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Notes on the Cenozoic Structural History of the Tunnel Spring Mountains Area, Western Millard County, Utah

By

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Contents

Illustrations

Tables

Page

NOTES ON THE CENOZOIC STRUCTURAL HISTORY OF THE TUNNEL SPRING MOUNTAINS AREA, WESTERN MILLARD COUNTY, UTAH

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INTRODUCTION

The Tunnel Spring Mountains are formed by a 12-km-long north-trending raised structural block in the Basin and Range province of west-central Utah. The location of the block relative to province boundaries and other major structural features is shown in figure 1. The high part of the range consists of a core of well-exposed lower Paleozoic sedimentary rocks and the flanks consist of poorly exposed Tertiary volcanic, intrusive, and sedimentary rocks and Quaternary alluvium.

A review of geologic maps of western Millard County, Utah, available at various scales reveals very few examples of faulted contacts between Tertiary and pre-Tertiary strata. A few examples are found on a recently published map of the Crystal Peak quadrangle (1:48,000) that includes part of the northern Tunnel Spring Mountains (Hintze, 1974a). Hintze shows mid-Tertiary volcanic rocks and overlying Tertiary sedimentary rocks to be offset by two north-trending normal faults, the traces of which are buried by Quaternary alluvium, and by one northeast-trending normal fault. Dips as high as 54° were recorded in the Tertiary rocks (Hintze, 1974a). Hintze's map and accompanying cross sections suggest that the Paleozoic marine sedimentary rocks were only slightly deformed prior to the fault event that tilted the Tertiary beds.

In the Wah Wah Summit quadrangle (1:48,000), mapping of the contiguous area to the south in the Tunnel Spring Mountains by Hintze (1974b) shows scattered exposures of Tertiary strata equivalent in age to those to the north. The scattered exposures are located south of and along the strike of highly faulted and tilted Paleozoic marine sedimentary rocks that make up the core of the Tunnel Spring Mountains. Because of the on-strike relationship the area offers an excellent opportunity to compare the style and intensity of deformation between Tertiary and Paleozoic rocks. Such a comparison, together with an interpretation of the Cenozoic structural history of the area and some comments on the mechanics of deformation, are the main purposes of this report.

In order to make the comparison in the southern part of the range the published map (Hintze, 1974b) was enlarged to 1:24,000, modified, and a large amount of detail was added. Additional reconnaissance mapping was done to the west in the contiguous Tunnel Spring quadrangle (1:24,000) and the two maps were combined to form plate 1. In general, the quality of the geologic mapping in the eastern part of plate 1 is substandard for compilation at that scale. The scale was chosen for convenience only. In order to evaluate deformation in the northern part of the range, scattered structural data were added to the published map (Hintze, 1974a, 1:48,000), and it was reduced to 1:62,500 so as to match the scale of the adjacent Burbank Hills quadrangle to the west. The Tertiary strata in the Burbank Hills were mapped over an area large enough to provide a data base for the construction of a structure section through the northern Tunnel Spring Mountains and their flanking areas. The two maps are combined in figure 2, which also includes the structure section.

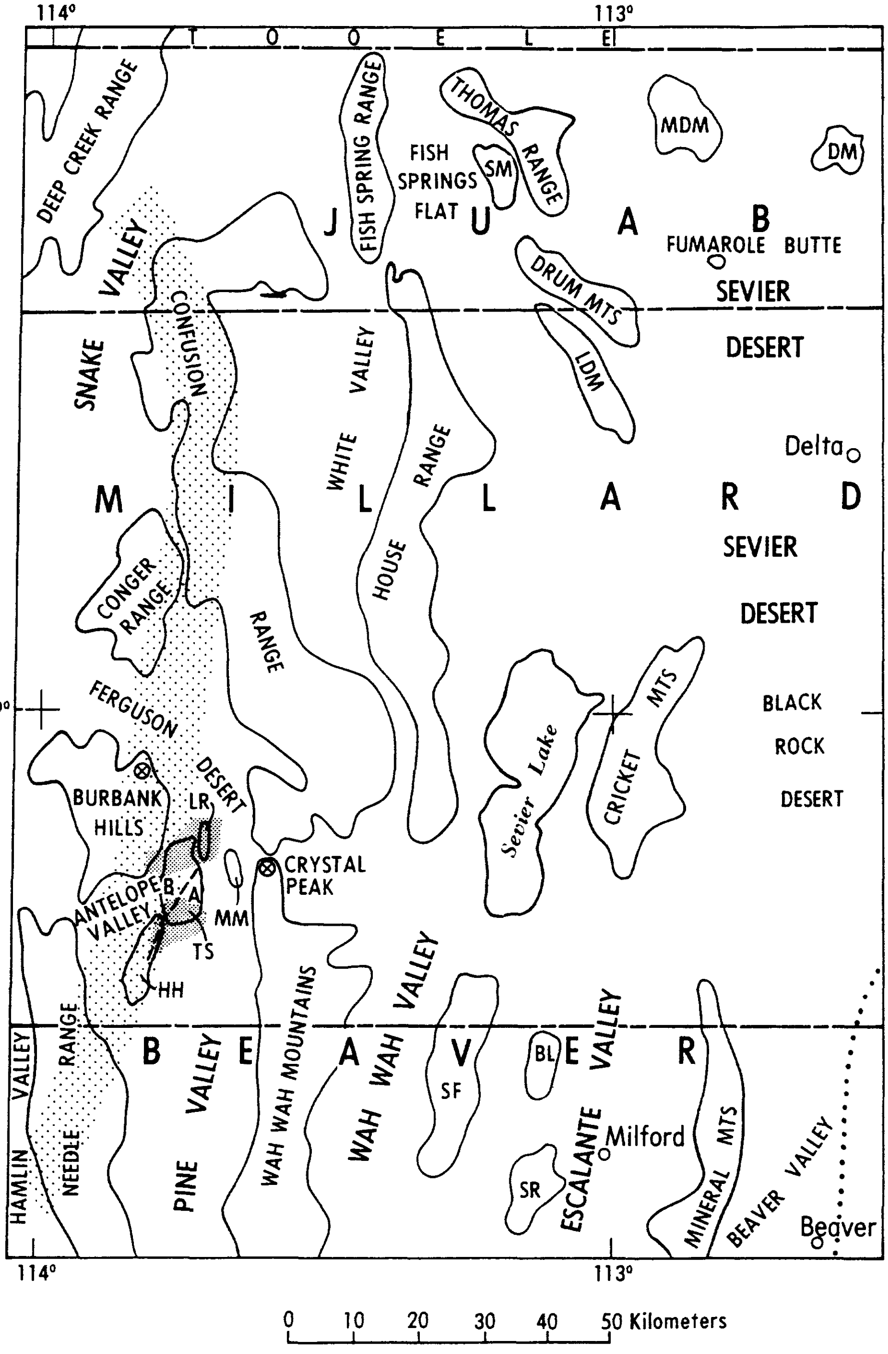


Figure 1.--Index map of west-central Utah showing the parts of the Tunnel Spring Mountains (TS) in southwestern Millard County that were mapped for the present study (shaded areas) and locations of Crystal Peak and north flank of Burbank Hills discussed in text (circles with cross). Dotted line near southeast corner encloses small part of Colorado Plateaus province included in map--the remainder of area is in the Basin and Range province. The heavy dotted line marks approximate boundary of domains A and B in the Tunnel Spring Mountains. North-trending belt (dot pattern) is the Confusion Range structural trough described by Hose (1977). SM, Spor Mountain; MDM, McDowell Mountains; DM, Desert Mountain; LDM, Little Drum Mountains; TS, Tunnel Spring Mountains; LR, Little Rough Range; MM, Middle Mountain; HH, Halfway Hills; SF, San Francisco Mountains; BL, Beaver Lake Mountains; and SR, Star Range.

ACKNOWLEDGMENTS

Robert Bucknam, Ron Henrisey, and Mary Anderson helped with the field work. I am very grateful to Charles Naeser and Robert Bohannon for fission-track analysis of mineral separates and to Harald Mehnert for K-Ar data. Lehi Hintze patiently attempted to familiarize me with selected parts of the lower Paleozoic stratigraphic sequence and made unpublished mapping available to me. He and Mary Lou Zoback made several helpful suggestions for improving the text. Ralph Holmgren and John Kinney of the U.S. Department of Agriculture graciously made the facilities of the U.S. Desert Range Experiment Station available during the mapping.

STRATIGRAPHY

For the present study rocks in and adjacent to the Tunnel Spring Mountains are separated into three highly contrasting categories. In order of decreasing age they are: (1) lower Paleozoic marine sedimentary rocks belonging to the Ordovician, Silurian, and Devonian Systems, (2) mid-Tertiary volcanic and intrusive rocks and coarse terrigenous detrital rocks that include landslide masses, and (3) fanglomerate and alluvial deposits of probable latest Tertiary and Quaternary age that flank the range (pl. 1, fig. 2). For descriptions of the Paleozoic and Quaternary units the reader is referred to the published maps (Hintze, 1974a, b). Brief descriptions of the Tertiary units are given herein.

Sedimentary and volcanic rocks

Sedimentary rocks, volcanic breccia, and flows of Tertiary age are mapped in scattered exposures in the west-central part of the area covered by plate 1. The sedimentary rocks are predominantly conglomeratic but include thin beds of flat-bedded sandstone, gravel, and bedded tuff. The volcanic rocks are porphyritic, reddish-gray to black, and are either flow-layered or flow-brecciated. The flows range from stoney to vitrophyric. In some areas, and especially near mapped faults, they are tectonically brecciated to highly comminuted and display disturbed flow foliation.

For the most part, the sedimentary and volcanic rocks of this basal Tertiary unit are exposed in areas that are separate from areas containing other Tertiary strata in the southern Tunnel Spring Mountains. Because of poor exposures and the geographic separation, neither the stratigraphic order of these variegated strata nor the stratigraphic position of the strata relative to other units of Tertiary age is known with certainty. The best exposures are found along the westernmost part of section B-B' (pl. 1) where the lowest beds are cobble- and boulder-bearing conglomerate overlain by andesitic to dacitic lahar and lava. The cobbles and boulders in the conglomerate include exotic types such as rhyolitic ash-flow tuff, granitoid intrusive rock, and upper(?) Paleozoic carbonate rocks indicating either transport by an integrated drainage system or derivation from mountain masses that are no longer exposed in contiguous areas. Clasts that could be correlated with stratigraphic members of the Oligocene Needles Range Formation were not found. The Needles Range is an ash-flow tuff unit that is widespread locally, is relatively resistant to erosion, and should be represented in a clast assemblage derived from terrain where it is exposed.

Exposures of Needles Range Formation are found within 1 km of the conglomeratic strata. Their absence in the conglomerate suggests that it is older than the Needles Range Formation. The relative stratigraphic positions of the Needles Range and the dacite and andesite is not known. A fault is inferred between the two units in the NW 1/4 sec. 29, R. 17 W., T. 24 S. (pl. 1). The displacement direction on that inferred fault is most likely down to the southeast, in which case the Needles Range Formation is younger than the andesite. If no fault exists there, attitudes in the Needles Range also indicate that it is younger than the andesite.

Some rounded clasts in the conglomerate consist of highly brecciated carbonate rock or brecciated quartzite that had been thoroughly recemented to a highly competent rock prior to transport and deposition into the conglomerate. If these conglomerates are older than the Needles Range Formation, as is inferred, they not only document the existence in the region of pre-Needles Range volcanism ranging from rhyolite to andesite, but they also suggest faulting and generally brittle deformation in the source terrains.

Tunnel Spring Tuff

The Tunnel Spring Tuff was named for exposures in the Tunnel Spring Mountains (Bushman, 1973; Hintze, 1974a), but its type section is at Crystal Peak in the Wah Wah Range (Bushman, 1973) where it consists of about 350 m of inconspicuously bedded, unsorted to very poorly sorted, friable, white to very light-gray, rhyolitic tuff that commonly contains sparse rock fragments (mostly limestone and quartzite). Doubly terminated quartz and black biotite phenocrysts are conspicuous. In the southern Tunnel Spring Mountains (pl. 1) rocks mapped as Tunnel Spring Tuff are for the most part very similar to those at the type section but are mapped to include beds of pale-green well-bedded sandstone and pale-pink massive tuff. The sandstone, which is exposed in the SE 1/4 sec. 28, T. 24 S., R. 17 W., probably underlies the massive main part of the tuff. Dikes composed of greenish sandstone lithologically identical to the bedded sandstone are intruded into the massive white tuff south of the exposures of bedded sandstone. The pale-pink massive tuff phase is also found on the eastern flank of the northern Tunnel Spring Mountains (fig. 2) where the unit also contains well-bedded intervals a few meters thick and reworked bedded tuff in its upper part. These accumulations of relatively pure volcanic tuff differ from those on the western flank of the northern Tunnel Spring Mountains where relatively pure tuffaceous beds are interstratified with tuffs that contain lithic inclusions and with beds of alluvial sand and gravel. The proportion of alluvial sediments in the stratigraphic interval occupied by the Tunnel Spring Tuff appears to increase northwestward. On the north flank of the Burbank Hills northwest of the northern Tunnel Spring Mountains (fig. 1), gravel beds are interstratified with volcanic tuffs in the middle part of a thick sequence of strata, the upper and lower parts of which are dominated by coarse alluvial sand, gravel, and conglomerate (unpublished mapping).

The basal contact of the Tunnel Spring Tuff was seen only on the west flank of the northern Tunnel Spring Mountains (fig. 2) where it rests on carbonate strata of Paleozoic age. At all other localities in the areas covered by plate 1 and figure 2, the lower contact is either covered or faulted. A thickness of about 125 m is assumed for the tuff in the south (cross section C-C', pl. 1), whereas the unit is probably more than twice that thick to the north (cross section A-A', fig. 2). Bushman (1973) summarized available K-Ar age data for three samples of the Tunnel Spring Tuff that indicate ages of 33.7±0.7, 32.7±1.3, and 30.9±1.2 m.y., and he tended to favor the older ages.

Rhyolite and quartz latite

In the southern Tunnel Spring Mountains (pl. 1) much of the rock in the core of the range is separated from Tertiary volcanic and sedimentary strata on the range flank by an intrusive mass consisting of porphyritic rhyolite and quartz latite. Hintze (1974b) described the mass as extrusive andesite. Most of the rock is pale reddish gray with weak flow layering or flow foliation and conspicuous phenocrysts of plagioclase, quartz, and biotite in an aphanitic to finely crystalline groundmass. Porphyritic vitrophyre is common at intrusive contacts that tend to be irregular and discordant to bedding of country rocks but which are paralleled by a step foliation in the intrusive rock. Many contacts are faulted, especially along the north margin of the mass (pl. 1). Country rocks consist of pre-Tertiary carbonate rocks that are locally altered and bleached and commonly brecciated as well as the Tunnel Spring Tuff which is commonly pale yellowish green and indurated as a result of mild to moderate silicification. Large xenoliths of silicified tuff are found near some contacts.

The age of the intrusive mass is not known. Discordant ages of 33.8±1.8 for biotite analyzed by the K-Ar method and 28.0±1.4 for zircon analyzed by the fission-track method were obtained on a single sample (tables 1a and 1b). Contacts with the Needles Range Tuff were not seen, so its stratigraphic position relative to that unit is inferred (pl. 1).

Needles Range Formation

The Needles Range Formation is composed of very widespread ash-flow tuffs of predominantly quartz latitic composition that Best and others (1973) divided into four tuff members. Exposures in the Tunnel Spring Mountains apparently consist of the two lowest members--the Cottonwood Wash Tuff Member and the overlying Wah Wah Springs Tuff Member (Hintze, 1974a, b; Bushman, 1973). Each is a separate cooling unit with cooling-dependent zonations, including thick devitrified interiors and basal vitrophyric and nonwelded zones. For a complete description the reader is referred to Best and others (1973), Bushman (1973), and Anderson and others (1975).

In the Tunnel Spring Mountains the Needles Range Formation rests mostly on tuffaceous sedimentary rocks, derived from erosion of the Tunnel Spring Tuff and mapped with the Tunnel Spring Tuff or on the Tunnel Spring Tuff itself. The two members of the Needles Range are of subequal thickness and their combined thickness ranges from 100 to 150 m. Only locally are the two members mapped separately.

The tuff is the most reliable time-stratigraphic marker of Tertiary age in the region and is of great value in making structural interpretations. The estimated age of the Needles Range Formation, indicated by 18 K-Ar age determinations summarized by Fleck and others (1975), is 28.9±1.2 m.y.

Isom Formation

A small area of densely welded, brick-red, crystal-poor, ash-flow tuff is mapped in the southeastern part of the area covered by plate 1 (see also cross section C-C'). A small exposure of similar ash-flow tuff that is not mapped was found in the NE 1/4 sec. 27, T. 24 S., R. 17 W. The ash-flow tuff possibly correlates with the Isom Formation--an ash-flow tuff sequence that is very widespread in southwestern Utah (Anderson and others, 1975) and has an age of about 25 m.y. (Fleck and others, 1975).

Conglomerate and breccia

Hintze (1974b) mapped Tertiary conglomerate and overlying breccia above the Needles Range Formation in the southern part of the Tunnel Spring Mountains and conglomerate in the northern part (Hintze, 1974a). The deposits in the two areas are described separately.

Southern part.--Beds of coarse detritus that are mostly conglomerate but include much interstratified coarse sand and gravel are found below and above the breccia (pl. 1). Because the breccia, which is of landslide origin, is contained within conglomeratic sedimentary materials,

Table 1a.--Fission-track age determinations

[Constants: $2_F = 7.03 \times 10^{-17}\ yr^{-1}$; $\gamma_D = 1.551 \times 10^{-10}\ yr^{-1}$; $I = 7.252 \times 10^{-3}$; $\sigma = 580 \times 10^{-24}\ cm^2$. The 28 m.y. fission-track age determined on zircon and the 33.8 m.y. K-Ar age determined on biotite are from a single sample (R1470-31) of intrusive quartz latite from the south flank of the Tunnel Spring Mountains. The 14.9 m.y. fission-track age determined on zircon (R1472-32) is from the basal 10-cm-thick air-fall part of a 2-m-thick bed of tuffaceous sedimentary rock interstratified with conglomeratic sediments.]

Sample (Field station)	Material (Analyst)	Quadrangle (Lat. N., Long. W.)	$\rho_s \times 10^6$ tracks/cm^2 (number of tracks counted)	$\rho_i \times 10^6$ tracks/cm^2 (number of tracks counted)	$\theta \times 10^{15}$ neutrons/cm^2	$T \times 10^6$ years	$\pm 2\sigma \times 10^6$ years	U ppm
DF-1529 (R1470-31)	Zircon (C. W. Naeser)	Wah Wah Summit (38°42',113°44')	4.79 (1021)	10.72 (1067)	1.00	28.0	1.4	290
DF-2267 (R1472-32)	Zircon (R. G. Bohannon)	Burbank Hills (38°48',113°46')	1.96 (412)	7.83 (824)	1.00	14.9	0.76	225

Table 1b--K-Ar age determination

Constants: $K^{40}\gamma_\varepsilon = 0584 \times 10^{-10}/yr$; $\gamma_\beta = 4.72 \times 10^{-10}/yr$; $K^{40}/K = 1.19 \times 10^{-4}$

Sample (Field station)	Material (Analyst)	Quadrangle (Lat. N., Long. W.)	Na_2O%	K_2O%	$*Ar^{40}$ (10^{-10}) moles/grams	%$*Ar^{40}$	$T \times 10^6$ years	$\pm 2\sigma \times 10^6$ years
DKA-3480 (R1470-31)	Biotite (H. Mehnert)	Wah Wah Summit (38°42', 113°44')	0.33, 0.32	8.22, 8.29	4.148	71.5	33.8	1.8

the units are described together, although they are mapped separately in the western part of the area (pl. 1).

Good exposures of the sedimentary strata beneath the breccia are found in SE 1/4 sec. 27, T. 24 S., R. 17 W. The strata consist of light-gray conglomerate, conglomeratic sandstone, and sandstone overlain by greenish-gray sandstone in which the detritus is predominantly volcanic rock waste. The overlying breccia consists of blocks several meters in diameter of quartzite and less common carbonate rock. To the west the breccia includes sheets as much as 500 m in extent of crackled limestone, dolomite, and quartzite that have maintained reasonable structural and stratigraphic integrity despite transport as landslide masses (fig. 3). Sheets of Ordovician Eureka Quartzite and Ely Springs Dolomite are easily recognized.

Figure 3.--View to south-southeast from the south flank of Tunnel Spring Mountains showing cuestas formed by caps of resistant southwest-dipping landslipped sheets of lower Paleozoic dark dolomite resting on alluvial debris of Tertiary age.

The conglomerate in the western part of the area (pl. 1) is inferred to overlie the breccia. It consists of pale-red to light-brownish-gray well-bedded sandy and conglomeratic alluvial deposits that are weakly cemented by calcium carbonate. Volcanic clasts are common. Some beds contain exotic boulders of contorted calcareous mudstone of lacustrine origin and probable Tertiary age which is not exposed in the modern range(s) (fig. 4).

The thicknesses of the conglomerate and breccia shown in cross section C-C' (pl. 1) result solely from geometric construction and are probably excessive. They could be reduced if more faults that repeat the beds are inferred.

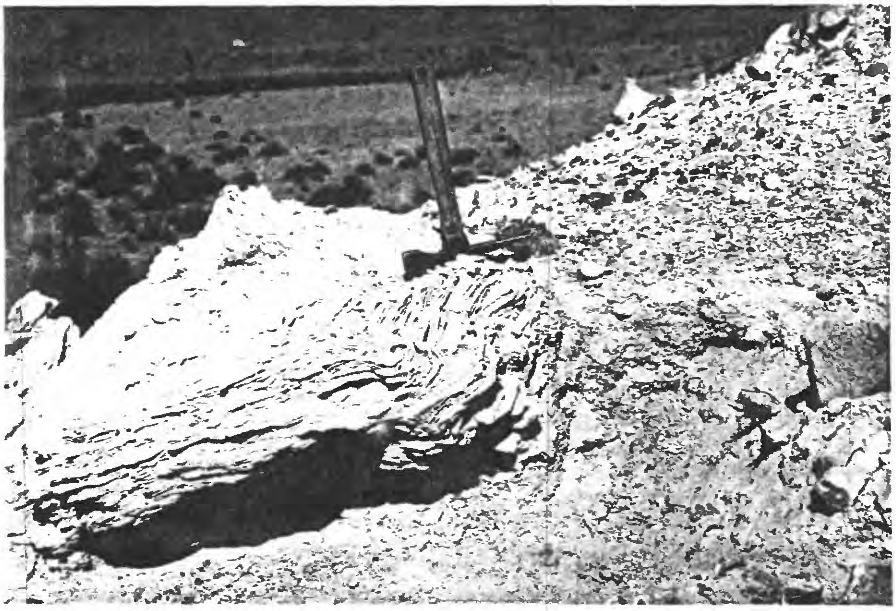


Figure 4.--Boulder of calcareous mudstone of probable lacustrine origin and Tertiary age included in southwest-dipping conglomeratic sediment in north-central part of sec. 5, T. 25 S., R. 17 W. (pl. 1). Primary bedding in this and other boulders in the area was folded prior to incorporation into the conglomeratic sediment.

Northern part.--Thick deposits of easterly dipping conglomerate are found on all flanks of the northern Tunnel Spring Mountains (fig. 2). On the east flank the conglomerate rests depositionally and conformably on the Needles Range Formation. Only the basal beds within a meter or so of the contact with underlying volcanic rock contain clasts of volcanic material larger than sand size. Large clasts in the remainder of the unit are of Paleozoic sedimentary rock, and the only clue one has that the conglomerate is postvolcanic is the presence of sparse quartz euhedra and biotite flakes in the sandy matrix or in the sandstone layers. Large boulders are common in the conglomerate. The thickness is estimated to be about 550 m, though it may be somewhat less if the fault density is higher than shown (cross section A-A', fig. 2). Deposits of Tertiary age on the north flank of the range are mainly conglomeratic sediments in lobate areas of low hills and ridges surrounded by Quaternary alluvium. Exposures of these deposits are found only in cut banks along washes where they consist of well-bedded alternations of poorly consolidated alluvial sand, gravel, and boulder conglomerate whose pebble to boulder fractions are composed exclusively of angular to poorly rounded Paleozoic clasts. The beds dip east to northeast (fig. 5), and quasi-continuous exposures along the northeast-trending wash in the north part of the map area (fig. 2) suggest that they are very thick--probably several hundred meters.

On the west flank of the northern Tunnel Spring Mountains conglomeratic deposits unconformably overlie the Needles Range Formation, the Tunnel Spring Tuff, and Paleozoic rocks. These deposits consist of a mixture of clasts of Tertiary volcanic and Paleozoic sedimentary rocks. Clasts that resemble the Needles Range Formation are common and in many places they are more than a meter in diameter. Clasts of other ash-flow tuffs that are not found in nearby volcanic sections are also found in the conglomerate. In the few exposures that were seen of these poorly exposed deposits they are well bedded and weakly consolidated. Unless normal faults that repeat these beds are more common than shown (fig. 2), their thickness exceeds 300 m. Zircon extracted from a sample of the basal 10-cm-thick air-fall part of a 2-m-thick bed of tuffaceous sediment yielded a fission track age of 14.9±0.76 m.y. (table 1a). The dated tuff bed is one of several tuff beds interstratified with the basal(?) beds of the conglomeratic deposits.

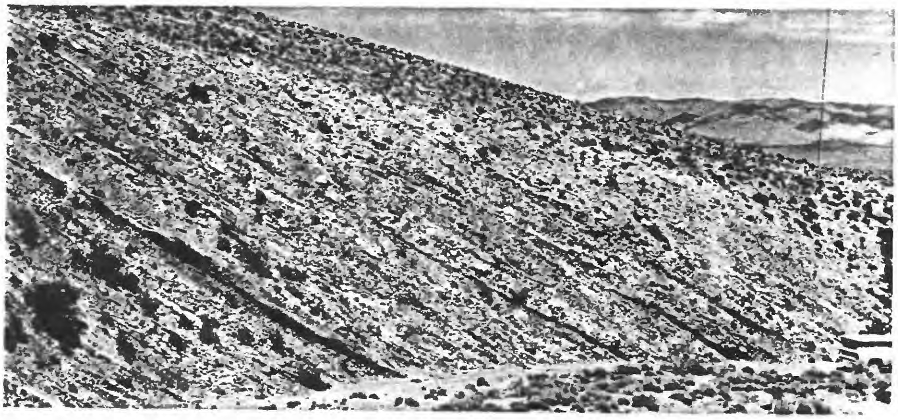


Figure 5.--View looking north at east-dipping conglomeratic sediments exposed quasi-continuously for about 1.5 km along northeast-draining wash in northernmost part of area covered by figure 2. Though of Tertiary age, the sediments are composed exclusively of clasts of pre-Tertiary rocks in the pebble to boulder fraction.

STRUCTURE

In order to adequately evaluate the late Cenozoic structural history of the Tunnel Spring Mountains and vicinity, it is necessary to draw heavily on stratigraphic and structural data acquired from poorly exposed strata beneath gravel-mantled pediment surfaces on the flanks of the range and on assumptions pertaining to the nature of unexposed contacts between Cenozoic and older rocks. In the evaluation that follows, some important assumptions are made regarding stratigraphic, structural, and contact relationships. It is assumed that clastic strata that include crackled but otherwise intact landslide sheets and large to huge boulders reflect a strong component of vertical structural relief of the type normally associated with faulting in the source terrain. Also, ash-flow tuffs are assumed to be reliable time-stratigraphic markers. Important structural assumptions are that compaction foliation in ash-flow tuffs and sandy partings or beds in conglomeratic sequences were horizontal or nearly so subsequent to emplacement or deposition. Where such foliation or bedding dips more than a few degrees, the dip is assumed to be the result of structural tilting. Structural tilting is assumed to be genetically related to faulting in areas where consistent angular relationships exist between stratal and fault attitudes. At localities where the contact between Cenozoic and Paleozoic strata is not exposed, the contact is assumed to be faulted if, (1) moderately to steeply dipping Cenozoic strata (ash-flow tuff or clastic strata) strike into the adjacent Paleozoic strata, (2) the Cenozoic strata dip steeply away from the buried contact in a manner suggestive of drag on a fault, (3) the Cenozoic clastic strata do not contain clasts derived from the adjacent exposures of Paleozoic rock, or (4) there is no suggestion of cooling-dependent lithologic zonations in the Cenozoic ash-flow tuffs near the contact that can be judged to be zonations related to deposition against irregular paleosurfaces formed on the adjacent Paleozoic rocks.

Very few depositional contacts between Tertiary and Paleozoic rocks are seen in the Tunnel Spring Mountains and vicinity. Most of the contacts are faulted and, where covered, are inferred to be faulted. Depositional contacts are, without exception, with Devonian rocks or with rocks of inferred Devonian age, and there is no area where buried depositional contacts are inferred to be with rocks older than Devonian age (see cross sections in pl. 1 and fig. 1). The Silurian and Ordovician rocks that crop out over large parts of the present range and which are so common as clasts in post-Needles Range Formation breccia and conglomerate were apparently not exposed in the area now occupied by the Tunnel Spring Mountains when Tertiary volcanism and sedimentation began. The area probably had low structural relief which is consistent with an absence of moderate to steep angular unconformities between Tertiary and Paleozoic rocks.

The Tunnel Spring Mountains consist of at least two structural domains of highly contrasting fault geometry. Domain A in the southern part of the range (includes all of the mapped area covered by plate 1 except a 1 to 2-km-wide strip along the western edge) in which strata are rotated to westerly dips on faults that strike north to northwest and an irregularly shaped domain B that includes the northern part of the range and extends west of domain A into the Halfway Hills. In domain B strata are rotated to easterly dips on faults that strike northerly (fig. 2 and western part of pl. 1). Although locally there are noticeable departures between the strike of faults of these systems and adjacent strata, the faults are referred to as strike faults. The approximate location of the boundary between the domains is shown in figure 1, and the reversal of fault and stratal dips of the domain boundary is illustrated very clearly in cross sections B-B' and C-C' (pl. 1).

With the exception of a small area of northeast- to east-striking Ordovician strata near Tunnel Spring (domain B, pl. 1), stratal strikes in both domains tend to be more consistent than fault strikes. In each of the domains there are faults whose strike departs greatly from that of the strike faults. For example, in the northern area (domain B) a major graben is formed by northeast-trending faults that cut across the strike faults (fig. 2), and in the southern area (domain A) northeast- to east-trending faults form the boundaries of major structural blocks (pl. 1). Some of these faults, especially in domain A, are probably transverse faults genetically related to the strike faults as discussed in a subsequent section on the mechanics of faulting.

The evaluation of the structural history of the Tunnel Spring Mountains is based largely on (1) construction and interpretation of cross-strike structure sections, and (2) interpretation of the structural significance of coarse clastic strata. These are considered in turn and are followed by a summary of the structural history. One of the most interesting structural features in the area is the boundary between the major structural domains. This feature is discussed in a final section on the mechanics of faulting.

Structure sections

Cross-strike structure sections that accurately depict stratal and fault dips and displacement amounts can be constructed across the well exposed main uplifted masses of Paleozoic strata but not across flanking areas of Tertiary strata, where exposures are discontinuous or of poor quality and where reliable marker beds are few. Notwithstanding these limitations on reliability, reasonable approximations of the extent to which Tertiary rocks are involved in deformation can be made. Such approximations for the northern and southern areas of the Tunnel Spring Mountains are described separately.

Northern area.--In the northern range an east-trending cross section (A-A', fig. 2) intersects three major uplifted masses of lower Paleozoic strata separated by blocks of down-faulted Tertiary strata. The west end includes a tiny piece of the uplifted Burbank Hills composed of Devonian strata that dip 20° to 50° easterly in the east limb of an anticline (Hintze, 1960). In the center is the Tunnel Spring Mountains block composed of Ordovician through Devonian strata that are tilted eastward from 16° to 40° (Hintze, 1960, 1974a). In the eastern part is the Little Rough Range--a horst block of highly faulted but gently tilted Silurian and Devonian strata (Hintze, 1974a). To the north of cross section A-A' the Tunnel Spring Mountains block wedges out, and downfaulted strata of Tertiary age can be traced quasi-continuously around the north end of that structural block.

In the eastern part of section A-A' the Tertiary strata appear to rest disconformably on the east-tilted Paleozoic strata of the Tunnel Spring Mountains block though the contact was not observed. Easterly dips in Tertiary strata range from 30° to 60°. These dip values are conspicuously greater than those of the Paleozoic strata of the Tunnel Spring block and much greater than in the Little Rough Range. A major down-to-west fault lies buried beneath the west base of the Little Rough Range. About 2 km north of cross section A-A' Hintze (1974a) interpreted 1,100 m of stratigraphic separation of Silurian rocks on that fault. A minimum separation of 1,200 m is indicated for Tertiary strata in cross section A-A'. For many normal faults in the Basin and Range, stratal dips in the downthrown block increase toward the fault as a result of reverse drag. The high dips in Tertiary strata and the somewhat lesser dips in Paleozoic strata to the west are probably related to reverse drag and do not suggest two episodes of deformation. Instead, they are caused by rotation on the major down-to-west fault that is buried beneath the west base of the Little Rough Range and possibly unrecognized subsidiary down-to-west faults.

In the western part of section A-A' the Tertiary strata are downfaulted into a graben in which stratal dips are predominantly easterly and range from 10° to 80°. The high dips are probably caused in part by drag on the western fault. Dips ranging from 25° to 55° are common, and they are comparable to those in the anticlinal limb of Paleozoic rocks in the adjacent Burbank Hills (Hintze, 1960). The Tertiary strata are repeated by west-dipping normal faults that have estimated stratigraphic offsets greater than faults in adjacent blocks of Paleozoic rock (Hintze, 1960, 1974a). Down-to-west faults are probably more abundant than shown in figure 2, especially in the area north of the line of section where easterly dipping Tertiary conglomerate is either extremely thick or repeated by faults.

To summarize, in the vicinity of the northern Tunnel Spring Mountains strata of Tertiary age are deformed on the same trends and by the same structures as strata of Paleozoic age. The Tertiary strata tend to be more steeply tilted and are displaced in greater amounts than strata in adjacent blocks of Paleozoic rock. This paradoxical relationship results from increasing stratal rotations as faults are approached from the downthrown block (reverse drag). The data suggest, as do cross sections constructed by Hintze (1974a), that the area was little deformed until the conglomerate and breccia were deposited, and it experienced an important episode of faulting and stratal tilting after the conglomerate and breccia were deposited. The last episode of deformation, or at least a late phase of it, produced the present Basin-Range configuration.

Southern area.--The relatively blunt southern end of the Tunnel Spring Mountains offers a better opportunity to make along-strike comparisons of style and intensity of deformation between Tertiary and Paleozoic strata than does the northern part which, because of its wedge-shaped plan, is unfavorable for along-strike projections. North to northwest strikes and west to southwest dips predominate in Paleozoic strata and along-strike Tertiary strata in the southern area (pl. 1.) An important reversal to easterly dips is seen in the northwest and west part of the mapped area. That dip reversal is discussed in a subsequent section.

Many of the fault planes crossed by section B-B' (pl. 1) are exposed and their attitudes are known as are the attitudes of the beds they cut. There is a strong tendency for bedding to form an angle of about 90° with fault planes when viewed in cross-strike vertical section (figs. 6, 7). This relationship is taken as proof that stratal rotations are fault-related. Indicated normal stratigraphic separation mapped on faults of the down-to-east system transected by section B-B' ranges from 20 to 540 m, with an average separation of 150 m for 26 faults that break the main range block. The cumulative normal separation is about 4 km on the 26 faults, but the structural relief across the 5.3-km-wide zone affected by them is negligible. This paradox results from the close genetic association between stratal rotation and fault displacement. Though the strata dip homoclinally westward, the 4 km of cumulative eastward throw on the faults is sufficient to completely negate all structural relief due to tilting. Thus, an eastward traverse along the line of section from the first downthrown block of Silurian Laketown Dolomite in the main range across the 25 fault blocks will result in a rise stratigraphically of about 200 m to near the Devonian-Silurian contact at the west margin of Pine Valley.

Cross section B-B' is constructed so as to suggest that some of the low-angle normal faults cut and displace earlier faults with steeper dips. This relationship is not known with certainty. Exposures in the eastern part of the main range block are probably adequate to evaluate the relationship, but time did not allow for the necessary detailed field studies.

Structure section C-C' (pl. 1) crosses an area that is largely covered by young alluvium and is, therefore, based on projections from scattered data. The scattered data indicate that stratal attitudes are similar to those of the on-strike Paleozoic rocks (fig. 8, and cross section B-B', pl. 1). Also, both structure sections indicate large cumulative normal fault separation but little net structural relief (actually a negative amount of structural relief of about -160 m from west to east across section C-C'). The eastern and western quarters of section C-C' are more reliable than the rest and are a fair approximation of the density and style of fault deformation in the Tertiary strata. There is a striking resemblance between the density and style of fault deformation in Tertiary strata and in on-strike Paleozoic strata indicating that deformation in the two areas is coeval and genetically related. A left-lateral component of movement is suggested on the northeast-trending transverse fault in sec. 27, T. 24 S., R. 17 W. by the presence of horse blocks of Needles Range Formation strewn along the trace of the fault between

Figure 6.--View looking north-northwest along bedding in carbonate rocks of Devonian age showing the tendency for joints to be oriented approximately normal to bedding. At this locality the principal joint set strikes approximately parallel to the strike of bedding. This geometric arrangement is common at many faults in the area.

the two main areas of mapped Needles Range. This and other transverse faults are probably genetically related to strike faults and stratal tilting as outlined in a subsequent section on fault mechanics.

The average separation indicated for faults along section C-C' is about 120 m compared to the average of about 150 m along B-B'. The area affected by the northwesterly trending down-to-the-east fault system broadens southward. If it is assumed that similar amounts of extension were accommodated throughout the area, the lesser average stratigraphic separation on faults crossed by section C-C' could be due solely to its geographic position.

The conglomerate and breccia unit that rests on the Needles Range Formation is involved in most, or possibly all, of the faulting and tilting and must, therefore, predate the deformation. If it is assumed that the unit is the age equivalent of the post-Needles Range conglomerate in the northern range (about 15 m.y. old near base), the intense fault deformation here, as in the north, is no older than mid-Miocene. The intrusive mass and the adjacent Tunnel Spring Tuff, which on the basis of isotopic data must also predate the deformation, appear relatively unfaulted (pl. 1), probably because recognizing faults in these massive rocks is difficult.

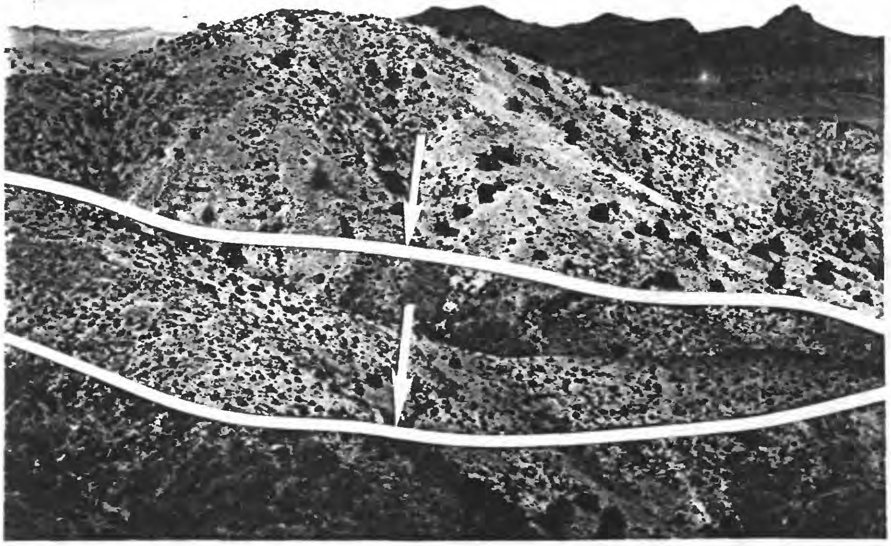
The northwest-trending system of faults produced little or no structural relief and therefore could not have been responsible for upiift of the core of the Tunnel Spring Mountains. Uplift of the range was accomplished on north- and northeast-trending faults that must, in large measure, postdate the northwest-trending faults. At least two ages of late Cenozoic normal faulting are indicated by the construction of cross-strike structure sections.

Clastic strata

Clastic strata in the Tunnel Spring Mountains and nearby areas suggest at least three separate tectonic events during Cenozoic time. The indicated events are numbered consecutively from oldest to youngest in the discussion that follows.

1.--Possibly the earliest record of Cenozoic tectonism is found in the volcanic-clast conglomerate exposed in the extreme western part of the southern area (pl. 1). The conglomerate is inferred to be the oldest Cenozoic deposit in the mapped area. Its assemblage of clasts includes a variety of exotic volcanic rocks as well as intrusive and pre-Tertiary sedimentary rocks that do not appear to have a local source. Some clasts in the conglomerate consist of recemented tectonic breccia. The clast assemblage suggests an early episode of volcanism and associated(?) plutonism followed by deroofing of plutons and possible associated fault-related brecciation in an unknown location within the Tunnel Spring Mountains region. Clasts 50 cm in diameter are included in the conglomerate, suggesting strong vertical structural and topographic relief in the source terrain.

7A



7B

Figure 7.--Views of faulted lower Paleozoic strata in southeastern part of Tunnel Spring Mountains. A, view south approximately parallel to strike of a 30° east-dipping fault that places light-gray Devonian dolomite over gray Silurian limestone; location directly west of center of sec. 15 along cross section B-B', plate 1. B, view to N. 55° E., approximately parallel to the down-dip direction of the two fault splays that project south-southeast toward and parallel to the 30° east-dipping fault shown in A (camera station located about 500 m west of center of sec. 15). The two fault splays merge a short distance to the right of the area covered by the photo. At point on the near fault marked by arrow, the fault dips about 65° away from camera; at distant arrow the far fault dips about 40° away from camera.

A small horse block of very coarse conglomerate composed mainly of clasts of Devonian Sevy Dolomite is situated between the Tunnel Spring Tuff and the uplifted pre-Devonian lower Paleozoic strata in a main northeasterly-trending fault zone at the southern end of the range (location A, pl. 1). The base of the Tunnel Spring Tuff is not exposed on the southern flank of the range, but the isolated horse block suggests that locally in that area the tuff is underlain by conglomeratic sediments. Studies of stratigraphic relationships at the type section (Bushman, 1973) of the Tunnel Spring Tuff at Crystal Peak (fig. 1) have shown that the tuff there is underlain[1/] by

[1/] A misassignment by earlier workers (Hintze, 1974a; Bushman, 1973) of the stratigraphic position of this very coarse debris to the interval between the Tunnel Spring Tuff and Needles Range Formation resulted from a misidentification of erosionally reworked debris as the primary debris. The erosionally reworked debris is probably of Quaternary age and does not occupy the stratigraphic position to which it was assigned.

Figure 8.--View to northwest into Tunnel Spring Mountains showing the similarity in stratal attitude between lower Paleozoic strata, which comprises the main range block in the distance, and Tertiary volcanic strata in the foreground. Bedding in the Tertiary strata, which are situated along strike of the Paleozoic strata, can be seen in the light-colored tuffaceous sediments (arrow) beneath the resistant dark vitrophyric zone in the basal part of the Needles Range Formation.

about 20 m of coarse debris that contains huge clasts of quartzite (fig. 9). Unpublished mapping on the north flank of the Burbank Hills (fig. 1) has shown that the Tunnel Spring Tuff there is underlain by thick coarse conglomeratic sediments. Volcanic clasts of identifiable Tertiary units were not found at any of these three widely separated localities, but the coarse debris and sediments are inferred to be of Tertiary age. On the north flank of the Burbank Hills this inference is supported by the common occurrence of biotite euhedra in fault gouge and breccia where the conglomeratic sediments are in fault contact with Paleozoic strata that form the core of the Burbank Hills. Presumably the biotite was derived from Tertiary igneous strata that underlie the conglomerate but are not exposed in the area.

Taken together, available data suggest basinal deposition of clastic debris that was probably fault-generated prior to eruption of the Tunnel Spring Tuff. The Tunnel Spring Tuff at its type section at Crystal Peak (Bushman, 1973) and in the southern Tunnel Spring Mountains is almost devoid of beds of "orogenic" gravel and conglomerate. On the western flank of the northern range the unit includes important sand and gravel, which contains cobbles and boulders as large as

Figure 9.--Concentration of huge boulders of quartzite and limestone beneath Tunnel Spring Tuff south of Crystal Peak. Large block that projects above skyline is about 4 m across.

30 cm, and northwest of there in the Burbank Hills (unpublished mapping), the Tunnel Spring Tuff is interstratified with beds of alluvial conglomerate. Major amounts of the clasts are angular limestone and quartzite, whereas volcanic clasts other than cognate inclusions are generally absent. These data suggest that deformation, which probably involved uplift of Paleozoic rocks along faults west of the Tunnel Spring Mountains, occurred at least intermittently during eruption of the Tunnel Spring Tuff.

The scattered exposures of ash-flow tuffs of the Needles Range Formation that are downfaulted along the margins of the Tunnel Spring Mountains have strikingly similar cooling zonations, suggesting that at about 29 m.y. ago the tuffs formed a continuous sheet across the area now occupied by the range. In the southern Tunnel Spring Mountains and on the east flank of the northern part of the range the Needles Range Formation rests on tuffaceous sedimentary rocks derived from erosion of the Tunnel Spring Tuff. On the west flank of the northern part of the range, the Needles Range is separated from the Tunnel Spring Tuff by several meters of alluvial gravels; in the northern Burbank Hills more than 100 m of Paleozoic-clast conglomerate separates the units. These relationships suggest that the Needles Range Formation in this area was extruded into a basin that was receiving coarse clastic strata from fault-generated Paleozoic highlands to the west or northwest and finer clastic strata from highlands of Tunnel Spring Tuff, possibly to the east.

In summary, coarse to very coarse clastic strata and debris in the vicinity of the Tunnel Spring Mountains indicate tectonic activity in the region before and during extrusion of the Tunnel Spring Tuff 32.7-33.7 m.y. ago and during the interval between extrusion of that tuff and extrusion of the Needles Range Formation about 29 m.y. ago. The area now occupied by the Tunnel Spring Mountains was probably part of a downfaulted basin of deposition during most of that time. The volume of volcanic rock received by that part of the basin appears to have exceeded that of clastic deposits, but the reverse appears to be so to the northwest in what is now the north flank of the Burbank Hills.

2.--The conglomerate and breccia unit that overlies the Needles Range Formation records an important tectonic event. The breccia, which is restricted to the southern part of the range and includes large landslipped sheets of crackled but stratigraphically intact rock, must have been deposited near its source terrain. Of special significance is the fact that it could not have been derived from the uplifted core of the adjacent Tunnel Spring Mountains because the appropriate rocks are not exposed there over large enough areas or at structurally high enough positions to yield large landslide sheets. The mountain mass from which the breccia was derived is no longer exposed. Perhaps it is downfaulted beneath Pine Valley (fig. 1).

The alluvial part of the conglomerate and breccia unit resembles fanglomerate and suggests basin deposition close to fault-front source terrain. As with the breccia part, it contains materials that have no obvious exposed local source. For example, clasts of ash-flow tuffs that have not been identified in nearby volcanic sections are included in the conglomerate on the west flank of the northern range, and clasts of equally exotic thin-bedded and contorted lacustrine mudstone and volcanic rocks are included in the conglomerate on the south flank of the range. Also, on the east flank of the northern range the abrupt disappearance of pebble- to boulder-size clasts of Needles Range Formation within a meter or so of the base of the alluvial deposits indicates that the detritus, which above that horizon is wholly Paleozoic rock, was derived from an area where the Needles Range Formation was either not deposited or had been removed by erosion. As noted above, a sheet of Needles Range ash-flow tuff probably covered the area now occupied by the Tunnel Spring Mountains.

It is clear that the fault fronts from which most, if not all, of the conglomerate and breccia unit were derived, no longer exist. The unit is of large volume and indicates a major structural event; perhaps an episode of Basin and Range faulting that was totally unrelated to the episode that produced strong internal deformation in the range and to the subsequent episode that produced the present Basin and Range configuration. The age of the deformation that gave rise to the conglomerate and breccia is approximated by a single fission-track determination of about 15 m.y. on a tuff bed near the base of the unit (table 1). If this age is characteristic of the unit, the area apparently contains no record of events that occurred between extrusion of the Needles Range Formation (about 29 m.y.) and the deposition of the conglomerate and breccia.

3.--The final structural event indicated by clastic strata in the area is recorded by the deposit of Quaternary alluvium in the area and by clastic deposits of latest Tertiary age that are inferred to conformably underlie the Quaternary alluvium. These deposits record the fault displacements that produced the present Basin-Range configuration. The earlier (but post 2.), structural event that produced the strong internal deformation in the range (as described under the preceding headings--structure sections) was probably not accompanied by deposition of thick clastic strata because it did not produce strong structural or topographic relief.

SUMMARY OF CENOZOIC STRUCTURAL HISTORY

The construction of cross-strike structure sections combined with stratigraphic studies of exposed Cenozoic rocks and clastic deposits on the flanks of the Tunnel Spring Mountains and adjacent areas shows that the region was the loci of several episodes of deformation since early Oligocene time. Whatever deformation occurred in the Tunnel Spring Mountains area prior to that time left no record either of strong topographic or structural relief or of significant stratal rotation.

Three main episodes of deformation are recognized. They are summarized in order of decreasing age.

1. Accumulation during early Oligocene time of coarse clastic strata together with volcanic strata of the Tunnel Spring Tuff in a basin that may have been fault-bounded. Hypabyssal masses of porphyritic rhyolite and quartz latite were intruded passively. These events were followed during later Oligocene time by emplacement into the basin of ash-flow tuffs of the Needles Range Formation.
2. During middle to late(?) Miocene time deformation that probably involved strong vertical displacement on faults produced highlands that shed coarse clastic debris and landslide sheets into the area now occupied by the Tunnel Spring Mountains. The part of the original basin situated in the area that is now west of the northern Tunnel Spring Mountains was exposed to erosion prior to or during the early stage of this episode of deformation. Clastic deposits accumulated throughout the Tunnel Spring Mountains area to thicknesses of several hundred meters. In general, the highlands and fault fronts from which these large volumes of materials were shed are no longer exposed. Presumably they were destroyed by erosion or by structural downfaulting (or by both processes) before or during the subsequent episode of deformation.
3. Possibly beginning in Miocene time and extending into Pleistocene time the Tunnel Spring Mountains area was involved in two or more phases of normal faulting that produced displacements and stratal rotations of all strata, including the newly deposited thick clastic units. The first phase involved large displacements on listric NNW- to NS-trending normal faults that apparently did not produce significant amounts of structural or topographic relief across the area; it did, however, account for most of the Cenozoic extensional tectonics of the area. The amount of extension varies widely. It is nominal in the small areas of flat-lying to gently dipping strata, but is about 70 percent (2.2 km across a 5.4 km distance) east of the boundary fault zone along cross section B-B' (pl. 1). Two domains of contrasting structural fabric developed. Most of the range consists of a domain of down-to-west faulting and easterly stratal rotations, but in the southern part there is a domain of down-to-east-northeast faulting and west-southwest rotations. The second phase of normal faulting produced the existing range by uplift on relatively high angle NNE- to NE-trending faults. Presumably this phase extended into Pleistocene time, though no fault scarps that can be judged to be of late Pleistocene age are found on the alluviated flanks of the range.

The age of the first episode of deformation (which is recorded as an episode of deposition in the Tunnel Spring Mountains area) is fairly well documented as being of Oligocene age. The age of the beginning of the second episode of deformation (which also is recorded as an episode of deposition) is suggested by a single age determination at about 15 m.y. Its duration is not known. The age of the beginning of the final episode is not known nor is its duration. It is inferred to be of late Tertiary age (post 15 m.y.) and to have extended into early Pleistocene time.

NOTES ON THE MECHANICS AND KINEMATICS OF FAULTING

Mapping in the Tunnel Spring Mountains area was done for the purpose of deciphering the Cenozoic structural history which is found to be much more complex than previously reported. Unfortunately time constraints precluded mapping the entire area or, indeed, mapping with uniform standards of quality throughout the parts that were mapped. Though this lack of completeness and uniformity of quality precludes a rigorous evaluation of the mechanics and kinematics of deformation, some generalized and tentative statements can be made.

The rocks in the Tunnel Spring Mountains and vicinity are unmetamorphosed. Structures of a broad range in size reflect brittle deformation. They include: (1) the mapped faults, which tend to be sharp breaks marked by narrow zones of recemented breccia or gouge or by secondary silica or carbonate, (2) areas of jostled rock, and (3) areas of brecciated rock. There is a gradation in size from large fault-bounded blocks of unbroken rock that can be mapped conveniently at scales of 1:62,500 or 1:24,000, through areas of closely spaced faulting or jostling that would require larger scale maps for adequate depiction to areas of thoroughly disrupted brecciated rock. The areas of jostled and brecciated rock are not shown on the geologic maps (fig. 2, pl. 1) which are, therefore, incomplete depictions of the nature and extent of brittle deformation. Careful study of the mesoscopic fabric of jostled blocks commonly reveals fracture patterns similar to those seen on maps and cross sections at macroscopic scales. This similarity suggests a common parentage in the regime of brittle failure. The variable-scale results of brittle deformation are not necessarily gradational in space. Areas of brecciated and jostled rock are as much as a few square kilometers in extent and are commonly sharply bounded against unbroken rock by faults or by stratigraphic contacts. Breccia in areas of Paleozoic strata tends to be more extensively developed in stratigraphic units composed of massive rock such as the Ely Springs Dolomite, Laketown Dolomite, or Eureka Quartzite than in thin-bedded shaley units such as are found in the exposed sequence of undifferentiated Ordovician strata. Hintze (1978) noted a similar selective distribution of breccia in nearby mountain ranges to the north.

Although Cenozoic strata are generally not brecciated, important exceptions are found in the massive andesite flows and quartz latite intrusive rocks which, in addition to being brecciated near contacts with Paleozoic rocks, also contain flow layering that is disrupted as a result of post-solidification jostling. Also, local areas of tectonically disrupted and jostled ash-flow tuff of the Needles Range Formation are indicated by the structurally exotic position of masses of vitrophyre in devitrified tuff. However, if internal disruptions are common in densely welded tuffs they are generally unrecognizable because of a lack of distinct marker horizons.

In an important recent report Hintze (1978) described great variations in thickness of Paleozoic strata in the Fish Springs and House Ranges to the north-northeast of the Tunnel Spring Mountains and interpreted the variations to be the result of structural attenuation by faulting. Recent geologic mapping and stratigraphic studies by Hintze and his students at Brigham Young University have documented similar stratal attenuation in the Tunnel Spring Mountains and vicinity (oral commun., 1979). Systematic stratigraphic studies that would permit an analogous evaluation of structural attenuation in Cenozoic strata would be extremely difficult and have not been made. Generally, Cenozoic strata are considered as lacking the lateral stratigraphic continuity that would permit such an evaluation. Hintze (1978) states that Cenozoic igneous rocks in the Fish Springs and House Ranges are not involved in attenuation faulting, but I have subsequently observed low-angle attenuation faults in Cenozoic intrusive rocks in the northern House Range. Also, I have observed numerous localities in the Tunnel Spring Mountains, Conger Range, and Confusion Range (fig. 1) where nonwelded to partly welded zones are absent from the basal parts of ash-flow tuffs situated adjacent to structurally attenuated masses of Paleozoic strata. Such zones should be present as a result of normal cooling-dependent processes (Smith, 1960; Ross and Smith, 1961), and I infer that they are absent as a result of structural attenuation. Available data suggest that Oligocene and Miocene strata were present during the full range of faulting, brecciation, stratal tilting, and structural attenuation that affected the Paleozoic strata, although the case for this full contemporaneity cannot be made as strongly as it can for faulting and stratal tilting alone.

Cross-strike structure sections show the dominant structure to be extensional normal faulting. The strong tendency for strata and faults along these sections to intersect at about 90° forms a basis for suggesting (A-A', fig. 2; B-B', C-C', pl. 1) that most faults decrease in dip with depth and are therefore concave upward (Anderson, 1971; Proffett, 1977). In domain A several strike faults can be traced continuously into transverse faults suggesting that the base of the faulted blocks are shovel-shaped or half-shovel-shaped and the faults are listric. Negligible structural relief across areas of strong stratal tilting and large-magnitude separation on associated listric faults is characteristic of areas in the Basin and Range province that have undergone extension on listric normal faults. The brittle nature of the deformation suggests that it took place under shallow conditions as suggested by Hintze (1978). Strain is assumed to pass upward from a zone of horizontally directed ductile extension and vertical attenuation through a transition zone of mixed brittle-ductile behavior within which fault deformation is penetrative on horizontal to subhorizontal planes to a zone of brittle failure. The faults representing strain effects in the zone of brittle failure are listric and reflect traction transmitted at the base of the zone resolved into pure tension at the top of the zone (ground surface).

Deformation on closely spaced listric faults results in structural attenuation above the level at which the faults become horizontal or subhorizontal. This separate evidence from faulting of late Cenozoic structural attenuation is consistent with the suggestion made above that the widespread structural attenuation in Paleozoic rocks indicated by stratigraphic studies is late Cenozoic in age.

Within domain A the bearing of lineations on fault surfaces of variable strike is recorded at nine localities (pl. 1). The average bearing of these lineations (which include slickensides, grooves, and corrugations) is approximately N. 65° E.--perpendicular to the average strike of the strata. The axis of least principal stress during the episode of listric faulting of domain A is inferred to be located in an approximately vertical plane whose strike is constrained within the range of variability of measured bearings (±25°). Bearings of lineations were not recorded in domain B. If the least principal stress direction for that domain is inferred to be normal to the average stratal strike, it would lie in a plane that strikes more easterly than that of domain A.

Boundary Fault Zone

The boundary between domains A and B in the area covered by plate 1 is marked by a N. 20° E. fault zone referred to as the boundary fault zone after excellent exposures near the northern boundary of the Desert Experimental Range in sec. 9, T. 24 S., R. 17 W. In that area strata with northwest strike and opposed dip in respective domains extend to the fault zone. In the southern part of sec. 9, faults in the zone dip easterly from 75° to 40° and enclose narrow horse blocks of strata such as the Eureka Quartzite and Ely Springs Dolomite that occupy a stratigraphic position between stratigraphically lower undifferentiated Ordovician strata in the footwall to the west and Silurian and Devonian strata in the hanging wall. In places in the northern part of sec. 9, the fault zone narrows to a single break although rock in the hanging wall block is jostled and brecciated. Throughout its mapped length the boundary fault zone places younger rock on older rock suggesting a major component of normal slip. In section 9 where the fault cuts the Devonian Simonson Dolomite the indicated stratigraphic offset is about 1.2 km.

Northeasterly dipping strike faults with large normal stratigraphic offset extend to the boundary fault zone from domain A. Some of these faults bend and merge with the boundary fault zone and none appear to displace it, suggesting that the strike faults are contemporaneous with the boundary fault zone. Also, the boundary fault zone does not appear to be offset by strike faults of domain B. In particular, the major west-dipping normal fault system that places Devonian rock against Ordovician rock in the structurally complex area crossed by the western part of cross section B-B' (pl. 1) does not appear to offset the boundary fault zone.

The approximate location of the boundary fault zone north of the area included in plate 1 can be seen on aerial photographs to project to the north-northeast and cross the eastern flank of the Tunnel Spring Mountains. Because of its continuity, apparent large displacement, and position separating structural domains, the boundary fault zone is interpreted as a major dislocation along which differential stresses between the two domains were accommodated. Because it dips beneath domain A and strike faults of that domain appear to merge with it, the boundary fault zone may represent a major transverse detachment fault or sole fault which, in its down-dip direction, accommodated most of the extensional deformation in domain A. Its temporal and genetic relationships to extension in domain B are less apparent. If extension in the two domains is coeval, the boundary fault zone may have served more to accommodate differential displacements related to contrasting extensional kinematics than to contrasting amounts of extension between the two domains.

The boundary fault zone coincides closely with the location of the east margin of a major structural trough or synclinorium of late Mesozoic to early Cenozoic age defined by Hose (1977) (fig. 1). The location and trend of the fault zone may have been controlled by this major trough, but at presently exposed levels the boundary fault zone is a late Cenozoic structure. There is no suggestion of strong folding associated with the old structural trough as is the case northward along the trough (Hose, 1977).

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