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GEOLOGIC MAP OF THE MOTOQUA AND GUNLOCK QUADRANGLES, WASHINGTON COUNTY, UTAH

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STRUCTURE

Structures characteristic of the structural transition from the Basin and Range province to the adjacent Colorado Plateaus province are found in the easternmost part of the map area (fig. 1). The map area also lies at the eastern edge of the Mesozoic Sevier orogenic belt and at the southern edge of the Oligocene-Miocene volcanic field of the Clover and Bull Valley Mountains (fig. 2).

Rocks in the map area were deformed mostly during three periods of differing regional tectonic conditions. During late Mesozoic–earliest Cenozoic time, Sevier-Laramide compression produced folds, thrust faults, and syntectonic sedimentary deposits. Then, the area was moderately extended during Oligocene–early Miocene explosive volcanism and plutonism in the Clover and Bull Valley Mountains (Best and Christiansen, 1991). Finally, strong late Cenozoic deformation produced northwest- and north-northeast-striking fault systems, and related fault basins filled with thick accumulations of synextension sedimentary deposits and some volcanic rocks.

Distinguishing between structures formed during each of the disturbances is more difficult in the southern part of the map area where Cenozoic rocks are sparse to absent than in the northern part where these rocks are widely distributed around the pre-Cenozoic rocks that contain the record of older deformation. This difficulty allows for alternative interpretations of the structural history, especially that of the southern part of the map area. In this discussion, two alternative interpretations are presented for one of the major structures of the region, the Beaver Dam Mountains anticline. Its resulting from Mesozoic compressional deformation is favored by Hintze and Embree, whereas Cenozoic extensional deformation is favored by Anderson.

LATE MESOZOIC AND EARLIEST CENOZOIC COMPRESSIONAL EVENTS

Pre-Cretaceous strata in the Motoqua and Gunlock quadrangles encompass many significant depositional hiatuses, but do not contain significant structural discordances. The initiation of the late Mesozoic Sevier orogeny in eastern Nevada is signaled by an increase in the volume of clastic materials from the west, represented by sand and gravel in the Iron Springs Formation. Continued latest Mesozoic and early Cenozoic compressional deformation of the Sevier and Laramide orogenies produced folds, thrusts, and syntectonic deposits such as the Grapevine Wash Formation. Three of these structures are discussed in the paragraphs that follow.

Beaver Dam Mountains anticline

The homoclinally northeast-dipping strata that dominate the structural pattern south and southeast of the Square Top Mountain thrust may be the northeast flank of a large northwest- to north-northwest-trending late Mesozoic anticline that Hintze (1986) referred to as the Beaver Dam Mountains anticline (BDMA) (fig. 3). In the West Mountain Peak 7 1/2-minute quadrangle, the anticline is cored by exposed Precambrian crystalline rocks (fig. 3). East of the Precambrian core in the West Mountain Peak and Shivwits quadrangles, a sequence of east- to northeast-tilted Paleozoic and Mesozoic strata is very well exposed in a 12-km-wide belt (fig. 3). These rocks are structurally continuous with the homoclinally northeast-dipping strata of the southeastern part of the Motoqua-Gunlock quadrangles, and together they form the eastern part of the BDMA. Smith and others (1987) and Wernicke and Axen (1988) interpreted the structure as part of a broad arcuate zone of uplift resulting from isostatic adjustment to late Tertiary tectonic denudation. This interpretation was challenged by Carpenter and others (1989) on the basis of seismic-reflection data and a cross section extending westward from the Beaver Dam Mountains to the Tule Springs Hills.

Shivwits syncline

Paleozoic and Mesozoic strata that form the east limb of the BDMA also form the west limb of the Shivwits syncline (fig. 3). The axial trace of the Shivwits syncline follows a slightly sinuous northerly course through the Shivwits 7 1/2-minute quadrangle. Eastward dips in rocks of the Iron Springs Formation and Navajo Sandstone directly east of Gunlock Reservoir indicate that the Shivwitz syncline does not extend northward into the Gunlock quadrangle, thereby precluding determination of its age relative to Cenozoic rocks in that quadrangle.

Square Top Mountain thrust

In the Red Hollow, Square Top Mountain, and Jackson Peak areas, autochthonous Mesozoic rocks of the BDMA are overridden by the Square Top Mountain thrust (STMT). This feature, which was previously mapped as a N. 70° W.-striking segment of the thrust between the Red Hollow and Square Top Mountain areas (Cook, 1960; Wiley, 1963; Hintze, 1986), is actually a steep dextral tear fault. Discontinuous thrusts that are subsidiary to the STMT are found to the north. The best exposures of the main STMT are in sec. 1, T. 40 S., R. 19 W., where Lower Pennsylvanian Callville Limestone is tectonically superposed upon overturned Triassic and Jurassic rocks. In that area, the upper-plate rocks appear to have been dragged down along the Red Hollow fault at the western edge of the Beaver Dam Mountains. Remnants of upper-plate rocks occur in scattered exposures for 5 km south to beyond Red Hollow Reservoir. Elsewhere, exposures of thrust surfaces are very sparse as a result of cover by talus, colluvium, alluvium, and, in some areas (such as northeast of Jackson Peak), postthrusting rocks downfaulted against the rocks of the allochthon. As a result, the attitude of the STMT is generally not known. Inferring its attitude from its approximate surface trace across irregular topography is imprudent because there is a high probability that rocks of the allochthon are currently bounded against those of the autochthon by postthrusting dip-slip or strike-slip faults (cross section *A–A'*).

The extent of the STMT to the east of Jackson Peak is not known. An area of overturned and attenuated Jurassic Carmel, Temple Cap, Navajo, Kayenta, and Moenave Formations near White Rocks (very close to the easternmost exposures of upper-plate Permian rocks) suggests that the easternmost limit of the thrust sheet may be near these overturned rocks. The synthrusting Grapevine Wash Formation is present only in the Gunlock quadrangle where it has a width of exposure (and presumably deposition) of only about 12 km. This width is typical of synorogenic conglomerate belts elsewhere in Utah (for example, the Red Narrows Conglomerate in Spanish Fork Canyon near Provo and the Echo Canyon Conglomerate near Coalville in northern Utah).

Across its 6.5 km of east-west extent, the stratigraphic level of the STMT in the allochthon climbs from the Callville Limestone through the Pakoon Dolomite to the Queantoweap Sandstone. In the autochthon, it climbs from Upper Triassic Chinle Formation through the entire section of Jurassic rocks to the Iron Springs Formation. Allochthonous rocks, especially the carbonate rocks, are strongly folded and faulted and locally brecciated. The least deformed of the allochthonous rocks seem to make up Square Top Mountain. Along the southeastern flank of Square Top Mountain, the allochthon apparently overrode a wedge of synthrusting unconsolidated tectonic breccia (**Ktm**, a tectonic mixture of Triassic and Jurassic rocks that lies between Permian rocks of the allochthon and Jurassic and Cretaceous strata of the autochthon). In the Red Hollow area, northwest-striking rocks of the BDMA bend to the north and northeast and are steeply tilted to overturned as they approach the STMT, suggesting that they are dragged beneath the thrust. The steep to overturned rocks with northeast strikes in both allocthon and autocthon in that area represent a trend that may be approximately perpendicular to the direction of thrusting. As described below, however, a strong likelihood of postthrusting stratal rotation precludes reliable determination of thrusting kinematics from the Red Hollow area.

The age of thrusting is not well constrained. If the upper part of the Iron Springs Formation records the approach of the thrust allochthon and the Grapevine Wash Formation records its arrival, as we suspect, then thrusting occurred during the Late Cretaceous and could have extended into the Tertiary. If the aspect of eastward stratigraphic climbing of the thrust in upper- and lower-plate rocks is interpreted to indicate that these rocks were tilted prior to thrusting, then thrusting must postdate development of the BDMA. This is highly unlikely because most rocks of the allochthon have attitudes similar to those of the adjacent autochthon (cross section *A–A'*), and attitudes in both plates are similar to attitudes of overlying upper Tertiary rocks. On the basis of regional structural history (Armstrong, 1968), we exclude from consideration the possibility that the thrust is late Tertiary and assume, instead, that it is Late Cretaceous or early Tertiary and has been extensively deformed by late Tertiary faulting.

In the unlikely possibility that the BDMA predates thrusting, an early episode of east-northeast- to northeast-directed compressional deformation would be suggested. This seems to be an equally unlikely possibility because the best indications of the direction of maximum compression during the later thrusting are the northeast strike of the overturned and attenuated Mesozoic rocks in the White Rocks area and the northeast strike of subsidiary thrusts and associated folds in the northern part of the Motoqua quadrangle, especially in sec. 30, T. 39 S., R. 19 W. Structures in both areas suggest northwest-southeast-directed maximum compression during thrusting.

EARLY CENOZOIC POSTOROGENIC DEPOSITION

The lower Tertiary Claron Formation represents postorogenic lacustrine and fluvial deposition in an area of lower relief than that in which the preceding Grapevine Wash Formation was deposited. Rocks that have been mapped as Claron Formation are widely distributed in the High Plateaus of southwestern Utah and the adjacent Basin and Range to the west (Rowley and others, 1979). Although the age of these rocks is not well constrained and correlations between widely separated exposures in the Basin and Range are tenuous, a general predominance of lacustrine limestone and mudstone over fluvial facies suggests Paleocene-Eocene deposition in a broad shallow basin similar in paleogeographic significance to others in the Western United States, as described by Fouch (1979) and Nilsen and McKee (1979).

OLIGOCENE–EARLY MIOCENE LIMITED EXTENSION AND EXPLOSIVE VOLCANISM

Sevier-Laramide compression was followed by a 30-m.y. period of quiescence during which little structural disturbance occurred and fluvial and lacustrine deposits of the Claron Formation accumulated thinly in basins of low relief. Major volcanic activity in the Indian Peak–Caliente area, some 80 km north of the Motoqua-Gunlock quadrangles, began abruptly about 33 m.y. ago when ash-flow tuffs were widely deposited in western Utah and eastern Nevada (Rowley and others, 1979; Best and Grant, 1987). The oldest representative of this volcanic activity to reach as far south as the Motoqua-Gunlock area is the 29-Ma Wah Wah Springs Tuff of the Needles Range Group, found here as a thin nonwelded unit within lacustrine rocks that are mapped as postdating the Claron Formation. Products of post-Needles Range volcanic eruptions began to overwhelm the lacustrine paleoenvironment in many areas. In several areas in and near the Motoqua-Gunlock quadrangles, lacustrine limestones are interstratified with ash-flow tuffs of the Quichapa Group, indicating at least local persistence of lacustrine paleoenvironments. At one locality directly east of Miners Canyon, the Harmony Hills Tuff is separated from the overlying Rencher Formation by lacustrine limestone, indicating that volcanism did not everywhere overwhelm the lacustrine paleoenvironment until after Quichapa time. These limestone beds and the sparse floras they contain are evidence of paleoenvironmental conditions of low relief, poor drainage, and subtropical climate.

LATE CENOZOIC EXTENSIONAL EVENTS

Cenozoic rocks are widely distributed across the northern parts of the Motoqua and Gunlock quadrangles, making that area critical in differentiating between middle and late Cenozoic structures and older structures. The most conspicuous structural aspect of the Oligocene and Miocene rocks is their predominant northwest strike; remarkably few strikes are outside the range from west-northwest to north-northwest. Dip directions of fault-repeated strata in the Gunlock quadrangle and the southeastern part of the Motoqua quadrangle are mostly northeasterly. The northeast-dipping Neogene strata near Bentley Spring and East Bunker Peak Wash in the western Motoqua quadrangle are part of a large area to the west where Neogene strata are also tilted northeast and repeated by extensional faults (Anderson and Hintze, 1993). This deformational pattern projects westward beneath basin-fill strata to the Red Hollow fault, in whose footwall it reappears as northeast-dipping fault-repeated Paleozoic and Mesozoic strata. A Neogene age is supported for the deformation east of the Red Hollow fault (northeast flank of BDMA) by the strong similarity in pattern and style to nearby areas of deformed Neogene rocks (Anderson and Hintze, 1993) as well as by the fact that the deformed Paleozoic and Mesozoic rocks are physically continuous with, and conformable to, overlying Neogene rocks in the northeastern part of the Gunlock quadrangle. Additional indirect support for a Neogene age is seen along Beaver Dam Wash north of Motoqua where a northwest-trending syncline is indicated by a major dip reversal in Neogene rocks. The dip reversal results from a reversal in the direction of downthrow on numerous faults that have small to large components of normal slip. On the basis of unpublished mapping directly north of these quadrangles by R.E. Anderson, the syncline is flanked on the northeast by an anticline that is also genetically related to Neogene extension. These structures show that northwest-trending folds in the area were produced during, and are compatible with, Neogene extensional deformation.

Tilted northwest-striking middle to upper Tertiary rocks are found above both the autochthon and the allochthon, showing that the extensional deformation is spread homogeneously across the thrust boundary. As noted above, this Neogene tilting is considered by one of us (Anderson) as indirect evidence that the broad area of homoclinal northeast tilting in the BDMA is Neogene.

Fault density varies widely throughout the quadrangles. The paucity of faults in areas underlain by the Muddy Creek Formation and Tertiary and Quaternary alluvium reflects a real increase with time in fault spacing and a decrease in faulting intensity. The paucity of mapped faults in areas underlain by thick units lacking conspicuous stratigraphic markers, such as the Queantoweap Sandstone and Navajo Sandstone, may, in part, reflect the difficultly in recognizing faults in those units. This is apparently not so southwest of Gunlock where unfaulted Navajo strata are widely exposed. Numerous north- and northwest-striking faults to the north of the exposed Navajo rocks apparently terminate southward and downward (see cross section *B–B'*) in rocks of the Carmel Formation and do not cut the Navajo. Several short north- and northwest-trending open folds in the Carmel rocks in that area are probably cogenetic with the faulting and reflect strain absorption in rocks of relatively low mechanical competence above the Navajo.

On the basis of a representative sampling of slickenline orientations within and adjacent to the Motoqua and Gunlock quadrangles, faults of all strikes range widely in sense of slip. For example, some west-northwest- to northwest-striking faults are strike slip and others are dip slip. Strike-slip and dip-slip faults predominate over oblique-slip faults. Despite this variability, faults with homogeneous slip sense are found in some domains. For example, northerly striking steep faults in the east-central and northwestern parts of the Gunlock quadrangle are sinistral, whereas those that strike north-northwest to northwest are predominantly dextral. Northwest-striking faults in the northwestern part of the Motoqua quadrangle are also mostly dextral.

The main phase of extensional deformation resulted in the strong northwest structural grain noted above. Average stratal dips vary widely from place to place and range from gentle, such as in the southeasternmost part of the Gunlock quadrangle, to steep to overturned, such as in the northwestern part of the Motoqua quadrangle. This deformation mainly preceded, but also merged with, development of two basins—the north-trending Beaver Dam basin west of the Red Hollow fault and the northeast-trending Tobin Wash basin, the southwestern part of which is in the northeast Gunlock quadrangle.

Tobin Wash basin is situated at the southeast margin of the Bull Valley Mountains, is transverse to the main northwest structural grain for about 16 km, and is filled with clastic strata and landslide deposits of the Muddy Creek Formation (fig. 3). Structurally it is a northeast-trending sag containing syntectonic basal strata that are conspicuously coarser and more steeply dipping than medial strata. The part of the basin located in the Gunlock quadrangle is offset sinistrally by at least three north-striking faults, the largest of which is the Gunlock fault. The Gunlock fault is situated along the northerly projection of the Grand Wash fault, which marks the boundary between the Colorado Plateaus and Basin and Range in Arizona. Most of its displacement predates deposition of the basalt near Gunlock, dated radiometrically at 1.6 Ma. Miocene strata between and adjacent to the strands of the Gunlock fault in the Gunlock and adjacent Veyo quadrangles are folded on east-west trends and show sinistral-sense bending. Stratigraphic mismatches of prebasin strata suggest a prebasin history of sinistral slip on the Gunlock fault. Development of Tobin Wash basin may be genetically linked to displacements on the north-striking sinistral-slip faults, especially the Gunlock fault.

Sinistral-slip displacement is recognized on north-striking faults other than the Gunlock. On the basis of mapped relationships, Cook (1960) suggested a left-oblique normal slip on the north-trending faults herein referred to as the Red Hollow, Jackson Spring, and Jackson Reservoir faults. Subhorizontal striae and offset contacts indicate the youngest episode of displacement to be left slip on the Cole Spring and Jackson Spring faults. Small-displacement unmapped faults east of the Manganese Wash fault, some of which parallel that fault, have striae with predominantly low rakes and offsets indicating left and right slip. The northerly striking Miners Canyon fault and most similarly oriented faults between it and the Gunlock fault are sinistral-slip faults that produce an estimated 5 km of cumulative displacement. Some of these faults cut the Muddy Creek Formation, suggesting displacements of Miocene or younger age. These faults apparently terminate downward in rocks of the Carmel Formation (cross section *B–B'*). Along Beaver Dam Wash north of Motoqua most northwest- to west-northwest-trending faults are predominantly right-slip faults. Some of these faults also cut the Muddy Creek Formation, suggesting late Miocene or younger displacement. A large-displacement right-slip fault of this trend was recognized a few kilometers north of the Motoqua quadrangle by Morris (1980), and others have been recognized and studied by one of us (Anderson) northwest of the Motoqua quadrangle. Collectively, these faults record an important episode of geologically young strike-slip faulting in this area.

The north-striking Jackson Reservoir and Jackson Spring faults are mechanically, kinematically, and temporally related to the nearby northwest-striking faults. On a lower-hemisphere projection, slip lineations for both of these fault systems plot near the poles to bedding, suggesting uniform-motion faulting and genetically related stratal tilting. The components of sinistral displacement on the Jackson Reservoir and southern Cole Spring faults and all other faults located directly west of them are interpreted as part of the regional pattern of sinistral displacement on northerly striking faults (Anderson and Barnhard, 1993). The components of dip-slip separation on those faults and on the numerous northwest- and west-northwest-trending faults that merge with them from the west are interpreted as an extensional strain signature directly associated with uplift and northeast tilting of the along-strike block located directly east of the Jackson Reservoir fault. These structural relations are illustrated in cross section *B–B'* where the steeply northeast-tilted footwall block of upper Paleozoic rocks is projected northwest beneath the highly extended but less steep along-strike rocks. The complex fault zone separating the two cross sectional tilt domains is interpreted to be convex upward.

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