmetrical graben (Cloos 1968). The remnant does not appear to be associated with the Twin Peaks silicic domes as these domes have been dated by Mehnent at 2.3 m.y. (P. D. Rowley 1975, written communication to M. G. Best of dates obtained by Harold Mehnent) and appear to be much older than the andesite remnant.

In the southernmost portion of this sector, the lowermost Cove Creek flows are intercalated with at least the younger Black Rock lavas. Here the flows are nearly coeval but in other localities, the Cove Creek andesites overlie the diabasic lavas of the Black Rock Field. Since no radiometric dates have been obtained from the Cove Creek flows, it is assumed that they consist of middle-to-late stage II flows, possibly 750,000-1,000,000 years old. Zimmerman (1961) and Condie and Barsky (1972) have described a locality where these lavas are overlain by the "Sevier River Formation" (SW $\frac{1}{4}$, section 3, T. 25 S, R. 8 W). Careful examination of this locality in the field revealed that these lavas were not stratigraphically beneath the carbonate sequence but flowed down a canyon cut in the carbonate rocks of Cove Creek, topographically lower. Several slump blocks of the carbonate sequence have partially covered portions of the andesite lavas, obscuring their stratigraphic relationship.

The southern portion of the Cove Creek flows has not been deformed to the same degree as the area to the north. However, in the northeastern corner of the southern area, tilted fault blocks appear as outliers surrounded by the recent Burnt Mountain flows. The lavas from this area appear to have originated from a large cinder cone along the southern margin of the area which rests on the Pliocene-Pleistocene carbonate units. Several flows from this cone rest directly upon lavas of the Black Rock Field.

Twin Peaks Flows.—The Twin Peaks flows lie in the north central portion of the Cove Fort region (fig. 8). They consist of stage II basaltic andesites, petrographically and petrochemically similar to those of the Burnt Mountain flow. The southern portion of them appears to have been highly deformed, and the result is elevated fault blocks similar to those found in the Cove Creek flows (fig. 9). In both areas, few individual flow units can be mapped owing to the degree of deformation. The only units that are mappable are the late stage II lavas that flow north onto the valley floor in the southern Black Rock Desert. These lavas have been partially covered with alluvium, which has preserved some of their margins and several tumuli. No radiometric dates are available for these lavas, but they appear to be approximately the same age as the Cove Creek flows. Their margins and surfaces are generally poorly preserved, no original lava tops are seen, and generally there seems to be no relationship between the surface upon which they were extruded and the present drainage system except for the lavas in the northern part of the area.

Cove Fort Field

The Cove Fort Field lies in the central portion of the study area within the Cove Fort graben and comprises two series of lava flows: (1) Cove Fort flows and (2) Cedar Grove flows (fig. 8). Both series consist of stage III lavas which have been deformed by a series of north-south trending normal faults.

Cove Fort Flows.—The Cove Fort flows are quartz-bearing basaltic andesite lavas which radiate from the proximity of a prominent cinder cone, forming a near perfect "shield-like" volcanic platform. They cover an area of nearly 90 square kilometers and rise from an elevation of approximately 1775 meters around the margins to 1950 meters at the base of the prominent cinder cone. There are 45 individual flow units mapped at the surface of the platform, undoubtedly covering hundreds of other flows.

The Cove Fort flows overlie the diabasic olivine tholeiites of the Black Rock Field in the northwest portion of the field, and in other areas they overlie the gypsum sands and alluvial units which in turn appear to overlie the Black Rock flows. The oldest flows in the field are stage IIIa and lie in the northwest section. The youngest are late stage III and lie in the central portion of the field adjacent to the cinder cone. They are possibly Holocene in age.

Myriads of relatively recent normal faults have deformed these basaltic andesite flows, as well as the alluvium in the adjacent valleys. Even though the density of these faults is high, the resulting deformation is not so great as that in the Cove Creek and Twin Peaks fields (fig. 11). There are no apparent wrench faults within the Cove Fort Field, and the displacements of the normal faults are smaller than those to the north.

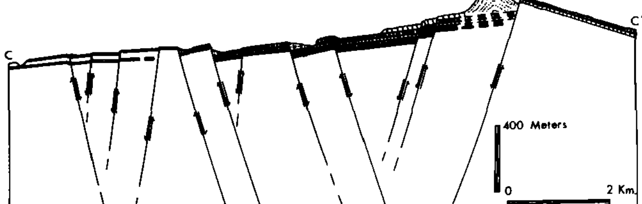


FIGURE 11.—East-west cross section through Cove Fort Field.

The Cove Fort cinder cone lies at the apex of the volcanic platform, rising to an elevation of 2125 meters. It is made up of alternating, inclined layers of sideromelane and palagonite tuff now being mined for road metal. Adjacent to it, on the southeast side, a portion of an older cone sits on the upthrown side of the prominent fault cutting through the field. This half of the older cone has been displaced more than 35 meters.

North of the Cove Fort Field, on the north side of Cove Creek, gypsum sands and unconsolidated coarse alluvial deposits form a south-facing terrace. Opposite the terrace, the northern edge of the volcanic platform is elevated approximately 35 meters above Cove Creek to the same height as the alluvial terrace. Apparently, as the path of Cove Creek was displaced by the succeeding lava flows, the terrace receded to the north. The northern margins of the basaltic andesites then reflect not only the previous paths of Cove Creek but also the topographic expression of the terrace to the north.

Cedar Grove Flows.—The volcanic deposits of the Cedar Grove flows comprise one cinder cone and several massive latite flows adjacent to the southwestern margin of the Cove Fort flows (fig. 8). There are two main flow units which originate from the vicinity of the cinder cone on the southwest margin of the field and flow for 11 to 12 kilometers to the northwest.

The most striking aspects of this small field are its geometry and the relationship of the flows. The two flows are middle-to-late stage III lavas, resting on the graben floor. The older flow is approximately 10 kilometers in length, and the younger is 13 kilometers long. The younger flow rides "piggy back" on top of the older for a distance of 8 kilometers, then cascades off the southwestern terminus of the older flow. Each flow unit is between 20 and 35 meters thick and has been cut by several normal faults (fig. 12).

There is no visible evidence that these two flows were confined to a narrow, steep-walled stream valley. On the surface of the younger flow, there are many collapsed lava tubes and lava levees. Lava levees are troughs which formed parallel to the direction of flow because of collapse due to the subsequent draining of magma from the core of the flow. These levees may be up to 10 meters high in basalt flows (Hoover 1974) and have been seen by the writer in andesite flows 5 kilometers south of Enterprise, Utah, to reach nearly 35 meters above the trough of the flow. If prominent levees were present on the older Cedar Grove flow during the extrusion of the younger flow, they may have controlled the latter.

Because of the high percentage of silica and the high viscosity in these lavas, the flow structures are somewhat more pronounced than the other lavas throughout the field. There are levees and collapsed tubes as mentioned above plus areas of ponded lava, splays, distributary channels, and a lava delta.

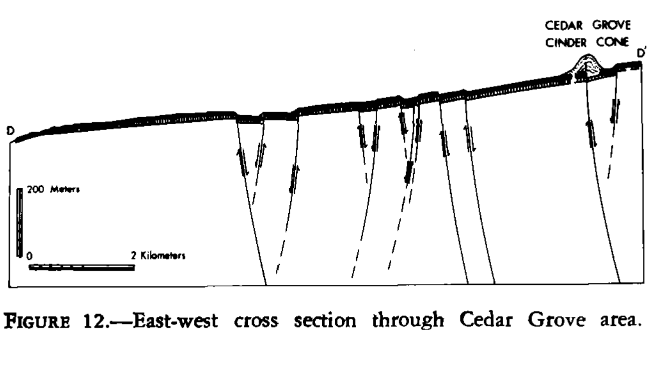


FIGURE 12.—East-west cross section through Cedar Grove area.

Crater Knoll Field

The Crater Knoll Field consists of two elongate volcanic platforms confined to a long, narrow valley between the Mineral Mountains and the rhyolitic domes at Four Mile Ridge in the southern portion of the Cove Fort area (fig. 8). In it are two series of stage III flows resting upon a stage II platform. It has been divided into two major flows: (1) the Red Knoll flow, and (2) the Crater Knoll flow.

Red Knoll Flows.—The Red Knoll area is a volcanic platform made up of a series of north-trending stage II latite flows partially covered by younger flows of similar composition which originate from the Red Knoll cinder cone. No absolute dates are available for these lavas, but the most recent flows geomorphically appear to be the youngest extrusion within the Cove Fort volcanic area.

Although the silica content of these flows is several percent below that of the Cedar Grove lavas, there are many similarities between the flow features of the two areas. The Red Knoll flows are thick and blocky, containing many tumuli and collapsed lava tubes, but they lack the deltalike features of the Cedar Grove lavas, which may have been obscured by erosion.

Crater Knoll and Manderfield Flows.—The Crater Knoll and Manderfield flows consist of late-stage-II-to-late-stage-III basaltic andesite lavas, which appear to be associated with the Crater Knoll cinder cone (fig. 8). The oldest lavas within this area are found at the extreme southern margin of the field. The flows form an inverted valley, rising more than 110 meters above the adjacent Cunningham Wash, 5 kilometers west of the town of Manderfield at Black Mountain, and are referred to herein as the Manderfield flows. The lavas appear to be associated with the Crater Knoll flows, but they are covered with alluvium at the southern margin of the Crater Knoll Field. Although the Manderfield lavas are exposed for only approximately 6 kilometers, they appear to extend beneath the Crater Knoll flows and possibly the Red Knoll lavas, forming the base of these two volcanic platforms.

In the Red Knoll Field, normal faulting appears to be evenly distributed, somewhat similar to the deformation in the Cove Fort Field. In the Crater Knoll area to the south, a prominent conjugate pattern is seen, somewhat like the pattern within the Burnt Mountain Field to the north (fig. 8). Two of the conjugate intersections in the central part of the Crater Knoll area appear to have a strike slip as well as a normal component of displacement.

GEOLOGIC HISTORY

The carbonate rocks of Cove Creek represent a relatively thick sequence of beds deposited on a graben floor in a lacustrine or playa environment during late Pliocene or early Pleistocene. Figure 6 is a generalized map of the location of some of the outcrops of these deposits. In general the outcrops are located in the central and northern portions of the Cove Fort area and the southern portion of the Black Rock Desert, possibly extending farther to the north in the subsurface. The present elevation of the upper units of these deposits in the southern Black Rock is approximately 1575 meters, and they lie at 1895 meters in the Burnt Mountain area and at 1680 meters in the Cove Fort graben to the south. It appears that in Pliocene-Pleistocene time there was one continuous graben from the Cove Fort area to the Black Rock desert (fig. 13A). Since that time, extensional deformation has formed a topographic high in the Burnt Mountain area, separating the two present-day grabens.

About one million years ago, the diabasic flood basalts covered much of the Cove Fort graben, flowing to the Beaver River, nearly 32 kilometers to the northwest and to Beaver Ridge, more than 40 kilometers to the northeast (fig. 13B). In the Burnt Mountain area and the Cudahy Mountains to the northwest there is an absence of lavas from the Black Rock Field. At the present time these areas are topographically high and were probably high during the extrusion of the Black Rock lavas as these lavas apparently flowed around the margins of Burnt Mountain and Cudahy Mountain. The topographic high must have developed sometime after the deposition of the carbonate sequence and prior to 1 m.y.

Within the Burnt Mountain area, the aphyric andesites of Cove Creek appear to have been extruded onto, and have flowed down, canyons cut into the carbonate units. The andesite lavas are post-carbonate and post-initial uplift, but because of their approximate coeval relationship to the Black Rock lavas, the intense amount of deformation would indicate continued uplift and deformation in the Burnt Mountain area after 1 m.y.

In the Cove Fort graben, the Black Rock lavas were covered by the thin veneer of gypsum and deposits which appear to be lacustrine or playa and are found only south of the Burnt Mountain-Black Point area, east of the Mineral Mountains, and west of the Pavant and Tushar Mountains within the present Cove Fort graben (fig. 13C). The Cove Fort graben is nearly 150 meters above the Black Rock desert graben, and the gypsiferous deposits are 100-180 meters above the highest Lake Bonneville level at 1575 meters (Bissell 1968) (fig. 13D).

It appears that the Cove Fort graben, by the time of the deposition of the gypsum beds, was an elevated, isolated basin, possibly containing a lake. During the extrusion of the Black Rock lavas in the Cove Fort graben, there were two passes where the lavas were able to flow out of the graben: (1) The Black Point area and (2) the low pass between the Mineral and Cudahy mountains (fig. 13B). The Black Point area is at the present time a topographic high and must have been at least partially deformed prior to the deposition of the gypsum beds. Now, all the drainage within the Cove Fort basin flows into Cove Creek, which exits the graben through a pass between the Mineral Mountains and the Cudahy rhyolitic domes and volcanic area. Figure 14 represents an east-west cross section through this pass, showing both the topographic profile and the gradient of Cove Creek. The profile shows a low-lying threshold at the pass caused by normal faults that have formed a small horst structure which is in fact an extension of the Mineral Mountains horst. East of the pass, the gradient of Cove Creek is 7 meters per kilometer whereas on the west side it is 6 meters per kilometer. At the pass the gradient is more than 17 meters per kilometer, indicating that the threshold was likely a topographic barrier during the deposition of the gypsum beds. After the deposition of these units, possibly during the deposition of the subsequent alluvial and gravel deposits, the threshold was dissected by Cove Creek, causing downcutting and exhuming of the gypsum deposits, Black Rock lavas, and carbonate units.

It appears that the rate of sedimentary supply vs. the rate of sedimentary transport in the Cove Fort area is controlled by the rate of strain or deformation. If the rates of normal faulting were to increase, the threshold at the pass between the Mineral and Cudahy mountains could be rejuvenated, and another isolated and elevated lake could form. If the relative rate of faulting on the west side of the Cove Fort area on the eastern flanks of the Tushar Mountains were to increase, the Cove Fort area could be partially buried by alluvium. If the relative rate of faulting on the west side of the Mineral Range pass were to increase, downcutting and sedimentary transport out of the Cove Fort graben would be the dominant process.

The Manderfield flows lie within the Beaver Valley graben are apparently a rather anomalous feature. Within the Cove Fort and Black Rock Desert grabens, inverted valleys of great topographic relief are not apparent as in areas in, and along the margins of, the Colorado Plateau which have undergone regional uplift (Hamblin 1970).

Within the Beaver Valley there is a series of at least six terraces formed by and cut into poorly consolidated late Tertiary and Quaternary silt, sand, and gravel units. Here, the entire drainage system meets the Beaver River and funnels through a narrow gap at Minersville whence it flows north to Sevier Lake. On either side of the gap are found remnants of late Tertiary or Quaternary basalt flows. These flows at one time probably formed a series of lava dams which not only formed a lake but raised the local base level, and the Manderfield lavas were extruded upon an elevated surface associated with the higher base level. As the lake "silted in" and overflowed, the basaltic dam must have been destroyed, thus lowering the local base level and producing sufficient downcutting to form the inverted valley.

The writer points out that little work has been done on the Beaver Valley terraces. The assumptions given here are based on only limited field observations. Certainly it is recommended that this problem be studied in much more detail.

STRUCTURE

From the standpoint of structural studies, it is fortunate that the Cove Fort and Black Rock Desert grabens have been partially covered with basaltic lava flows because they provide a means by which the surface expression of the structural features in the basins are preserved. Within the Cove Fort area alone, there are more than 300 normal faults that lie in a north-south trending zone which displace either the basaltic lavas or alluvium. Wallace (1975) demonstrates that small fault scarps in alluvium are nearly expunged after approximately 12,000 years. Since the oldest basaltic lavas in the Cove Fort area are no older than one million years, the faults observed in the area represent a minimum of extensional deformation or strain.

Figure 8 illustrates the faults within the Cove Fort area and indicates that there is an obvious, near-parallel,

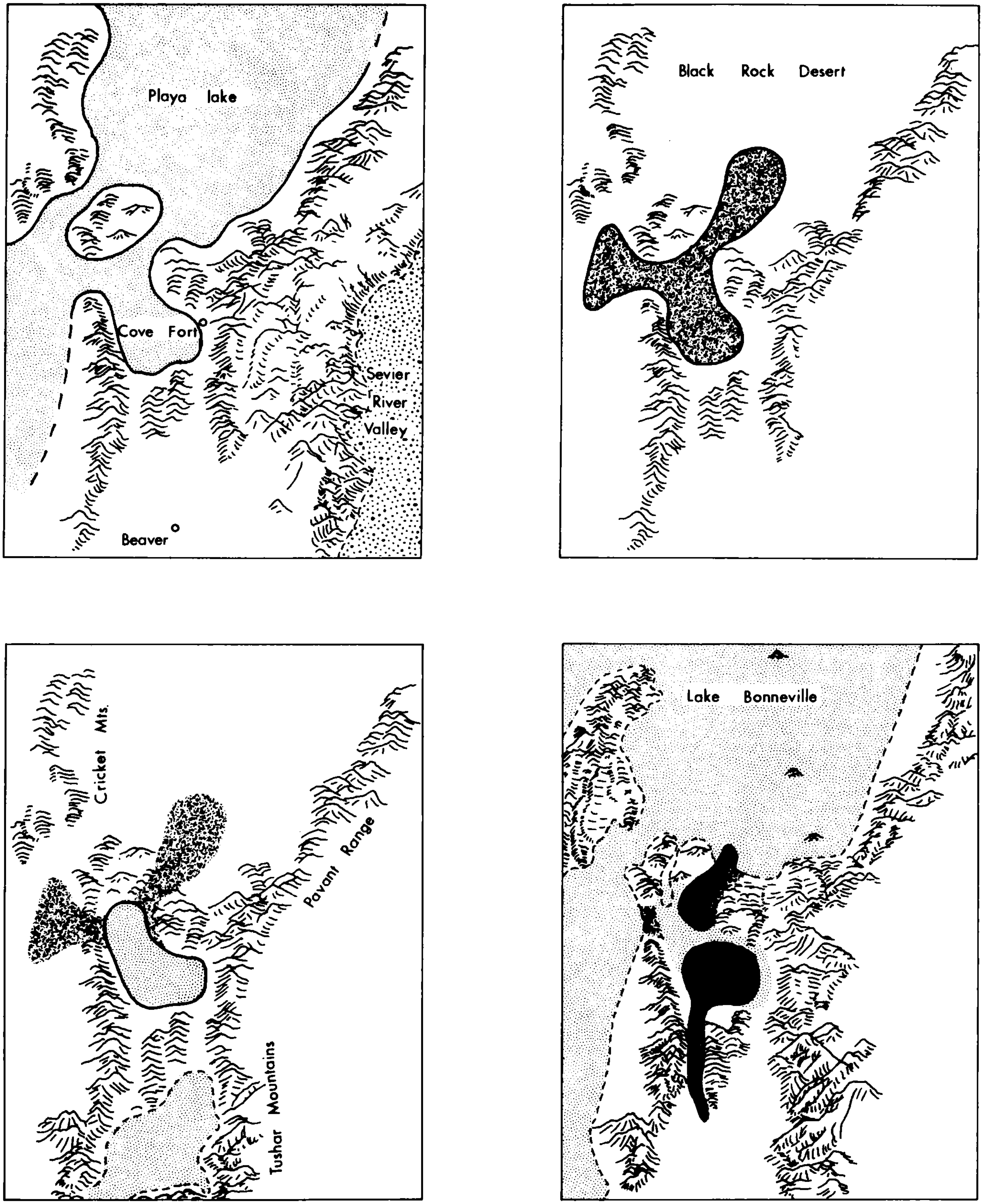


FIGURE 13. A.—Schematic physiographic map showing the playa lake which deposited the Pliocene-Pleistocene carbonate units. B.—Schematic physiographic map showing extent of diabasic flows at 1 m.y. C.—Schematic physiographic map showing playas or lakes which deposited gypsum and sand units and silts and gravels in Beaver Valley. D.—Schematic physiographic map showing extent of intermediate volcanism, post-1 m.y.

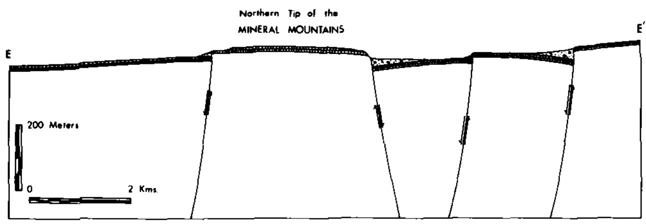


FIGURE 14.—East-west cross section across the Antelope Springs Pass.

sinuous pattern to the majority of them. Figure 15 is a series of maps showing the recent faults in other grabens throughout the Great Basin which indicate the sinuous nature of the normal faults. This pattern is dominant in areas under extensional tectonic stresses (Anderson 1951).

Although the majority of the faults in the Cove Fort area have a monotonous alignment and orientation, there are some differences from one area to the next. In the Black Point area, the diabasic olivine tholeiite lavas rest upon Paleozoic sediments or upon a thin veneer of alluvium which in turn rests upon Paleozoic units. There are approximately 40 normal faults, each of which is downthrown to the west (fig. 9). Here the faults form a series of en echelon tilted blocks and are possibly caused by the sliding or slumping of the blocks off the competent Paleozoic sediments by gravity or extensional stresses.

In the Cove Fort Field, basaltic andesites and latites rest upon poorly consolidated alluvium and gypsiferous units where there seems to be no apparent pattern as to which sides are up or down on the faults (fig. 11). This is the general rule throughout most of the study area. Even where faults cut basaltic rocks which rest on the lithified carbonate units or rhyolitic domes, there appear to be as many faults downthrown to the east as to the west.

Nearly all the cinder cones or basaltic vents within the Cove Fort and Black Rock Desert grabens fall within the prominent fault zone that trends N 15 E. Hoover (1974) indicates that the pattern of volcanism in the Black Rock Desert graben is controlled by faulting. This control is evidenced also in the Cove Fort graben as all the cinder cones lie on or adjacent to major faults (fig. 8).

In his description of the wrench-fault system that cut nearly a thousand meters of basaltic lavas in the Summer Lake area of south central Oregon, Donath (1962) infers that the fault planes are nearly vertical. Evidence for such an inference is found in the fact that fault traces appear to be near vertical at the surface and that pivotal faults are found in the area. However, in basaltic terrain it would be difficult to observe any type of fault plane at the surface other than vertical. Where there are great thicknesses of Tertiary basaltic rocks, as in the Summer Lake area, near-vertical columnar joints control the fault plane at the surface. Even a fault plane that dips 50 or 60 degrees at depth could exhibit a vertical plane at the surface in basaltic flows. Certainly the diagonal tensile strength of basaltic rocks is much greater than the tensile strength normal to the columnar joint planes.

Gilbert (1928), Fuller and Waters (1929), Herring (1967), and Stewart (1971) indicate that the average dip of normal fault planes in the Great Basin is approximately 60°. In the Cove Fort area, where normal faults cut volcanic flows at the surface, the fault planes appear to dip nearly vertically as described by Donath (1961). However, where the fault planes have been observed in outcrops of rhyolitic domes or the carbonates of Cove Creek, they appear to dip from 55° to 70° toward the downthrown block.

To accurately demonstrate the amount of horizontal deformation or extensional strain, it is necessary to have a relatively good knowledge as to the actual dips of the normal fault planes. Since a fault plane below the basaltic rocks is not directly observed in the field and since the vertical fault plane seen at the surface may not be a valid representation of the dip, some other method must be used in attempting to evaluate the true dip of the fault plane near the surface, below the volcanic rocks.

Within the Cove Fort area, horizontal gaps are commonly found between the upthrown and downthrown blocks of normal faults and may provide one method of estimating the dips of fault planes (fig. 16). The gaps appear as troughs 5-10 meters wide and nearly 5 meters deep and are 1-2 kilometers in length parallel and adjacent to the fault scarp. The floors of these gaps are filled with silt and volcanic talus to an unknown depth. Deep crevices are commonly found in the silt and talus floor of the troughs and enable one to view as much as 7 or 8 meters deeper into the gap; however, the actual fault relationships cannot be observed directly. Upon first examination, these gaps were thought to have been caused by antithetic faults parallel to the main faults, dropping a wedge of rock between the two fault planes. There are two major objections to this conclusion: (1) It is highly improbable that antithetic faults could parallel the main faults at such a close and even separation, and (2) it is also highly unlikely that the ratios $\overline{AB}$: $\overline{BC}$ would remain nearly the same as is the case with faults and gaps measured in the field.

A simple explanation for these gaps is that they may be related to a change in fault plane dip. If a normal fault plane in the subsurface has a dip of 50° and intersects a basalt flow with vertical columnar joints at the surface, an abrupt change in dip will occur at the base of the basalt flow, a change from 50° to near vertical. As extension occurs and progresses, a gap will appear between the up- and downthrown sides of the fault (fig. 16B). The horizontal width of this gap $\overline{BC}$ is the true horizontal displacement which, when divided by the vertical displacement $\overline{AB}$, gives the tangent of the dip angle of the fault plane. The average dip calculated by using these fault gaps is approximately 63°, which agrees with those observed in the rhyolitic domes and carbonate units.

Of course, these descriptions are of faults at shallow depths. Hamblin (1965) demonstrates that the dips of high-angle faults decrease with depth, but Stewart (1971) implies that they do not flatten at depths above 1000 meters. At increased depth the vertical σ_3 increases, which in turn changes the dip of the fault and increases the 2Θ angle of the conjugate shear (Cummings 1967). A two-dimensional model described by Cummings (1967) shows that at the surface the minimum principle stress, or compressive stress, is horizontal (fig. 17). At point A the greater compressive stress is vertical and is near zero. As depth is increased, the greater stress becomes vertical and is under active compression, and the lesser stress is horizontal. At point B both stresses are compressional, result-

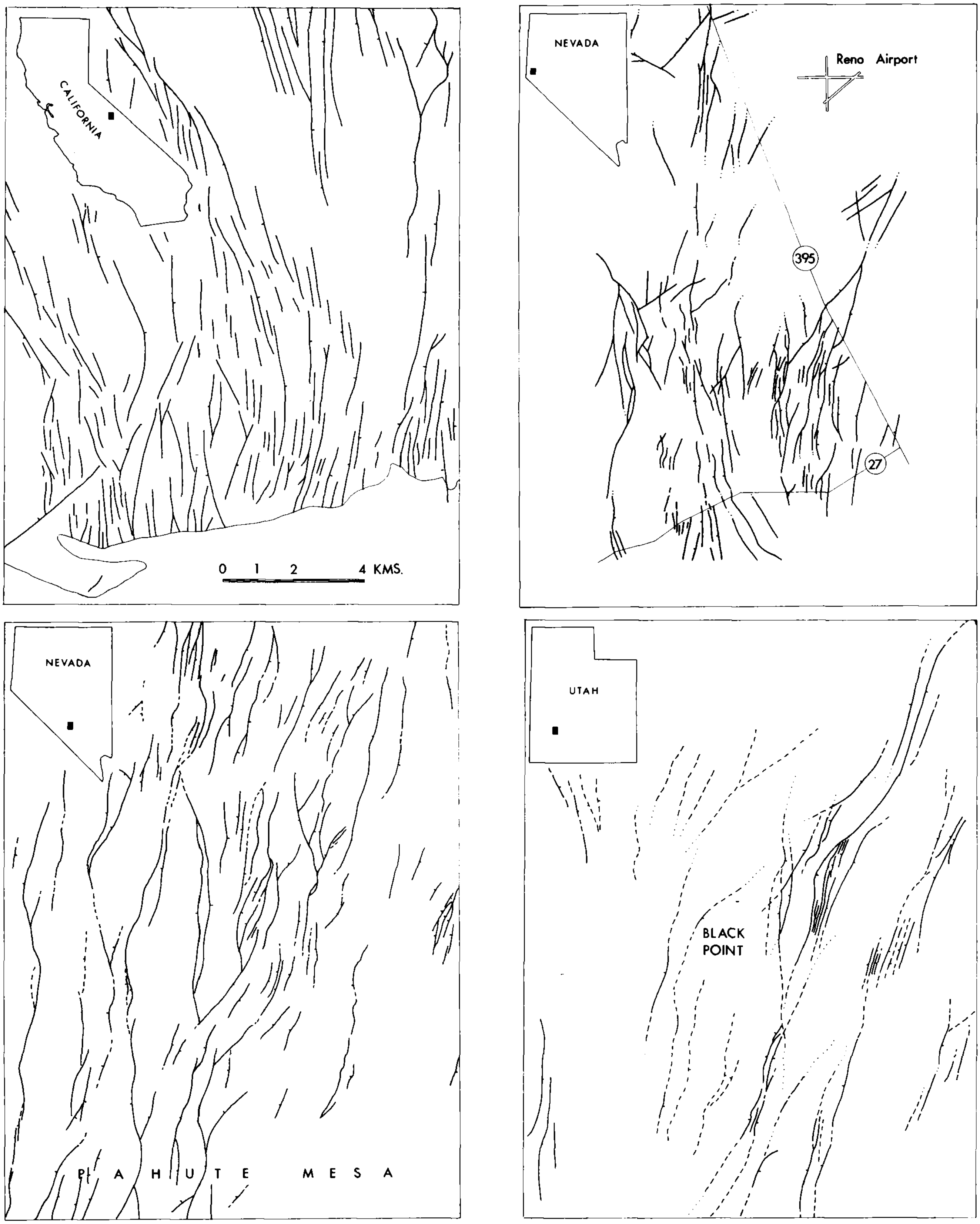


FIGURE 15. A.—Map of recent normal faults in Bishop Tuff, near Bishop, California (after Sheridan 1975). B.—Map of recent normal faults near Reno, Nevada (after Slemmons 1975). C.—Map of recent normal faults in the Pahute Mesa area, near Burnt Mountain Caldera, Nevada. D.—Map of recent normal faults in the Black Point area near Summit, Utah.

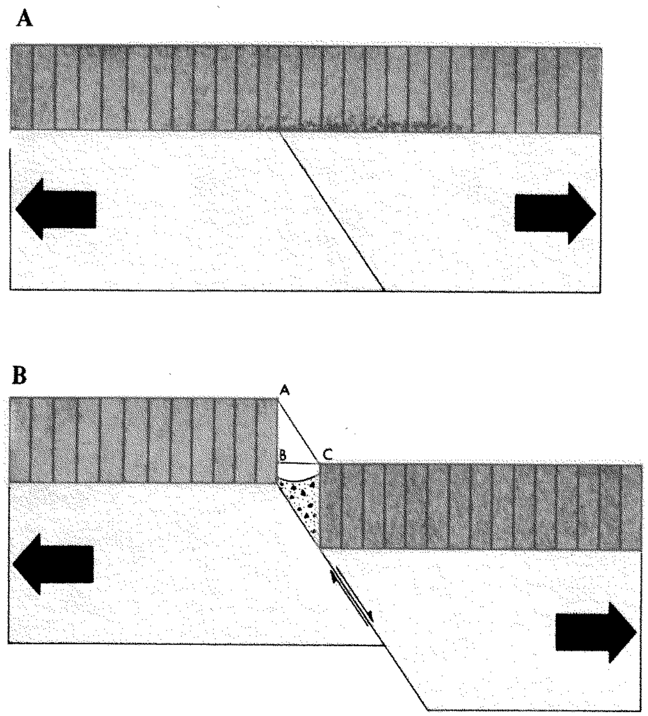


FIGURE 16 A.—Schematic cross section of a normal fault intersecting vertical columnar joints. B.—Schematic cross section showing horizontal gap (BC) produced by extension. ACB represents the dip of the fault plane.

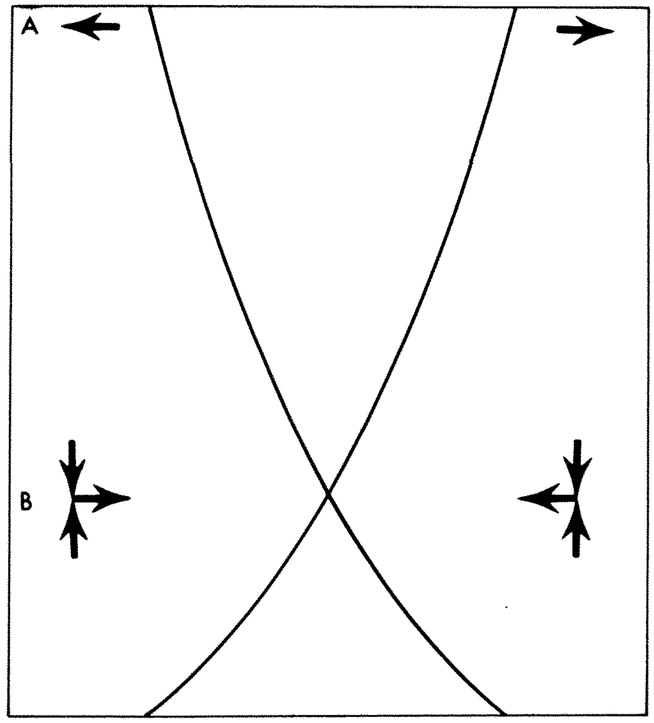


FIGURE 17.—Fracture (or fault) orientation at different depths with stress system orientation constant, a two-dimensional representation. A.—At and near surface: lesser principal stress is horizontal and tensile; greater principal stress is vertical and essentially zero. B.—At depth: both stresses are compressive; greater principal stress is vertical. Orientation of this stress system results in normal faulting (after Cummings 1967).

ing in a stress system where the dip of fractures is greater than 45°. The magnitude of the stresses then varies from the surface downward, and the dip of fracturing varies also decreasing from the vertical (Cummings 1967).

Hamblin (1965) demonstrates that reverse drag is common along faults in the Colorado Plateau Province. Reverse drag as well as normal drag commonly occurs in the Cove Fort area. Figure 18 illustrates a major fault in the Cedar Grove area where segment A represents a portion of a latite flow which has been normally deformed by the normal fault offset. Segment B represents a portion of the flow that has been deformed in a reverse direction owing to the filling of space along the fault scarp, but because of its modification by the reverse and normal drag, the horizontal and vertical displacements observed are likely distorted. It should be noted that tilted fault blocks appear to have a reverse drag relationship, and in fact both features may have a close genetic relationship.

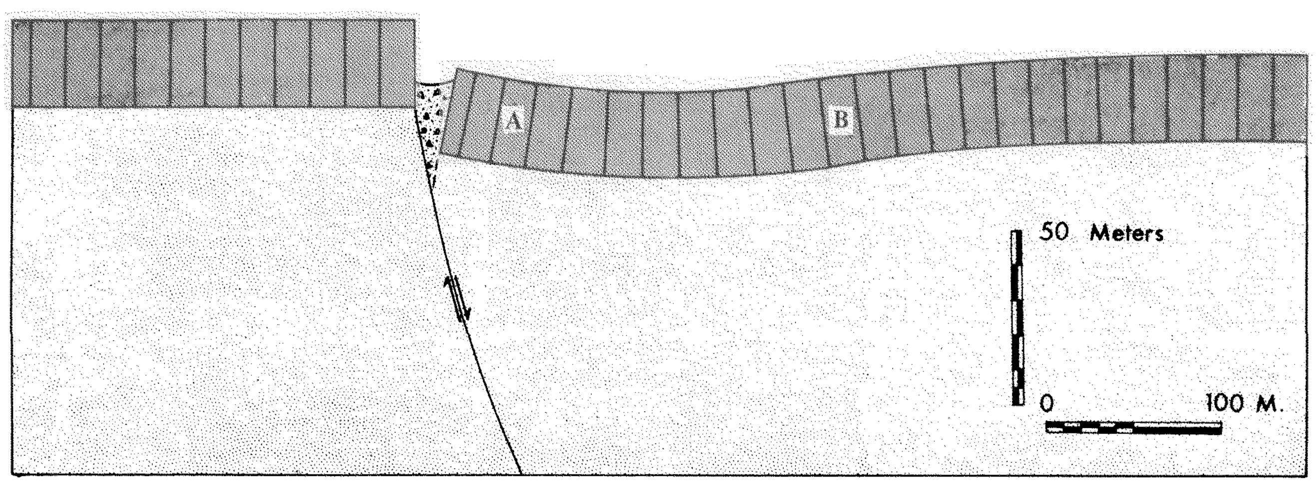


FIGURE 18.—Schematic cross section in Cedar Grove area showing normal and reverse drag on the downthrown block of the fault.

Fault Types

Within the Cove Fort area, in addition to the simple normal faults described above, there are pivotal faults, ramp faults, and wrench (oblique slip) faults.

Pivotal faults have been recognized along the western margin of the Great Basin (Sheridan 1975 and Slemmons 1975), in south central Oregon (Donath 1962), as well as in the Cove Fort area. In each of these areas, the vertical slip of the pivotal faults gradually decreases along the strike of the fault until the offset is zero. From this point the vertical slip increases on the reverse side to form a scarp facing in the opposite direction. There appear to be three major possibilities as to the mechanics involved: (1) The fault plane is vertical, and there has been a vertical rotation about some point on the fault plane as described by Donath (1962); (2) The fault plane dips in some direction, and the rotation is not vertical but at the angle of the dip of the fault about some point on the fault plane; (3) The dip of the fault plane is twisted and changes dip laterally along the strike of the fault. Thus the fault plane may swing from one direction to the opposite along the strike of the fault (fig. 19).

Adjacent to the Cove Fort cinder cone and in the Red Knoll and Twin Peaks areas are found several series of bifurcated faults which appear to be sheared. They are referred to as ramp faults because of the appearance of en echelon ramps along the strike of the main fault (fig. 20). Bateman (1965) indicates that as these ramps continue to shear, small-scale thrusting occurs near the surface.

In the Burnt Mountain Field and the Crater Knoll Field, the prominent conjugate shear patterns appear to have not only normal extensional deformation but also a minor amount of left lateral strike-slip movement, indicating the possibility of a prominent N-S compressive stress component. It is interesting to note that in a microseismic survey of the Cove Fort area, several percent of the first motion studies indicated strike-slip movement and thrusting as well as normal movement (James Olsen, pers. comm. 1975).

Mechanics

The principle stress component σ_1 in the Cove Fort graben is an extensional stress in an east-west direction, perpendicular to the strike of the normal faults (Anderson 1951). At low confining pressure or at near atmospheric pressure, brittle materials fall along planes normal to the tensile load. As the confining pressure approaches zero, the conjugate shear angle (2Θ) decreases (Anderson 1951, Bagley 1967).

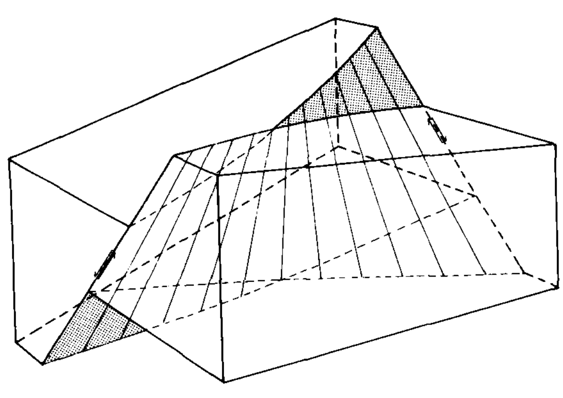


FIGURE 19.—Schematic block diagram of a pivotal fault showing the dip of the fault plane twisting as it is traced laterally along the strike of the fault.

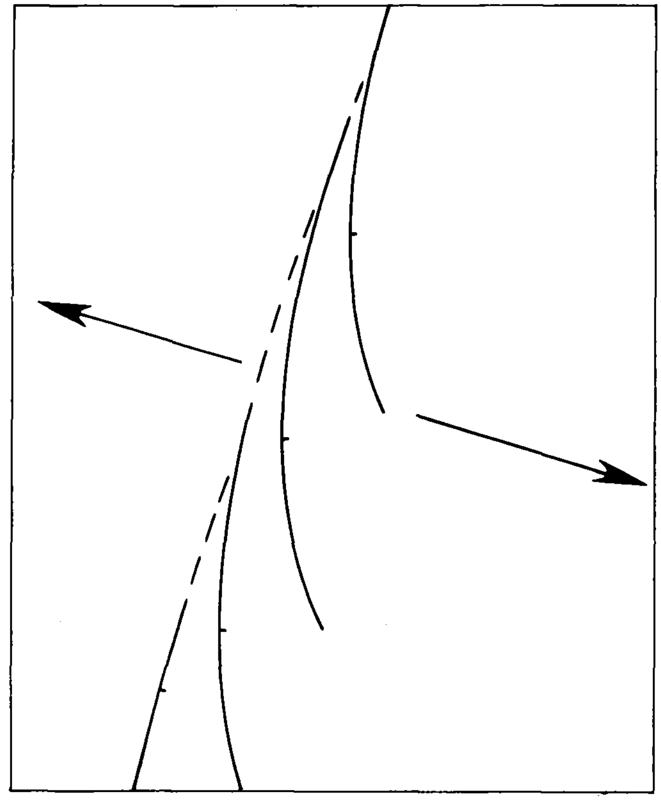


FIGURE 20.—Generalized map showing relationship of ramp faults.

Figure 21 represents a series of Rose diagrams of the strike directions of faults in the Cove Fort area. For the most part these diagrams are unimodal representing a low 2Θ angle or no conjugate fault system. In the Burnt Mountain and Crater Knoll fields, however, a bimodal distribution of strike directions may be seen (figs. 21C and D). The Burnt Mountain Field has a conjugate system of intersecting faults of approximately 60° whereas the Crater Knoll Field has a 50° conjugate pattern. There seem to be three possibilities as to the origin of these conjugate shears or 2Θ angles: (1) They may be an inherited fault system from the basement complex. (2) The large 2Θ angle could be caused by normal faulting at depth under a large confining pressure and later being exhumed. (3) A principal north-south compressional stress σ_2 may have been great enough in these zones to create a large 2Θ angle and produce wrench faulting.

Donath (1962) states that a conjugate relationship is proved only if the sense of displacement is correct for each shear and, more important, if it can be demonstrated that the shears developed at essentially the same time. Contemporaneity of origin is the key to structural analysis in general, for it indicates that the structures developed in, or at least are related in some way to, a common stress system. Demonstrating the contemporaneity of origin of two sets of faults is, of course, a difficult task if there is no accurate method of dating such events. In the Burnt Mountain and Crater Knoll fields, the conjugate shear

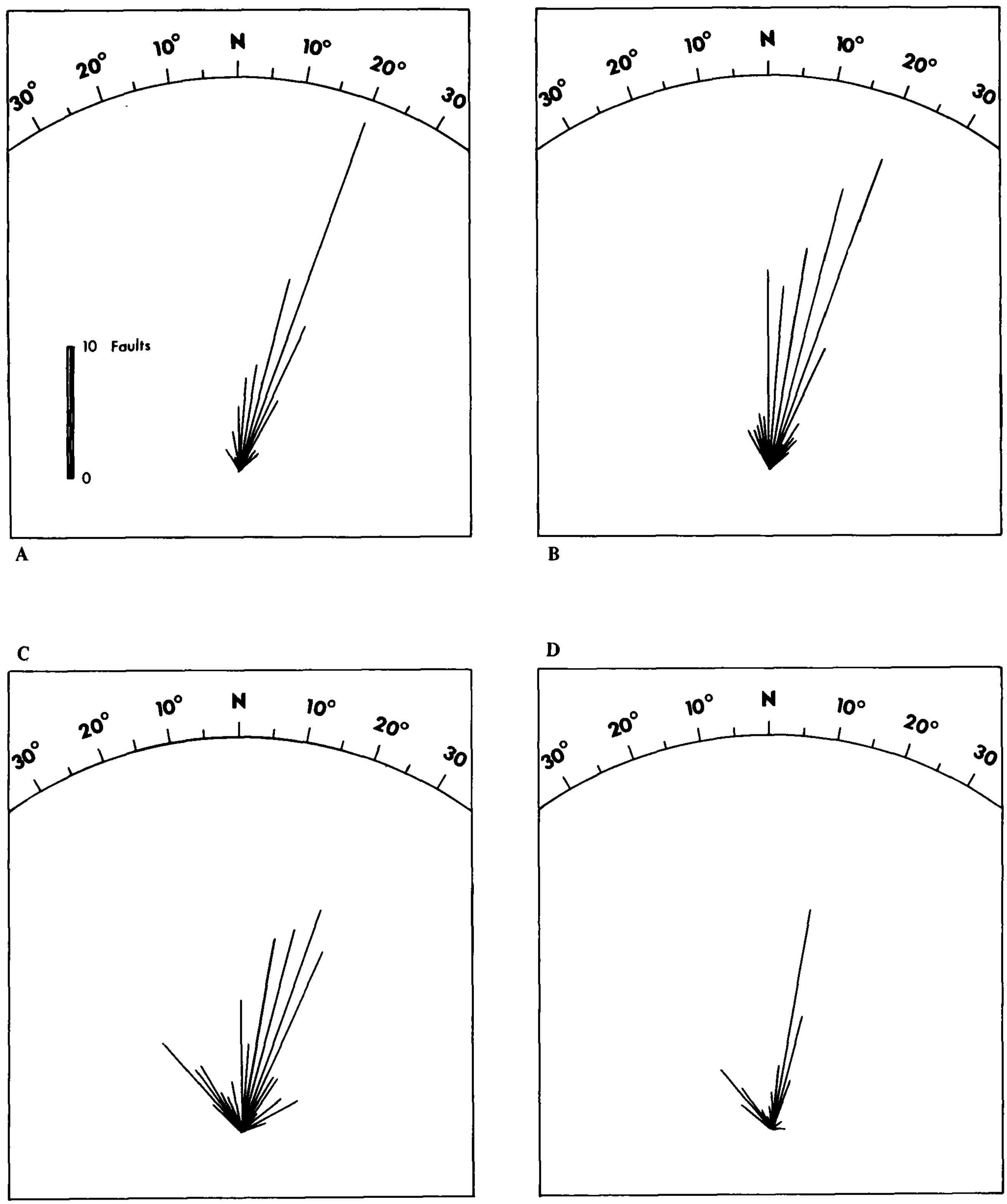


FIGURE 21. A.—Rose diagrams of strike direction of faults in Cove Fort Field. B.—Rose diagrams of strike direction of faults in Black Point area. C.—Rose diagrams of strike direction of faults in Burnt Mountain Field. D.—Rose diagrams of strike direction of faults in Crater Knoll Field.

systems cut relatively young basaltic lavas, thus suggesting contemporaneity of origin.

The unimodal direction of the fault strikes is so distinctive that throughout the Black Rock Desert and Cove Fort grabens the two zones of conjugate shear stand out. Since the basaltic and andesitic lavas have never been buried to any great depth, the large 2Θ angles either are inherited from the basement complex or are caused by a wrench system. Intuitively, it seems that a conjugate pattern would have a difficult time being transmitted through poorly consolidated, incompetent valley fill even though incompetent materials deform in much the same way as do competent materials (Hubbert 1951). If a north-south maximum principal compressional stress could be modeled for these two specific zones, wrench faulting would certainly appear to be a good possibility for the origin of the conjugate shear.

From the mapped fault and fault dip estimates, stress trajectories and strain diagrams have been calculated. Stress trajectories have been described in some detail by Anderson (1951), Hubbert (1951), Ode (1957), Donath (1962), and Cummings (1967). Figure 22 represents a series of stress trajectories of the Cove Fort area.

If an east-west regional tensile stress is responsible for the normal faulting in the Cove Fort area, the stresses should be transmitted monotonously, if the area is homogeneous. The faults shown on figure 8 indicate, not a uniform direction of strike, but deviations from the general N 15° E trend. Near the margins of the Mineral Mountains and the area around the Cudahy and Twin Peaks rhyolitic domes, the faults seem to be deflected toward these structures. When plotting the two principal stresses, σ_1 and σ_2, for these faults, two anomalous structural bodies are found (fig. 22).

Cummings (1967) described a similar structural feature in and around the Timber Mountain Caldera, Nye County, Nevada. In this area, which is also under an east-west regional extensional stress system, the presence of the caldera acts as a hole in the structural plate, changing the boundary conditions and the stress distribution. Figure 23 shows the orientation and relative magnitude of the principal stresses found at various points around the hole. The stippled areas represent zones where no tensile fractures should occur or at least where σ_1 is at a minimum. In these zones $O \leqq \sigma_1 < S$ where S equals the regional stress and tensile strength. Figure 23 also shows the stress distribution and trajectories in the Timber Mountain vicinity (Cummings 1967).

In the stress trajectory diagram of the Cove Fort area (fig. 22), the two voids do not represent holes or calderas, but structurally they behave in a similar manner. The oblong void in the southwest represents the Mineral Mountains granitic body, and the near circular void in the north represents a structural body in the Cudahy Mountains and Twin Peaks area. The Cudahy Mountains and Twin Peaks are a series of rhyolitic domes and flows dated at 2.3 ± 0.15 m.y. (P. D. Rowley 1975, written comm. to M. G. Best, of dates obtained by Harold Mehnent). These rhyolitic domes—or possibly a shallow intrusion below the domes—behave in a similar manner to the Mineral Mountains and the Timber Mountain Caldera. Emphasis must be made that no caldera has been described in the Cove Fort area. There are, however, similarities in the boundary conditions and the stress distributions of these two regions.

The Mineral Mountains may be viewed as a structurally competent body with a great enough tensile strength dif-

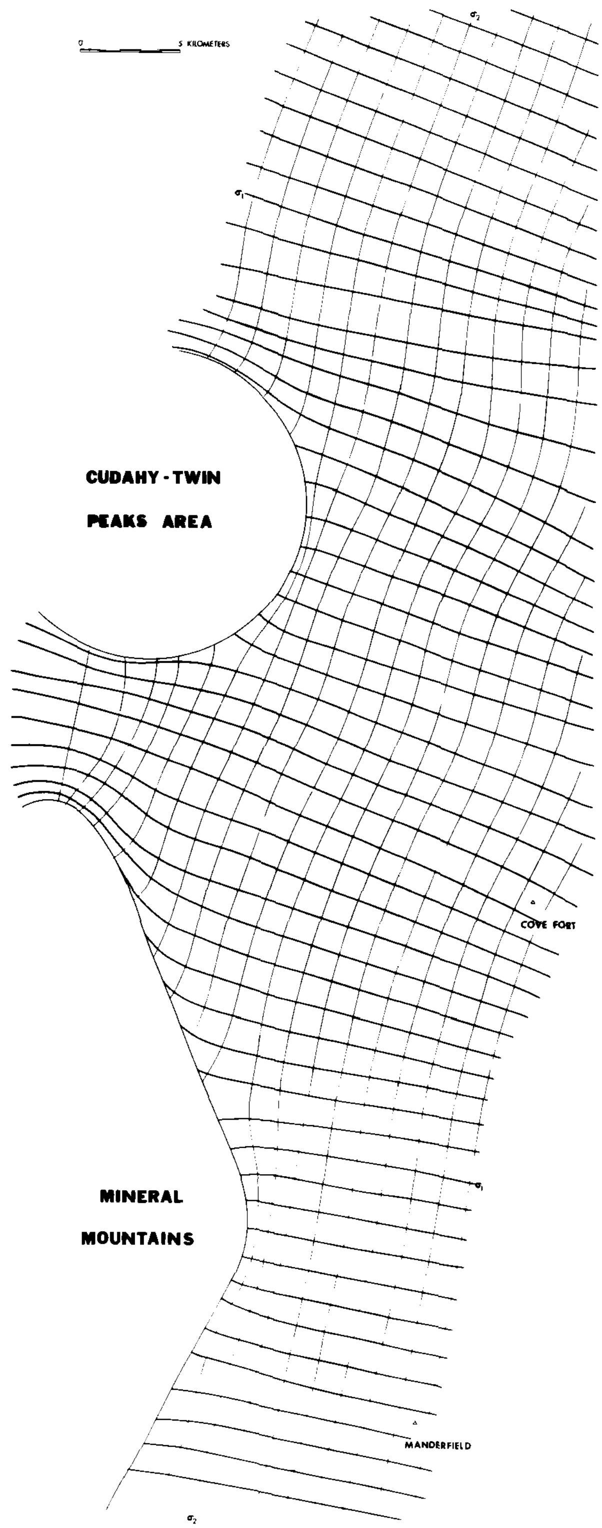


FIGURE 22.—Map of principal stress trajectories in the Cove Fort region. Wide east-west lines represent σ_1 and thin lines represent σ_2.

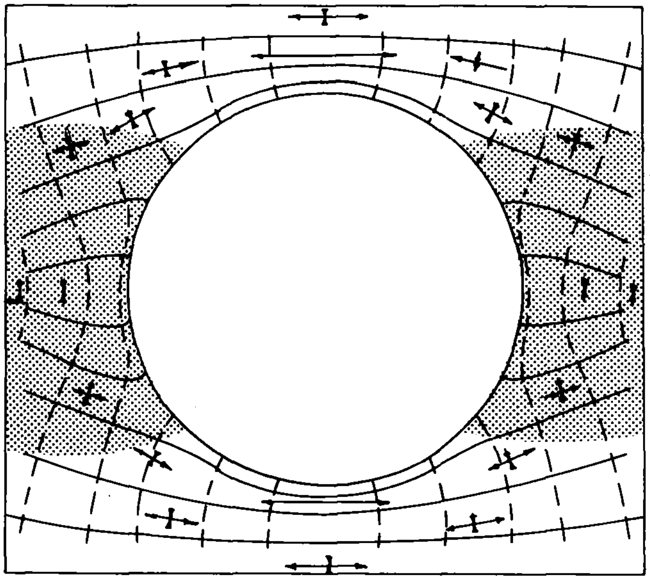


Figure 23.—Map of principal stress trajectories in vicinity of hole. Solid lines represent directions of σ_1 and dashed lines represent directions of σ_2. Superimposed are the orientations and magnitudes of principal stresses at various points around the hole. Arrows show directions of stress. Scale is arbitrary unit length of principal stresses; unity = S, where S is regional stress and tensile strength of rock. Stippled pattern represents area where $O \leqq \sigma_1 < S$ (after Cummings 1967).

ference between it and the surrounding material within the grabens to deflect the stresses and thus the resulting strain or deformation. There appears to be a similar body in the Cudahy Mountains-Twin Peaks area; however, this latter body may be in the subsurface, below the rhyolitic domes. (Note that the stress trajectories are not completed on the west side of the Mineral Mountains as no field work or mapping was undertaken there.)

Within the Cove Fort Field, the vertical displacements of the faults are shown in figure 24, and figure 25 is a strain diagram of the same area. In this field the stress pattern is nearly uniform. The vertical displacements of the faults in the field were measured and summed up on 1.6-kilometer traverses along each σ_1 trajectory. The bars represent the magnitude of the vertical displacements for each 1.6-kilometer segment of the σ_1 trajectories within the Cove Fort Field. Along each trajectory the summation of any six of these segments range from 125 to 130 meters. If the average angle of dip of the fault planes in the Cove Fort Field is 60°, then along each σ_1 trajectory, there are 7.5 meters per kilometer of east-west extension. This can be easily calculated by adding up the vertical displacements of all faults along lines running normal to the σ_1 trajectories in the field. The horizontal extension does not depend on whether or not on the faults, the east or west sides are up. It is only a function of the dip of the fault plane and the amount of vertical displacement.

The uniformity of strain diminishes north and south of the Cove Fort Field within the stippled zones (fig. 23), especially in the Crater Knoll and Burnt Mountain fields. In these fields, fault displacements are much greater than in adjacent areas, and the prominent conjugate shear patterns are found.

In the Cove Fort Field, the relative rates of recurrent

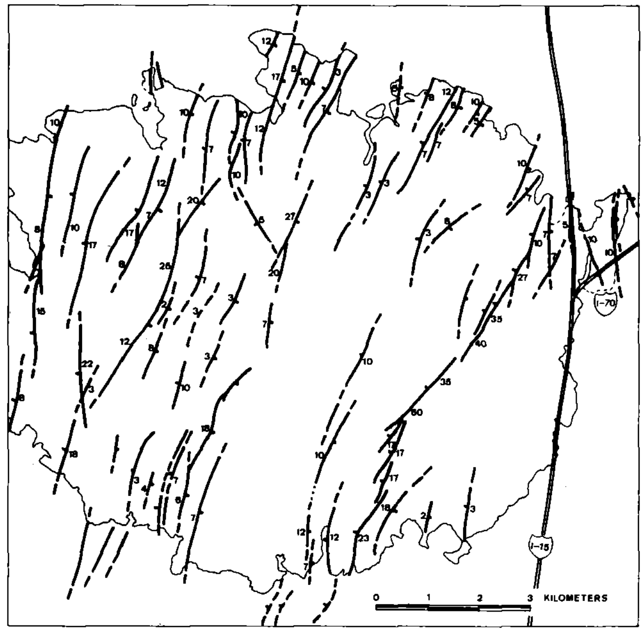


Figure 24.—Map of Cove Fort Field showing normal faults and their vertical displacements in meters.

movement along an individual fault may be measured by dating the lava flows cut by the fault and measuring the amounts of displacement at each flow. By this method, Hoover (1974) concludes that the present rate of displacement in the Black Rock Desert fault zone 50 kilometers north of Cove Fort is 20 times that in the Beaver Ridge volcanic episode, approximately 1 m.y. ago. However, this does not mean that the rate of faulting is increasing with time; it indicates only that some zones of

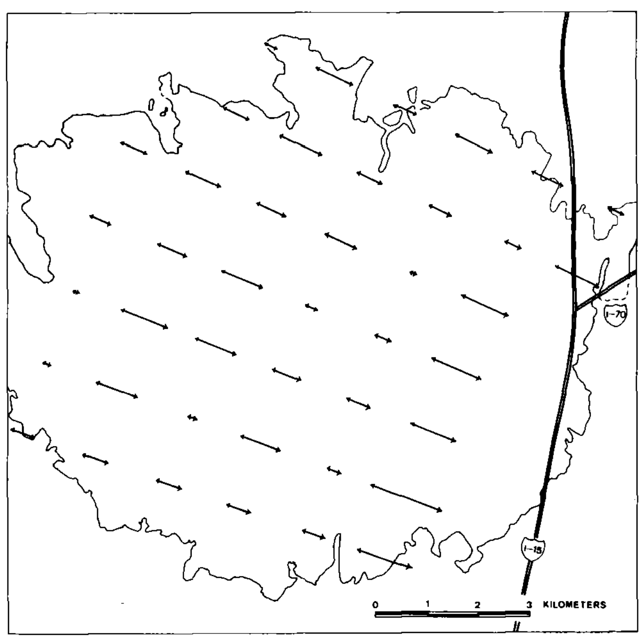


Figure 25.—Map of Cove Fort Field showing relative strain in 1.6-kilometer segments of the σ_1 trajectories. Scale is arbitrary unit length of principal stresses.

faulting are more active than other zones during a given period. Such disparity appears to be a dominant factor in grabens throughout the Great Basin.

In the Cove Fort Field, older flows have been much more deformed than younger flows (fig. 8). Intuitively, this would seem obvious, the greater deformation being a function of time. But in contrast, the lavas along the northwestern arm of the Black Rock Field have a conspicuous lack of deformation. Even though these flows are significantly older than the Cove Fort flows, the fault density is much lower in the Black Rock Field. This variation indicates either that there is a variation in the stress in the two areas or that the resultant strain or deformation is not homogeneous at any given time.

MICROSEISMICITY

A microseismic survey of the Cove Fort area was completed in the summer of 1975 by James Olsen of the University of Utah (pers. comm.). Figure 26 is a plot of the epicenters in the Cove Fort region which indicate that the area is seismically active. Note the density of epicenters northeast of the thorpe at Cove Fort. Throughout the remainder of the region epicenters are sparse, and along the west arm of the Black Rock Field, there are no epicenters. Careful study in the field and with aerial photos shows few recent fault scarps in the seismically active zone, whereas 8 kilometers to the west fault scarps are seen commonly even in the alluvium.

FIGURE 26.—Microseismic epicenter plot and recent normal faults in Cove Fort area (after Olson 1976).

Seismicity appears to be demonstrated in two ways: (1) by using seismic techniques, and (2) by studying and evaluating faulting. For the past one million years, the amount of extensional deformation in the Cove Fort area is well recorded in the volcanic fields. The greatest amount of deformation is found in a north-south trending belt that extends from the Beaver Valley graben north through the Cove Fort area into the Black Rock Desert. Specifically, the Burnt Mountain and Crater Knoll fields show the greatest number and amount of displacement of the Quaternary faults. These areas, however, appear to have little microseismic activity, which certainly indicates some discrepancy between the microseismic activity during the summer of 1975 for the relatively short period of a few weeks and the entire Quaternary record.

Allen (1975) argues that the geologic record, and the late Quaternary history in particular, is a far more valuable tool in estimating seismicity and seismic hazards than has generally been appreciated. "No amount of sophisticated statistics or extreme value theory can throw much light on the nature and frequency of large events based on a time sample that is too brief to include any such events unless a specific physical model is assumed" (Allen 1975:1041). It appears that the microseismic epicenter plot shown in figure 26 indicates only the microseismic activity during a part of the summer of 1975. In a year or in a hundred years, an epicenter plot may have an entirely different pattern. If, from any given period of time to the next, seismicity appears to wander, and if the plots of these events are integrated over a long period of time, the seismic activity should eventually coincide with the deformation. Of course, in the Cove Fort area, this long period of time has equaled one million years.

PETROGRAPHY

Geologically recent bimodal volcanism along the western margin of the Colorado Plateau has been described by Nash and Hansel (1975). This bimodality is comprised of basaltic and rhyolitic compositions with little or no intermediate lavas. Volcanic rocks within the Cove Fort are, however, not bimodal but range from tholeiitic basalts through basaltic andesites, andesites to latites. Rhyolitic lavas dated at 0.5 and 0.8 m.y. are found in the adjacent Mineral Mountains (P. D. Rowley 1975, written communication to M. G. Best, of dates obtained by Harold Mehnent).

The classification used for the volcanic rocks of the Cove Fort Province is based on petrographic relationships as well as chemical data. Correlation between the petrographic name and description may seem vague unless the chemical data as well are taken into consideration. Volcanic rocks in the province are classified as olivine tholeiites, quartz-bearing basaltic andesites, basaltic andesites, andesites, and latites. Figure 27 represents the modal compositions of these lavas and are average visual estimates only.

Olivine Tholeiite

Diabasic olivine tholeiites are found in the Black Rock Field, in eroded cinder cones along the eastern flank of

	Olivine Tholeiite		Quartz-bearing basaltic andesite	Basaltic andesite	Andesite	Latite	
	A	B				A	B
Phenocrysts							
Plagioclase		20 (An_{60})	15 (An_{40})	25 (An_{55})	3 (An_{55})	20 (An_{70})	20 (An_{72})
Olivine		12 (Fo_{80})	1	4	1	2	
Orthopyroxene				8	1	3	10
Clinopyroxene				6		5	12
Quartz			5				
Oxides						1	
Groundmass							
Plagioclase	50 (An_{55})	20 (An_{50})	30 (An_{50})	25 (An_{50})	40 (An_{40})	25 (An_{50})	25 (An_{50})
Olivine	15-20 (Fo_{80})	5-15	10				
Orthopyroxene				5	5		
Clinopyroxene	20	15	10	3	5	15	5
Oxides	5-10	15	10	5	15	5	5
Glass	5	5-10	20	20	30	30	20
Apatite	1	1-2					

*These modal percentages are average visual estimates of several thin sections; no point counts were taken.

FIGURE 27.—Modal composition in percentages of Cove Fort volcanic rocks.

the Mineral Mountains (fig. 8), and at Beaver Ridge in the Black Rock Desert to the north (Hoover 1974). There are two general petrographic types within these diabasic lavas: (1) a fine-grained nonporphyritic type and (2) a coarse-grained porphyritic type. Each has a diktytaxitic fabric.

Plagioclase laths are weakly zoned labradorite with cores of approximately An_{60} and rims of An_{50}. The laths are euhedral to subhedral, up to 5 mm in length, and commonly encircled or partially encircled by subhedral to anhedral augite grains. Olivine phenocrysts are easily recognized by partial alteration or replacement by iddingsite. Small magnetite cubes are seen dotting the groundmass and included in plagioclase and olivine grains and glass. The glass contains extremely fine-grained clinopyroxene and oxide specks.

Quartz-Bearing Basaltic Andesite

Quartz-bearing basaltic andesites are found in the Cove Fort flows (fig. 8). Plagioclase phenocrysts are commonly as long as 1.5 cm. They are well zoned with cones of An_{30-40} and rims of approximately An_{50}. These large laths are often corroded, containing a reaction rim of glass, oxides, and tiny clinopyroxene microlites near the outer portion of the phenocrysts. The quartz grains are extensively corroded, with deep embayments and encircled by brown reaction rims containing cpx microlites in a glassy matrix. The quartz grains are always found singly; no clusters or aggregates have been seen. Although generally anhedral, several bipyramidal crystals have been located. They are considered to be phenocrysts owing to their singular habit and occasional bipyramidal form. Nowhere do these quartz phenocrysts appear to be associated with biotites or amphibole xenocrysts. The olivine microphenocrysts rest in a groundmass of oriented plagioclase laths, augite, and magnetite grains with interstitial glass.

Basaltic Andesite

Basaltic andesite lavas are found in the Burnt Mountain, Twin Peaks, Crater Knoll, and Manderfield flows in the extreme northern and southern portions of the Cove Fort area (fig. 8). Petrographically they look very similar to the Red Knoll flows, but chemically they are quite dissimilar. These lavas are strongly porphyritic with 40-45 percent of the rock as phenocrysts. The plagioclase phenocrysts are up to 1 centimeter in length, riddled with holes, and partially resorbed. The mafic phenocryts are fractured and are also riddled with holes. The clinopyroxene phenocrysts have 2 V-angles of 25° and are considered to be subcalcic.

Andesite

Aphyric andesites in the Cove Fort Province are found exclusively in Cove Creek Field (fig. 8). These nearly aphyric lavas generally contain fewer than 5 percent phenocrysts; several thin sections show only 1-2 percent phenocrysts, and often in hand sample none are visible.

The plagioclase phenocrysts are generally less than 1 millimeter long, often rounded, and partially resorbed with a frothy glass filling the spaces. Encircling these plagioclase laths may be found glassy rims with included plagioclase and oxide microlites. The orthopyroxene phenocrysts are hyperthene with a similar glassy reaction rim and included microlites. The groundmass contains a great deal of glass with plagioclase, magnetite, and pyroxene microlites. The pyroxenes commonly are small splotches in the glassy matrix.

Latite

High potassium latites are found in the Cedar Grove and Red Knoll fields (fig. 8). They are the most siliceous flows within the Cove Fort Province (60-61 percent SiO_2). The lavas are strongly porphyritic, with 30-45 percent phenocrysts in an extremely fine-grained groundmass. The Red Knoll lavas have approximately 15 percent more phenocrysts, but their silica content is 3-5 percent lower than the Cedar Grove lavas.

The plagioclase phenocrysts are subhedral to euhedral, weakly zoned, fractured laths up to 3 centimeters in length. Some of them are partially resorbed. The clinopyroxene phenocrysts are subhedral, often elliptical, subcalcic augite. They have the same general subhedral, elliptical form as the hypersthene phenocrysts, both having been partially resorbed. The oxide phenocrysts are generally large anhedra and may be accumulated oxide microlites. Common in these lavas are glomerophyric clusters of plagioclase, pyroxene, and olivine phenocrysts surrounded by the fine groundmass. In several of these clusters, subcalcic augite phenocrysts are jacketed by hypersthene. The groundmass is a glassy, felty matrix of tiny plagioclase, magnetite, hypersthene, and subcalcic augite microlites.

The modal analysis does not indicate the high silica concentration or the high K_2O to Na_2O ratios found in the chemical analysis. These constituents are believed to be occult in the glassy matrix, although no microprobe analyses are available to demonstrate this.

PETROCHEMISTRY

The Quaternary lavas within the Cove Fort volcanic area range in chemical composition from olivine tholeiites with a relatively high concentration of aluminum, through basaltic andesites, andesites, to latites with a high amount of potassium. In the major element analysis and the normative compositions of these lavas, none of the samples are nepheline normative, and all except the olivine tholeiites and one sample of the basaltic andesites are quartz normative. The weight percent of SiO_2 ranges from 48 to 62, and Al_2O_3 ranges from 16 to 18. The lavas all appear to be subalkaline and transitional between calc-alkaline and tholeiitic.

MacDonald and Katsura (1964) and MacDonald (1968) developed a system of subdividing suites of basaltic lavas into either alkaline or subalkaline fields according to the weight percents of $Na_2O + K_2O$ and SiO_2. Irvine and Baragar (1971) modified the boundary line of MacDonald (1968) with the addition of empirical data to form a nonlinear boundary. Figure 28 is a plot of the Cove Fort lavas with the addition of the averages of the basaltic rocks in the Black Rock Desert taken from Hoover (1974). The solid line represents Irvine and Baragar's (1971) modification of MacDonald's (1968) boundary represented by the dashed line. It is evident that the Cove Fort and Black Rock Desert lavas fall within the subalkaline field. Figure 29 is a modification of the ternary diagram of Yoder and Tilley (1962) by Irvine and Baragar (1971) with the dark-solid line representing the boundary between the alkaline and subalkaline fields on the Ne′, Ol′, Q′ plot. Again the lavas from the Cove Fort area and the averages

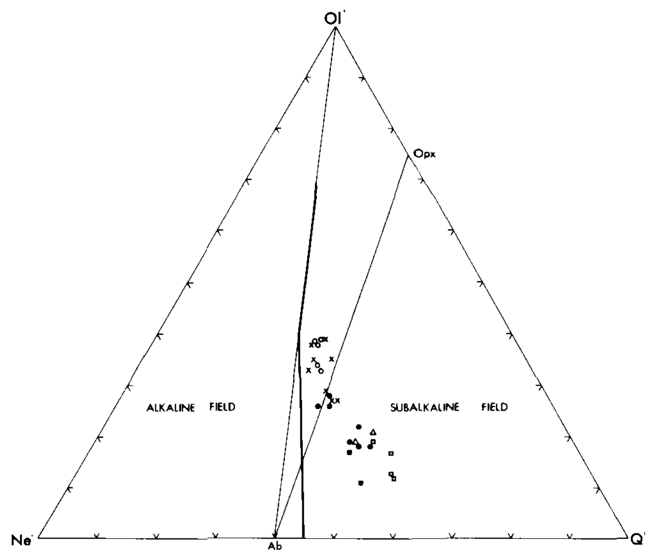


FIGURE 29.—Ol′ - Ne′ - Q′ projections of tholeiitic, alkaline, and calc-alkaline suites of volcanic rocks.

from the Black Rock Desert fall within the subalkaline field.

Figure 30 represents a plot of Al_2O_3 versus An/An + Ab percentage which Irvine and Baragar (1971) have utilized in subdividing subalkaline rocks into either tholeiitic or calc-alkaline fields. The lavas from the Cove Fort area fall within the calc-alkaline field, and the lavas from the Black Rock Desert are transitional. Clearly, the Quaternary lavas in the Cove Fort-Black Rock Desert region are not associated with either a subductive plate or an area under regional compressional stresses as is typical for calc-alkaline volcanic rocks in general.

Lavas of similar composition to those of the Cove Fort area have been described in other areas within the Basin and Range and the Colorado Plateau provinces by a number of authors. Lavas with chemical compositions close to that of the diabasic olivine tholeiites are found at Steamboat Springs in eastern Nevada along the western margin of the Great Basin (Thompson and White 1964), in

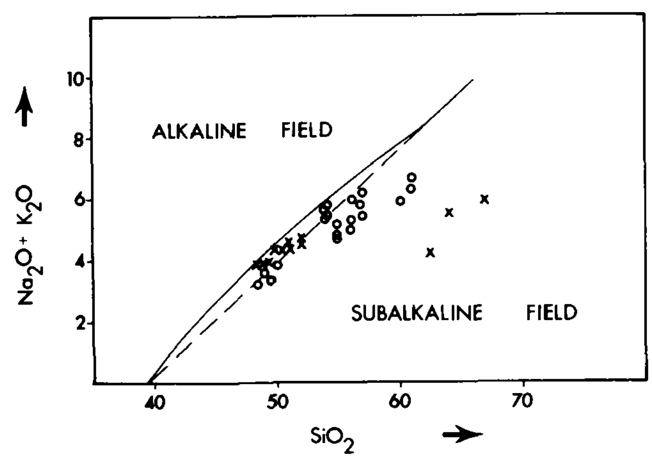


FIGURE 28.—Alkali-silica plot showing alkaline and subalkaline fields. Dashed line is MacDonald's (1968) dividing line. After Irvine and Baragar (1971).

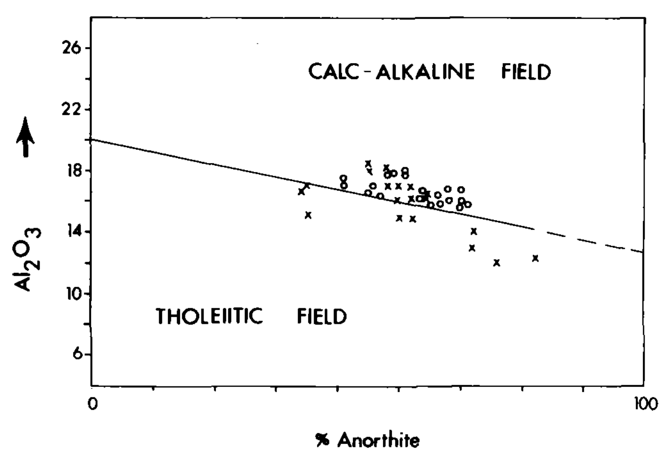


FIGURE 30.—Al_2O_3-normative plagioclase composition An plot showing tholeiitic and calc-alkaline fields.

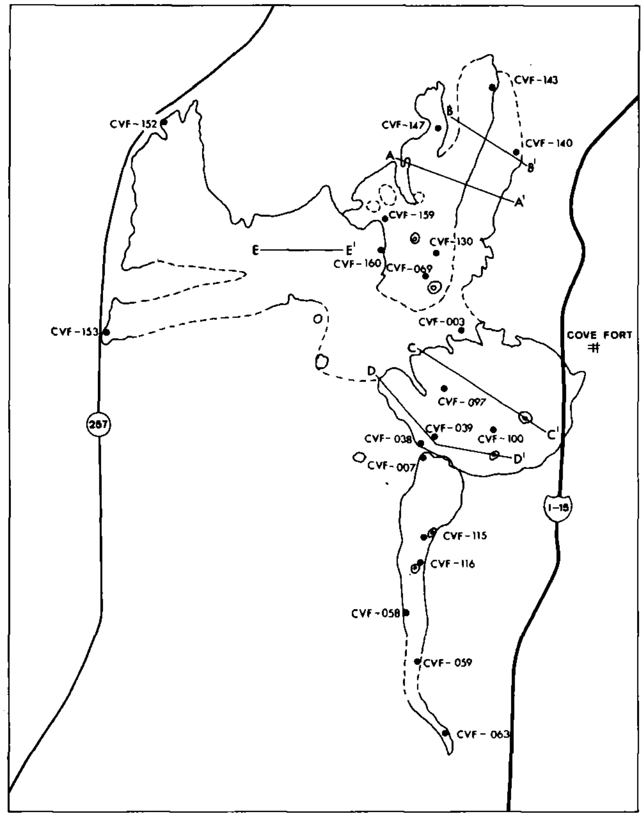


FIGURE 31.—Index map of cross sections and sample sites.

southern Nevada (Luft 1964), in southwestern Utah (Lowder 1973), and in New Mexico (Aoki and Kudo [pers. comm. to M. G. Best]). Basaltic andesites similar to those found at Cove Fort are also found in New Mexico (Fodor 1972), Nevada (Thompson and White 1964), and in southwest central Utah (Hogg 1972) where, however, they are of mid-Tertiary age. Quartz-bearing basaltic andesites in the St. George Basin, Utah, have been described by Best and Brimhall (1974) and have also been found along the western margin of the Great Basin at Cosos, California, by the writer. Latites of similar composition to those found at Cove Fort are described near Panguitch Lake, Utah (Lowder 1973), and west central Utah (Hogg 1972). Except for those lavas described by Hogg (1972), all appear to be associated with extensional tectonic activity. Eastwood (1974) and Moore et al. (1974) have described lavas in the San Francisco Mountains near Flagstaff, Arizona, that closely parallel the basaltic to intermediate volcanic rocks of the Cove Fort area.

The latite lavas found at Cedar Grove are rich in potassium and could be classed as shoshonitic latites. Although these lavas have a sodium-potassium ratio of nearly one, use of the term *shoshonitic* may be tectonically deceiving because the latites of the Cedar Grove area are not associated with a subduction zone.

CONCLUSIONS

The southeastern margin of the Great Basin is characterized by high seismicity, active normal faulting, high heat flow, and periodic basaltic to intermediate volcanism. These features are a distinguishing trait of a region under extensional stresses and are manifestations of the dynamics of the upper mantle. This area has been assessed for a clearer understanding of these dynamic processes and their resulting features along this structural margin.

Whether found along the margins or within the central portion of the Great Basin, grabens are traditionally thought of as being simple downfaulted blocks covered by thick sequences of alluvium, containing little internal structure. However, a veneer of a competent rock unit such as a basaltic flow covering a portion of a basin surface may preserve structural features, thus providing a unique opportunity to observe the dynamics and evolution of a graben. It is likely that the structural patterns apparent in the Cove Fort area are an approximation of the deformation in many other grabens within the Great Basin, especially those located along the eastern and western margins, whether or not there appears to have been recent volcanism.

Within the Cove Fort area, the primary stresses are extensional along a generally east-west trajectory. There are areas, however, where the secondary north-south compressional stresses have been great enough to cause a significant wrenching pattern and conjugate shear system. This pattern is interpreted as resulting from a deflection of the primary stresses owing to the presence of two structural bodies to the west which have a much greater tensile strength than do the grabens on the east.

The observed strain in the areas of wrench faulting is homogeneous; the strain in the Cove Fort Field appears to be uniform. In this area along any primary E-W stress trajectory there are approximately 7.5 meters per kilometer of extension, which represents only a minimum of strain for one million years.

The microseismicity patterns observed in the Cove Fore area do not coincide with recent deformation but tend to wander about. The microseismic areas are interpreted as an indication of the seismically active zone for only one particular time but may in fact have no bearing on past or future activity unless they are integrated over a significantly long period of time.

Although the usual composition of the recent volcanic rocks along the margins of the Basin and Range are sometimes referred to as being bimodal, consisting of basalts and rhyolites, the young lavas in the Cove Fort area are much more diverse. Chemical analysis of representative samples reveal bulk compositions ranging from basalts, through basaltic andesites, andesites to latites. In addition, young rhyolite flows are found in the Mineral Mountains on the western margin of the Cove Fort area. All the volcanic rocks of the Cove Fort area fall within a subalkaline field but seem to be transitional between calc-alkaline and tholeiitic.

EPILOGUE

Since the manuscript was submitted for review, a K-Ar date of 2.0 m.y. of sample CVF-177 taken from the northern portion of Black Point has been obtained (M. G. Best, pers. comm.). Several inferences may be drawn from this new date. First, basaltic volcanism within the Cove Fort area began at least 2 m.y. ago with the extrusion of the diabasic lavas, which appear to have erupted periodically for at least one million years. Second, the older diabasic lavas may be coeval with at least the younger units of the lacustrine carbonates of Cove Creek. Third, although the strain rates calculated for the Cove Fort Field are probably not affected by the 2.0 m.y. date of the Black Point lavas, any calculation of strain within the Black Point area would have to take this date into consideration.

APPENDIX

The following major element analyses have been produced by x-ray fluorescence spectrometry using the methods of Norrish and Hutton (1969). Each value is an average of two sample determinations. Table 1 is a list of the average percent of relative deviation from the mean of the two determinations for twenty samples.

The summation of the weight percents of the samples range from 99.25 to 101.26. The higher values may reflect oxidation of iron in sample preparation. Care was taken in obtaining fresh samples in the field. There is no apparent alteration, and the H_2O^+ is small.

In comparison to international standards, our values appear to agree within 1 percent relative.

The Fe_2O_3-FeO ratio is assumed to be 0.4 in the calculation of the norms.

TABLE 1

RELATIVE DEVIATION FROM MEAN OF TWO DETERMINATIONS FOR 20 SAMPLES

SiO_2	.31%
TiO_2	.42
Al_2O_3	.45
Fe_2O_3	.48
MnO	5.9
MgO	.70
CaO	.47
Na_2O	2.7
K_2O	.52
P_2O	1.7

TABLE 2

GEOCHEMICAL AND NORMATIVE COMPOSITIONS

	Diabasic Olivine Tholeiites				
Sample	1 CVF-152*	2 CVF-003	3 CVF-153	4 CVF-160	5 CVF-140
SiO_2	48.7	49.7	49.2	50.3	48.8
TiO_2	1.26	1.56	1.26	1.57	1.61
Al_2O_3	17.0	17.0	17.4	16.4	16.4
Fe_2O_3	10.2	11.1	10.2	11.0	11.4
MnO	.17	.18	.16	.17	.18
MgO	8.01	7.40	8.35	7.01	8.12
CaO	11.1	10.1	10.5	10.2	10.2
Na_2O	2.6	3.1	2.8	3.0	2.9
K_2O	.59	.70	.54	1.03	.70
P_2O_5	.29	.39	.28	.50	.43
TOTAL	100.09	101.18	100.60	101.16	100.63
Fe_2O_3	2.7	2.9	2.7	2.9	3.0
FeO	6.8	7.3	6.7	7.3	7.5
CIPW norms					
Q	.00	.00	.00	.00	.00
Or	3.51	4.12	3.20	6.06	4.14
Ab	22.57	26.21	23.47	25.04	24.50
An	33.13	30.35	33.49	28.32	29.65
Di	16.44	13.64	13.47	15.41	14.59
Hy	8.56	9.92	10.73	12.29	9.31
Ol	8.74	7.66	8.66	4.54	9.34
Mt	3.96	4.22	3.92	4.19	4.37
Il	2.41	2.95	2.40	2.97	3.06
Ap	.69	.92	.66	1.18	1.02
TOTAL	100.00	100.00	100.00	100.00	100.00
An/An + Ab	.60	.54	.59	.53	.55

Quartz-bearing Basaltic Andesites

Sample	6 CVF-097	7 CVF-100
SiO_2	56.0	55.9
TiO_2	1.37	1.39
Al_2O_3	15.7	15.7
Fe_2O_3	9.0	9.0
MnO	.12	.13
MgO	4.01	4.03
CaO	6.97	7.02
Na_2O	3.7	3.1
K_2O	2.33	2.22
P_2O_5	.68	.71
TOTAL	100.44	99.25
Fe_2O_3	2.4	2.4
FeO	5.9	6.0
CIPW norms		
Q	6.50	8.76
Or	13.79	13.30
Ab	31.11	26.94
An	19.55	22.52
Di	8.70	6.61
Hy	12.67	13.98
Mt	3.45	3.51
Il	2.61	2.68
Ap	1.61	1.71
TOTAL	100.00	100.00
An/An + Ab	.39	.46

Basaltic Andesites

Sample	8 CVF-063	9 CVF-059	10 CVF-058	11 CVF-116	12 CVF-147	13 CVF-130	14 CVF-143
SiO_2	55.6	56.3	55.5	55.9	54.2	54.0	54.5
TiO_2	1.04	1.07	1.07	.97	1.15	1.18	1.15
Al_2O_3	18.0	17.8	17.8	17.9	16.4	16.6	16.7
Fe_2O_3	7.80	7.74	8.18	7.22	8.37	8.71	8.27
MnO	.12	.11	.13	.10	.13	.14	.15
MgO	4.23	3.97	4.76	3.46	6.14	6.46	6.14
AO	8.38	8.08	8.41	7.93	8.04	8.17	8.14
Na_2O	3.5	3.5	3.2	3.2	3.5	3.4	3.7
K_2O	1.58	1.74	1.58	1.87	1.98	1.96	2.14
P_2O_5	.30	.33	.27	.35	.32	.33	.33
TOTAL	100.57	100.51	100.83	99.00	100.25	100.99	101.26
Fe_2O_3	2.06	2.05	2.17	1.91	2.22	2.30	2.22
FeO	5.16	5.12	5.41	4.78	5.54	5.76	5.54
CIPW norms							
Q	5.19	6.61	5.55	8.07	.80	.33	.00
Or	9.34	10.29	9.31	11.22	11.74	11.54	12.56
Ab	29.78	29.21	27.27	27.75	29.80	28.75	31.10
An	28.62	27.85	29.17	29.35	23.34	24.16	22.44
Di	8.94	8.23	8.68	6.81	11.77	11.35	12.54
Hy	12.46	12.03	14.22	11.29	16.37	17.52	13.68
Ol	0.00	0.00	0.00	0.00	0.00	0.00	1.55
Mt	2.99	2.97	3.13	2.81	3.22	3.33	3.19
Il	1.97	2.03	2.03	1.87	2.19	2.23	2.17
Ap	.71	.78	.64	.82	.76	.78	.78
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00
An/An + Ab	.49	.49	.52	.51	.44	.46	.42

Andesites

Sample	15 CVF-159	16 CVF-069
SiO_2	57.0	56.0
TiO_2	1.24	1.25
Al_2O_3	16.7	16.0
Fe_2O_3	7.69	7.53
MnO	.12	.12
MgO	3.55	2.72
CaO	6.97	7.92
Na_2O	3.8	3.5
K_2O	2.40	2.36
P_2O_5	.50	.48
TOTAL	100.06	100.30
Fe_2O_3	2.04	1.99
FeO	5.09	4.98
CIPW norms		
Q	6.33	8.09
Or	14.25	14.32
Ab	32.49	30.07
An	21.49	21.76
Di	8.14	12.65
Hy	10.78	6.55
Ol	.00	.00
Mt	2.97	2.97
Il	1.19	1.17
Ap	....	....
TOTAL	100.00	100.00
An/An + Ab	.39	.42

Latites

Sample	17 CVF-115	18 CVF-007	19 CVF-038	20 CVF-039
SiO_2	60.2	57.1	60.6	61.5
TiO_2	.94	.97	.87	.88
Al_2O_3	15.8	16.1	15.6	15.8
Fe_2O_3	7.21	7.35	6.11	5.94
MnO	.13	.12	.12	.10
MgO	3.62	4.24	3.03	2.86
CaO	6.27	7.52	6.20	5.67
Na_2O	3.3	3.1	3.3	3.4
K_2O	2.62	2.36	2.98	3.21
P_2O_5	.33	.31	.28	.27
Loss on Ign.	.00	.57	.38	.36
TOTAL	100.38	99.68	99.54	99.88
Fe_2O_3	1.91	1.95	1.62	1.57
FeO	4.77	4.86	4.04	3.93
CIPW norms				
Q	12.22	8.55	12.91	13.73
Or	15.50	14.15	17.84	19.14
Ab	27.88	26.52	28.63	28.61
An	20.69	23.39	19.04	18.71
Di	6.77	10.07	8.37	6.44
Hy	11.60	11.85	8.50	8.74
Mt	1.79	1.87	1.67	1.69
Ap	.78	.74	.76	.65
TOTAL	100.00	100.00	100.00	100.00
An/An + Ab	.43	.47	.40	.40

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