Magmatic, structural, and hydrothermal evolution of the Mineral Mountains intrusive complex, Utah

DENNIS L. NIELSON *University of Utah Research Institute, Salt Lake City, Utah 84108*
STANLEY H. EVANS, JR. *Department of Physics, University of Utah, Salt Lake City, Utah 84112*
BRUCE S. SIBBETT *University of Utah Research Institute, Salt Lake City, Utah 84108*

ABSTRACT

The Mineral Mountains intrusive complex records the interaction since Oligocene time between magmatic, structural, and hydrothermal processes. These processes continue to the present, as exemplified by the Roosevelt Hot Springs geothermal system, which is structurally controlled and driven by a pluton emplaced during the Pleistocene. The intrusive rocks of the complex show changes in composition from an early calc-alkaline suite (Oligocene) to a slightly alkaline main intrusive sequence (Miocene) that makes up most of the range. At about 9 Ma, the intrusive activity was associated with low-angle faulting. The oldest volcanic rocks are dated at ~7 Ma. Volcanic activity continued in the region until ~0.5 Ma and may be active still. Examples of the youngest volcanism include a sequence of rhyolite flows, domes, and pyroclastic deposits that were erupted along the crest of the range between 0.8 and 0.5 Ma. Minor basaltic flow and pyroclastic eruptions also were localized in the northern part of the range.

A major low-angle detachment fault, containing as much as 200 m of cataclasite, is preserved in the southern Mineral Mountains. This fault separates lithologies of the Mineral Mountains intrusive complex from an overlying Paleozoic sedimentary sequence. We propose that this zone developed at the brittle-ductile transition and has been exposed because of the extreme uplift of the range. The range also preserves a series of listric faults which may sole into a major low-angle fault at depth. High-angle normal faults strike both north and east. Both sets have important controls on the flow of fluid in the Roosevelt Hot Springs geothermal field. The east-west structures are presently seismically active.

Hydrothermal activity has been associated with all intrusive events in the Mineral Mountains. Base-metal mineralization accompanied the older events, whereas precious-metal mineralization accompanied the younger.

We propose an evolution of the intrusive complex, involving the interaction of magmetic, structural, and hydrothermal components. From oldest to youngest, each phase of activity reflects emplacement of magma into progressively higher levels of the crust. Uplift reflected by this progression has been quite rapid at times, as shown by fission track dating. As a consequence, the Mineral Mountains constitute a profound structural high in the region. This extreme uplift probably was caused by diapiric rise of this area under the influence of repeated magmatic intrusion.

INTRODUCTION

The Mineral Mountains are located along the western side of the Marysvale volcanic field in central Utah (Fig. 1). The mountain range is in the transition zone between the Colorado Plateau and Basin and Range provinces. The eastern limit of known thrust faults in the Sevier orogenic belt is exposed in the northern Mineral Mountains and also in the southeastern part of the mountain range (Fig. 1).

Most of the Mineral Mountains is underlain by phases of the Mineral Mountains intrusive complex (Sibbett and Nielson, 1980a, 1980b) that constitutes the largest exposed area of plutonic rocks in Utah. Magmatic activity in this complex began in Oligocene time and has continued episodically until Quaternary time. The Roosevelt Hot Springs geothermal system attests to continued thermal activity in the area.

The Roosevelt Hot Springs geothermal system is a hot-water–dominated system localized by faults and fractures cutting plutonic rocks and granulite facies metamorphic rocks. Extensive research has generated a large amount of geological, geophysical, and geochemical data for Roosevelt Hot Springs (Ross and others, 1982). That work was specifically directed toward exploration methods and formulation of conceptual models of the geothermal resource. This paper focuses on the magmatic, structural, and associated hydrothermal history. Our ideas are based on the 1:24,000 scale geologic mapping of Nielson and others (1978), Sibbett and Nielson (1980b), and Sibbett and Nielson (unpub. data). Copies of these maps are available from the senior author by request. Previous geologic mapping in the area includes the work of Liese (1957), Earll (1957), Condie (1960), Petersen (1975), and Evans (1975).

REGIONAL GEOLOGY

The Mineral Mountains intrusive complex is located in an area that has experienced magmatic and hydrothermal activity since Oligocene time. Magmatic activity through the Miocene was largely localized along a feature that has been called the Wah Wah-Tushar mineral belt (Fig. 1). This is a local segment within a broader belt of igneous rocks and related mineral deposits called the "Pioche-Marysvale belt," whose geologic relations have been described by Steven and Morris (1984). The Wah Wah–Tushar segment is an east-west–trending feature defined on the basis of magnetic anomalies that are thought to be produced by largely unexposed intrusive bodies (Mabey and others, 1978; Stewart and others, 1977; Rowley and others, 1978). Hydrothermal mineralization took place

Additional material for this article (Tables A and B) may be secured free of charge by requesting Supplementary Data 86-14 from the GSA Documents Secretary.

Geological Society of America Bulletin, v. 97, p. 765–777, 7 figs., 2 tables, June 1986.

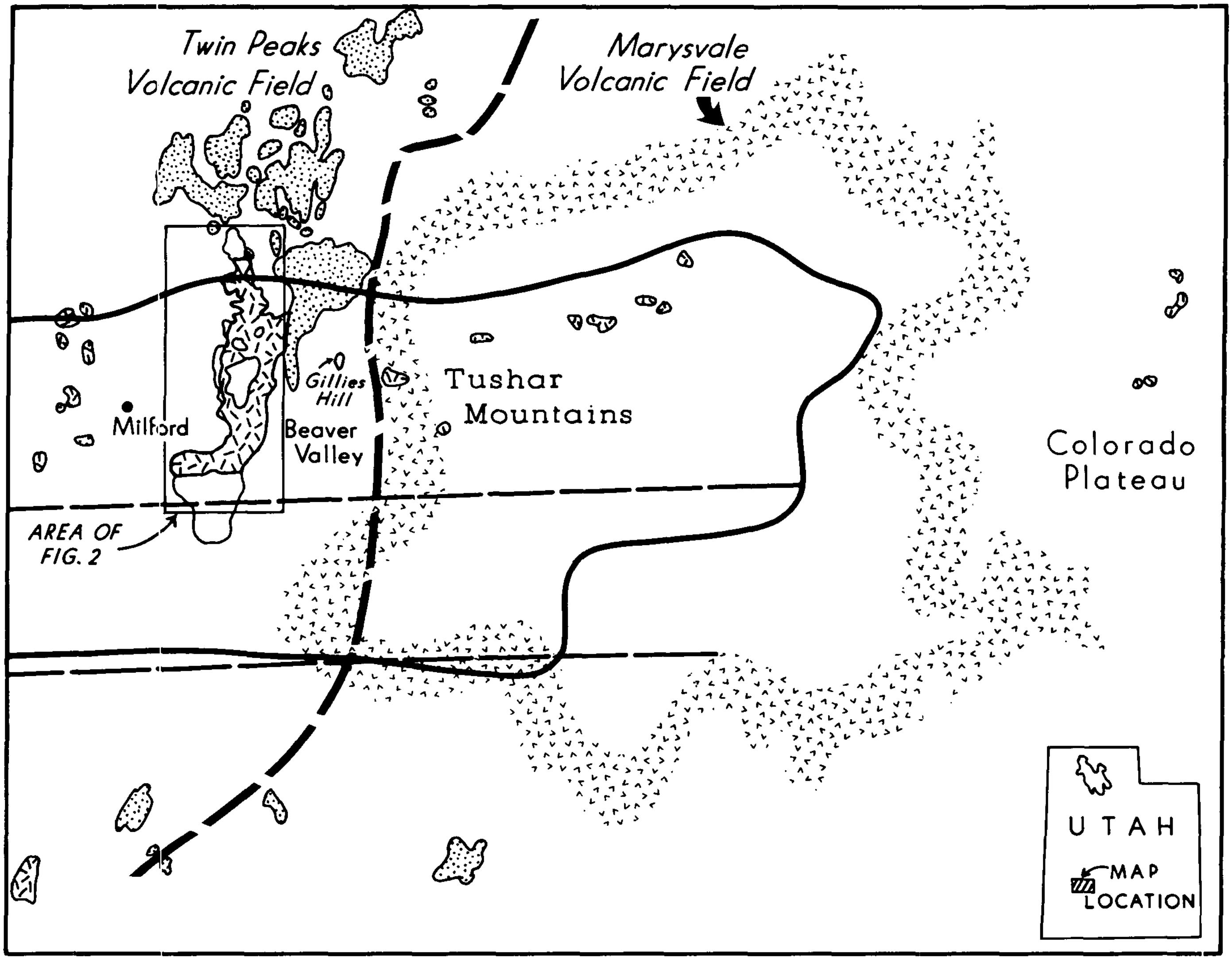


Figure 1. Map showing the regional setting of the Mineral Mountains intrusive complex (dashed pattern). Heavy dashed line is the topographic boundary between the Basin and Range and Colorado Plateau provinces. Thin dashed line defines the Blue Ribbon lineament (Rowley and others, 1978). Solid line defines the outer limit of magnetic anomalies associated with the Wah Wah–Tushar mineral belt (Mabey and others, 1978). Outer edge of check pattern shows present extent of volcanic rocks in the Marysvale volcanic field. Simplified geology is from the Geologic Map of Utah (Hintze, 1975). Dotted pattern shows distribution of rocks of the Twin Peaks volcanic field.

around many of the intrusive centers (Hilpert and Roberts, 1964; Shawe and Stewart, 1976). The Wah Wah–Turshar segment is also marked by relatively abundant east-west–trending faults (Stokes, 1968).

Volcanic activity in the Pioche-Marysvale area of Utah has been summarized by Rowley and others (1979) and Steven and Morris (1984). Steven and others (1984) give a more complete summary of the Marysvale volcanic field at the eastern end of this broad area of igneous activity. Magmatism along the east-west Wah Wah–Tushar segment began in the west and became younger eastward. Tertiary magmatic activity began about 34 Ma with the local eruption of intermediate to felsic flows and tuffs at the present site of the Wah Wah Mountains (Lemmon and others, 1973; Best and Grant, in press). In late Oligocene time, voluminous ash-flow sheets that comprise the Needles Range Group (Best and Grant, in press) were erupted from sources southwest of the Wah Wah–Tushar segment. These sheets cover ~20,000 km^2, and their distribution suggests that they were emplaced over broad plains of low relief. Following the Needles Range episodes, igneous activity continued in the central and eastern parts of the Wah Wah–Tushar segment when plutons were emplaced in the Mineral Mountains, and large intermediate-composition volcanoes formed farther east. In the Marysvale volcanic field, eruption of the Bullion Canyon Volcanics and other intertongued stratovolcano sequences formed rhyodacitic to andesitic stratovolcanoes from before 30 Ma to about 22 Ma. Between 23 and 21 Ma, high-level quartz monzonite plutons were emplaced within and near the Monroe Peak caldera at the east end of the Wah Wah–Tushar segment.

Bimodal igneous activity began in the Marysvale volcanic field about 22 Ma when silicic rocks of the Mount Belknap Volcanics and scattered basaltic rocks were first erupted in the Tushar Mountains and areas just to the east and south (Steven and Morris, 1984). Silicic activity in the Tushar Mountains continued until about 14 Ma.

At approximately 9 Ma, rhyolites were erupted in the Gillies Hill area (Fig. 1) at the north end of Beaver Valley (Evans and Steven, 1982). Related activity continued until about 5 Ma, with eruptions that took place in the Mineral Mountains, adjacent to the Blue Ribbon Lineament, and in the Sevier Plateau (Lipman and others, 1978; Rowley and others, 1978, 1981) along the southern edge of the Wah Wah–Tushar segment.

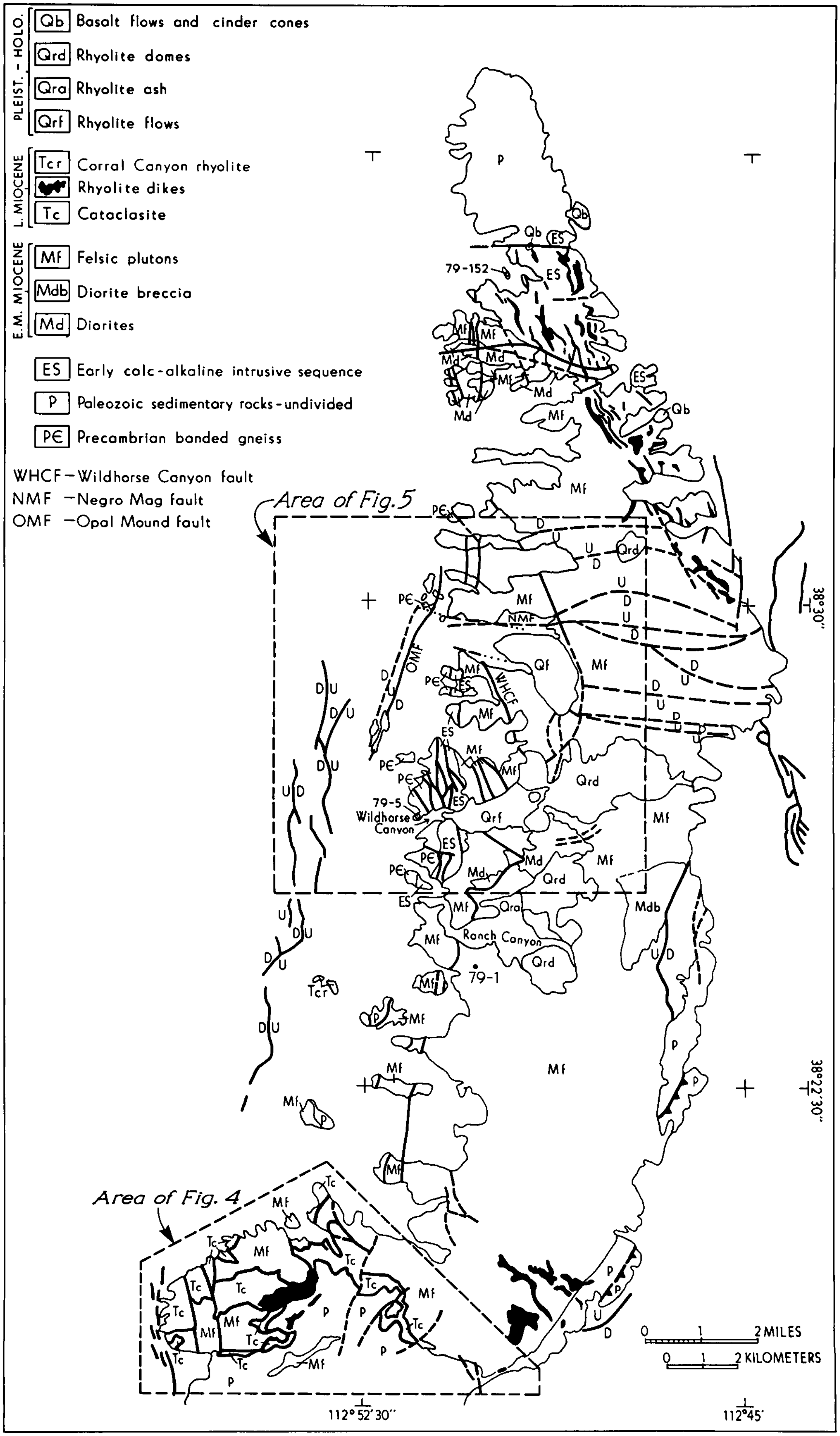


Figure 2. Generalized geologic map of the Mineral Mountains intrusive complex from Nielson and others (1978) and Sibbett and Nielson (1980a and unpub. data).

The youngest igneous episode near the Mineral Mountains started about 2.7 Ma and continued into Holocene time. Initial activity erupted rhyolite domes in the Twin Peaks area north of the Mineral Mountains (Mehnert and others, 1978; Crecraft and others, 1981). Subsequently, basaltic andesite flows were erupted 1.5 Ma ago in the Black Rock Desert north of Twin Peaks followed by bimodal basalt-rhyolite volcanism. During this period of time, rhyolite flows and domes were emplaced in the central Mineral Mountains between 0.8 and 0.5 Ma (Lipman and others, 1978).

Within this regional framework, the Mineral Mountains constitute an extreme structural high, with Precambrian gneisses as well as the batholithic equivalents of the Marysvale volcanic pile exposed. The relationships between the intrusive bodies and the associated structures and hydrothermal mineralization permit the subvolcanic levels elsewhere beneath the entire igneous belt to be interpreted with greater confidence.

MINERAL MOUNTAINS INTRUSIVE COMPLEX

The Tertiary Mineral Mountains intrusive complex forms most of the central Mineral Mountains (Fig. 2). Outcrops of Precambrian metamorphic rocks form some of the western foothills and Paleozoic carbonate rocks and quartzites occur on the southeast side of the range (Sibbett and Nielson, 1980b). Regionally metamorphosed Precambrian rocks (Fig. 2) consist of banded gneiss and minor quartzite and sillimanite schist. Aleinikoff and others (in press) have determined that the banded gneiss was last metamorphosed 1.72 Ga.

Early Calc-Alkaline Intrusive Sequence

The oldest phases of the Mineral Mountains intrusive complex consist of a coarse-grained, foliated, hornblende quartz monzonite that intruded the Precambrian rocks on the west side of the range and a medium-grained hornblende granodiorite which was emplaced into Cambrian carbonates in the northern part of the map area (ES, Fig. 2). These rocks are characterized by strong flow foliation which dips steeply and parallels contacts with older rocks. Aleinikoff and others (in press) showed that Pb/U and Pb/Th ages of these rocks cluster around 25 ± 4 Ma with initial $^{87}Sr/^{86}Sr$ ratios of 0.70548, similar to andesitic rocks erupted at about this time in the Marysvale volcanic system to the east. We consider these rocks to be plutonic equivalents of the Bullion Canyon volcanics in the Marysvale volcanic field, as previously suggested by Steven and others (1984). Chemical analyses of the early calc-alkaline series are presented in Aleinikoff and others (in press), and the analyses are plotted on an alkali-silica diagram (Fig. 3).

Main Intrusive Sequence

Rocks of the main intrusive sequence form most of the plutonic rocks of the Mineral Mountains intrusive complex (Mf, Mdb, and Md; Fig. 2). Detailed maps of the distribution of intrusive phases and petrographic descriptions of these rocks can be found in Nielson and others (1978) and Sibbett and Nielson (1980a). In Figure 2, the rocks are defined by the general sequence to which they belong. In Figures 4 and 5, however, the rocks are named according to their plutonic phase. These latter designations are consistent with the detailed maps of Nielson and others (1978) and Sibbett and Nielson (1980a).

The first plutons emplaced during intrusion of the main intrusive sequence are diorite to granodiorite in composition and are designated "Md" in Figure 2. These rocks are medium grained and nonfoliated in contrast to the coarse-grained foliated rock types of the early intrusive sequence. Figure 3 shows the more alkaline and silicic character of these rocks in contrast with the earlier calc-alkaline rocks. The stock of Md in the central part of the range (Fig. 2) is biotite granodiorite that is now surrounded by younger granitic rocks. The biotite-rich granodiorite has a uniform, fine-grained texture that is weakly foliated in some exposures. A body of medium-grained biotite hornblende diorite is exposed in the northern Mineral Mountains, where it intrudes the foliated hornblende granodiorite of the early calc-alkaline series and is intruded by biotite quartz monzonite.

Another body of rock that formed early in the main intrusive sequence is a heterogeneous pyroxene-hornblende diorite intrusive breccia (Mdb) that underlies an area of about 4 km^2 in the central part of the range (Fig. 2). Clasts and matrix in the breccia are variable in grain size, texture, and mineral composition. The diorite was pervasively sheared and chloritized after emplacement, probably during injection of the younger granites.

Six felsic plutons (Mf, Fig. 2) compose more than three-fourths of the exposed Mineral Mountains intrusive complex (Sibbett and Nielson, 1980a). Two of the plutons are quartz monzonite, three are granite, and one is syenite. They are typically medium to coarse grained, and grain size increases from the margins to the interiors of the plutons. These plutons will be discussed below in order of decreasing age. A pluton of coarse-grained biotite quartz monzonite (Tqm), forms most of the north half of the Mineral Mountains and is the largest intrusive body in the complex. The body cuts Precambrian rocks, hornblende diorite, and biotite diorite and is in turn cut by most of the other felsic phases. The other quartz monzonite pluton (Ti) is a medium-grained, porphyritic rock that is exposed at the southern end of the range. The porphyritic quartz monzonite is not in contact with the biotite quartz monzonite (Tqm), and their relative ages cannot be determined from field relations.

A pluton of coarse-grained biotite granite (Tbg) forms the southwest quarter of the Mineral Mountains. Dikes of the biotite granite intrude the diorite breccia and the biotite quartz monzonite described above, and

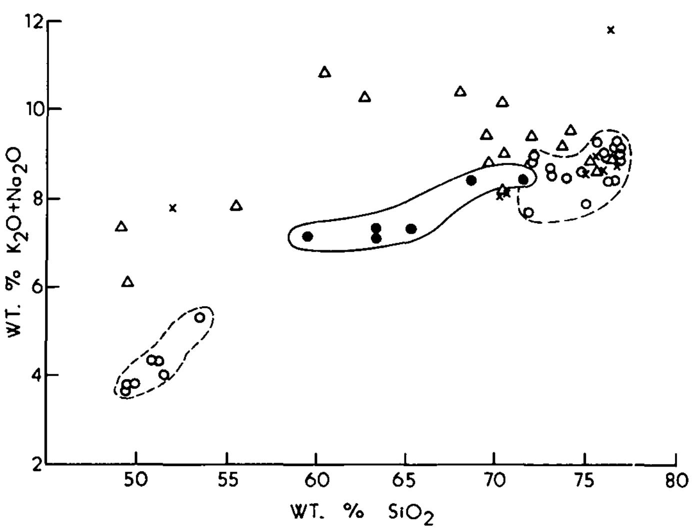


Figure 3. Alkali-silica plot for rocks of the Mineral Mountains intrusive complex. Solid dots represent the early calc-alkaline intrusive sequence; triangles, the main intrusive sequence; x's, the upper Miocene plutonic-volcanic sequence; and open circles, the lower Pliocene to Holocene volcanic sequence. Analyses from this latter sequence are bimodal as emphasized by the dashed lines.

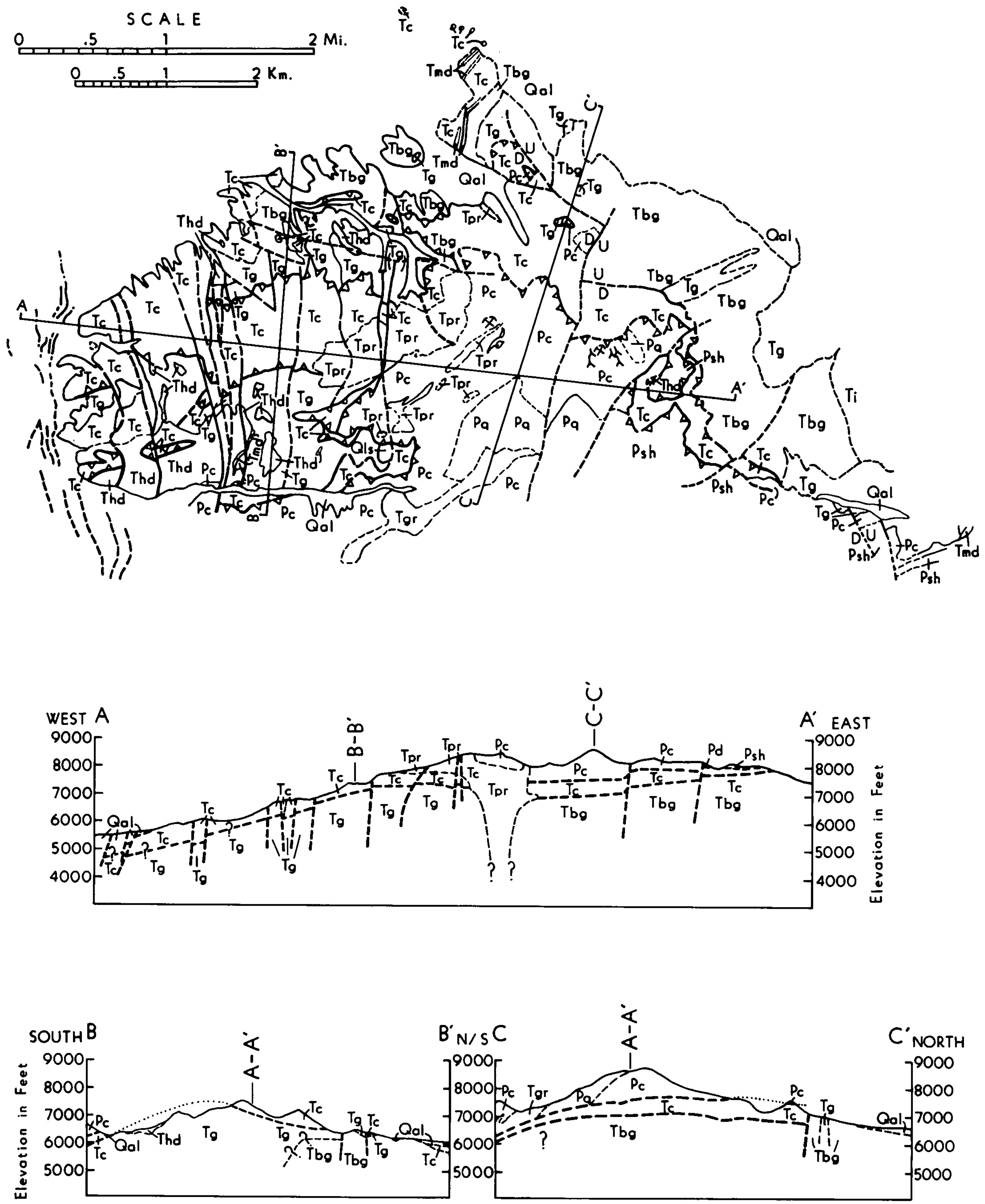


Figure 4. Geologic map of the southern Mineral Mountains. See Figure 2 for location. Open teeth define detachment plane of Cave Canyon cataclasite.

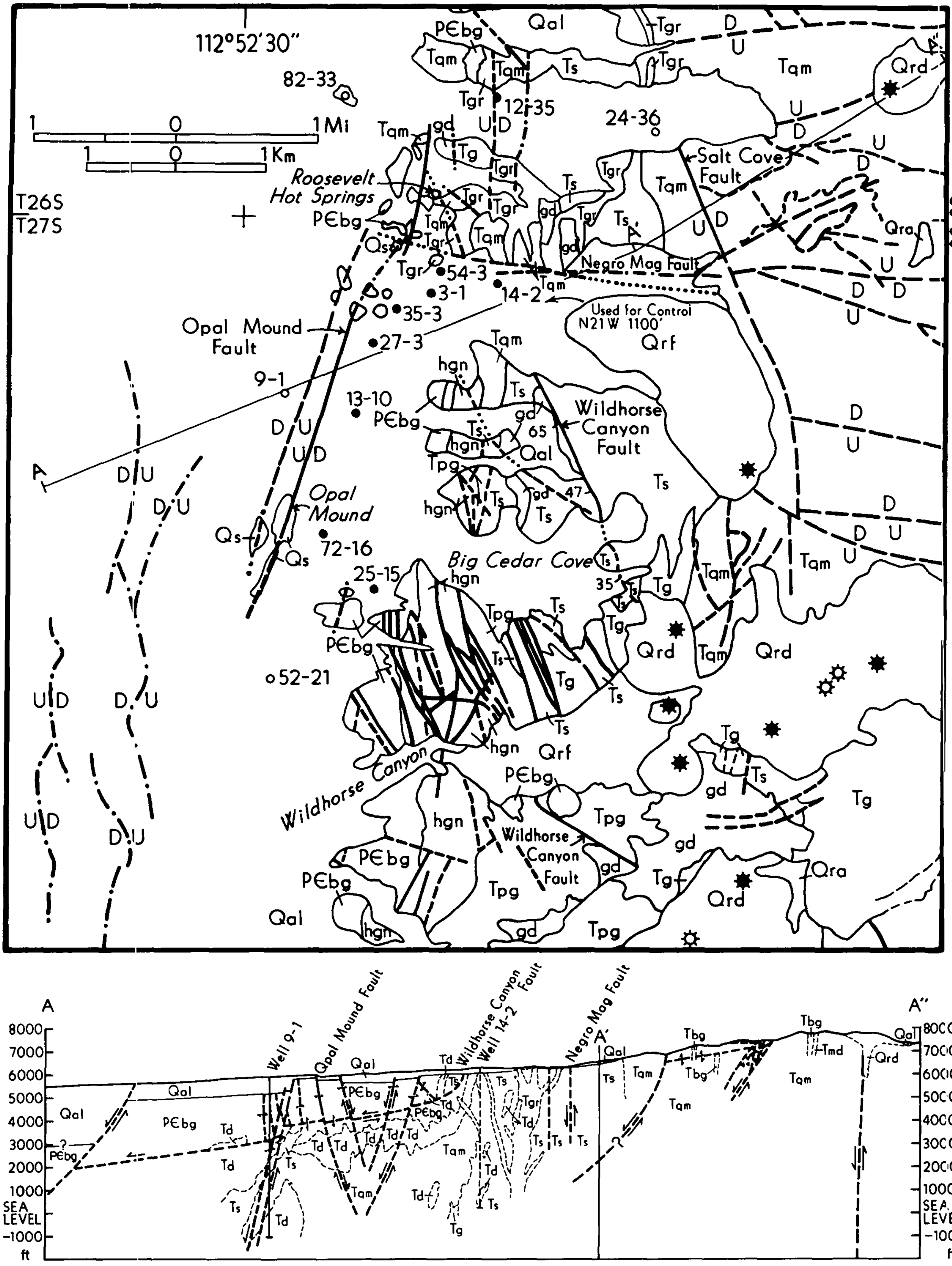


Figure 5. Geologic map of the Roosevelt Hot Springs geothermal area. See Figure 2 for location and text for unit abbreviations.

biotite granite in turn is intruded by younger bodies of leucocratic granite and the syenite described below.

A medium-grained syenite (Ts) forms an elongate stock in the west-central part of the Mineral Mountains where it intrudes the biotite quartz monzonite and the biotite granite and is intruded by leucocratic granite and fine-grained granite dikes.

A pluton of medium- to coarse-grained leucocratic granite composes most of the southeast quarter of the intrusive complex. This granite intrudes the syenite, the biotite granite, and the porphyritic quartz monzonite, and is intruded by porphyritic rhyolite dikes. The granite has the same textural and outcrop characteristics as the syenite but can be distinguished by its abundant quartz. It has less biotite than most other felsic rocks in the intrusive complex.

A fine- to medium-grained granite (Tgr) forms dikes and a small stock in the west-central part of the range. The unit intrudes all of the major plutons of the intrusive complex and is intruded by diabase and microdiorite dikes. This rock is the oldest unit in the intrusive complex to form extensive dikes.

We believe that the main intrusive sequence is broadly contemporaneous with eruption of the Mount Belknap Volcanics in the Marysvale volcanic field (Steven and others, 1984). The rocks are more alkaline than earlier rocks, but certainly are not undersaturated. This switch to alkaline magmatism correlates with the initiation of Basin and Range extensional tectonism at about this time (Rowley and others, 1979). The earlier plutons are more mafic than the later intrusive bodies. Through time, the intrusive bodies changed their general configuration from equidimensional bodies composed of coarse- to medium-grained rocks, through generally medium-grained rocks that occur in plutons with a general north-south elongation, to fine-grained phases that form dikes trending north and dipping both nearly vertical and at shallow angles to the east. This change in style represents progressive changes in the thermal and stress regime as plutons were emplaced at progressively shallower depths in the crust, apparently documenting the rise of the intrusive complex as a coherent block.

Upper Miocene Plutonic-Volcanic Sequence

Dikes of microdiorite, diabase, and porphyritic rhyolite form a bimodal igneous sequence which was emplaced about 9.0 to 9.6 Ma. Analyses of these rocks are plotted for reference on the alkali-silica diagram of Figure 3. Although crosscutting relationships between the mafic and felsic components of this sequence are not present, both intrude westward-dipping fault zones trending between N40°E and N40°W, and both are brecciated by renewed movement on those fault zones. Additional episodes of injection placed unfractured dikes in the same fault zones. The porphyritic rhyolite dikes generally occur in the northeastern part of the range, the western part around Wildhorse Canyon, the southeastern part, and in the south (Fig. 2). The microdiorite dikes are generally found in the north-central part of the range. This distribution may document the locations of several contemporaneous but separate bodies of magma. Within the Mineral Mountains, the volume of upper Miocene felsic rocks is much larger than the volume of associated mafic rocks.

The earliest evidence of volcanic activity in the Mineral Mountains area is represented by small porphyritic rhyolite flows along the western range front (Fig. 2) where they overlie gravels derived from erosion of the Mineral Mountains block. These flows have a K-Ar age of 7.9 ± 0.3 Ma (Lipman and others, 1978).

Upper Pliocene and Quaternary Bimodal Volcanic Rocks

The final volcanic episode in the Mineral Mountains started in the Twin Peaks (Fig. 1) volcanic complex about 2.7 Ma (Crecraft and others, 1981) when rhyolite domes and flows and more widespread basalt flows were erupted. Subsequently, the activity moved south into the Mineral Mountains while continuing in the Twin Peaks complex. This magmatism was also bimodal in composition; rhyolites were dominant in the Mineral Mountains, but basalts were dominant regionally. Chemical analyses of rocks formed during this episode (Evans and Nash, 1978; Crecraft and others, 1981) are summarized in the alkali-silica diagram of Figure 3.

Rhyolitic volcanism produced flows, pyroclastic rocks, and domes in the Mineral Mountains between 0.8 Ma and 0.5 Ma. The activity started with obsidian-rich, nonporphyritic flows. Subsequent eruptions produced nonwelded ash-flow tuffs, air-fall tuffs, water-laid tuffs, and surge deposits. Twelve domes formed in the central Mineral Mountains during the final stage of rhyolitic activity. Young basaltic volcanism that probably represents the youngest volcanic activity in the Mineral Mountains has formed two cinder cones and a small area of flows in the northern part of the Mineral Mountains (Fig. 2).

STRUCTURAL GEOLOGY

The structural geology has been studied both through detailed field mapping in the Mineral Mountains and by using data from deep holes in and near the Roosevelt Hot Springs geothermal system. Although the deep holes are located only in a small portion of the study area, they provide a three-dimensional perspective that is invaluable in interpreting the structural complexity of the range. Detailed lithologic logs of wells Utah State 72-16, 52-21, 14-2, (Nielson and others, 1978; Glenn and Hulen, 1979) and 9-1 (Glenn and others, 1980) have been used in this compilation.

Thrust Faults

During the Sevier orogeny, thrust faulting in Late Cretaceous time emplaced sheets from the west over autochthonous rocks in the Mineral Mountains area. Thrusts involving Cambrian carbonate and quartzite were mapped on the northern end of the range by Liese (1957). Crawford and Buranek (1945) recognized thrust faults in the Bradshaw Mountain area and at the Big Pass mine in the southern part of the range. Our study delineated thrust faults in the sedimentary rocks on the eastern side of the range where emplacement of the pluton rotated sedimentary rocks and thrust faults on end, and so the upper plate is now to the east (Fig. 2).

Tertiary Low-Angle Faults

Recent detailed mapping and acquisition of new seismic data led to the recognition of abundant important low-angle faults in the Basin and Range province (Armstrong, 1972; Proffett, 1977; Allmendinger and others, 1983; Smith and Bruhn, 1984). Low-angle fault surfaces in the Mineral Mountains are of two distinct types. The older is a major (as much as 200 m thick) zone of cataclasis that separates rocks of the Mineral Mountains intrusive complex from overlying sedimentary rocks. The other type is a series of listric normal faults that cut rocks principally of the Mineral Mountains intrusive complex.

A geologic map of the southern Mineral Mountains (Fig. 4) shows a major low-angle detachment and associated cataclasite (Tc) that is as much as 200 m thick. We named this sequence the "Cave Canyon cataclasite." The base of the cataclasite in the western part of the study area is a highly sheared detachment surface below which the rock is relatively undeformed. Several discontinuous detachment surfaces, not mapped separately, are exposed within the cataclasite. What we have classified as a cataclasite is a heterogeneous rock with earlier foliated textures cut by later nonpenetrative, steeply dipping, brittle fractures. Foliated textures are best developed near the base of the cataclasite, and the foliation is parallel the base. These include mylonites and ultramylonites with foliation defined principally by concentrations of chlorite: augen of quartz can at times be observed. We interpret these textures to indicate an earlier phase of deformation characterized by ductile flow. Superimposed on the foliated textures, and at times obliterating them, there are crush breccias to ultracataclasites, with protocataclasite dominating within the unit. This later fracturing is near vertical. These fractures were produced by later movement on the fault which took place within a brittle regime.

The cataclasite was formed almost exclusively from Tertiary plutonic rocks. Where overlying Paleozoic rocks are present the contact with the cataclasite is a well defined detachment surface. The sedimentary rocks are sheared for only a few centimetres to a metre above the detachment surface. Above this level, the sedimentary rocks are relatively undeformed. Evidence of metamorphism is generally absent along the fault contact, suggesting an allochthonous relationship with the underlying granite. The detachment surfaces above and below the cataclasite define a broad dome (Fig. 4) in which the detachment surfaces curve down to the south, the west, and the northwest. Smaller scale undulations in the fault surfaces are also present.

Much of the crest of the Mineral Mountains is an old weathering surface. Large areas of relatively flat terrain along the crest of the range result from stripping of less resistant cataclasite zones associated with low-angle faults. Due to poor exposure and absence of marker horizons in the crystalline rocks, the character of this faulting is incompletely understood.

The Wildhorse Canyon fault is characteristic of the listric low-angle faults (Figs. 2 and 5) and was first recognized by Nielson and others (1978). It is a continuous feature in the western Mineral Mountains; through the southern portion of its exposed length, it maintains a dip of ~15° to the west. It steepens north of Wildhorse Canyon, however, and dips increase from 15° to 65° in a distance of about 3 km. In the area between Ranch Canyon and Wildhorse Canyon, the offset of xenoliths indicates normal movement with a displacement of about 610 m in a S80°W direction (Fig. 5).

The upper plate of the Wildhorse Canyon fault contains a number of largely northwest-trending, high-angle, cataclasite zones found principally in the hills south of Big Cedar Cove (Fig. 5). These zones are as much as 4 m thick and dip steeply east and west. Because of the absence of marker horizons, the direction of displacement and the total amount of offset on these structures cannot be documented. South of Wildhorse Canyon (Fig. 5), it is apparent that high-angle, northwest-striking faults are present in the hanging wall of the major low-angle fault but not in the foot wall. This, as well as the localized nature of these structures, implies that the northwest-striking faults were developed in the upper plate in response to low-angle faulting through differential movement between relatively rigid blocks. Supporting evidence for this interpretation is that the northwest fault direction is at approximately right angles to the direction of movement inferred by realigning the geology of the upper and lower plates of the listric faults.

The Wildhorse Canyon and associated high-angle faults host microdiorite dikes of the upper Miocene plutonic-volcanic sequence. In some places, both brecciated and nonbrecciated dikes occupy the same zone, demonstrating several periods of dike intrusion during repeated movement on the faults. The relationships also demonstrate the contemporaneity of the low-angle faulting and the late Miocene magmatic activity.

Although the Wildhorse Canyon fault is the best exposed of the listric structures in the central Mineral Mountains, the Salt Cove fault (Fig. 5) is a parallel structure that is probably also listric in form and can be expected to flatten with depth. As shown in Figure 5, the Salt Cove fault cuts older flat faults that have been mapped along the crest of the Mineral Mountains.

In the northeastern Mineral Mountains (Fig. 2), an extensive volume of rhyolite of the upper Miocene plutonic-volcanic sequence was emplaced along northwest-striking faults parallel to the Wildhorse Canyon and Salt Cove structures. These dikes dip 60° to 90° west, but some flatten to angles of 45° or less, and therefore they are also listric. These faults also develop cataclasites similar to those in the Wildhorse Canyon fault. In addition, the rhyolite dikes commonly are either completely sheared or sheared only along their margins, indicating that offset was taking place along the fault zones during intrusion of the rhyolite dikes.

High-Angle Normal Faults

High-angle normal faults are the youngest faults in the Mineral Mountains area. Some are seismically active (G. Zandt and D. L. Nielson, unpub. data), but the recent activity of others is evidenced by offsets in alluvium and hot-spring deposits. Although alluvium on the west side of the Mineral Mountains is cut by numerous north-trending normal faults (Fig. 2), seismic-reflection and -refraction surveys (Ross and others, 1982; Smith and Bruhn, 1984) demonstrate that the range is not bounded by high-angle faults with large vertical offsets. The data show that the bedrock surface slopes uniformly to the west toward the center of the Milford Valley and that disruptions of this surface by high-angle faults are minor.

The relationships of the high-angle faults are most clearly seen near the Roosevelt Hot Springs geothermal field where mapping information is supplemented by numerous deep drill holes (Fig. 5). The Opal Mound fault is one of the youngest high-angle normal faults in the area. It offsets alluvium and has localized deposition of siliceous sinters at several times during the recent past. As seen in Figure 5, the Opal Mound fault is the eastern boundary fault of a small horst. It also serves as a hydrologic boundary that defines the western extent of the active hydrothermal system. The other side of the horst is a similarly trending fault about 0.2 km to the west that is down to the west.

Recent hot-spring activity has been concentrated along the Opal Mound fault, particularly at Opal Mound (Fig. 5), where there is evidence of at least two periods of spring activity. Opal Mound is underlain up by an older sinter of chalcedony that has been broken by movement along the fault, forming a conduit now lined by vertical flow-banded opaline sinter containing fragments of older chalcedonic sinter. The vertical conduit-fed springs deposited an apron of opaline sinter around the central chalcedonic core. Brogan and Birkhahn (1981) have mapped trenches dug perpendicular to the Opal Mound fault to investigate characteristics of the fault that might bear on the exploration for geothermal resources. They documented the offset of a bahada surface by as much as 15.6 m down to the east. The last recorded hot-spring activity along the Opal Mound fault zone was reported from the Roosevelt Hot Springs in 1957. A visit nine years later found the spring dry (Mundorff, 1970). Present activity consists of fumaroles and warm ground.

The Negro Mag fault is an east-striking, high-angle fault forming the axis of a complex graben that cuts across the Mineral Mountains (Figs. 2, 5). Because of the nondistinctive nature of rock types cut by the fault, the relative offset and throw are conjectural. Nielson and others (1978) mapped the offset on the Negro Mag fault as down to the north on the basis of apparent offset of an east-dipping dike and alluvium exposed on the north side of Negro Mag Wash. Brogan and Birkhahn (1981), however, stated that the morphological expression of the fault is not compelling and that the dike offset is the best evidence for displacement. Ward and others (1978) stated that gravity data showed the south side was down. As we interpret the structure, the complex graben containing the Negro Mag fault is ~6 km across. It separates a Pleistocene rhyolite dome complex to the south from lower and more dissected ground containing no rhyolite to

TABLE 1. POTASSIUM-ARGON DATES FROM THE MINERAL MOUNTAINS, UTAH

Sample no.	Mineral	Unit	Weight (g)	%K	$^{40}Ar^*$, mol/gm ($\times10^{11}$)	$\%^{40}Ar$ at	T m.y.	±S m.y.
MR 79-1	Biotite	Tbg	0.40065	7.21	13.082	62	10.4	0.5
MR 79-1	Hornblende	Tbg	2.00465	0.77	1.588	69	11.8	0.6
MM 79-5	Whole rock	Tpr	1.52316	4.10	6.462	50	9.06	0.34
MM 79-152	Whole rock	Tpr	1.23059	4.34	7.271	74	9.63	0.55

the north. Flat areas which represent paleo-weathering surfaces are offset and tilted by the faulting along the graben. The age of the Negro Mag graben is uncertain; however, the northernmost Pleistocene rhyolite dome and the Bailey Ridge rhyolite flow appear to have been erupted from faults that are part of the graben, suggesting that the structure has been present since at least early Pleistocene time.

Seismic monitoring (G. Zandt and D. L. Nielson, unpub. data) has shown that the Negro Mag zone is presently active. Two well defined, east-west zones localize episodic swarms of quakes with magnitudes of less than 1. A third parallel zone of active swarms is on the northern edge of Wildhorse Canyon. This southern zone is not closely tied to any recognized faults.

HYDROTHERMAL ACTIVITY

At least some hydrothermal activity has accompanied all episodes of intrusion and faulting of the Mineral Mountains intrusive complex. This activity has been responsible for concentrating metals and altering country rock, particularly along fault zones. The youngest hydrothermal event is still active as evidenced by the high-temperature Roosevelt Hot Springs geothermal system.

Hydrothermal activity associated with the early calc-alkaline sequence was responsible for forming small chalcopyrite-bearing skarn deposits, as well as lead-barite veins and replacement deposits in the northern end of the range and replacement deposits in the Bradshaw and Lincoln mining districts at the southern end of the range. Skarns are now principally exposed along the contact between these rocks and Cambrian carbonates in the northern Mineral Mountains. In addition, carbonate xenoliths within rocks of this series commonly contain minor quantities of copper minerals.

Hydrothermal activity associated with the main intrusive sequence mineralized carbonate beds along the southeastern portion of the range where the Granite and North Granite mining districts have produced $50,000 worth of base metals, most of it from the Beaver View Mine (Earll, 1957). Many small prospect pits are located on quartz veins within the diorite breccia (Fig. 2, Mdb). The visible ore mineral in these pits is chalcopyrite, with associated galena, barite, molybdenite, and ferrimolybdite. During World Wars I and II, tungsten was produced from some metal mines. More detailed coverage of the district has been given by Crawford and Buranek (1945), Earll (1957), and Hobbs (1945).

Hydrothermally altered rock is ubiquitous along the low-angle fault zones. Chlorite formed after mafic minerals in fractured rock adjacent to the fault. Within the fault zone, the rock is extensively altered, and both chlorite and clays developed after the original silicate phases. Silica was mobile within the cataclasites and was in some cases removed from the rock and in other cases concentrated. Both microdiorite and rhyolite dikes within the fault zones are also commonly altered by hydrothermal solutions. Chlorite and epidote formed after the original mafic minerals, and sericite formed after feldspars.

Small exploration pits along the low-angle faults attest to the spotty mineralization that accompanied the hydrothermal process. Analyses of grab samples collected along the Wildhorse Canyon fault show anomalous Cu, Zn, and Hg contents, but no ore-grade material. The character of hydrothermal alteration appears similar in both the listric faults such as the Wildhorse Canyon fault and the Cave Canyon cataclasite. Bruhn and others (1982) studied the Wildhorse Canyon fault and concluded that fluids present along the fault zone significantly lowered the coefficient of friction along the fault, and that the presence of fluids was a prerequisite for faulting to have taken place. They estimated that the maximum depth that this faulting could have taken place is 5 km, although the depth is poorly constrained.

The limits of the present hydrothermal system at Roosevelt Hot Springs are controlled largely by high-angle faulting and have been partly defined by deep drilling. The principal wells are shown in Figure 5; important facts about the wells are presented in Ross and others (1982). The area of geothermal production is bounded on the east by the range front of the Mineral Mountains. On the west, the system is bounded by the Opal Mound fault; on the south, it terminates between Utah State 72-16, which is a hot-water producer, and Utah State 52-21, which is a hot (206 °C) but dry hole. The northern boundary of the system has not been determined. The deep wells confirm that the host rocks for the hydrothermal system are Tertiary and Precambrian crystalline rocks which have been mapped in the adjacent Mineral Mountains (Fig. 2) and that permeability of the system is controlled by faults and fractures (Nielson and others, 1978; Ross and others, 1982). Maximum measured fluid temperature in the Roosevelt Hot Springs geothermal system is 268 °C. Recent work on fluid geothermometry (Capuano and Cole, 1982) showed that the reservoir fluids have a maximum temperature of 288 ± 10 °C and a total dissolved solids content of ~9,700 ppm. The isotopic composition of the geothermal fluids indicates that they are of meteoric origin (Rohrs and Bowman, 1980). Isotopic compositions of the geothermal fluid suggest that the thermal fluids could be derived either from the Mineral or Tushar Mountains. East-west faults may provide the conduits through which fluids are transported from Beaver Valley through the Mineral Mountains structural block to the geothermal system.

The hydrothermal alteration assemblages associated with the present geothermal system are crudely zoned with depth. The uppermost assemblage, occurring around fumaroles, is characterized by quartz, alunite, kaolinite, montmorillonite, hematite, and sericite. Parry and others (1980) studied the near-surface alteration and suggested that formation above the water table occurred by downward percolating, acidic sulfate waters. Upward convecting, geothermal brines have produced, with increasing depth, alteration assemblages characterized by (1) montmorillonite + mixed layer clays + sericite + quartz + hematite and (2) chlorite + sericite + calcite + pyrite + quartz + anhydrite (Ballantyne, 1978). Thermochemical calculations and petrologic observations suggest that the brines are in equilibrium with the alteration assemblages produced by the upward migrating fluids (Capuano and Cole, 1982).

Christensen and others (1983) summarized trace-element concentrations associated with the presently active hydrothermal system. They report a zonation which consists of anomalous concentrations of As, Sb, Be, and Hg associated with siliceous sinter, Mn, Br, W, Be, Cu, Co, As, Sb, and Hg in manganese- and hematite-cemented alluvium, Hg near fumaroles, and As in sulfides and Li in silicates associated with high-temperature fluid entries in wells.

GEOCHRONOLOGY

Early chronologic work on rocks from the Mineral Mountains produced ages that were not consistent with geologic relationships. We concluded that the dates had been influenced by both recurrent thermal events and rapid uplift of the Mineral Mountains structural block. A cooperative program with the U.S. Geological Survey started to unravel the dating systematics (Aleinikoff and others, in press), and some anchor points in the geologic history have been established. Rb-Sr and U-Pb dating has shown that the gneisses exposed along the western margin of the Mineral Mountains were metamorphosed 1.72 Ga. Th-Pb and U-Pb ages of samples of the early calc-alkaline intrusive sequence cluster around 25 ± 4 Ma. Additional data show that closure of the U-Th-Pb system in sphene did not take place until 21 Ma (Aleinikoff and others, in press).

TABLE 2. APPARENT UPLIFT RATES FOR THE NORTH AND CENTRAL PORTIONS OF THE MINERAL MOUNTAINS INTRUSIVE COMPLEX, UTAH

Sample	Apatite age (m.y.)	Zircon age (m.y.)	Elevation (m)
Northern Mineral Mountains			
79-150	8.5	. .	1890
79-153	8.2	8.3	1830
79-154	8.1	8.4	1840
79-155	8.7	8.7	1990
Uplift rate:	0.25 mm/yr	0.42 mm/yr	
Central Mineral Mountains			
79-1	8.3	8.4	2120
81-2	9.0	8.9	2760
81-3	9.1	8.7	2440
81-4	8.2	8.3	2130
Uplift rate:	0.56 mm/yr	1.08 mm/yr	

Note: data are from Evans and Nielson (1982). Uplift rates calculated from linear least-squares regression of the data.

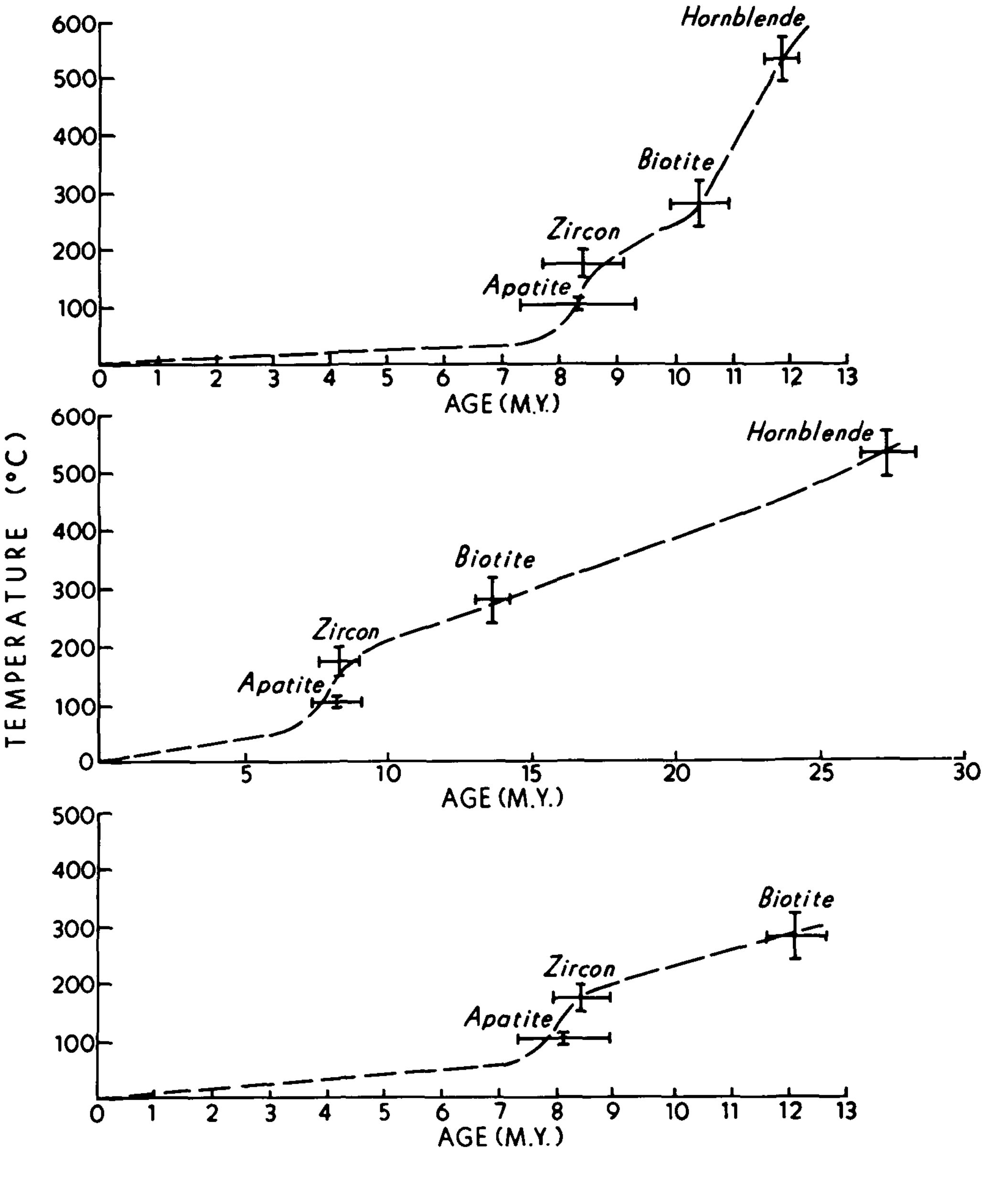
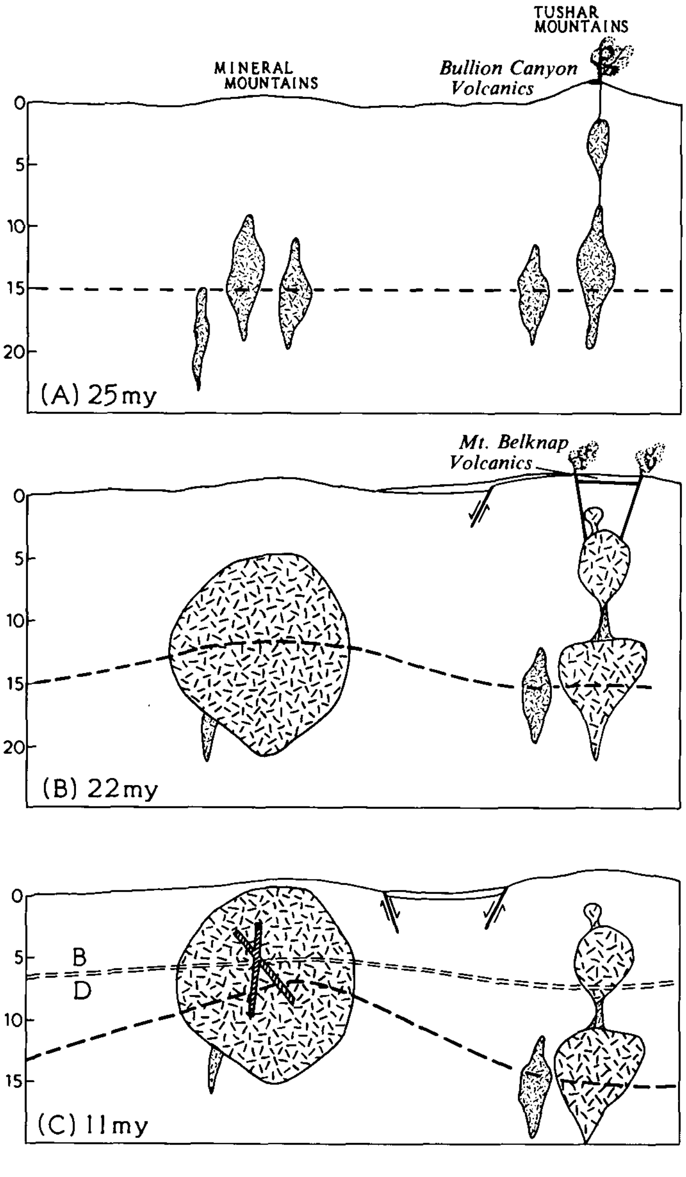


Figure 6. Cooling histories of three samples from the Mineral Mountains intrusive complex based on K-Ar and fission track data (Evans and Nielson, 1982). Dashed lines represent hypothetical cooling curve followed by each sample.

K-Ar dates of biotites from the main intrusive sequence are as old as 20.8 Ma, and we interpret this as representing a minimum age for the emplacement of those plutons. Bowers (1978) has dated the Lincoln stock south of the area of Figure 2 at 21.9 ± 2 Ma. We interpret the Lincoln stock as being a satellite pluton of the main intrusive sequence, and from this evidence, we conclude that this event began in the Mineral Mountains at about 22 Ma.

K-Ar ages of biotite and hornblende from a biotite granite (Table 1, MR 79-1) that is one of the youngest plutons in the Mineral Mountains intrusive complex are concordant, and they indicate that this pluton and its time equivalent units Tg and Ti were intruded 12 to 11 Ma. This event was closely timed to the formation of fine-grained granitic dikes throughout the northern Mineral Mountains. These dikes represent the terminal products of the main intrusive sequence. The Upper Miocene plutonic-volcanic sequence has contributed to the extensive resetting of K-Ar dates within the Mineral Mountains. This event produced swarms of rhyolite dikes in the northeastern portion of the range as well as a pluton of porphyritic rhyolite which intrudes the cataclasite zones in the southern Mineral Mountains (Tpr, Figs. 2, 4). Two whole rock K-Ar dates of these rocks document this activity at 9.06 ± 9.63 Ma (Table 1). Because of the intimate relationship between those dikes and the listric faults, these dates also document the timing of movement on these fault zones. This activity is related to the rhyolitic Gillies Hill volcanism at 9.1 Ma (Evans and Steven, 1982) in the Beaver Valley to the east of the Mineral Mountains.

Fission track dating methods have been applied to gain an understanding of the thermal history of the Mineral Mountains (Evans and Nielson, 1982). Some of the results of these analyses are shown in Figure 6, where mineral ages are plotted against estimates of closure temperatures made by Harrison and McDougall (1980). Our study demonstrates rapid uplift rates for the Mineral Mountains at 8 to 9 Ma, calculated from fission track ages of both apatite and zircon (Table 2). The apatite ages yield uplift rates one-half that of zircons but are the more reliable because closure temperature data are much better than for zircon. The data of Table 2 and Figure 6 demonstrate that uplift rates were different for different areas in the Mineral Mountains and that these rates varied with time throughout



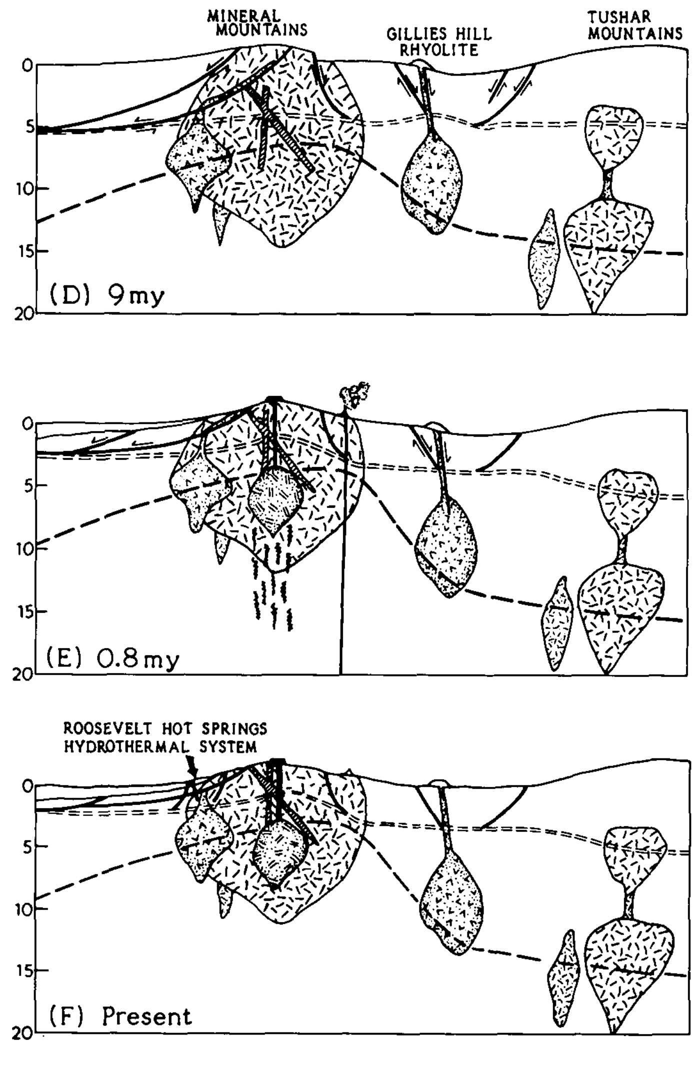


Figure 7. Diagrammatic east-west cross sections showing the magmatic, structural, and hydrothermal evolution of the Mineral Mountains intrusive complex. The dashed lines represent an imaginary datum that was horizontal about 25 Ma ago and that was deformed subsequently by magmatic and faulting events. In 7C, B-D represents the separation between brittle and ductile behavior.

the range. Because fission track ages document cooling, the data show relaxation of isotherms following periods of rapid uplift. We suggest that the periods of uplift documented in Figure 6 took place at the time of formation of the listric faults and injection of rhyolites dated at 9.0–9.6 Ma.

SYNTHESIS

Our concept of the Tertiary through Quaternary development of the Mineral Mountains is illustrated in Figure 7. During Oligocene time, andesitic stratovolcanoes were forming along the east-west–trending Wah Wah-Tushar segment of the Pioche-Marysvale igneous belt. There is at present no evidence that one of these volcanoes occupied the present site of the Mineral Mountains. What is clear is that calc-alkaline magma was generated and emplaced about 25 Ma at a deep level, resulting in a composite pluton now represented by rocks of the early intrusive sequence (Fig. 7A).

Following a hiatus of perhaps only a couple of million years, igneous activity resumed with the emplacement of relatively alkaline diorites of the main intrusive sequence. These mafic rocks were followed by intrusion of voluminous felsic magmas and were emplaced at progressively shallower levels and with increasing fracture control of pluton geometry through time (Figs. 7B and 7C). The timing of the main intrusive sequence is poorly understood due to extensive thermal resetting, but it is constrained between ~22 and 11 Ma. During this time the Mount Belknap Volcanics were erupted in the Marysvale area, resulting in felsic ash-flow tuffs and lava flows.

Between ~11 and 10 Ma, the Cave Canyon cataclasite developed at or near the brittle-ductile transformation. The detailed geology of this zone has not been completed, and we cannot rule out an origin by regional rotation, such as has been proposed by Davis (1983). Although there is this question, we have depicted the development of the zone at the brittle-ductile transformation in Figure 7C. After this detachment formed, it is likely that it continued to be active while the range was being uplifted through the brittle portion of the crust. If the thermal gradients at the time of low-angle detachment faulting were similar to those measured today adjacent to the Roosevelt Hot Springs geothermal field, it is likely that the detachment nucleated at depths of about 7 km and temperatures of 430 to 480 °C.

Listric faulting accompanied rapid uplift throughout the Mineral Mountains sometime ~10 to 9 Ma (Fig. 7D). This faulting took place in a brittle regime at a maximum depth of 5 km (Bruhn and others, 1982) and resulted in the development of intense zones of cataclasis. We speculate that these faults sole into a regional low-angle detachment fault such as the Cave Canyon cataclasite at depth. After final movement on the low-angle faults and near and following the cessation of movement on the listric faults, a bimodal sequence was intruded at ~9 Ma, largely along the structural paths created by the listric faulting. Rhyolites and microdiorites were emplaced at this time; the rhyolites were the more voluminous. The Gillies Hill rhyolite event at ~9.1 Ma is probably the volcanic equivalent of this episode, and it occurred at the junction between the Mineral Mountain block and the Tushar Mountain block (Evans and Steven, 1982). Gravity, as well as geological relationships, suggests that this junction is along a high-angle normal fault zone along which the Mineral Mountains block was uplifted with respect to the Tushar Mountain block.

Late Miocene magmatism persisted through eruption of the Corral Canyon rhyolite that has been dated at 7.9 ± 3 Ma (Lipman and others, 1978). The Corral Canyon dome was emplaced on top of coarse alluvial gravels that are essentially indistinguishable from the gravels presently being deposited on alluvial aprons from the Mineral Mountains. These relationships (rhyolite on top of alluvial gravels) have also been observed in some of the distal portions of flows that originated in the Gillies Hill area north of Beaver Valley. These gravels suggest that erosion of the Mineral Mountain intrusive complex was already taking place by 9 Ma.

Uplift probably continued after late Miocene time, but it was evidently at a much reduced rate. Weathering and erosion predominated as the most important geologic processes until the most recent magmatic-tectonic-hydrothermal event began at ~2.5 Ma. This weathering and erosion produced a widespread surface of low relief now represented by extensive flat surfaces underlain by deeply weathered grus along the top of the Mineral Mountains. In some places, the flat tops seem to be controlled by preferential erosion of less resistant brecciated zones overlying unfractured rock.

Renewed tectonic activity in Quaternary time offset remnants of the flat weathered surfaces, reflecting differential uplift of various segments of the Mineral Mountains block along generally east-striking faults. Some zones may have developed earlier in the history of the range as a response to different uplift rates (Evans and Nielson, 1982) and were reactivated in Quaternary time by magmatic pressure that was a precursor to the 0.8 to 0.5 Ma rhyolite volcanism (Fig. 7E). The 0.8 Ma Bailey Ridge flow contains basalt xenoliths, suggesting that basalt underplating may have played a part in the formation of the underlying magma chamber and the ascent of these rhyolite magmas to the surface. During the subsequent 0.3 m.y. of flow and pyroclastic activity, volcanic products were deposited on the previously formed, weathered surfaces.

Hydrothermal activity began at the Roosevelt Hot Springs area at an undetermined time and is thought to have been powered by the plutonic equivalents of the Pleistocene rhyolite domes and flows (Fig. 7F). Deposition of siliceous sinter seems to be related to movement on the Opal Mound fault and associated structures where there is clear evidence of two periods of sinter deposition.

We have presented a picture of continued uplift of the Mineral Mountains structural block from about 25 Ma to the present, during the formation of the Mineral Mountains intrusive complex. This has produced an extreme structural high for this region. The cause of this uplift remains an intriguing question and one for which we have little supporting evidence. The fact that the Mineral Mountains preserve a long history of intrusive activity implies uplift through buoyancy. Continued emplacement of magmas thus resulted in a block of hot rock that moved upward as a buoyant diapir that modern seismicity indicates is still active.

ACKNOWLEDGMENTS

This work was sponsored by the U.S. Department of Energy under contracts EG-78-C-07-1701, DE-AC07-78ET28393, and DE-AC07-80ID12079. Mapping in the southern portion of the Mineral Mountains was supported by the U.S. Geological Survey. We express our appreciation to T. A. Steven of the USGS for his support, enthusiasm, and careful review of the manuscript. We have also benefited from reviews by R. L. Bruhn, P. E. Wannamaker, P. D. Rowley, and M. G. Best.

REFERENCES CITED

Aleinikoff, J. N., Nielson, D. L., Hedge, C. E., and Evans, S. H., Jr., in press, Geochronology of Precambrian and Oligocene rocks in the Mineral Mountains, south-central Utah: U.S. Geological Survey Bulletin 1622.

Allmendinger, R. W., Sharp, J. W., VonTish, D., Serpa, L., Brown, L., Kaufman, S., Oliver, J., and Smith, R. B., 1983, Cenozoic and Mesozoic structure of the eastern Basin and Range province, Utah, from COCORP seismic reflection data: Geology, v. 11, p. 532–536.

Armstrong, R. L., 1972, Low-angle (denudation) faults, hinterland of the Sevier orogenic belt, eastern Nevada and western Utah: Geological Society of America Bulletin, v. 833, p. 1729–1754.

Ballantyne, J. M., 1978, Hydrothermal alteration at Roosevelt Hot Springs thermal area, Utah—Model mineralogy and geochemistry of sericite, chlorite, and feldspar from altered rocks, Thermal Power Company, Well Utah State 14-2: Utah Unviersity, Department of Geology and Geophysics Report, 42 p.

Best, M. G., and Grant, S. K., in press, Stratigraphy of the volcanic Oligocene Needles Range Group in southwest Utah, *in* Mid-Tertiary volcanic rocks in the central Pioche-Marysvale igneous belt, western Utah and eastern Nevada: U.S. Geological Survey Professional Paper.

Bowers, D., 1978, Potassium-argon age dating and petrology of the Mineral Mountains pluton, Utah [M.S. thesis]: Salt Lake City, Utah, Utah University, 76 p.

Brogan, G. E., and Birkhahn, P. C., 1981, Faults and occurrence of geothermal anomalies: Final report for contract number 14-08-0001-16310: U.S. Geological Survey, 103 p.

Bruhn, R. L., Yusas, M. R., and Huertas, F., 1982, Mechanics of low-angle normal faulting—An example from Roosevelt Hot Springs geothermal area, Utah: Tectonophysics, v. 86, p. 343–361.

Capuano, R. M., and Cole, D. R., 1982, Fluid-mineral equilibria in a hydrothermal system, Roosevelt Hot Springs, Utah: Geochimica et Cosmochimica Acta, v. 46, p. 1353–1364.

Christensen, O. D., Capuano, R. M., and Moore, J. N., 1983, Trace-element distribution in an active hydrothermal system, Roosevelt Hot Springs thermal area, Utah: Journal of Volcanology and Geothermal Research, v. 16, p. 99–129.

Condie, K. C., 1960, Petrogenesis of the Mineral Range pluton, southwestern Utah [M.S. thesis]: Salt Lake City, Utah University, 92 p.

Crawford, A. L., and Buranek, A. M., 1945, Tungsten deposits of the Mineral Range, Beaver County, Utah: Department of Mining and Metallurgical Research, Utah University State Engineering and Experiment Station Bulletin 25, 48 p.

Crecraft, H. R., Nash, W. P., and Evans, S. H., Jr., 1981, Late Cenozoic volcanism at Twin Peaks, Utah: Geology and petrology: Journal of Geophysical Research, v. 86, p. 10303–10320.

Davis, G. H., 1983, Shear zone model for the origin of metamorphic core complexes: Geology, v. 11, p. 342–347.

Earll, R. N., 1957, Geology of the central Mineral Range, Beaver County, Utah [Ph.D. thesis]: Salt Lake City, Utah, Utah University, 112 p.

Evans, S. H., Jr., 1975, Geologic map of the central and northern Mineral Mountains, Utah: Utah University Department of Geology and Geophysics, Technical Report, v. 77-7.

Evans, S. H., Jr., and Nash, W. P., 1978, Quaternary rhyolite from the Mineral Mountains, Utah, U.S.A.: Utah University, Department of Geology and Geophysics Report, 59 p.

Evans, S. H., Jr., and Nielson, D. L., 1982, Thermal and tectonic history of the Mineral Mountains intrusive complex: Geothermal Resources Council Transactions, v. 6, p. 15–18.

Evans, S. H., Jr., and Steven, T. A., 1982, Rhyolites in the Gillies Hill–Woodtick Hill area, Beaver County, Utah: Geological Society of America Bulletin, v. 93, p. 1131–1141.

Glenn, W. E., and Hulen, J. B., 1979, Interpretation of well log data from four drill holes at Roosevelt Hot Springs KGRA: Utah University Research Institute, Earth Science Laboratory Report 28, 74 p.

Glenn, W. E., Hulen, J. B., and Nielson, D. L., 1980, A comprehensive study of LASL well C/T-2 (Phillips 9-1), Roosevelt Hot Springs KGRA, Utah, with applications to geothermal well logging: Los Alamos Scientific Laboratory Report LA-8686-MS, 175 p.

Harrison, T. M., and McDougall, I., 1980, Investigations of an intrusive contact, northwest Nelson, New Zealand. I. Thermal chronological and isotope constraints: Geochimica et Cosmochimica Acta, v. 44, p. 1985–2003.

Hilpert, L. S., and Roberts, R. J., 1964, Metallic mineral resources—Uranium, *in* Mineral and water resources of Utah: U.S. 88th Congress, 2nd session, p. 28–38.

Hintze, L. F., 1975, Geological highway map of Utah: Brigham Young University Geology Studies, Special Publication 3.

Hobbs, S. W., 1945, Tungsten deposits in Beaver County, Utah: U.S. Geological Survey Bulletin 945-D, p. 81–111.

Lemmon, D. M., Silberman, M. L., and Kistler, R. W., 1973, Some K-Ar ages of extrusive and intrusive rocks of the San Francisco and Wah Wah Mountains, Utah, *in* Hintze, L. F., and Whelan, J. A., eds., Geology of the Milford area, 1973: Utah Geological Association Publication 3, p. 23–26.

Liese, H. C., 1957, Geology of the northern Mineral Range, Millard and Beaver Counties, Utah [M.S. thesis]: Salt Lake City, Utah, Utah University, 88 p.

Lipman, P. W., Rowley, P. D., Mehnert, H. H., Evans, S. H., Jr., Nash, W. P., and Brown, F. H., 1978, Pleistocene rhyolite of the Mineral Range, Utah: Geothermal and archeological significance: U.S. Geological Survey Journal of Research, v. 6, no. 1, p. 133–147.

Mabey, D. R., Zietz, I., Eaton, G. P., Kleinkopf, M. D., 1978, Regional magnetic patterns in part of the Cordillera in the western United States, *in* Smith, R. B., and Eaton, G. P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 313–340.

Mehnert, H. H., Rowley, P. D., and Lipman, P. D., 1978, K-Ar ages and geothermal implications of young rhyolites in west-central Utah: Isochron/West, no. 21, p. 3–7.

Mundorff, J. C., 1970, Major thermal springs of Utah: Utah Geological and Mineralogical Survey Water-Resources Bulletin 13, 60 p.

Nielson, D. L., Sibbett, B. S., McKinney, D. B., Hulen, J. B., Moore, J. N., and Samberg, S. M., 1978, Geology of Roosevelt Hot Springs KGRA, Beaver County, Utah: Utah University Research Institute, Earth Science Laboratory Report no. 12, Salt Lake City, 121 p.

Parry, W. T., Ballantyne, J. M., Bryant, N. L., and Dedolph, R. E., 1980, Geochemistry of hydrothermal alteration at the Roosevelt Hot Springs thermal area, Utah: Geochimica et Cosmochimica Acta, v. 44, p. 95–102.

Petersen, C. A., 1975, Geology of the Roosevelt Hot Springs area, Beaver, Co., Utah: Utah Geology, v. 2, no. 2, p. 109–116.

Proffett, J. M., Jr., 1977, Cenozoic geology of the Yerington District, Nevada, and implications for the nature and origin of Basin and Range faulting: Geological Society of America Bulletin, v. 88, p. 247–266.

Rohrs, D. T., and Bowman, J. R., 1980, A light stable isotope study of the Roosevelt Hot Springs thermal area, southwestern Utah: Utah University, Department of Geology and Geophysics Report, 89 p.

Ross, H. P., Nielson, D. L., and Moore, J. N., 1982, Roosevelt Hot Springs geothermal system, Utah—Case Study: American Association of Petroleum Geologists Bulletin, v. 66, no. 7, p. 879–902.

Rowley, P. D., Lipman, P. W., Mehnert, H. H., Lindsey, D. A., and Anderson, J. J., 1978, Blue Ribbon lineament, an east-trending structural zone within the Pioche mineral belt of southwestern Utah and eastern Nevada: U.S. Geological Survey Journal Research, v. 6, p. 175–192.

Rowley, P. D., Steven, T. A., Anderson, J. J., and Cunningham, C. G., 1979, Cenozoic stratigraphic and strucutural framework of southwestern Utah: U.S. Geological Survey Professional Paper 1149, 22 p.

Rowley, P. D., Steven, T. A., and Mehnert, H. H., 1981, Origin and structural implications of Pleistocene and upper Miocene rhyolite in Kingston Canyon, Piute County, Utah: Geological Society of America Bulletin, v. 92, p. 590–602.

Shawe, D. R., and Stewart, J. H., 1976, Ore deposits as related to tectonics and magmatism, Nevada and Utah: Society of Mining Engineers Transactions, v. 260, p. 225–230.

Sibbett, B. S., and Nielson, D. L., 1980a, Geology of the central Mineral Mountains, Beaver Co., Utah: Utah University Research Institute, Earth Science Laboratory Report no. 33, Salt Lake City, 42 p.

——— 1980b, The Mineral Mountains intrusive complex, Utah: Geological Society of American Abstracts with Programs, Rocky Mountain Section, v. 12, no. 6, p. 305.

Smith, R. B., and Bruhn, R. L., 1984, Intraplate extensional tectonics of the eastern Basin Range: Inferences on structural style from seismic reflection data, regional tectonics, and thermal-mechanical models of brittle-ductile deformation: Journal of Geophysical Research, v. 89, p. 5733–5762.

Steven, T. A., and Morris, H. T., 1984, Mineral resource potential of the Richfield 1°×2° quadrangle, west-central Utah: U.S. Geological Survey Open-File Report 84-521, 53 p.

Steven, T. A., Rowley, P. D., and Cunningham, C. G., 1984, Calderas of the Marysvale volcanic field, west central Utah: Journal of Geophysical Research, v. 89, p. 8751–8764.

Stewart, J. H., Moore, W. J., and Zietz, I., 1977, East-west patterns of Cenozoic igneous rocks, aeromagnetic anomalies, and mineral deposits, Nevada and Utah: Geological Society of America Bulletin, v. 81, p. 67–77.

Stokes, W. L., 1968, Relation of fault trends and mineralization, eastern Great Basin, Utah: Economic Geology, v. 63, p. 751–759.

Ward, S. H., Parry, W. T., Nash, W. P., Sill, W. R., Cook, K. L., Smith, R. B., Chapman, D. S., Brown, R. F., Whelan, J. A., and Bowman, J. R., 1978, A summary of the geology, geochemistry, and geophysics of the Roosevelt Hot Springs Thermal area, Utah: Geophysics, v. 43, no. 7, p. 1515–1542.

MANUSCRIPT RECEIVED BY THE SOCIETY MAY 6, 1985
REVISED MANUSCRIPT RECEIVED NOVEMBER 11, 1985
MANUSCRIPT ACCEPTED NOVEMBER 20, 1985
UTAH UNIVERSITY EARTH SCIENCE LABORATORY CONTRIBUTION NO. ESL-85006-JP

Printed in U.S.A.