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An Outline of Tectonic, Igneous, and Metamorphic Events in the Goshute-Toano Range Between Silver Zone Pass and White Horse Pass, Elko County, Nevada: A History of Superposed Contractional and Extensional Deformation

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By Keith B. Ketner, Warren C. Day, Maya Elrick,
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An Outline of Tectonic, Igneous, and Metamorphic Events in the Goshute-Toano Range Between Silver Zone Pass and White Horse Pass, Elko County, Nevada: A History of Superposed Contractional and Extensional Deformation

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ABSTRACT

Rocks of the Goshute-Toano Range, Elko County, Nevada, between White Horse Pass on the south and Silver Zone Pass on the north, record a complex Mesozoic and Tertiary history of metamorphism, contractional and extensional deformation, and igneous activity. Paleozoic strata comprise seven distinctive structural tracts, separated from each other by low- or high-angle faults. These tracts are grouped here into three structural-thermal levels separated by low-angle faults: (1) a lower level of Cambrian to Mississippian sedimentary rocks that were strongly folded and metamorphosed in Mesozoic time, (2) a middle level of Cambrian to Mississippian, nonmetamorphosed sedimentary strata that were heated moderately, weakly folded, thinned by bedding-parallel faults, and segmented by high-angle faults, and (3) an upper level of Pennsylvanian, Permian, and younger rocks that were heated only slightly and, over large areas, were broken up, tilted, and dispersed by normal faulting in Miocene time.

Lower-level rocks were intruded in Middle Jurassic time by a granodiorite stock that transected metamorphic fabric. Middle-level strata were intruded in the Late Jurassic by granite bodies of extremely irregular shape and in Late Jurassic to middle Miocene time by stocks, dikes, and sills. Upper-level strata lack outcrops of intrusive rocks of any kind. Extensive Miocene rhyolite flows cover parts of middle- and upper-level strata.

The Goshute-Toano Range is replete with well-developed examples of contractional and superposed extensional structures and offers abundant opportunities for potentially very productive detailed structural studies.

INTRODUCTION

The Goshute Mountains and the Toano Range are segments of a continuous mountain range in northeastern Nevada separated only by Morgan Pass, a high divide in the central part of the range. Our investigation extends from White Horse Pass, 32 km south of Morgan Pass, to Silver Zone Pass, almost 32 km north of Morgan Pass (fig. 1). This segment is herein termed the Goshute-Toano Range. The Goshute-Toano Range, as so defined, lies within a region of Mesozoic contraction (Coats and Riva, 1983; Ketner, 1984; Thorman and others, 1991) and Mesozoic to Tertiary extension (Hodges and Walker, 1992).

Our investigation began in 1984 as an effort sponsored by the U.S. Bureau of Land Management to assess the mineral potential of the Bluebell and Goshute Peak Wilderness Study Areas, which occupy much of the Goshute-Toano Range. That task, which involved mapping the entire range between White Horse and Silver Zone Passes, was completed in 1986. Recently, part of the mapped area was revised in an attempt to understand more fully the basic features of the structural and igneous history. The geology of large parts of the Goshute-Toano Range was described previously (Day and others, 1987; Ketner 1987; Ketner and others, 1987). The geology north of Silver Zone Pass was mapped and described by Glick (1987); the area immediately south of the pass within the Silver Zone Pass quadrangle was mapped by D.M. Miller (unpub. mapping).

Acknowledgments.—Paleontological age determinations by Olgerts L. Karklins and Raymond C. Douglass were indispensable and greatly appreciated. Richard H. Blank, Jr. assisted in the gravity survey. Scott Gum, Dirk Hovorka,

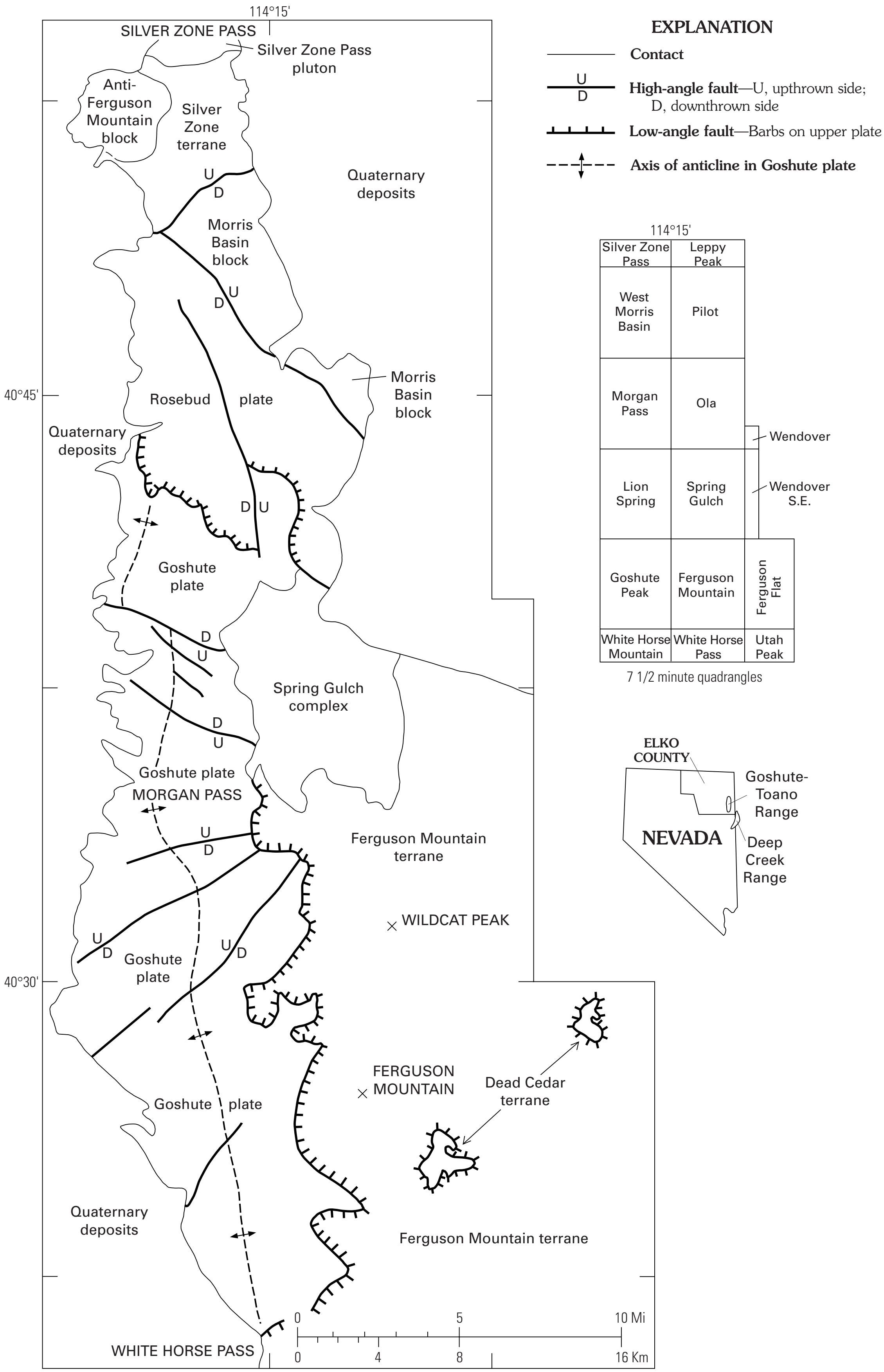
114°15'
SILVER ZONE PASS
Silver Zone Pass pluton
Anti-Ferguson Mountain block
Silver Zone terrane
Quaternary deposits
Morris Basin block
Rosebud plate
40°45'
Morris Basin block
Quaternary deposits
Goshute plate
Spring Gulch complex
Goshute plate
MORGAN PASS
Ferguson Mountain terrane
WILDCAT PEAK
Goshute plate
40°30'
FERGUSON MOUNTAIN
Dead Cedar terrane
Goshute plate
Quaternary deposits
Ferguson Mountain terrane
WHITE HORSE PASS
0 5 10 Mi
0 4 8 16 Km
U D
EXPLANATION
Contact
High-angle fault—U, upthrown side; D, downthrown side
Low-angle fault—Barbs on upper plate
Axis of anticline in Goshute plate
114°15'
Silver Zone Pass
Leppy Peak
West Morris Basin
Pilot
Morgan Pass
Ola
Wendover
Lion Spring
Spring Gulch
Wendover S.E.
Goshute Peak
Ferguson Mountain
Ferguson Flat
White Horse Mountain
White Horse Pass
Utah Peak
7 1/2 minute quadrangles
ELKO COUNTY
Goshute-Toano Range
NEVADA
Deep Creek Range

Figure 1 (previous page). Generalized geologic map of the Goshute-Toano Range showing seven structural tracts: Silver Zone terrane, Dead Cedar terrane, Goshute plate, Morris Basin block, Rosebud plate, Ferguson Mountain terrane, and anti-Ferguson Mountain block.

Robert Walker, and Robert Yambrick assisted in the mapping. David M. Miller permitted use of unpublished data from his map of the Silver Zone Pass quadrangle in the northern part of the range. John E. Welsh freely shared his deep knowledge of the stratigraphy and structure of the region and permitted use of data from his detailed maps of the Ferguson Mountain and Ferguson Flat quadrangles adjacent to the southern part of the range. R.A. Zimmermann determined the fission track dates herein, and L.W. Snee determined the Ar/Ar dates. Leroy Brown provided safe, efficient helicopter service. Suggestions by David M. Miller, Constance J. Nutt, James K. Otton, Christopher J. Potter, and Charles H. Thorman greatly improved presentation and interpretation of the data.

STRATIGRAPHY

The Goshute-Toano Range is composed of Middle Cambrian to Lower Triassic marine sedimentary rocks, Jurassic to Miocene intrusive rocks, Tertiary sedimentary deposits including rock-avalanche deposits, and Miocene volcanic rocks. Quaternary unconsolidated deposits of gravel and lake sediments form fans and flats on both sides of the range. Descriptions of the strata comprising the Goshute-Toano Range are given by Day and others (1987), and descriptions of Cambrian rocks are given by McCollum and Miller (1991). The Paleozoic and Triassic sedimentary rocks in the Goshute-Toano Range constitute a miogeoclinal shallow-water sequence similar to that of many other ranges in the Basin and Range Province of western Utah and eastern Nevada (fig. 2). However, the Permian and Middle to Upper Devonian intervals are unusually thick, and, owing to structural attenuation, many stratigraphic units are locally abnormally thin. The thickness of Devonian strata given in Day and others (1987) is erroneously high; figure 2 of the present report depicts the corrected thickness. Mississippian shale, in comparison with correlatives in adjacent ranges, is abnormally thin throughout the range. Triassic rocks are sparsely and poorly exposed in the Goshute-Toano Range, and their original thickness can only be inferred to be about the same as in the neighboring Pequop Mountains, about 900 m. Jurassic and Cretaceous sedimentary rocks were not identified. Tertiary sedimentary units are incompletely exposed but apparently were deposited in local lacustrine basins or as fans on the flanks of the mountain range, and their thicknesses vary widely.

STRUCTURE

The Goshute-Toano Range records a history of intense Mesozoic contraction overprinted by intense Tertiary, and possibly older, extension. The contraction is expressed as large-scale folding and thrust faulting; the extension is expressed as pervasive normal faulting, stratigraphic attenuation, tilting of fault blocks, and formation of lake deposits and rock-avalanche deposits.

The Goshute-Toano Range is herein divided into seven structural tracts on the basis of data from the geologic map of part of the range (Day and others, 1987), detailed maps of selected areas (Ketner, 1997), and unpublished mapping by Ketner. The seven tracts, all in fault contact with one another, are shown in figure 1 and are herein described from structurally lowest to structurally highest.

STRUCTURAL TERMS FOR FAULT-BOUNDED TRACTS

In this report, the term *terrane* is used for extensive tracts of undetermined thickness that conform to the definition in Bates and Jackson (1987): "...a fault-bounded body of rock of regional extent, characterized by a geologic history different from that of contiguous terranes...;" the term *plate* is used for fault-bounded tracts that are laterally extensive relative to thickness; *block* is used for tracts that are of relatively small extent in relation to thickness. The term *listric fault* is used for high- to low-angle, curved, downward-flattening, normal faults. These may be curved on one axis (cylindrical or snow-shovel-shaped) or two (ovoidal or spoon-shaped)—in either case, the listric faults resulted in tilted beds that toe into the fault. The term *planar fault* is used for normal faults that appear to be uncurved. *Bedding-parallel* or *attenuation faults* are planar faults nearly parallel to bedding that commonly result in thinning or omission of strata.

In accordance with the above definitions, the fault-bounded tracts of the Goshute-Toano Range are designated as the Silver Zone terrane, Dead Cedar terrane, Goshute plate, Morris Basin block, Rosebud plate, Ferguson Mountain terrane, and anti-Ferguson Mountain block.

SILVER ZONE TERRANE

The Silver Zone terrane, at the north end of the Goshute-Toano Range, consists of Cambrian and Ordovician carbonate and shale sequences deformed into map-scale, northeast-plunging folds (fig. 3) (Ketner, 1997). The rocks are metamorphosed to greenschist grade and locally display small-scale, penetratively deformed beds. Limestone has been bleached and marbleized; shale has been converted to phyllite and, in some places, to coarse muscovite

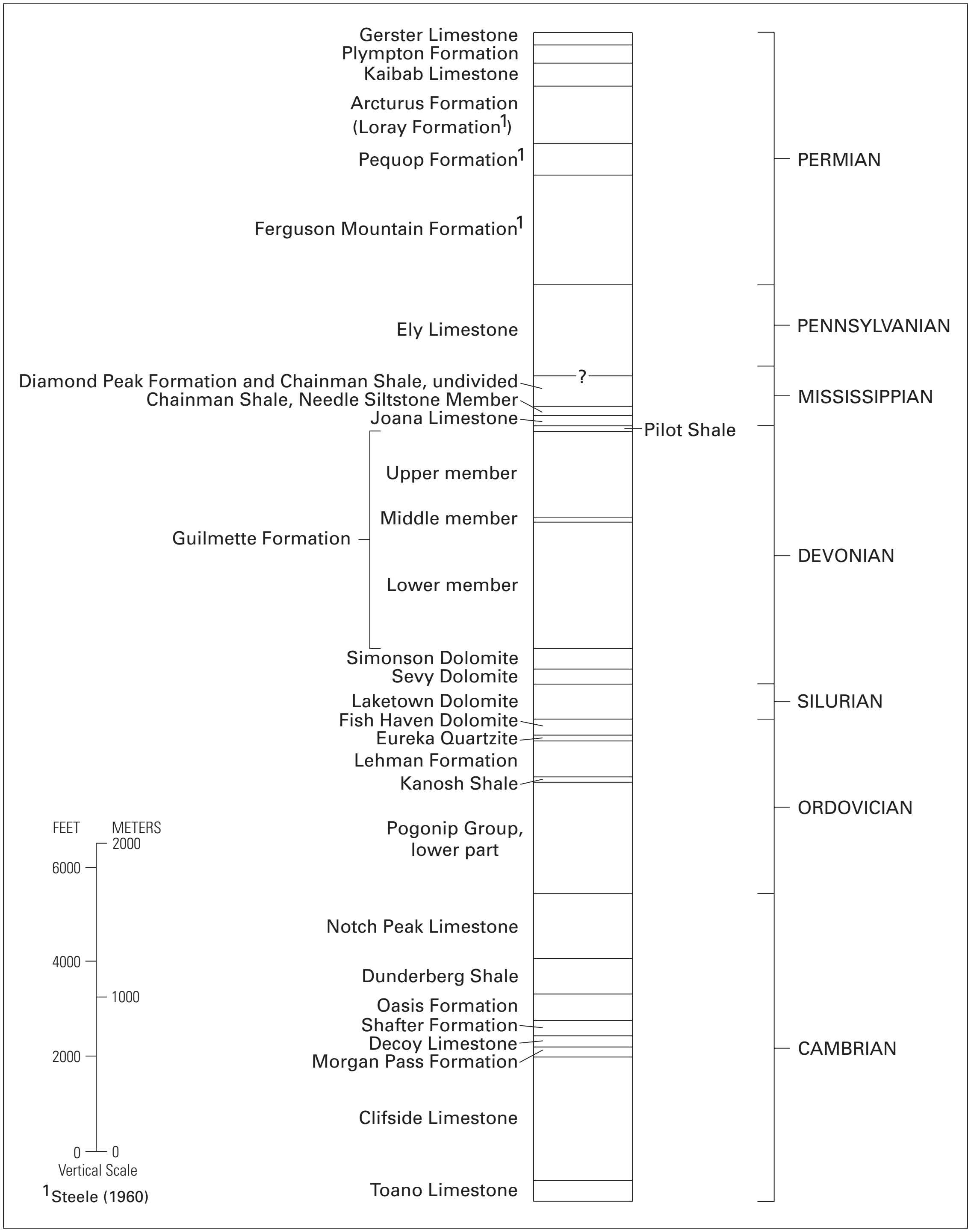

Figure 2. Stratigraphic column of Paleozoic rocks in the Goshute-Toano Range modified from Day and others (1987) and from McCollum and Miller (1991). The thickness of the Guilmette Formation is corrected from the erroneous figure in Day and others (1987). The thicknesses of the Cambrian units are from the Silver Zone terrane, and they therefore differ from those in Day and others (1987), which are from the Goshute plate. Triassic and Tertiary sedimentary rocks are present, but because their thicknesses are totally unknown, they are not shown. Low-angle faulting is pervasive and has affected the original thicknesses of all Paleozoic stratigraphic units to a greater or lesser degree.

schist. Some strata appear to be significantly thinner than correlative unmetamorphosed strata in the central part of the range, possibly owing to tectonic attenuation.

The Silver Zone terrane consists of two structural plates separated by a poorly defined, approximately horizontal fault zone. Strata of the upper plate, composed of Cambrian and Ordovician rocks, are folded into a northeast-plunging, upright syncline. Strata of the lower plate, composed of the same strata, are folded into a southeast-vergent, overturned anticline. The lower plate displays north- to northwest-dipping overturned beds passing northward through vertical to upright strata that dip to the southeast. The overturned bedding attitude in southern exposures is indicated especially by inverted stratigraphic order but also by sparse inverted cross-beds, borings, and stromatolites. The upright orientation of strata in northern exposures of the lower plate is indicated by conspicuous, abundant, upright cross-bedding.

The map-scale folding and subsequent duplication of the Cambrian and Ordovician sequences are interpreted as contractional features of probable Jurassic age. The normal planar and listric faults are extensional structures of Tertiary age. The horizontal fault zone is undated.

The Silver Zone terrane was intruded by the Middle Jurassic Silver Zone Pass pluton (Miller and others, 1990). This stock transects greenschist-grade metamorphic fabric of the terrane, indicating that the metamorphism is Jurassic or older.

DEAD CEDAR TERRANE

The Dead Cedar terrane is sporadically exposed beneath the Ferguson Mountain terrane to the east and southeast of Ferguson Mountain. Exposures consist principally of Middle and Upper Devonian carbonate rocks that display large-scale upright folds, locally with vertical limbs. Metamorphism and ductile deformation are expressed as bleached marble, penetratively deformed beds, stretched fossils, and microscopic foliation. The two relatively large exposures of this terrane shown on figure 1 display northwest- and southeast-plunging anticlines. Several other exposures near Ferguson Mountain are outlined on an unpublished detailed map of the Ferguson Mountain quadrangle by John E. Welsh, consulting geologist. The various outcrops of the Dead Cedar terrane are similar in degree of deformation and metamorphism to the Silver Zone terrane, but, because (1) these exposures are geographically far from Silver Zone Pass, (2) the terrane differs in orientation of folds, and (3) it consists of different Paleozoic strata, it is given a different name.

GOSHUTE PLATE

The Goshute plate, which crops out extensively over the southern two-thirds of the Goshute-Toano Range, is composed of Cambrian to Mississippian shallow-water deposits totaling at least 4,500 m in thickness. The western boundary of the Goshute plate consists of north-striking, west-dipping basin-range normal faults not clearly exposed but identified by both physiographic and gravity data. The eastern boundary of the plate is arbitrarily placed in figure 1 at the western margin of the Ferguson Mountain terrane; the two tracts actually overlap.

Rocks of the Goshute plate are relatively free from folds and are not visibly metamorphosed. However, conodont color alteration indices (CAI) of Cambrian to Mississippian strata indicate that the plate has been heated to a relatively high temperature. (Note: CAI values can range from 1 to 7 or more. In undeformed sequences of sedimentary rocks free from igneous intrusions, they commonly correlate with depth of burial as indicated by stratigraphic thicknesses of the original overlying rock column.) CAI values in the Cambrian to Mississippian interval of the Goshute plate range randomly from 4 to 6, regardless of geographic or stratigraphic position (Karklins and others, 1989). The lack of correlation between the temperatures attained as indicated by the CAI values and the depth of burial as indicated by stratigraphic position suggests that the original array of CAI values was thermally altered by intrusive rocks. We consider that tectonic frictional heating is probably too ephemeral to be an important factor in altering the original CAI values.

The sharp contrast in degree of folding and metamorphism between the Goshute plate and the Silver Zone Pass and Dead Cedar terranes requires juxtaposition by faulting. Unfortunately, the Silver Zone terrane is now clearly separated from other tracts by high-angle faults of probable Tertiary age, and the contact between the Dead Cedar terrane and other tracts is obscure. Tentatively, the Goshute plate is herein interpreted to be underlain by extensions of the Silver Zone and Dead Cedar terranes, with a low-angle fault contact. This interpretation implies duplication of thick stratigraphic sequences and therefore contractional deformation. Faults nearly parallel to bedding are present throughout the Goshute plate but are most common in the Middle to Upper Ordovician strata and in the Mississippian shale. Such faults are here interpreted to be extensional features because they eliminate strata or result in significant reduction in their thickness. If these interpretations are valid, the assumed contractional sole fault and the visible extensional internal faults must be genetically unrelated. A satisfactory understanding of the apparent disparity between the nature of the sole fault and internal bedding-parallel faults awaits further study. The age of the internal extensional faults can be inferred to be of Tertiary age as described under the heading “Ferguson Mountain Terrane.”

Most of the Goshute plate has been warped into a north-trending, low-amplitude anticline and is cut by abundant incipient listric faults and bedding-parallel faults. It is also cut by a conspicuous set of convergent, planar, vertical

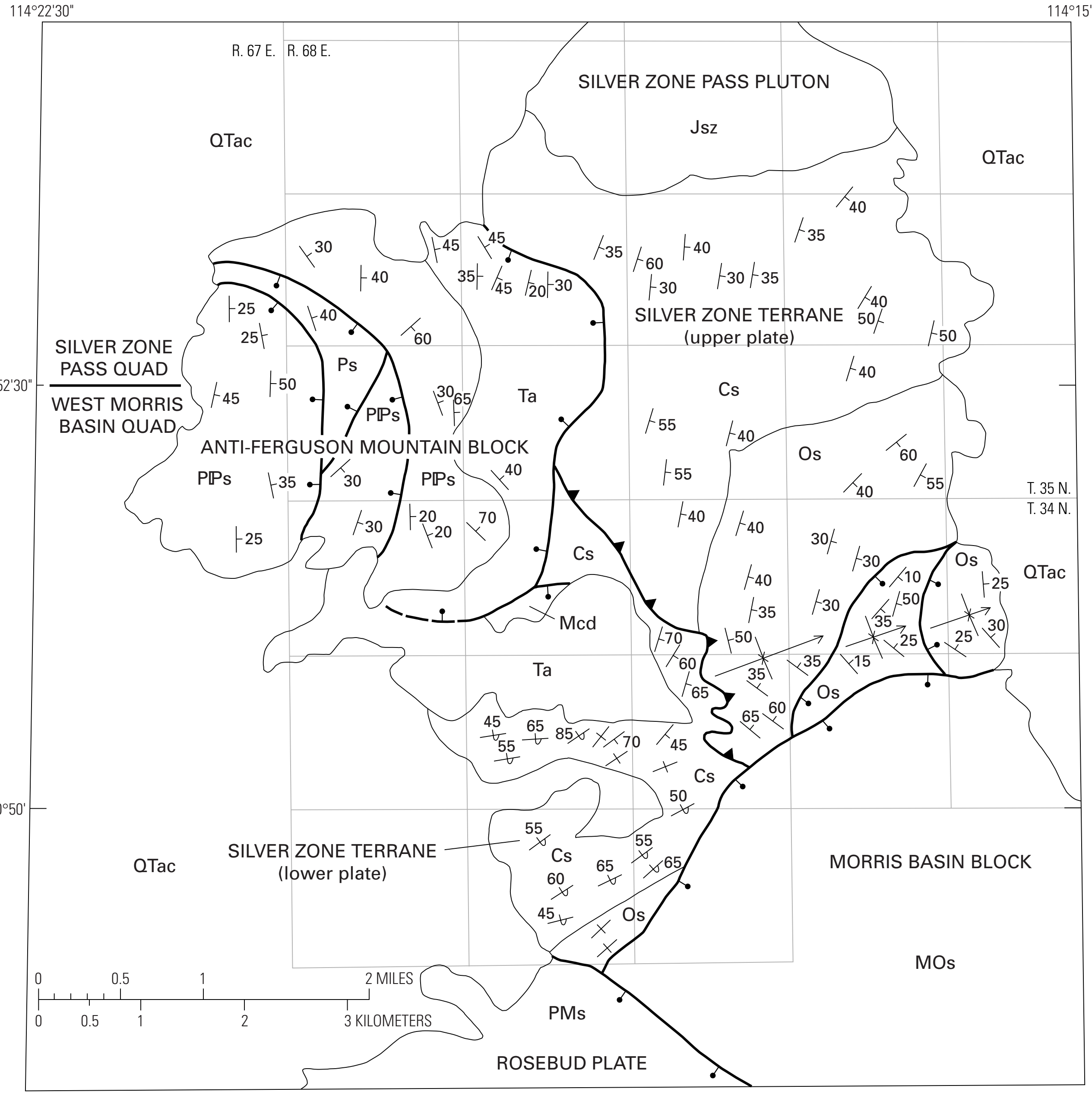

Figure 3 (above and facing page). Geologic map of the north end of the Goshute-Toano Range, showing the anti-Ferguson Mountain block, the Silver Zone Pass pluton, and both upper and lower plates of the Silver Zone terrane. The Silver Zone terrane was folded, metamorphosed, and intruded by the Silver Zone Pass pluton in Jurassic time. The anti-Ferguson Mountain block is a listric fault block of Pennsylvanian and Permian rocks derived from the Rosebud plate that broke loose and rotated down-to-the-east in Tertiary time. The block includes tilted beds of avalanche, alluvium, and lake deposits derived principally from the Pennsylvanian and Permian rocks during rotation of the block.

faults. The anticlinal axis, located by means of bedding attitudes that do not appear to be strongly tilted by listric faults, follows a sinuous path that trends northward, ending at the southern margin of the Rosebud plate. Incipient listric faults in the Goshute plate dip toward the east on the east side of the anticlinal axis and to the west on the west side. The relation of the anticline in the Goshute plate to detachment faulting in younger strata is discussed under the heading “Ferguson Mountain Terrane.”

The planar vertical faults in the Goshute plate converge toward the Spring Gulch complex on the east side of the range. Vertical offsets on these faults in the southern part of the array indicate relative uplift on the north sides; those in the northern part of the array indicate uplift on the south

DESCRIPTION OF MAP UNITS

QTac	**Alluvium and colluvium (Quaternary and Tertiary)**—Unconsolidated sand and gravel
Ta	**Avalanche and alluvial deposits (Tertiary)**—Coarse breccia composed of clasts mainly from the anti-Ferguson Mountain block, alluvial conglomerate, and lake deposits. Much of this complex deposit is separated from underlying Mississippian and Cambrian strata by a curved fault; unit is tilted to the east
Jsz	**Silver Zone Pass pluton (Jurassic)**—Grandodiorite stock that intruded metamorphosed Cambrian strata; intrusion age is 162 Ma and cooling age is 152 Ma (Miller and others, 1990)
Ps	**Sedimentary rocks (Permian)**—Silty, sandy limestone, dolomite, phosphatic and cherty rocks
PIPs	**Sedimentary rocks (Permian and Pennsylvanian)**—Limestone and silty sandy limestone
PMs	**Sedimentary rocks (Permian, Pennsylvanian, and Mississippian)**—Limestone, dolomite, conglomerate, phosphatic, cherty rocks; part of Rosebud plate
Mcd	**Diamond Peak Formation and Chainman Shale, undivided (Mississippian)**—Shale and conglomerate; probably separated from underlying Cambrian strata by a low-angle extensional fault
MOs	**Sedimentary and metasedimentary rocks (Mississippian to Ordovician)**—Limestone, dolomite, shale, quartzite, and conglomerate; part of the Morris Basin block; some strata are significantly metamorphosed and penetratively deformed
Os	**Metasedimentary rocks (Ordovician)**—Limestone, dolomite, shale, and quartzite; forms part of the Silver Zone terrane; slightly metamorphosed and, in places, penetratively deformed; folded to form a northeast-plunging syncline
Cs	**Metasedimentary rocks (Cambrian)**—Limestone, marble, shale, phyllite, and siltstone; forms part of Silver Zone terrane; metamorphosed and penetratively deformed; divided into two parts by thrust fault; strata below the thrust fault form part of an overturned anticline; strata above the thrust fault form part of a northeast-plunging syncline

MAP SYMBOLS

Contact

Normal fault—Ball on downthrown side

Thrust fault—Sawteeth on upper plate

Trough line of syncline—Showing direction of plunge

Attitude of beds—Showing degree of dip

45 Upright

65 Overturned

Vertical

sides. As a result, the central part of the plate has been elevated by these faults relative to the southern and northern parts, and exposures in the center of the plate therefore contain the oldest stratigraphic units. The anticlinal axis is cut, but not measurably offset, by all but one of these faults. The most northerly vertical fault does appear to offset the axis, however, and the evidence of age of the anticline in relation to the age of the radial faults is therefore ambiguous. Cross-cutting relations with other faults indicate that the radial faults are of Tertiary age. The radial faults transect listric and bedding-parallel faults that are confidently interpreted to be of Tertiary age, but they do not cut the upper Miocene rocks in the Spring Gulch complex.

MORRIS BASIN BLOCK

The Morris Basin block is an Ordovician to Mississippian sequence separated from other principal structural units by high-angle faults and segmented by low-angle faults nearly parallel to bedding. Aligned mineral fabric in the Devonian beds indicate some degree of metamorphism, whereas the Ordovician and Mississippian beds are unaffected. Beds are less strongly folded than those of the Silver Zone terrane. Although the block displays features of both the Silver Zone terrane and the Goshute plate, the lack of either large-scale folds or pervasive metamorphism ally it more closely with the Goshute plate. Additional study is required to resolve this ambiguity.

ROSEBUD PLATE

The Rosebud plate covers the Goshute plate in much of the northern third of the Goshute-Toano Range. It lies extensively on attenuated Mississippian shale and, less extensively, on older carbonate rocks of the Goshute plate with a low-angle fault contact.

The plate is composed mainly of earliest Pennsylvanian to mid-Permian strata that total more than 2,200 m in thickness. Mississippian rocks may form part of the plate in one area as described below. Triassic rocks are exposed extensively in northeastern Nevada, and small remnants are present within and near the Goshute-Toano Range. Prior to their removal by erosion, the Rosebud plate undoubtedly included extensive Triassic strata and probably younger rocks as well. The Rosebud plate is segmented by steep, incipient, listric and planar normal faults of small displacement but remains essentially intact.

Rocks of this plate are not metamorphosed, and, with one exception, CAI values range from 1 to 3, representing relatively low temperatures in contrast to uniformly higher CAI values in the underlying Goshute plate.

The contact between the Goshute and Rosebud plates is interpreted to be a low-angle fault nearly parallel with bedding. The evidence is in (1) the extreme attenuation and elimination of Mississippian strata of the Goshute plate immediately underlying the Rosebud plate, (2) local truncation of beds immediately above the contact, and (3) an abrupt contrast in CAI values across the contact that separates the plates.

The stratigraphic position of the contact between the Rosebud and Goshute plates along the western margin of the Rosebud plate north of lat 40°45′N. is uncertain. South of this point, the underlying Mississippian strata are extremely attenuated and consist mainly of shale and sandstone—the contact with the overlying Rosebud plate is clearly a fault. North of this point, the exposed Mississippian rocks are composed of a relatively thick sequence of limestone and conglomerate, and clear evidence of a fault along their contact with the overlying Pennsylvanian beds is lacking. In this area, the sole fault may cut down-section and disappear under Quaternary sediments. The Rosebud plate may, as a result, include Mississippian strata at its base. More detailed stratigraphic studies and more paleontological dating are needed for a solution to this problem.

FERGUSON MOUNTAIN TERRANE

The Ferguson Mountain terrane lies to the east and southeast of the southern part of the Goshute-Toano Range and extends southeastward toward the Deep Creek Range, covering an area of as much as 1,000 km^2. Some of it almost certainly lies buried under Quaternary sediments of the Bonneville Salt Flats, which extend eastward from the Goshute-Toano Range. Unpublished detailed geologic maps of the Ferguson Mountain and Ferguson Flat quadrangles by John E. Welsh, consulting geologist, are the principal documentation for the nature and extent of the Ferguson Mountain terrane, but structures in the Spring Gulch complex mapped by us are representative (Day and others, 1987; Ketner, 1997).

The terrane consists of tilted blocks, mainly of Pennsylvanian and Permian strata identical to those of the Rosebud plate and apparently derived from a former extension of that plate. The blocks now lie widely dispersed, commonly on attenuated Mississippian shale of the Goshute plate and on metamorphosed and strongly folded strata of the Dead Cedar terrane. In addition to Pennsylvanian and Permian strata, some of the blocks include limestone beds of Triassic age and limestone, tuff, sandstone, and rock-avalanche deposits of Tertiary age.

Nearly all of the blocks are tilted to the southwest toward the Goshute-Toano Range or toward exposures of the Goshute plate south of White Horse Pass. The blocks are bounded by faults that are either curved or straight in plan view. Ferguson Mountain, a single very prominent fault block of 4 km^2, is the largest block but in most other respects is typical. It is composed of Pennsylvanian and Permian strata, lies on attenuated Mississippian rocks, and is tilted to the west.

The direction of Tertiary extension during formation of the Ferguson Mountain terrane is predominantly N. 65° E. as indicated by the strike of bedding in most of the tilted blocks.

The southern part of the Goshute plate adjacent to the Ferguson Mountain terrane is almost entirely denuded of upper Paleozoic and Triassic rocks of the Rosebud plate. Although it is not clear whether extensive translation of fault blocks of the Ferguson Mountain terrane has taken place, the juxtaposition of the denuded part of the Goshute plate with that terrane is suggestive. The denuded part of the Goshute plate seems to be a probable source for some of the blocks of this terrane. The Ferguson Mountain terrane is apparently absent adjacent to the northern part of the Goshute-Toano Range where the Rosebud plate remains intact.

Formation of the Ferguson Mountain terrane, and also the anti-Ferguson Mountain block in the northern part of the range, took place in the Tertiary, probably in the early to middle Miocene. Tilted strata of the anti-Ferguson Mountain block in Silver Zone Basin were dated at about 14.7 Ma ($^{40}Ar/^{39}Ar$, sanidine). We dated a dike in the Goshute plate at 46.6±5.1 Ma (fission track, zircon) and 17.6±2.6 Ma (fission track, apatite)—these ages are here interpreted to indicate, respectively, the times of intrusion and of tectonic unroofing of that plate.

Unroofing of the Goshute plate and tilting of blocks comprising the Ferguson Mountain terrane were completed prior to late Miocene, as indicated by stratigraphic-structural relations at Wildcat Peak. There, Pennsylvanian strata tilted to a near-vertical position are overlain by horizontal rhyolite flows of 10.7±1.4 Ma (fission track, biotite).

The Rosebud plate in the northern part of the Goshute-Toano Range is virtually intact, and, although it lies on greatly attenuated Mississippian strata, it does not display notable internal attenuation. However, many of the rotated fault blocks comprising the Ferguson Mountain terrane include abnormally thin Pennsylvanian and Permian strata (John E. Welsh, consulting geologist, unpub. mapping). We infer that the abnormally thin strata had been attenuated by bedding-parallel faulting in part of the Rosebud plate prior to its breakup.

The breakup of the Rosebud plate could take place only during, or soon after, extension of the Goshute plate, which removed laterally confining support and created the lateral space into which blocks, spalled from the Rosebud plate, could rotate and disperse. Because the rotation and dispersal are of Tertiary age, the stretching of the underlying Goshute plate by attenuation faulting is most likely to be of Tertiary age also.

As stated previously, the Goshute plate is warped to form a north-trending anticline of low amplitude. The question arises: what is the relation of the anticline to the breakup of the Rosebud plate and formation of the Ferguson Mountain terrane? Two hypotheses are suggested: (1) the anticline is older than the breakup and caused the Rosebud plate to break up and disperse both east and west, or (2) the anticline is younger than the breakup and represents isostatic rebound due to tectonic unroofing. A corollary of the first hypothesis is that the late Paleozoic Rosebud plate remains intact in the northern part of the range because the anticline died out to the north. A corollary of the second hypothesis is that the continued presence of the unextended Rosebud plate in the northern part of the range accounts for the northern termination of the anticline.

ANTI-FERGUSON MOUNTAIN BLOCK

The anti-Ferguson Mountain block in the northern part of the Goshute-Toano Range is a tilted fault block composed of a core of Pennsylvanian and Permian strata derived from the Rosebud plate and a poorly stratified mass of Tertiary deposits (fig. 3). The Paleozoic component of the block is segmented by a number of nested listric faults. The block lies partly on a Mississippian remnant of the Goshute plate and partly on Cambrian and Ordovician metamorphic rocks of the Silver Zone terrane. Its structural position is analogous to that of the Ferguson Mountain terrane, which lies partly on attenuated Mississippian shale of the Goshute plate and partly on metamorphosed rocks of the Dead Cedar terrane—an analog of the Silver Zone terrane. The fault block is similar to Ferguson Mountain in its Paleozoic stratigraphy and size, but it lies on the west side of the range rather than the east side and is tilted to the east rather than to the west—hence “anti-Ferguson Mountain”—a term invented for the purpose of discussion only.

The Tertiary component of the anti-Ferguson Mountain block consists of rock-avalanche, alluvial, and lake deposits. Most large clasts of the avalanche and alluvial deposits are composed of Pennsylvanian and Permian rock derived from the anti-Ferguson Mountain block, but a small proportion was derived from Cambrian rocks of the Silver Zone terrane. The Tertiary deposits of the anti-Ferguson Mountain block are tilted to the east in the same manner as the Paleozoic strata comprising most of the block. The older Tertiary lake deposits dip about 40° to 45°, but the younger ones dip only 20° to 30°. This indicates the deposits accumulated in the trough formed between the rotating block and its substrate during rotation and, as they accumulated, became part of the rotating block.

We dated a tuff bed among tilted lake deposits in the upper part of the Tertiary sequence that dip about 30° at 14.7 Ma ($^{40}Ar/^{39}Ar$, sanidine). This dates rotation of the fault block as at least partly of middle Miocene or younger age.

SPRING GULCH COMPLEX

The northwestern corner of the Ferguson Mountain terrane and part of the adjacent Goshute plate is designated as the Spring Gulch complex because it is the site of a large intrusive body; tilted lake beds; tilted giant-clast, rock-avalanche deposits; and a high concentration of Miocene volcanic rocks.

ROCK-AVALANCHE DEPOSITS

Avalanche deposits composed partly of giant clasts of both upper and lower Paleozoic rock constitute part of the Ferguson Mountain terrane and the anti-Ferguson Mountain block. They constitute a large part of the Ferguson Mountain terrane in the Spring Gulch complex. Clasts of the deposits are generally angular and range in size from sand to more than 1 km in greatest dimension. Those comprising part of the anti-Ferguson Mountain block are composed mainly of upper Paleozoic rocks, but those in the area of the Spring Gulch complex were derived mainly from lower Paleozoic formations, commonly of Devonian age. The source of most of the clasts in the vicinity of the anti-Ferguson Mountain block was the block itself as previously stated. Apparently, as the block rotated, the slope of its oversteepened east face was progressively reduced by repeated avalanches.

Avalanche deposits in the Spring Gulch area probably were derived from adjacent exposures of the Goshute plate, and it seems likely that they originated as rockfalls from the upthrown sides of the vertical radial faults that segment this plate and that converge toward the Spring Gulch area (Ketner, 1994, 1997).

Most of the rock-avalanche deposits are interbedded with Tertiary lake deposits. Evidently, lake sediments were deposited in closed depressions on the surfaces of early-formed avalanche deposits and were buried by subsequent avalanches. Many of the avalanche deposits with their enclosed lake beds are tilted by normal faulting, and, in one place, Tertiary lake beds enclosed in avalanche deposits were contorted possibly during emplacement of the overlying deposit or by later, renewed movement of the entire mass.

INTRUSIVE ROCKS

SILVER ZONE PASS PLUTON

The Silver Zone Pass pluton is a coarse-grained biotite-hornblende granodiorite stock exposed at the north end of the mapped area and beyond (Glick, 1987). The geophysical data of Grauch and others (1988) indicate the pluton extends well beyond its outcrop area.

The pluton intruded Cambrian rocks of the Silver Zone terrane, which, in this area, had been previously deformed and metamorphosed to greenschist facies. Petrographic features of the pluton, as well as its age, are discussed by Miller and others (1990), whose data indicate a Middle Jurassic age.

SPRING GULCH CHONOLITH AND RELATED APLITIC DIKES

The Spring Gulch chonolith is a fine-grained leucocratic granite, perhaps more properly termed aplite. It forms extensively exposed hypabyssal intrusive bodies centered in the Spring Gulch complex. Geophysical evidence (Grauch and others, 1988) and our gravity data indicate the chonolith may extend well beyond the outcrop area in all directions. The term “chonolith,” rather than sill or stock, is used because of its complex shape as revealed in outcrops. Outcrops of the chonolith are commonly associated with exposures of Mississippian shale and appear to lie mainly within or just below the shale.

Phenocrysts, 1–3 mm in diameter, constituting as much as 15 percent of the rock, are composed of anhedral quartz, alkali feldspar, plagioclase, garnet, and abundant muscovite set in a fine-grained groundmass of similar composition. Ferromagnesian minerals are eliminated or altered almost beyond recognition. Euhedral, oxidized pyrite is common. Iron and manganese oxides form characteristic dendrites along fractures in the generally very light colored rock. Similar muscovite granites of various ages extend from Canada to Mexico (Miller and others, 1987; Miller and others, 1988; Miller and Bradfish, 1980).

The Spring Gulch chonolith is probably a species of two-mica granite as determined by microscopic comparison with the two-mica Toano Springs pluton (Miller and others, 1990) (“Toana Range” pluton of Lee and others, 1981, 1986), which crops out just north of the map area. In the Toano Springs pluton, muscovite contains biotite inclusions parallel with cleavage. In the more altered Spring Gulch chonolith, layers of opaque matter in the muscovite parallel to cleavage are interpreted to be the remains of biotite. The chonolith contrasts with the very coarse grained Toano Springs pluton, however, because the chonolith is fine grained and intensely bleached; it locally displays intense argillic alteration; and its age is different.

Some dikes and small plugs within the Goshute plate are composed of leucocratic aplite. Although finer in grain size, these dikes are probably genetically associated with, and correlative with, the Spring Gulch chonolith, based on their similar chemistry and mineralogy.

We determined the Spring Gulch chonolith to be of Late Jurassic age (156.4±0.23 Ma, $^{40}Ar/^{39}Ar$, muscovite).

DIKES AND SMALL STOCKS

Rhyodacite dikes and small granodiorite stocks are concentrated mainly in lower Paleozoic rocks of the Goshute plate. The dikes are medium- to fine-grained biotite-plagioclase rhyodacite porphyry. Phenocrysts include euhedral to subhedral glomerocrysts of plagioclase, subhedral biotite, and subhedral hornblende. Moderate to high degrees of alteration of both groundmass and phenocrysts has produced chlorite after biotite and hornblende, sericite, and calcite after plagioclase. A rhyodacite dike in the Goshute plate yielded fission track ages of 46.6±5.1 Ma (zircon) and 17.6±2.6 Ma (apatite). We interpret these ages to indicate, respectively, a middle Eocene time of intrusion and an early Miocene time of tectonic unroofing. The latter date is important as an indicator of the time of formation of the Ferguson Mountain terrane by breakup and dispersal of the Rosebud plate.

Eocene granodiorite forms a very few small stocks in lower Paleozoic rocks of the Goshute plate. These bodies are smaller than the granodioritic Silver Zone Pass pluton, have a higher ratio of hornblende to biotite, and are much younger. A granodiorite stock in the southern part of the range yielded ages of 36.9±4.6 Ma (fission track, apatite) and 36.2±3.6 Ma (zircon).

Widely scattered, small, irregular and tabular mafic bodies intruding the Goshute plate range from gabbro to diorite. The mafic rocks are in the form of dikes in carbonate strata and sills in the Mississippian shale. They consist of moderately altered, coarse-grained thatches of amphibole, pyroxene, and plagioclase set in a small amount of interstitial fine-grained quartz and feldspar.

VOLCANIC ROCKS

Volcanic rocks are extensively exposed along the eastern side of the Goshute-Toano Range but are concentrated in the Spring Gulch complex near the center of the range. Rhyolitic flows and domes are greatly predominant over intercalated rhyolitic tuffs and lahar deposits.

Almost all of the volcanic rocks were erupted after tilting of structural blocks had ceased. Fission-track dates of samples from untilted flows at six scattered localities indicate that the rhyolite flows and domes erupted during the middle and late Miocene. These determinations, which are closely clustered, have a mean age of 11.4±1.0 Ma.

A thin tuff bed in a moderately tilted deposit of landslides, alluvium, and lake deposits in Silver Zone Basin yielded a middle Miocene age, as previously stated.

SUMMARY

Three principal structural levels separated by major low-angle faults are recognized among Paleozoic rocks in the Goshute-Toano Range. The Silver Zone and Dead Cedar terranes are interpreted as the footwall rocks of an extensive low-angle fault and comprise the lowest of the three structural levels. The overlying Goshute plate represents the middle structural level. The Rosebud plate, the Ferguson Mountain terrane, and the anti-Ferguson Mountain block constitute the uppermost of the three levels. The rocks of all three levels were brittlely deformed by low- and high-angle planar faults and by listric faults.

The three structural levels correspond to three thermal levels. Rocks of the lowest structural level have been metamorphosed to the greenschist grade. Carbonate rocks are recrystallized to marble; shales are phyllitic and locally schistose. Locally, some beds are penetratively deformed. Rocks of the middle structural level, the Goshute plate, were heated to moderate levels according to their relatively high CAI values but were not significantly recrystallized or penetratively deformed. Upper Paleozoic rocks of the upper structural level were only slightly heated and are completely free from any recrystallization or penetrative deformation.

Lower-level rocks were intruded in Middle Jurassic time by the Silver Zone Pass pluton, a granodiorite stock that transected metamorphic fabric. Middle-level strata were intruded in Late Jurassic time by fine-grained two-mica granitic bodies of irregular shape and in Late Jurassic to middle Miocene time by stocks, dikes, and sills. Upper-level strata lack outcrops of intrusive rocks of any kind.

Map-scale folds, metamorphism, and outcrop-scale penetrative deformation in the Silver Zone terrane represents deformation at relatively great depth. Duplication of the Cambrian and Ordovician sequences by thrusting within the Silver Zone terrane represents more brittle deformation and probably took place at shallower depth. In any event, map-scale folds, especially if they are overturned, and repetition of strata commonly are considered to be contractional features, and we interpret those features displayed in the Silver Zone terrane as such. The folds and metamorphic fabric of the Silver Zone terrane were cut by the Jurassic Silver Zone Pass pluton and are therefore older. Direct evidence for a more precise date is lacking in the Goshute-Toano Range, but evidence from the region generally points to a Jurassic age (Miller and others, 1987; Thorman and others, 1991).

Attenuation faults in the Goshute plate are interpreted to represent extensional deformation. Breakup of the Rosebud plate and dispersal of the resulting blocks could take place only during or immediately after extension of the substrate by near-bedding-parallel faulting. Such faulting removed laterally confining support and created space for the blocks to occupy. Because the rotation of blocks and their dispersal is of Tertiary age, the extension of the Goshute plate by attenuation faulting, especially evident in the Mississippian strata but present at lower levels also, is most likely to be of Tertiary age also.

If the Goshute plate structurally overlies the Silver Zone and Dead Cedar terranes on a low-angle fault as here tentatively interpreted, the resulting repetition of thick sequences of Paleozoic strata must be regarded as a contractional feature. More data are needed to resolve the discrepancy between the apparently contractional nature of the putative sole fault of the Goshute plate and the extensional nature of the internal attenuation faults. Although it seems likely that the internal attenuation faults are of Tertiary age, the time of assumed emplacement of the Goshute plate on its substrate cannot be determined without more data.

Although strata of the Rosebud plate are generally in normal stratigraphic sequence with those of the underlying Goshute plate, we interpret the contact to be tectonic because the Mississippian strata at the top of the Goshute plate are greatly attenuated, overlying strata are truncated locally, and there is an abrupt contrast between the CAI values above and below the contact. The attenuation of the Mississippian strata and the younger-on-older relation are interpreted to indicate the sole fault is an extensional feature rather than a contractional one.

The part of the original Rosebud plate remaining intact in the northern part of the range does not appear to be reduced in thickness by bedding-parallel faults. In contrast, some strata in some of the rotated blocks derived from the Rosebud plate, and now forming part of the Ferguson Mountain terrane, are abnormally thin. Evidently they had been thinned by near-bedding-parallel faults before fault block movement, but why this had taken place in the southern part of the range and not in the northern part is unknown.

The Ferguson Mountain terrane and the anti-Ferguson Mountain block clearly display several near-surface extensional features including dispersal of structural blocks, tilting of the blocks toward their source area, stratigraphic attenuation of the substrate of the blocks, and attenuation of strata within the blocks.

The age of extension is clear. The Goshute plate was unroofed in the early Miocene: rocks as young as middle Miocene are included in tilted blocks, and late Miocene volcanic rocks are untilted.

Near-vertical radial faults of the Goshute plate are late-phase features. They cut Tertiary, probably Miocene, extensional faults but do not cut late Miocene volcanic rocks. Topographic relief caused by vertical movement on the radial faults are the probable cause of the mega-block avalanche deposits, which are concentrated at the radial-fault focal point in the Spring Gulch complex.

The nature and origin of many structural features of the Goshute-Toano Range remain obscure, and the range provides exciting opportunities for future research.

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