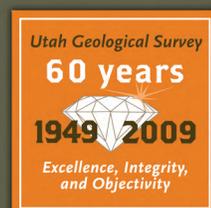


GEOLOGIC MAP OF THE KELTON PASS QUADRANGLE, BOX ELDER COUNTY, UTAH, AND CASSIA COUNTY, IDAHO

by Michael L. Wells



MISCELLANEOUS PUBLICATION 09-3
UTAH GEOLOGICAL SURVEY
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Utah Department of Natural Resources
2009



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by Michael L. Wells

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Cover Photo: Crystal Peak and the north side of upper Ten Mile Canyon, looking to the northeast. The Raft River detachment is marked by black ledge of resistant fault rocks, overlying the prominent gently dipping white Elba Quartzite. Photo by Michael L. Wells.

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GEOLOGIC MAP OF THE KELTON PASS QUADRANGLE, BOX ELDER COUNTY, UTAH, AND CASSIA COUNTY, IDAHO

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ABSTRACT

The Kelton Pass 7.5' quadrangle is located in northwestern Utah and southern Idaho and contains portions of the Raft River and Black Pine Mountains, and Curlew and Raft River valleys. The quadrangle is so geologically complex that a typical geologic map at 1:24,000 scale (plate 1) cannot show the detail needed to decipher the geologic history of the area. Therefore an additional map (plate 2), that shows an area of detailed bedrock mapping at 1:12,000 scale, has been included. Bedrock exposed in the quadrangle includes Archean monzogranite, amphibolite, and schist; Proterozoic metasedimentary rocks of enigmatic regional stratigraphic affinity; and Ordovician to Permian metasedimentary miogeoclinal rocks. These rocks contain a record of burial by thrusting and protracted exhumation by normal faulting and plastic flow, in which tectonic contraction and extension alternated during late Mesozoic to early Cenozoic time. Archean to Pennsylvanian rocks were metamorphosed and penetratively strained at upper greenschist- to lower amphibolite-facies metamorphic conditions in Mesozoic time, during folding and thrusting related to the Sevier orogeny. Subsequently, Proterozoic to Pennsylvanian rocks were further attenuated by two episodes of low-angle normal faulting, the first prior to the middle Late Cretaceous, and the second in the latest Cretaceous to early Paleocene. Following stratigraphic attenuation, the Proterozoic to Pennsylvanian rocks were deformed into large-scale recumbent folds during renewed crustal shortening prior to the late Eocene. The earliest crustal extension of Cenozoic age is manifest in a low-angle normal fault (middle detachment) with westward translation that emplaced Mississippian to Permian rocks of the middle allochthon over the recumbently folded Proterozoic to Pennsylvanian rocks of the lower allochthon, and juxtaposed greenschist-facies over amphibolite-facies metamorphic rocks. Proterozoic to Permian rocks were subsequently deformed into open folds with north-trending axes. The east-directed Raft River detachment fault began movement in the early Miocene; detachment faulting was over by 7.5 Ma (late Miocene). Miocene conglomerate, tuff, tuffaceous sandstone, and limestone were deposited within a deepening basin or basins, either prior to or during movement along the Raft River detachment fault. Continued movement on the detachment fault, and high-angle faulting within the upper

plate, folded and tilted the Tertiary and older rocks. Extensive erosion in highlands and deposition at the range flanks developed expansive alluvial fans of Pleistocene age. Late Pleistocene Lake Bonneville covered the Curlew Valley, depositing a blanket of sediments, and cutting shorelines into bedrock and alluvial-fan surfaces.

INTRODUCTION

The Kelton Pass 7.5' quadrangle is located in northwestern Utah and southern Idaho, 5 miles (8 km) northeast of Park Valley, Utah, and 22 miles (35 km) west of Snowville, Utah. The northern boundary of the quadrangle is 0.2 to 0.26 mile (0.3 to 0.4 km) north of the Utah-Idaho border. Bedrock exposures within the quadrangle form the eastern end of the Raft River Mountains and the southern terminus of the Black Pine Mountains (figure 1).

Kelton Pass (elevation 5305 feet [1617 m]), on Utah State Highway 42 in the northern part of the quadrangle, separates the Raft River Valley to the northwest from the Curlew Valley to the east and southeast. This divide separates drainage into the Great Salt Lake to the south from drainage into the Snake River to the north. The lowlands to the east within the Curlew Valley are underlain, in part, by Tertiary strata. Between the 5200 foot (1585 m) and 4720 foot (1439 m) (the lowest point in the quadrangle) elevations, these strata have been modified and partially buried by the deposits of latest Pleistocene Lake Bonneville. State Highway 42 approximately marks the boundary between detritus shed from the Black Pine Mountains (north of the highway) and sediment shed from the Raft River Mountains (south of the highway). The topographically highest regions in the quadrangle, maximum elevation 7957 feet (2425 m) in the Raft River Mountains, are underlain by the Permian and Pennsylvanian Oquirrh Formation.

The Kelton Pass 7.5' quadrangle lies within the Cenozoic Basin and Range extensional province, and within the hinterland of the late Mesozoic to early Cenozoic Sevier orogenic belt (Armstrong, 1968a). Because of this superposition, differentiating Mesozoic from Cenozoic deformations is of first-order importance to structural investigations in this region; hence the need for the detailed geologic map (1:12,000-scale plate 2) in addition to the typical quadrangle

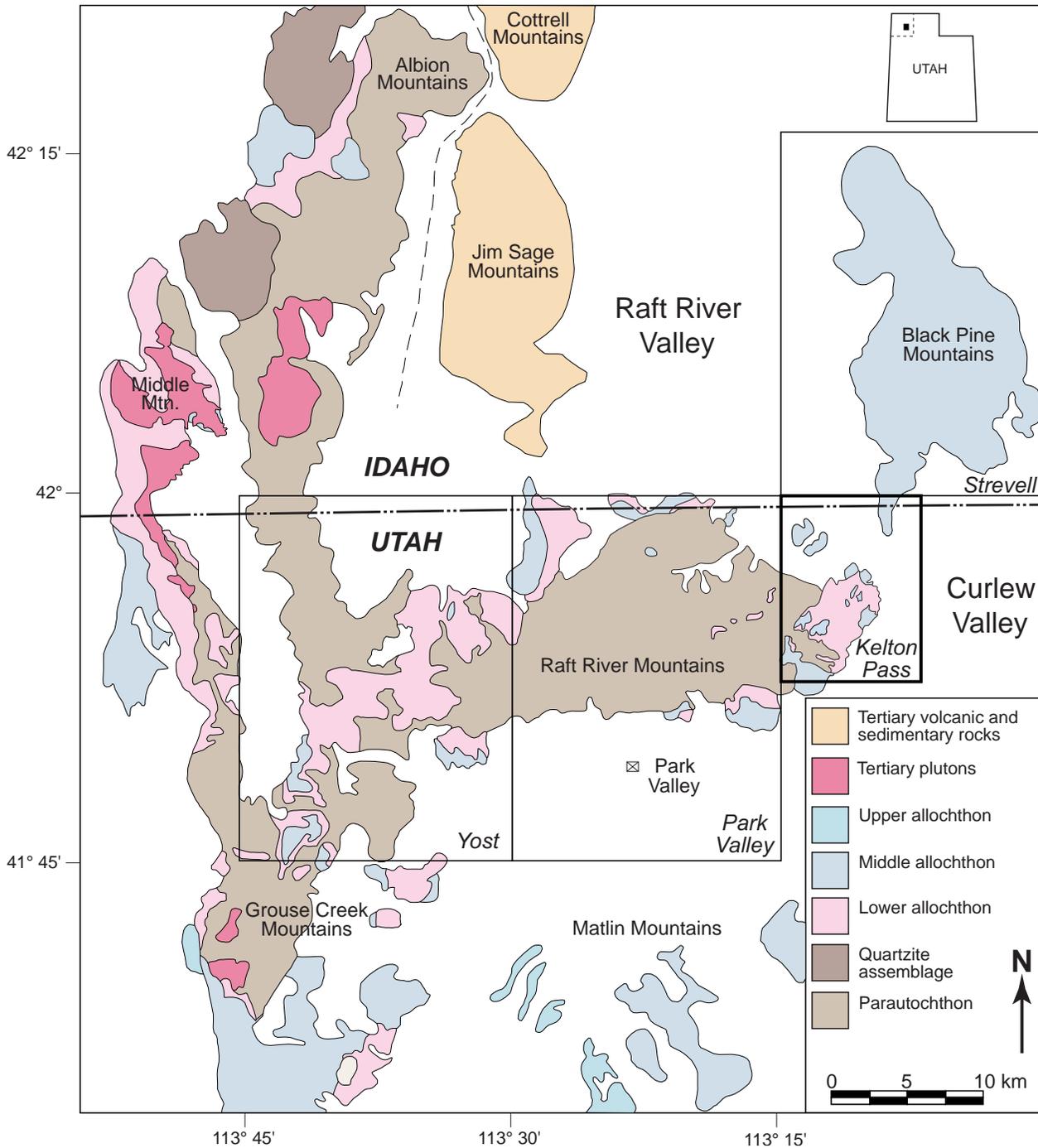


Figure 1. Tectonostratigraphic map of pre-Tertiary rocks and simplified Tertiary geology of the Raft River, Black Pine, Albion, Grouse Creek, and Matlin Mountains, with locations of the Kelton Pass 7.5' quadrangle and other published geologic quadrangles in the region. Modified from Compton (1972, 1975), Compton and others (1977), Todd (1980), Smith (1982), Miller (1983), and author's mapping. Dashed line between Jim Sage-Cottrell Mountains and Albion Mountains is inferred breakaway to the Raft River detachment.

map (1:24,000-scale plate 1). Structural studies in the eastern Raft River Mountains were initiated to correlate structural events recorded in greenschist-facies metamorphic rocks in the Black Pine Mountains, where the distinction between Mesozoic and Cenozoic deformations has been made (Smith, 1982; Wells and Allmendinger, 1990), to the stratigraphically equivalent but more highly attenuated upper greenschist- to lower amphibolite-facies strata in the Raft River Mountains (Wells and others, 1990). The sequence of deformation events recorded in the Raft River Mountains (Wells, 1997) is largely borne out through detailed geologic mapping presented here and in Wells (1991). Because of the completeness of the record, the structural history is described in some detail. Further details of the structural history are described in Wells (1992, 1997, 2001).

Within the Sevier orogenic belt hinterland of northwestern Utah, southern Idaho, and northeastern Nevada, faults that place older rocks on younger rocks, or place higher grade metamorphic rocks on lower grade metamorphic rocks are rare, in marked contrast to the foreland fold and thrust belt to the east (Armstrong and Oriel, 1965). More commonly, low-angle faults within the Sevier belt hinterland place younger rocks on older rocks, and unmetamorphosed rocks on metamorphosed rocks (Armstrong, 1972). Many of these younger-over-older faults have documented Cenozoic ages (for example, Miller and others, 1987; Compton, 1983). However, there are also younger-over-older faults of Mesozoic to early Tertiary age (for example, Allmendinger and Jordan, 1984; Wells and others, 1990, 1998).

Both Mesozoic and Cenozoic younger-over-older faults are present in the eastern Raft River Mountains. A generally consistent tectonostratigraphy is preserved throughout an area greater than 1560 square miles (4000 km²) in the Raft River, Albion, and Grouse Creek Mountains. Within this stratigraphic succession, several major low-angle faults divide the rocks into four major allochthons and a parautochthon, as defined by Compton and others (1977) and Miller (1980) (figures 1 and 3). Numerous smaller low-angle faults are found within these allochthons. All of these faults, with few exceptions, place younger rocks on older rocks, and apparently are subparallel to bedding over large areas.

The Raft River Mountains were mapped at the scale of 1:68,500 and described by Felix (1956). More recently, areas to the west of the Kelton Pass 7.5' quadrangle (the Park Valley and Yost 15' quadrangles) were mapped at the scale of 1:31,680 by Compton (1972, 1975) (figure 1). Compton and others (1977) described the regional extent of low-angle faults and the stratigraphic, metamorphic, and structural relationships within and between low-angle fault-bounded allochthons. Additionally, they highlighted the youthfulness of metamorphism. Miller and others (1983) described the similarities in stratigraphy, and structural, metamorphic, and igneous histories between the Raft River, Albion, and Grouse Creek Mountains. Sabisky (1985) studied a shear zone present at the Archean-Proterozoic unconformity in the eastern and central Raft River Mountains, and determined the kinematics to be top-to-the-east shearing. Malavieille and Cobb (1986) suggested that the shear zone was a Mesozoic thrust, and later Malavieille (1987a, 1987b) suggested that the shear zone and associated brittle fault (Raft River detachment) represented a Tertiary extensional fault system. This later interpretation has been borne out by subsequent geochronology

(Wells and others, 2000a). Wells and others (2000a) interpreted the shear zone as a low-angle, normal-sense shear zone of Miocene age. The upper plate rocks to the Miocene Raft River detachment in the eastern Raft River Mountains were described by Wells and others (1990) and Wells (1992, 1997), and were mapped at 1:12,000 scale by Wells (1991) (area of detailed bedrock mapping on plates 1 and 2); these reports emphasized the pre-Miocene structural history. The Black Pine Mountains (Strevell 15' quadrangle), to the northeast, were mapped and described by Smith (1982, 1983) (figure 1). The structural and metamorphic history of Devonian to Permian rocks in the Black Pine Mountains was re-evaluated and described by Wells and Allmendinger (1990).

Mapped quadrangles adjoining the Kelton Pass 7.5' quadrangle are the Strevell 15' quadrangle (to the north) and the Park Valley 15' quadrangle (to the west, figure 1). There are differences in the mapped geology between the Strevell 15' and Kelton Pass 7.5' quadrangles, in particular, the location of the contacts separating Quaternary deposits from both Tertiary deposits and the Oquirrh Formation. These differences reflect a greater emphasis in this study on the Cenozoic geology and the more detailed scale of the mapping in this study (1:24,000 [plate 1], compared to 1:62,500). Plate 2 in this publication is a modification of my Ph.D. map. The geologic contacts match reasonably well across the boundary between the Kelton Pass and Park Valley quadrangles, with several exceptions. The principal mismatches result from a greater emphasis on Cenozoic geology in the present study, resulting in a greater subdivision of Cenozoic lithologic units. For example, deposits mapped by Compton (1975) as Qo (a unit designation with a broad use as older alluvium and other deposits) in the NE¼ section 6, T. 14 N., R. 12 W., would be designated QTaf according to the lithologic map units used in the Kelton Pass 7.5' quadrangle. Additionally, lithologies mapped as Ts (in the present study) were included in the Qo unit of Compton (1975). I also mapped exposures of the mafic intrusive rocks unit (Ami), located adjacent to the quadrangle boundaries in sections 17 and 20, T. 14 N., R. 12 W., that Compton (1975) included within the older schist (Aos).

STRATIGRAPHY

Overprinting Mesozoic and Cenozoic deformation episodes have produced an incomplete and greatly attenuated stratigraphic section in the Raft River, Albion, and Grouse Creek Mountains (figure 2). A tectonically thinned sequence of metasedimentary and sedimentary units of Proterozoic to Triassic age overlies an Archean basement complex (figures 2 and 3) (Armstrong, 1968b; Compton and others, 1977; Wells and others, 1998). Within the eastern Raft River Mountains, these rocks have been subdivided into three low-angle, fault-bounded, tectonostratigraphic units (figures 3 and 4) (Compton and others, 1977; Miller, 1980, 1983; Todd, 1980, 1983; Wells, 1992, 1997). From structurally lowest to highest (figure 3), these are: (1) the parautochthon, (2) the lower allochthon, and (3) the middle allochthon. An upper allochthon of unmetamorphosed Permian and younger rocks is present in the Grouse Creek Mountains (for example Todd, 1980), but is not represented in the quadrangle. Although these allochthons are bounded by major faults in many areas

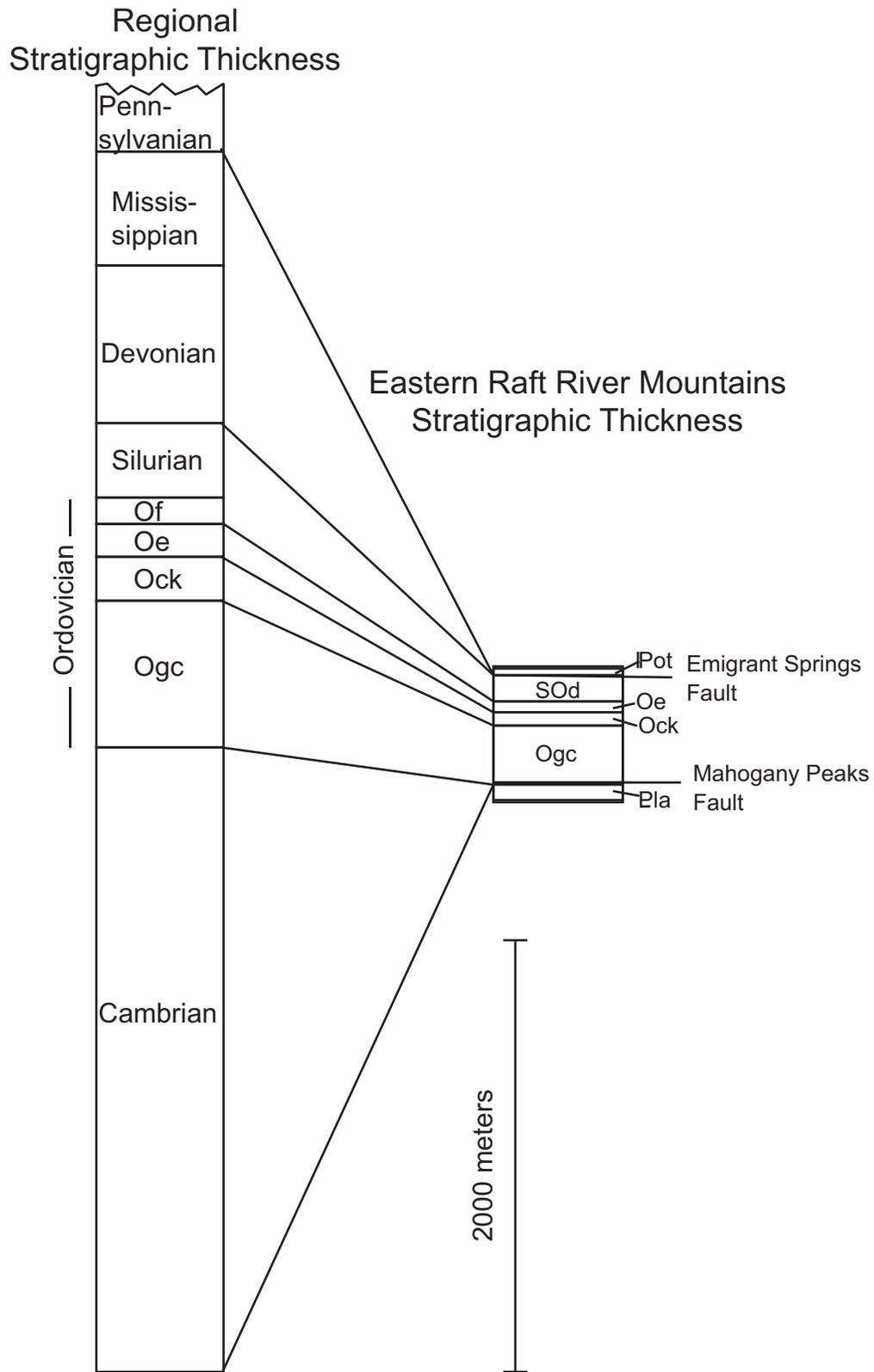


Figure 2. Comparison between attenuated stratigraphic thicknesses within the eastern Raft River Mountains and representative stratigraphic thicknesses from nearby localities in northwestern Utah (from Hintze, 1988). Attenuation occurred during D₁ and D₂ deformation events (see table 1). Of = Ordovician Fish Haven Dolomite.

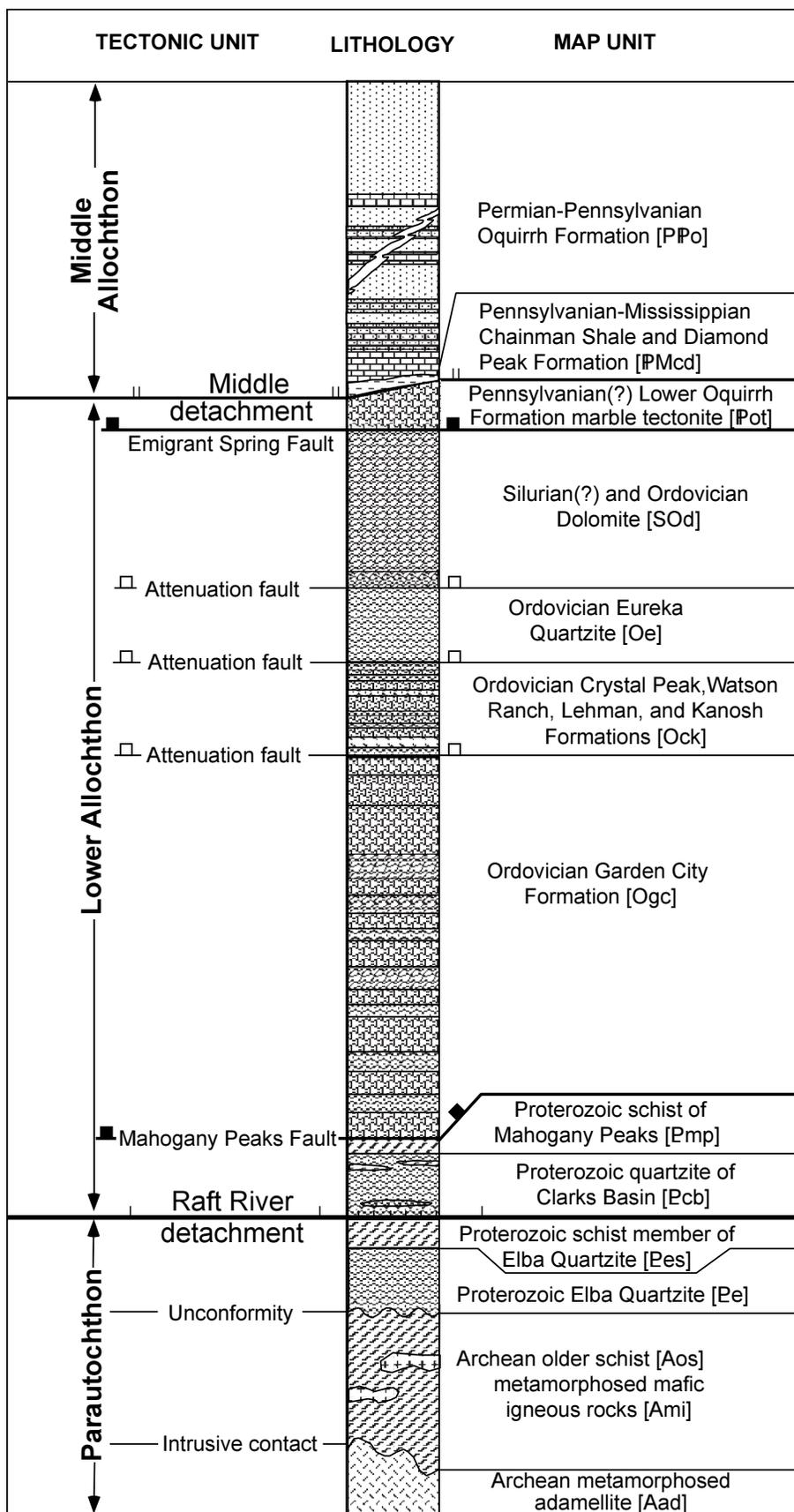


Figure 3. Tectonostratigraphic column of the eastern Raft River Mountains. Thicknesses are maximums, and are highly variable. Positions of major faults are indicated. Note that all stratigraphic contacts within the lower allochthon are low-angle faults.

of the Raft River, Albion, and Grouse Creek Mountains, the faults or shear zones which bound them are not necessarily correlative in age or origin from one locality to another. Until further work is carried out, the allochthon designations imply only stratigraphic affinity and general tectonostratigraphic position, rather than structural continuity. These older rocks are overlain by Tertiary sedimentary and volcanoclastic rock and deposits, and Quaternary deposits.

Parautochthon

The parautochthon consists of the Green Creek Complex (Armstrong and Hills, 1967; Armstrong, 1968b) and the unconformably overlying Elba Quartzite. The Green Creek Complex is comprised of approximately 2.5 to 2.6 Ga gneissic monzogranite (metamorphosed adamellite of Compton, 1972; unit Aad of this report) that intrudes older schist (Aos) and metamorphosed mafic igneous rock (Ami) (Compton, 1975; Compton and others, 1977). The Elba Quartzite forms the lowermost part of the Raft River Mountains sequence of Miller (1983), and has been assigned Paleoproterozoic, Proterozoic, and Paleozoic ages (Armstrong, 1968b; Compton and others, 1977; Compton and Todd, 1979; Crittenden, 1979). Rock units that normally lie above the schist member of the Elba Quartzite farther to the west (including the schist of the Upper Narrows, quartzite of Yost, and schist of Stevens Spring; Compton, 1972, 1975) have been structurally omitted by the Raft River detachment fault in the Kelton Pass 7.5' quadrangle. This detachment separates the parautochthon from the lower allochthon. Following the usage of Compton (1972, 1975), the rock units comprising the Archean basement are the older schist (Aos), metamorphosed mafic igneous rocks (Ami), and the metamorphosed adamellite (Aad) (figure 3).

Older Schist (Aos)

The older schist unit of Compton (1972) makes up a large percentage of the Archean rocks in the quadrangle and is the oldest unit of the Green Creek complex. Light-brown to medium-gray-weathering, monotonous, fine-grained biotite-muscovite-feldspar-quartz schist and schistose phyllite comprise this unit. Foliation-parallel lensoidal quartz veins are locally common. A fine-grained schistose amphibolite that occurs near the top of this unit in the northwest part of the quadrangle was mapped as part of the metamorphosed mafic igneous rocks unit (Ami), but may be part of the older schist unit. A prominent 3 to 10 foot (1-3 m) thick, greenish, chlorite-muscovite schist at the top of the older schist directly underlies the Elba Quartzite, and may represent a metamorphosed paleosol. Compton (1975), in his study of the older schist unit farther to the west, considered the protolith to be sandstone, siltstone, mudstone, and sandy shale. This unit is especially well exposed in Ten Mile Creek canyon, where a 400-foot (122-m) vertical thickness is exposed.

Metamorphosed Mafic Igneous Rocks (Ami)

The metamorphosed mafic igneous rocks unit of Compton (1972) (Archean) is well exposed in the quadrangle and intrudes the older schist. Dark-green to dark-gray to black,

massive, generally medium-grained, gneissic and schistose amphibolite, comprised of hornblende, andesine, quartz, and zoisite comprise this unit. These mafic rocks are in turn intruded by monzogranite (Aad). The mafic rocks show a wide variation in intrusive morphology and internal texture. Intrusive shapes vary from sheet-like, foliation-parallel, horizontal sills to irregular pods highly discordant to foliation and lithologic layering in country rocks. It should be noted, however, that much of the sheet-like morphology may partly reflect post-intrusive strain. At the structurally deepest levels within Ten Mile Creek canyon, this unit is locally undeformed, and medium to coarse ophitic to subophitic igneous textures typical of gabbro are preserved.

Metamorphosed Adamellite (Aad)

The metamorphosed adamellite unit of Compton (1972) (Archean) is exposed within the Kelton Pass 7.5' quadrangle only at the head of Ten Mile Creek canyon, although it probably underlies most of the quadrangle. The metamorphosed adamellite unit is monzogranitic in composition and is comprised of plagioclase, quartz, potassium-feldspar, biotite, and muscovite, with accessory garnet, zircon, and apatite. Textures range from medium to coarse grained, granular to porphyritic, and become more gneissic toward the upper contact. Within the uppermost 50 feet (15 m) of the adamellite below the unconformity, the rock fabric grades upwards into protomylonite, mylonite, and locally ultramylonite and phyllonite. At least 130 feet (40 m) of adamellite is exposed. The metamorphosed adamellite unit crops out extensively within the Raft River Mountains outside of the quadrangle, and also in the Albion and Grouse Creek Mountains. In the latter two mountain ranges, the metamorphosed adamellite unit has been dated at approximately 2.5 Ga by the Rb-Sr isochron method (Armstrong and Hills, 1967; Compton and others, 1977). Egger and others (2003) reported a SHRIMP U-Pb discordia-line upper-intercept age on zircons from the unit of ~2.62 Ga.

Elba Quartzite (Ee)

The Elba Quartzite (Proterozoic) unconformably overlies the Archean Green Creek Complex. Locally, at or near the base is a pebble and cobble conglomerate with clasts composed of quartzite. This conglomerate, common on the north side of the range in the Park Valley 15' quadrangle, is only exposed west of Crystal Peak in the Kelton Pass 7.5' quadrangle. The overlying quartzite is white, muscovite quartzite with thin beds of muscovite schist. The unit generally becomes more feldspathic upwards.

The age of the Elba Quartzite has not been determined directly by isotopic methods, although reasonable inferences can be made. The Elba Quartzite has been assigned various ages including Paleoproterozoic, Proterozoic and Paleozoic (Armstrong, 1968a; Compton and others, 1977; Compton and Todd, 1979; Crittenden, 1979). Recently, the structurally and probably stratigraphically overlying quartzite of Clarks Basin has been shown to be of either Neoproterozoic or Paleoproterozoic age, suggesting that the Elba Quartzite is at least as old as Neoproterozoic (Wells and others, 1998). The Elba Quartzite may correlate with the Paleoproterozoic formation of Facer Creek of the Willard Peak area (now known

as the Facer Formation [Crittenden and Sorensen, 1980]), as suggested by Crittenden (1979). However, a cryptic low-angle attenuation fault separates the quartzite of Clarks Basin from older metasedimentary rocks elsewhere in the Raft River, Albion, and Grouse Creek Mountains (Compton, 1972, 1975), allowing rocks above and below this fault to be of different age.

The present thickness of the Elba Quartzite in the Raft River Mountains is highly variable, principally as a result of strain within the Miocene shear zone (Wells, 2001). The shear zone is localized at the Archean-Proterozoic unconformity, and the entire Elba Quartzite is mylonitic (Wells and others, 2000a; Wells, 2001). In the Park Valley 15' quadrangle to the west, the maximum thickness of the Elba Quartzite is 600 feet (180 m). In the Kelton Pass 7.5' quadrangle (south and west of Crystal Peak) the Elba Quartzite has a maximum thickness of 164 feet (50 m), and the unit thins to zero thickness eastward at the mouth of Ten Mile Creek canyon.

Schist Member of Elba Quartzite (Ees)

The youngest unit in the parautochthon in the Kelton Pass 7.5' quadrangle is 16 to 82 feet (5-25 m) of Proterozoic, dark-brown to dark-gray, quartz-muscovite-biotite-feldspar schist and foliated cataclastite that overlies the main part of the Elba Quartzite. This map unit is a tectonite produced by movement along the Raft River detachment. However, the tectonite was not derived from the quartzite below because, where not an ultracataclastite, it is rich in biotite and muscovite, similar to the schist member of the Elba Quartzite as mapped by Compton (1975). Overlying rocks within the parautochthon to the west (Compton, 1972, 1975), including the schist of the Upper Narrows, quartzite of Yost, and schist of Stevens Spring, have apparently been structurally omitted in the Kelton Pass 7.5' quadrangle by the Raft River detachment fault.

Lower Allochthon

The lower allochthon is separated from the parautochthon by the Raft River detachment and from the middle allochthon by the middle detachment. The lower allochthon in the quadrangle consists of Proterozoic quartzite and pelitic schist; Ordovician calcitic marble, phyllite, quartzite and dolomitic marble; Silurian(?) dolomitic marble; and Pennsylvanian(?) calcitic marble. These units correlate with those mapped within the lower allochthon to the west (Compton, 1975; Compton and others, 1977; Compton and Todd, 1979), with the exception of two modifications to this stratigraphy: (1) rocks mapped as the Pogonip Group by earlier workers are mapped as two units, the Garden City Formation and a unit comprised of undivided Kanosh, Lehman, Watson Ranch, and Crystal Peak Formations; and (2) two packages of Mississippian and Pennsylvanian rocks are differentiated, one of upper greenschist- to lower amphibolite-facies rocks in the lower allochthon and the other of lower to middle greenschist-facies metamorphic rocks in the middle allochthon.

The stratigraphic section represented within the lower allochthon has been greatly attenuated by several periods of deformation. This stratigraphic section in neighboring mountain ranges is from 2.5 to 4.4 miles (4-7 km) thick, but is only

165 to 1650 feet (50-500 m) thick in the quadrangle (figure 2). The attenuation is a result of penetrative plastic thinning and later low-angle faulting. Two major low-angle faults omit strata within the lower allochthon, the Emigrant Spring and Mahogany Peaks faults. The Emigrant Spring fault removes about 3 miles (5 km) of stratigraphic section throughout the entire mapped area, including most or all of the Silurian, all of the Devonian, and all but thin (half inch) remnants of Mississippian rocks (Wells, 1997). The Mahogany Peaks fault places Ordovician on Proterozoic rocks, and removes, at a minimum, the entire Cambrian stratigraphic section (Wells and others, 1998). Additionally, most other formation contacts are low-angle attenuation faults.

Many attenuated rock units could not be represented at 1:24,000 scale. Where a map unit within the lower allochthon is attenuated to less than 50 feet (15 m) in thickness, the unit is included in adjacent older or younger units, or lumped into an undivided unit, with the only consistency being inclusion in the same tectonostratigraphic package as the adjacent units.

Quartzite of Clarks Basin (Ecb)

The oldest unit within the lower allochthon is the quartzite of Clarks Basin (Proterozoic). The quartzite of Clarks Basin characteristically consists of flaggy, muscovite quartzite lacking feldspar, and lesser interlayered muscovite schist and marble. The maximum thickness of this unit is approximately 164 feet (50 m), and it crops out only along the southeastern margin of the bedrock exposures in the quadrangle. The units stratigraphically beneath the quartzite of Clarks Basin farther to the west (Compton, 1972, 1975) have been tectonically omitted by the Raft River detachment fault. The quartzite of Clarks Basin was tentatively assigned a Cambrian age (Compton, 1975) due to the apparent depositional contact between the overlying schist of Mahogany Peaks and Pogonip Group strata. However, the contact between the schist of Mahogany Peaks and Pogonip Group strata has been subsequently interpreted as a fault (Wells and others, 1998), and carbon isotope analyses from marble interbeds, as outlined below, suggest a Proterozoic age (see also Wells and others, 1998).

Samples from two, distinct, 3-foot (1-m) thick, calcite-rich marbles (>93% calcite) in the quartzite of Clarks Basin (300 feet [90 m] south of locality 11, plate 1), exhibit high $\delta^{13}\text{C}$ values ($\delta^{13}\text{C} = +6.4$ and $+7.6\text{‰}$). These values are interpreted as primary $\delta^{13}\text{C}$ values (Wells and others, 1998) because metamorphic processes (for example, decarbonation and/or fluid flow) will tend only to decrease the $\delta^{13}\text{C}$ values of carbonate rocks (Wickham and Peters, 1993).

The high $\delta^{13}\text{C}$ values measured in marbles within the quartzite of Clarks Basin are not present in Cambrian carbonate rocks in the western United States or worldwide. Except for multiple positive $\delta^{13}\text{C}$ excursions of up to $+4.5\text{‰}$ in the Cambrian (see for example Brasier and others, 1994; Saltzman and others, 1998), abundant data from Phanerozoic carbonate rocks worldwide reveal limited variation of $\delta^{13}\text{C}$ values through time ($\delta^{13}\text{C} = 0\text{‰} \pm 2$) (Veizer and Hoefs, 1976; Veizer and others, 1980). The measured values are also higher than those present in Mesoproterozoic sequences (Buick and others, 1995), including the Belt Supergroup of western North America (Mora and Valley, 1991). Analyses of two

samples of the pale-gray, massive, limestone unit of the Paleoproterozoic Facer Formation (Crittenden and Sorensen, 1980) revealed $\delta^{13}\text{C}$ values of -0.1‰ and $+0.7\text{‰}$ (Wells and others, 1998); these low values suggest that the lower Raft River sequence does not correlate with the Facer Formation, a correlation proposed by Crittenden (1979). Though these Facer values resemble those believed to be typical of most Paleoproterozoic carbonate rocks (Veizer and others, 1992a, 1992b), a major positive excursion of $\delta^{13}\text{C}$ values in excess of $+10\text{‰}$ has been documented between ~ 2.22 and 2.06 Ga (Baker and Fallick, 1989; Karhu, 1993), including values from the Paleoproterozoic Snowy Pass Supergroup of Wyoming (Bekker and Karhu, 1996); thus, a correlation with other Paleoproterozoic sequences in western North America cannot be precluded.

The high $\delta^{13}\text{C}$ values of marbles in the quartzite of Clarks Basin resemble those measured in Neoproterozoic sequences worldwide (Kaufman and Knoll, 1995; Halverson and others, 2005). In the western Cordillera, high $\delta^{13}\text{C}$ values have been measured in the McCoy Creek Group of Nevada and Utah (Wickham and Peters 1993), the Brigham Group of Idaho (Smith and others, 1994), and the Windermere Supergroup and equivalents in Canada (Narbonne and others, 1994). The data are, therefore, consistent with either a Neoproterozoic or Paleoproterozoic age for the quartzite of Clarks Basin.

Schist of Mahogany Peaks (Pmp)

Proterozoic pelitic schist, 0 to 33 feet (0-10 m) thick, separates the quartzite of Clarks Basin from the overlying Ordovician rocks, and is assigned to the schist of Mahogany Peaks of Compton (1972) because of its similar stratigraphic position and bulk composition. The mineralogy of the schist varies with its bulk composition. Typically, near the base of the unit, poorly exposed, graphitic schist contains the assemblage muscovite + quartz + kyanite \pm staurolite \pm garnet \pm zoisite. This grades upwards into a more resistant knobby, porphyroblastic schist containing the mineral assemblage staurolite + biotite + garnet + muscovite + plagioclase + quartz, typical of the schist of Mahogany Peaks in the region (Compton, 1972, 1975). These assemblages indicate peak metamorphic conditions in the amphibolite facies, and on the petrogenetic grid for the KFMASH system, indicate minimum temperatures and pressures of approximately 600°C and 6.5 kb (fields l-7 and m-7 in figure 2 of Spear and Cheney, 1989). Extensive retrograde alteration of staurolite to chloritoid and white mica, biotite to chlorite, and kyanite to white mica has taken place at greenschist-facies conditions.

Schist of Mahogany Peaks and Quartzite of Clarks Basin, Undivided (Pla)

In several localities south of Ten Mile Creek canyon, lithologies that are representative of the quartzite of Clarks Basin and the schist of Mahogany Peaks (see descriptions above) are interlayered in a non-systematic fashion. It was not determined whether the alternating lithologic layers or lenses represented repetition by faulting or folding, and the rock package was mapped as undivided Proterozoic rocks of the lower allochthon (Pla). Of special note are sparse, 3-foot

[1-m] thick resistant beds of pure ($>93\%$ calcite), light-blue gray, fine-grained marble within this unit that were sampled for $\delta^{13}\text{C}$ analyses (Wells and others, 1998).

Garden City Formation (Ogc)

The stratigraphically lowest Ordovician unit mapped by Compton (1972, 1975) was the metamorphosed limestone of the Pogonip(?) Group and the metamorphosed Pogonip Group, respectively. These strata are here reassigned to the Garden City Formation and the overlying Kanosh, Lehman, Watson Ranch, and Crystal Peak Formations. The Pogonip Group terminology (which includes the Kanosh and Lehman Formations) as well as the overlying Watson Ranch Quartzite, Crystal Peak Dolomite, and Eureka Quartzite terminology is generally applied southwest of the Tooele Arch, and the Garden City Formation, and overlying Swan Peak Quartzite, terminology is generally applied northeast of the Tooele Arch (Hintze, 1988). The Garden City Formation as used in this report could be termed lower Pogonip Group, but the typical lithology of the House Limestone (basal Pogonip) is missing in the quadrangle. The Garden City Formation here consists of up to 985 feet (300 m) of calcitic marble, and subordinate dolomitic marble, sandy marble, and quartzite. Typically, this unit has a three-part stratigraphy, although these parts were not mapped separately. The lower part is primarily thin-bedded and laminated brown-weathering silty to sandy calcitic marble, and a few beds of brown quartzite and muscovite phyllite (possible Fillmore Formation equivalent). The middle part of the unit is mainly massive light-gray dolomitic marble, and subordinate laminated calcitic marble and quartzite (more possible Fillmore Formation equivalent). The upper part consists of medium- to thick-bedded, light-gray to buff calcitic marble, with abundant silty laminations (possible Juab Limestone and Wah Wah Limestone equivalent). The top of the upper part is characteristically clean, finely laminated calcitic marble, underlain by 6 to 33 feet (2-10 m) of chert-rich calcitic marble. Conodonts extracted from the upper part of the Garden City Formation yielded Early Ordovician ages and correlate to the lower half of the upper part of the Garden City Formation near Logan, Utah (J.E. Repetski, U.S. Geological Survey, written communication, 1989).

Crystal Peak, Watson Ranch, Lehman, and Kanosh Formations, Undivided (Ock)

The Garden City Formation is overlain by a unit as thick as 230 feet (70 m) consisting of (from base to top) brownish quartzite and muscovite phyllite (Kanosh Shale), interbedded quartzite and sandy calcitic marble (Lehman Formation and Watson Ranch Quartzite), and dolomitic marble (Crystal Peak Dolomite). The calcitic marble is dark gray and commonly contains quartz and feldspar sand, muscovite, and much pyrite. The quartzite is commonly reddish brown, well bedded, and has interbeds of clean white quartzite. At the top of this unit, a light-gray, fine-grained dolomitic marble up to 13 feet thick (4 m) is commonly found.

The lower part of this unit in the quadrangle is tentatively equated to the Kanosh Shale to the southwest, which is correlative with the lower member of the Swan Peak Quartzite to the east (Oaks and others, 1977). In the absence

of biostratigraphic control, I tentatively equate the upper part of this unit in the quadrangle to the Lehman Formation, Watson Ranch Quartzite, and Crystal Peak Dolomite in western Utah, which is correlative to the middle member of the Swan Peak Quartzite in northeastern Utah (Oaks and others, 1977).

Eureka Quartzite (Oe)

The Eureka Quartzite (Ordovician) in the eastern Raft River Mountains is a prominent, ledge- to cliff-forming, compositionally mature, vitreous white quartzite. It is generally composed solely of well-rounded and well-sorted, medium-sized quartz grains and silica cement, but locally contains sparse, fine-grained muscovite. The thickness of the unit ranges from 0 to 200 feet (0-60 m). Locally the unit is highly brecciated. To the east, this unit is correlative with the upper member of the Swan Peak Formation (Oaks and others, 1977).

Dolomite Unit (SOd)

Up to 425 feet (130 m) of fine-grained, dolomitic marble (Silurian[?] and Ordovician) overlies the Eureka Quartzite. The marble typically is dark gray, rich in black chert at its base, and grades upward into buff to white, laminated to massive dolomitic marble. The lower cherty part of this unit probably correlates with the Ordovician Fish Haven Dolomite or the Ely Springs Dolomite; however, it is not biostratigraphically constrained and upper sections of this unit did not yield information to indicate an Ordovician or Silurian age. Attempts to extract conodonts from the dolomite for biostratigraphic control were unsuccessful.

Lower Oquirrh Formation Marble Tectonite (IPot)

The Silurian(?) and Ordovician dolomitic marble unit (SOd) is overlain by less than 130 feet (40 m) of highly deformed and banded, fossiliferous, light-gray to buff and dark-blue-gray marble (Pennsylvanian?). Abundant crinoids, minor brachiopods, lenses of siltstone and chert, the dark-blue-gray color, and the banded nature of this unit make it easily distinguishable from other Paleozoic marbles. The IPot unit commonly crops out within the cores of recumbent synclines.

The basal contact of this unit is a major low-angle fault (Emigrant Spring fault), and thin slivers of metaclastic rock lie within the fault zone. These slivers are up to two inches (several centimeters) in thickness and probably represent tectonic remnants of the Chainman Shale and Diamond Peak Formation (see below), but are too thin to map at a scale of 1:12,000 and are only evident in float. Rusty-brown-weathering, graphitic phyllite and fine-grained schist and phyllitic black quartzite mark the presence of this unit. Similar rocks occur at the contact between the dolomite (SOd) and marble tectonite (IPot) at Vipont Mountain in the Goose Creek Mountains 30 miles (48 km) to the west.

Two stratigraphic correlations for the marble (IPot) are possible. First, the marble may represent limestone of the lower part of the Oquirrh Formation, with chips of phyllite and quartzite representing remnants of the Mississippian Chainman Shale, and Pennsylvanian and Mississippian Diamond Peak Formation. Alternatively, this marble may represent metamorphosed Mississippian limestone (Kinder-

hookian Joana Limestone), and the phyllite and quartzite would correlate with the underlying Pilot Shale. The former correlation is favored, based on: (1) a remarkable similarity in appearance between this marble tectonite and marble assigned to the lower part of the Oquirrh Formation exposed in the Grouse Creek Mountains—where it overlies a thick section of metamorphosed, undivided Chainman Shale and Diamond Peak Formation (Todd, 1980; Miller and others, 1983)—and (2) the lack of quartzite and scarcity of black shale in the Pilot Shale to the southwest (Miller, 1985). Attempts to extract conodonts for biostratigraphic control were unsuccessful, and brachiopods are too highly strained and recrystallized for identification.

Paleozoic, Undivided (IPola)

Several areas underlain by Pennsylvanian(?), Silurian(?), and Ordovician rock units were mapped as undivided Paleozoic rocks of the lower allochthon (see above descriptions for individual units). The combination of poor exposure, structural complexity, and the narrow outcrop width of the highly attenuated Ordovician to Pennsylvanian units precluded subdividing this unit, even at a map scale of 1:12,000.

Middle Allochthon

The middle allochthon is separated from the lower allochthon by the middle detachment fault. Rocks of the middle allochthon are composed mainly of the Permian and Pennsylvanian Oquirrh Formation, with a thin (0 to 50 feet [0 to 15 m] thick) sliver of Mississippian Chainman Shale and Diamond Peak Formation locally present along its base. Thin layers of attenuated lower allochthon units, principally Eureka Quartzite (Oe) and the dolomite unit (SOd), are common beneath the middle detachment. These layers cannot be shown at 1:24,000 scale.

Chainman Shale and Diamond Peak Formation, Undivided (IPMcd)

The undivided Chainman Shale and Diamond Peak Formation (Lower Pennsylvanian and Upper Mississippian) crops out as thin slivers (0 to 50 feet [0 to 15 m], typically 16 feet [5 m] thick) along the middle detachment fault, and only the largest are shown on maps. The outcrops are poorly exposed, and are commonly marked by the development of dark sooty soil. Where exposed, the unit is a dark-gray to black, quartz-rich slate that contains interbeds of black quartzite.

Oquirrh Formation (IPo)

The Oquirrh Formation (Permian and Pennsylvanian) generally consists of three units which were not mapped separately. The lower unit is dark-blue-gray limestone with sandy interbeds and common bryozoans and brachiopods. An Early Pennsylvanian age for the lower limestone has been confirmed by conodont identification (J.E. Repetski, U.S. Geological Survey, written communication, 1989). The marble tectonite (IPot) at the top of the lower allochthon is considered to have been derived from these rocks. Platy, tan-, maroon-, and gray-weathering, sandy to silty limestone and

subordinate calcareous sandstone of the middle unit overlies the lower limestone. The upper unit is dominantly light- to medium-gray, weathering tan to brown, sandstone and calcareous sandstone, locally containing fusulinids, and is the most common lithology in the middle allochthon. The Oquirrh Formation is 4000 feet (1200 m) thick in the quadrangle, although this thickness may be overestimated due to repetition by unrecognized gently dipping normal faults. Conodonts from the lower Oquirrh Formation yield conodont alteration index (CAI) values of 5, indicating temperatures of 350° to 400°C and metamorphic conditions of the greenschist facies (Wells and others, 1990; 1998).

Tertiary Rocks

Sedimentary Rocks (Ts)

Tertiary sedimentary rocks (Miocene) are exposed along the east flank of the Raft River Mountains and the west flank of the Black Pine Mountains. This unit consists of moderately lithified, interbedded, tuffaceous sandstone and siltstone, water-lain tuff, coarse-grained sandstone, mudstone, conglomerate, and limestone. The Tertiary sedimentary rocks unit is presumably Miocene in age, on the basis of lithic similarity with Miocene strata in the northern Pilot Range (Miller, 1985). Its thickness is unknown due to poor exposures and structural complications, but probably exceeds 1700 feet (520 m) as determined from traverses through dipping sections along washes. South of the Kelton Pass 7.5' quadrangle, the Tertiary sedimentary rocks unit (Ts) is overlain by latest Miocene basalt flows (5–7 Ma; Fiesinger in Miller and others, 1995).

On the east side of the quadrangle, in Curlew Valley, the Tertiary sedimentary rocks generally crop out within or along the sides of washes, or at the wave-cut Bonneville shoreline. However, they probably underlie most of the Quaternary deposits. They are commonly overlain by 10 to 100 feet (3–30 m) of Quaternary deposits, which suggests that the Quaternary deposits may overlie a pediment surface on the Tertiary deposits.

The conglomerate is generally matrix supported and moderately to poorly sorted, consisting of subangular to subrounded clasts within a disorganized framework. Locally, the conglomerate is clast supported with well-rounded clasts. The largest clasts are generally 0.4 to 1.2 inches (1 to 3 cm) in diameter, but occasionally up to 5 inches (13 cm) in size. The conglomerate is bedded, but internally massive, with beds 1.5 to 8.2 feet (45 cm to 2.5 m) thick. Clasts derived from the Oquirrh Formation (unit P_{Po}) are most common (generally 75%), with other Paleozoic lithologies comprising 20 percent, and locally minor components of the Elba Quartzite, and Tertiary volcanic and sedimentary rocks.

The conglomerate is interbedded with coarse-grained sandstone; water-lain tuff; tuffaceous sandstone, siltstone, and mudstone; and limestone. Tuffaceous siltstone and sandstone are tan, light green to yellow and white, and are locally 90 percent glass shards. The tuffaceous sandstone varies from well-bedded to massive. Tuffaceous siltstone and mudstone is well laminated, commonly thin bedded, calcareous, buff white to yellowish with beds of pumice-pebble conglomerate. The interbedded limestone is finely crystalline, sugary and tan, and less commonly vuggy, crystalline, and

light tan to light gray.

Most contacts between Paleozoic and Tertiary rocks are faults. However, in Crystal Hollow near Crystal Spring in the west half of section 27, T. 14 N., R. 12 W., conglomerate and sandstone rest positionally on marble of the Garden City Formation, and define a Tertiary extensional basin. Here, east-dipping Tertiary strata lap onto west-dipping Paleozoic rocks; this basin developed as a result of down-to-the-east normal faulting, probably developed during movement along the Raft River detachment fault. Additionally, at a locality 1.25 miles (2 km) north of the quadrangle, at the north end of an outcrop belt of Tertiary sedimentary rocks on the west flank of the Black Pine Mountains, conglomerate rests positionally on the Oquirrh Formation (unit P_{Po}) (Smith, 1982).

Conglomerate and interbedded coarse-grained sandstone that generally lack tuffaceous material are of alluvial origin. Much of the tuffaceous sandstone, siltstone, and mudstone is thinly bedded and laterally extensive, suggesting a lacustrine depositional setting.

Tertiary and Quaternary Units

Oldest Alluvial-Fan Deposits (Q_{Taf})

Unconsolidated deposits of boulders, cobbles, pebbles, sand, and silt form hills in the northwestern part of the quadrangle. These deposits are mapped as the oldest alluvial-fan deposits (Pleistocene and Pliocene). Clasts are composed predominantly of Precambrian lithologies. These deposits are possibly remnants of an old alluvial fan that extended outward from the mouth of the Clear Creek drainage in the Park Valley 15' quadrangle, that has since been eroded and covered by younger deposits in the Clear Creek valley.

Quaternary Units

Lacustrine and alluvial-fan deposits are the most common Quaternary sediments in the quadrangle. Pleistocene alluvial fans were overlapped by lacustrine sediments deposited during the rise of Lake Bonneville, the youngest and deepest of large pluvial lakes that formed in northern Utah. The lake rapidly rose across the Kelton Pass area from about 20 ka to 18 ka and reached its maximum depth at about 15 ka, when it formed the Bonneville shoreline. Shortly thereafter, the alluvial overflow threshold in southern Idaho catastrophically failed (Bonneville Flood) and the lake lowered to a stable threshold, forming the Provo shoreline (Oviatt and others, 1992). Elevations of the principal shorelines in the quadrangle are: Bonneville, 5180 ± 10 feet (1579 ± 3 m), and Provo, 4835 ± 2 feet (1474 ± 0.5 m). From about 14 ka to 12 ka, the lake level fell to very low elevations, leaving the northwestern part of Curlew Valley blanketed by marl, sand, and gravel. Subsequent erosion and alluvial deposition has only slightly modified the landscape.

Older Alluvial-Fan Deposits (Q_{f3})

Unconsolidated, poorly-sorted boulders, gravel, sand and silt comprise the older alluvial-fan deposits (Pleistocene) and form broad fans along the eastern flank of the Raft River Mountains. These fans are overlain by Lake Bonneville

deposits or cut by lake erosion, and are distinguished from unit Qaf₂ by being more dissected and having a distinctly different clast composition (predominantly metamorphosed Paleozoic marble, quartzite, and phyllite). These deposits are 40 to 200 feet (12-60 m) thick, and probably overlie a pediment surface on Tertiary strata.

Old Alluvial-Fan Deposits (Qaf₂ [p \mathcal{C}]), Qaf₂[PP])

Unconsolidated, poorly-sorted gravel, sand, and silt comprise these old alluvial-fan deposits (Pleistocene). Similar to Qaf₃, these fans are overlain by Lake Bonneville deposits and are cut by lake erosion, but are less dissected. These deposits form broad fans along the north flank of the eastern Raft River Mountains, and south end of the Black Pine Mountains. Clast composition varies between different original fan lobes (predominantly Precambrian clasts, p \mathcal{C} on map, or Permian and Pennsylvanian clasts, PP on map), depending on the source area and the chronology within the unroofing sequence.

Lacustrine Lagoonal Deposits (Qll)

These fine-grained deposits of Lake Bonneville (latest Pleistocene) are minor surficial deposits within the Kelton Pass 7.5' quadrangle. They are restricted to exposures near the junction between State Highway 42 and the Cedar Creek road (NE $\frac{1}{4}$ section 1, T. 14 N., R. 12 W.; NW $\frac{1}{4}$ section 6, T. 14 N., R. 11 W.). However, they probably underlie many lacustrine gravel deposits that form various barrier bar complexes. Lagoonal deposits consist of unconsolidated buff-white to tan, silty marl, calcareous silt, and fine sand. Lagoonal deposits are the same age as deposits in nearby beach and offshore lacustrine environments.

Lacustrine Sand (Qls)

Lacustrine sand (latest Pleistocene) consists of fine to coarse sand and minor granule to pebble gravel deposited in Lake Bonneville. In addition to the lacustrine sand deposits mapped on the eastern margin of the quadrangle, lacustrine sand also underlies regressive barrier beach and gravel deposits (Qlg).

Lacustrine Gravel (Qlg)

Lacustrine gravels (latest Pleistocene) were widely deposited along shorelines of Lake Bonneville in beach and barrier beach complexes. These materials are unconsolidated, generally moderately to well-sorted, well-rounded cobble and pebble gravel with subordinate sand. A particularly well-exposed example of a barrier beach is on the south side of State Highway 42, just east of the intersection with the Cedar Creek road. There, gravels in a barrier bar have well-bedded, silty lagoonal deposits draped over and infilling the lagoonal trough on the shoreward side of the bar. The silt is in turn overlain by sand, which is capped by a deposit of gravel. The barrier beach complexes in the Kelton Pass 7.5' quadrangle generally have steep sides that faced towards open water, and are elongate north-south, parallel to the shoreline. Second-order, low-amplitude arcuate depositional ridges are prominent on aerial photographs, and are convex northward, indicating northward progradation. Long-shore transport is also

indicated by clast lithologies seemingly out of place relative to clasts in local drainages. For example, Precambrian clasts are always contained within the Lake Bonneville gravels, even in areas where drainages only tap a Paleozoic source; local relations suggest a northward transport. Additionally, clasts of vesicular basalt are present in Lake Bonneville gravels at the southern margin of the quadrangle, and are probably derived from prominent basalt mesas present south of the quadrangle.

Lacustrine and Alluvial Deposits, Undivided (Qla)

An undivided Holocene and Pleistocene unit of lacustrine and alluvial origin was mapped where alluvial and lacustrine deposits could not be confidently distinguished, or were too complexly interfingered or interlayered to map separately. In places, lacustrine fines are deposited over pre-Lake Bonneville alluvial fans. Elsewhere, lacustrine deposits have been reworked by alluvial processes, and locally overlain by thin alluvial deposits.

Lacustrine and Alluvial Deposits that overlie Tertiary Rocks (Qla/Ts)

Tertiary sedimentary rocks (Ts) underlie thin, undivided lacustrine and alluvial deposits (Qla), as indicated by either the occurrence of tuffaceous soils or exposures of Tertiary deposits within "windows" through the Quaternary deposits. The deposits (Qla/Ts) occur below the Lake Bonneville highstand, are commonly marked by irregular topography, and represent Holocene and Pleistocene lacustrine and alluvial veneers on irregular topography formed in relatively resistant Tertiary deposits.

Colluvium (Qc)

Colluvial deposits (Holocene and latest Pleistocene) are common along steep slopes flanking the deeper valleys that dissect the eastern Raft River Mountains. The colluvium consists of unconsolidated gravel and sand locally derived from Precambrian and Paleozoic strata.

Mass-Movement Deposits (Qms)

Incoherent landslide deposits and a single coherent slump (Holocene and latest Pleistocene) are present along the flanks of canyons cut into Precambrian bedrock, and along the northern dip slope to the range-scale anticline within Precambrian rocks. The landslide deposits create hummocky and irregular topography, and generally have headwall scarps. The slump on the north wall of Ten Mile Creek canyon contains a coherent but displaced section of Precambrian rocks.

Stream Alluvium (Qal)

Deposits of unconsolidated, poorly sorted gravel, sand, silt, and clay (Holocene and latest Pleistocene) are mapped in active ephemeral stream beds and washes. The grain size of these deposits generally decreases downstream. Included within these deposits is locally derived colluvium along the base of slopes bordering these drainages, particularly in mountain valleys.

Younger Alluvial-Fan Deposits (Qaf₁)

Unconsolidated alluvial-fan deposits (Holocene) of poorly sorted gravel, sand, and silt form small alluvial fans that breach Lake Bonneville shorelines and overlie lake deposits. These fans postdate the development of the Bonneville and younger shorelines, and are located along the eastern margin of the quadrangle.

Eolian Sand and Silt (Qe)

Eolian sand and silt (Holocene) is present in small dunes and sheets south of Hardup (site), mostly in deposits less than 6 feet (2 m) thick. These unconsolidated, light-gray to light-brown deposits are most likely locally derived from stratified alluvial sand and silt deposits (Qla) present in the surrounding region. The eolian sand and silt accumulations are associated with vegetation, commonly cedar trees.

STRUCTURE

The eastern Raft River Mountains display many features of crustal extension. In particular, the Raft River Mountains expose a Miocene low-angle normal fault (the Raft River detachment) that separates mylonitic Precambrian rocks in the footwall (lower plate) from Proterozoic, Paleozoic and Tertiary strata in the hanging wall (upper plate). The Precambrian rocks are the parautochthon and the overlying upper plate contains the lower and middle allochthons in the eastern Raft River Mountains (figures 3 and 4). In contrast to Miocene plastic deformation of Precambrian footwall rocks, the hanging-wall rocks were rotated and extended along high-angle brittle normal faults that root into the Raft River detachment, also in the Miocene. These structural features are common to metamorphic core complexes (for example, Crittenden and others, 1980), which are products of large-magnitude crustal extension.

Study of allochthons of the upper plate enabled reconstruction of the deformational sequence that predates Miocene detachment faulting, and provided constraints on the absolute age of metamorphism. Study of Precambrian rocks in the lower plate of the Raft River detachment yielded information on the timing and kinematics of Miocene movement on the Raft River detachment fault.

The eastern Raft River Mountains show seven phases of deformation (table 1): (D₁) attenuation of units within the lower allochthon by intrabed plastic flow at upper greenschist- to lower amphibolite-facies conditions; (D₂) attenuation of lower allochthon units by top-to-the-west low-angle normal faulting; (D₃) recumbent folding (F₃) of attenuated strata and faults; (D₄) emplacement of the middle allochthon (to the west) over the lower allochthon along the middle detachment fault; (D₅) upright, open folding (F₅) of the middle and lower allochthons; (D₆) progressive top-to-the-east normal-sense shearing along the shear zone at the top of the parautochthon and along the Raft River detachment fault, with concomitant high-angle normal faulting in the upper plate; and (D₇) doming of the Raft River detachment fault and earlier structures. A brief description of these deformations follows; for a more complete description and a discussion of these deformations, see Wells (1991, 1992, 1997, 2001) and Wells and others (1998, 2000, 2008).

D₁ - Stratigraphic Attenuation

The Proterozoic through Pennsylvanian(?) units within the lower allochthon are markedly attenuated by both plastic and brittle deformation. The attenuation was achieved by penetrative plastic thinning during metamorphism at upper greenschist- to lower amphibolite-facies conditions (D₁), and later by low-angle younger-over-older ductile and brittle faulting (D₂) (referred to here as attenuation faulting, after Hintze, 1978). The D₂ attenuation faults are interpreted as postdating penetrative foliation development (D₁) for the following reasons: (1) attenuation faults locally truncate D₁ foliation; (2) quartzite microstructural fabrics within attenuation fault zones are of distinctly lower temperature than D₁ fabrics, and (3) D₁ fabrics have distinct kinematics from the attenuation fault zones (Wells, 1997).

The most pervasive fabric in the lower allochthon is a penetrative foliation that is generally parallel to lithologic layering and inferred bedding. At the few locations where foliation is distinct from bedding, foliation is slightly inclined to the southwest relative to bedding, whether in upright or overturned rocks. Lineation varies in degree of development, is not ubiquitous, and generally trends north-east. With the exception of a few asymmetric structures that indicate eastward and northeastward shearing, the majority of strained features are symmetric, suggesting a major component of shortening nearly perpendicular to bedding.

The D₁ fabric in the lower allochthon is interpreted as a prograde metamorphic fabric (Wells, 1997). Oxygen isotope ($\delta^{18}\text{O}$) mineral-pair geothermometry of muscovite, biotite, and quartz that microscopically define the D₁ foliation in Ordovician rocks yields temperatures between 490° and 520°C (Wells and others, 1990; Wells, 1991). This is consistent with conodont color alteration index (CAI) values >7 (Wells and others, 1990; J.E. Repetski, U.S. Geological Survey, written communication, 1989), and calcite-dolomite thermometry on the Garden City Formation in the western Raft River Mountains (Wolff, 1997; Wells and others, 1998). Additionally, the metamorphic assemblages from the Proterozoic schist of Mahogany Peaks (as outlined earlier) suggest pressures and temperatures in excess of 6.5 kb and 600°C, respectively (Spear and Cheney, 1989), further suggesting a doubling of the stratigraphic section (Wells and others, 1998). Thus, the metamorphic conditions indicate tectonic burial, not thermal metamorphism at stratigraphic burial depths (in contrast to metamorphism in the Pilot Range to the southwest) (Miller and Hoisch, 1992).

In contrast to the Proterozoic to Permian rocks above the Raft River detachment, the Archean and Proterozoic rocks below the detachment exhibit vestiges of a variably directed, top-to-the-NNE to -NNW shear zone. This shear zone clearly predates, and is preserved beneath, the D₆ top-to-the-east extensional shear zone. Additionally, the generally top-to-the-N fabric is also preserved locally within the D₆ shear zone, in lenses that have escaped the younger deformation, commonly in mechanically strong amphibolites. This fabric represents the earliest deformation fabric within the parautochthon, and may be coeval with D₁ described above (table 1).

D₂ - Attenuation Faults

Two major discontinuities in stratigraphy within the

Table 1. Deformation events in the eastern Raft River Mountains. Sources for upper plate (Lower and Middle Allochthons) are: Wells and others (1990, 2008) and Wells (1992, 1997). Sources for lower plate (Parautochthon) are: Compton and others (1977), Compton (1980), Sabisky (1985), Malavieille (1987a), Wells (1992, 1997), and Wells and others (2000, 2008). Arrows between two deformations of Parautochthon indicate that these deformations may be part of a single progressive deformation, rather than two distinct events.

LOWER AND MIDDLE ALLOCHTHONS (UPPER PLATE)

Deformation event	Mesostructures	Kinematics	Interpretation	Timing
D ₁ : Penetrative attenuation of strata within lower allochthon during amphibolite-facies metamorphism	(S ₁) Low angle to bedding (L ₁) NE-trending	Flattening and top-to-NE shear	Extension	Pre-90 to 102-105 Ma
D ₂ : Attenuation faulting within lower allochthon during greenschist-facies metamorphism	(S ₂) Low angle to S ₁ (L ₂) E-trending	Top-to-west shear	Extension	~90 Ma
D ₃ : Recumbent folding of lower allochthon			Contraction	
D ₄ : Middle Detachment (places middle on lower allochthon)		Top-to-WSW shear	Extension	Late Eocene-Oligocene(?)
D ₅ : Open folding of middle and lower allochthons	N-trending fold axes, generally upright			
D ₆ : Raft River Detachment (RRD) and high-angle faulting (HAF)		RRD top-to-the-east HAFs generally down-to-the east	Extension	Middle - early Late Miocene
D ₇ : Doming	~E-W axis, doubly plunging			

PARAUTOCHTHON (LOWER PLATE)

Deformation event	Mesostructures	Kinematics	Interpretation	Timing
Northward shearing	Subhorizontal foliation; ~N-S lineation	Northward-shearing and apparent constriction		Pre-90 to 102-105 Ma
▼ Footwall shear zone (D ₆ of upper plate)	Subhorizontal foliation; ~E-W lineation; recumbent folds w/E-W hingelines	Top-to-the-east shearing and vertical shortening	Extension	Late Early - Middle Miocene
▲ Raft River Detachment (D ₆ of upper plate)	Top-to-the-east brittle faulting		Extension	Middle - early Late Miocene
Doming (D ₇ of upper plate)	~E-W axis, doubly plunging			

lower allochthon mark faults: the Emigrant Spring fault (Wells, 1997; LAF1 of Wells, 1992) and the Mahogany Peaks fault (LAF2 of Wells, 1992; Wells and others, 1998) (figure 3). The fault placing Pennsylvanian(?) lower Oquirrh Formation tectonite marble (IPot) over Ordovician and Silurian(?) dolomitic marble (SOD) is named the Emigrant Spring fault for a well-exposed locality of this fault near Emigrant Spring in the quadrangle. This fault removes most or all of the Silurian, all of the Devonian, and all but thin slivers of Mississippian rocks throughout the entire mapped area. A plastic shear zone is present within the basal part of the Pennsylvanian(?) marble tectonite (IPot) adjacent to the Emigrant

Spring fault. This marble is highly foliated, and locally contains a well-developed east-trending stretching lineation that is parallel to fold axes of locally developed isoclinal folds. Crystallographic preferred orientation and microstructural analysis of this marble indicate a significant component of westward shearing (Wells, 1992, 1997).

The second major discontinuity in stratigraphy separates the Proterozoic schist of Mahogany Peaks (Pmp) and quartzite of Clarks Basin (Ecb) from the Ordovician Garden City Formation (Ogc). This contact was interpreted by Compton (1975) and Compton and Todd (1979) to be depositional, and was interpreted as a fault by Crittenden (1979) and Wells

(1992, 1997). The faulted nature of this stratigraphic discontinuity has recently been clarified by carbon isotopic data, metamorphic petrology, $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology, and structural data (Wells and others, 1998). Together, these data suggest that the contact is a large-displacement low-angle normal fault that excised 2.5 to 3 miles (4-5 km) of stratigraphic section; it has been named the Mahogany Peaks fault (Wells and others, 1998).

In addition to the two major low-angle faults described above, all other formational contacts within the lower allochthon are low-angle attenuation faults that place younger rocks on older rocks. The faults are generally subparallel to foliation (and bedding) in the adjacent units, and are recognized by ductile high-strain zones localized along bedding-parallel contacts between stratigraphic units along which section is commonly missing. However, locally there is moderate discordance between the fault zone and the adjacent units, and between units on either side of faults. Slivers of units are commonly strung out along low-angle faults, and locally, units have been completely omitted. Additionally, significant lateral changes in map-scale unit thicknesses indicate faulting.

Within the attenuation fault zones, fabrics range from ductile to brittle, and in many localities a progression from early ductile to later brittle shearing is evident. The majority of observations from within these fault zones suggest top-to-the-west shearing. Mylonitic shear zones, ranging in thickness from 0.4 to 60 inches (1-150 cm), are recognized within quartzites of the greatly attenuated undivided Crystal Peak, Watson Ranch, Lehman and Kanosh Formations map unit (Ock) and the Eureka Quartzite (Oe). Kinematic indicators including S-C fabrics, oblique grain-shape fabrics and asymmetric lattice-preferred orientations indicate westward shearing (Wells, 1997). The shear zones separate Silurian(?) and Ordovician dolomite (SOD) from the Garden City Formation (Ogc).

D₃ - Recumbent Folding (F₃)

Large inverted sequences of Ordovician to Pennsylvanian(?) rocks, coupled with upright packages of the same rocks, are common in the lower allochthon (figure 4). These relationships indicate the presence of upright and overturned limbs of large recumbent folds. The hinges of these inferred folds, however, are not unequivocally exposed, and because later high-angle normal faults have since altered the dips of the fold limbs, their geometries are not known. The youngest unit involved in the recumbent folding is the Pennsylvanian(?) marble tectonite (IPot); it generally occupies the cores of recumbent synclines (figure 4; cross-section A-A'). D₃ recumbent folds deform D₁ foliation and unequivocally fold the D₂ Emigrant Spring fault.

D₄ - Emplacement of the Middle Allochthon along the Middle Detachment Fault

Subsequent to recumbent folding, greenschist-facies metamorphosed Permian and Pennsylvanian rocks (Oquirrh Formation) of the middle allochthon were emplaced onto the lower allochthon along the middle detachment fault. The transport direction for this fault is derived from study of a thin sliver of Chainman Shale present locally along the base

of the middle allochthon. Highly asymmetric quartz and calcite pressure shadows around pyrite consistently indicate top-to-the-west shearing (Wells, 1992, 1997). This translation direction is consistent with data from the Black Pine Mountains (figure 1) that also indicate westward transport of the middle allochthon (Wells and Allmendinger, 1990).

Movement along the middle detachment fault probably occurred at metamorphic conditions no higher than lower greenschist facies. This is evident from the metamorphic discontinuity across this fault in the study area and farther to the west (Compton and others, 1977; Wells and others, 1997), and the deformation mechanisms within the sheared base of the middle allochthon (Wells, 1997). The displacement along the middle detachment was, therefore, probably late metamorphic to post metamorphic.

D₅ - Open Folding (F₅)

Both the lower and middle allochthons are folded into broad, upright, open folds whose axes generally trend N-S (figure 4). The most prominent of these folds lies southeast of Crystal Peak, where an open fold (F₅) with a wavelength greater than 4900 feet (1500 m) is well exposed. This fold clearly deforms both the middle detachment and underlying low-angle faults within the lower allochthon and is truncated by the Raft River detachment (see cross-section B-B').

D₆ - Raft River Detachment Fault and Shear Zone

Structurally beneath the Raft River detachment and within the parautochthon is an approximately 660-foot (200-m) thick shear zone that is parallel to bedding in the Proterozoic units and the underlying unconformity with Archean rocks. There is a close spatial and kinematic association between the detachment fault and the underlying shear zone. The shear zone always directly underlies the brittle detachment fault. Fabrics within the uppermost shear zone are commonly retrograded, and where a cataclastite is present, the mylonite is progressively overprinted by cataclastic deformation structurally upward toward the detachment fault. Both plastic and brittle structures exhibit the same top-to-the-east shear sense.

Mylonitic fabrics are most highly developed within the Elba Quartzite and its schist member, and fabric intensity related to eastward shearing typically dies out abruptly downward within the Green Creek Complex. Studies of the shear zone have documented large-scale, top-to-the-east displacement (Compton, 1980; Sabisky, 1985; Malavieille, 1987a; Wells and others, 2000; Wells, 2001; Sullivan, 2008). The shear zone is continuous to the extreme eastern exposures of the parautochthon within the Kelton Pass 7.5' quadrangle. Within the shear zone, a generally flat-lying foliation and a pronounced stretching lineation (trending $083 \pm 10^\circ$) record significant strain resulting from a combination of vertical flattening and top-to-the-east simple shear (Compton, 1980; Sabisky, 1985; Malavieille, 1987a; Wells, 1992, 1997, 2001; Sullivan, 2008).

Superposed on the shear zone in the parautochthon is the brittle Raft River detachment fault. This major structural discontinuity everywhere forms the upper contact of the schist member of the Elba Quartzite. The detachment fault is con-

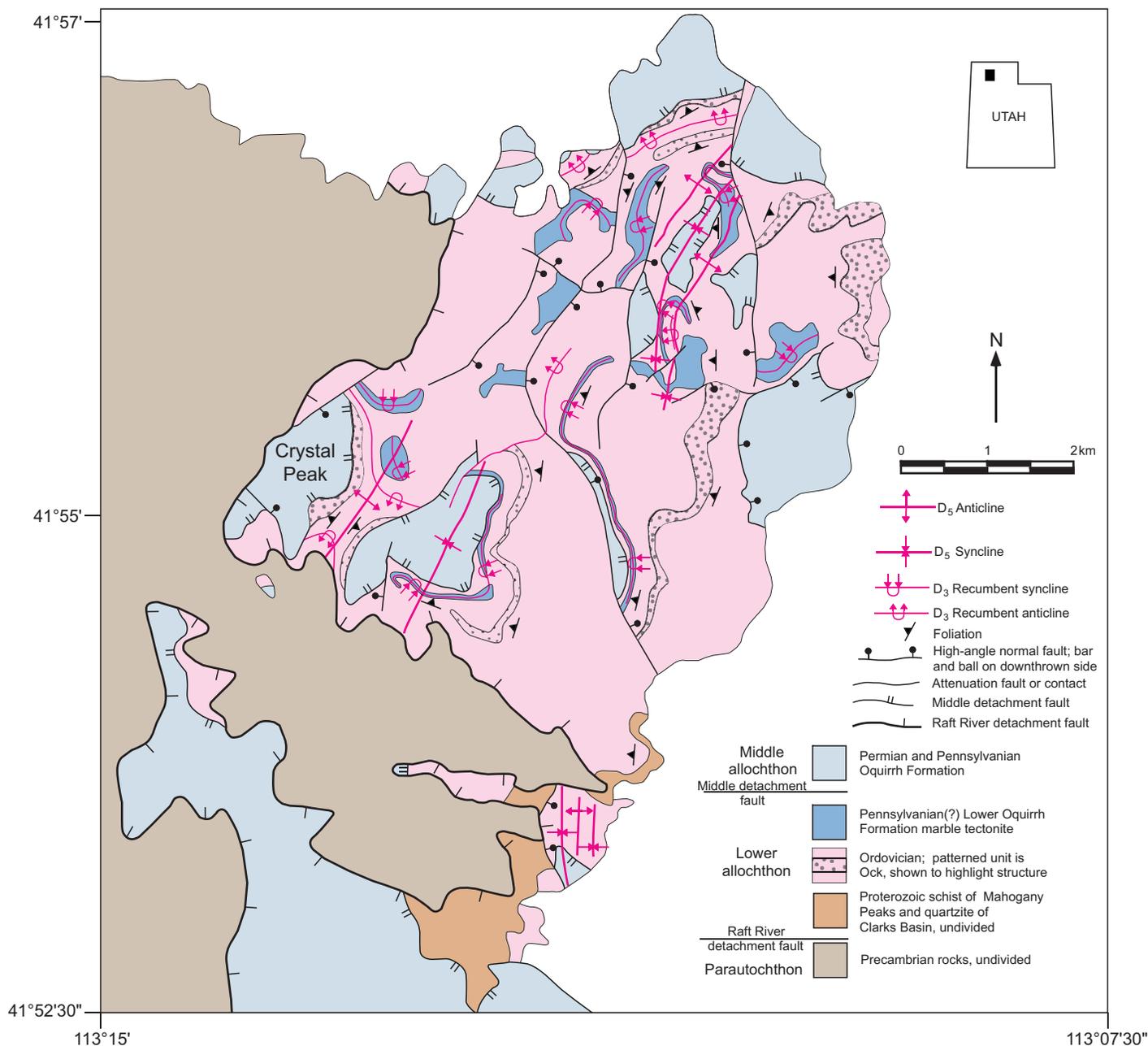


Figure 4. Generalized geologic map of the eastern Raft River Mountains indicating distribution of allochthons and parautochthon and their bounding detachment faults, and axial traces of D_3 (F_3) recumbent folds and D_5 (F_5) open folds. Note that the Pennsylvanian(?) marble tectonite (IPot) commonly occurs within the cores of D_3 (F_3) recumbent synclines.

cordant with foliation and bedding within the lower plate, but truncates most structures within the upper plate. The fault surface is not exposed, but float blocks of brecciated and oxidized marble are common. However, on the east side of Indian Creek in the southwest corner of the Kelton Pass 7.5' quadrangle, and in lower reaches of Ten Mile Canyon, fine-grained schist in the footwall adjacent to the detachment has been subjected to cataclasis. In these localities, resistant ledges of black cataclasite demarcate the detachment fault.

Both brittle and ductile cataclastic rocks are present, as are many shear fabrics common to ductile shear zones.

The rocks above the Raft River detachment fault are cut by numerous high-angle normal faults with displacements from an inch to about 1.25 miles (cm to km) (plate 2 and 3). The strikes of the faults vary greatly, but the majority are roughly north. Only two faults, both of small displacement, were noted that cut the Raft River detachment fault, and their separations were too small to map, even at 1:12,000 scale

(plate 2). All other high-angle faults, therefore, root geometrically into the Raft River detachment fault, and formed either prior to or during movement of the detachment fault.

D₇ - Broad Folding

The present structure of the rock units in the Raft River Mountains is an east-west trending, doubly plunging anticline of 16.25 miles (26 km) length and 3960 feet (1200 m) of exposed structural relief (figure 1). The shear zone, strata in the parautochthon, and the detachment fault outline this large structure. The axis of the elongate anticline is parallel to the transport direction of both the footwall shear zone and the Raft River detachment fault. The near parallelism of the shear zone and detachment fault to the footwall strata over a wide area of the Raft River Mountains, particularly in the orientation perpendicular to the anticlinal axis, strongly suggests that the fold developed after detachment faulting.

Other

Tertiary sedimentary rocks exhibit variable bedding attitudes suggesting they have been folded and tilted. Generally, bedding strikes northward and dips westward, possibly due to down-to-the-east faulting in the upper plate of the Raft River detachment fault. However, locally continuous outcrops in washes indicate that the Tertiary rocks are also involved in large-wavelength (>1.25 miles [2 km]) folds that plunge moderately (30° to 35°) to the southwest. It is unclear whether these folds were generated during detachment faulting (D₆), or during the more recent doming of the range (D₇).

No range-bounding faults were identified along the northern, southern, and eastern margins of the Raft River Mountains, and the range morphology probably results from doming rather than block-faulting typical of other ranges in the Basin and Range Province.

GEOCHRONOLOGY

The upper and lower plate rocks in the Raft River Mountains experienced similar peak metamorphic conditions of upper greenschist to lower amphibolite facies, most likely in the mid-Cretaceous (Wells and others, 2000), but their timing of cooling (a probable proxy for unroofing) differs significantly. Muscovite ⁴⁰Ar/³⁹Ar ages from the upper plate are Late Cretaceous, whereas muscovite (as well as biotite and potassium feldspar) ⁴⁰Ar/³⁹Ar ages from the lower plate are late early to early late Miocene (table 2).

Wells and others (1990) described four muscovite ⁴⁰Ar/³⁹Ar age determinations from four samples of marble and schist from the lower allochthon in the eastern Raft River Mountains (table 2). Muscovite separates from the Garden City Formation (Ogc) containing D₁ fabrics yielded a total gas age of 81.3 ± 0.2 Ma (MWRR59-88) and plateau ages of 87.8 ± 0.3 Ma (MWRR41-88) and 90.4 ± 0.3 Ma (MWRR40-88); a muscovite separate from Pennsylvanian(?) marble tectonite (IPot) adjacent to the D₂ Emigrant Spring fault yielded a similar plateau age of 88.5 ± 0.3 Ma (MWRR12-89). The similarity in age and in morphology of age spectra from muscovite defining D₁ and D₂ fabrics indicates that both fabrics developed prior to or synchronous

with earliest Late Cretaceous cooling; however, the cooling age may predate D₂ deformation as the temperatures of deformation may have been less than argon closure in muscovite.

Phlogopite growing in D₁ strain fringes around pyrite from the Oquirrh Formation of the middle allochthon in the Grouse Creek Mountains yielded laser-probe ⁴⁰Ar/³⁹Ar ages of ~105-102 Ma (Wells and others, 2008). Evidence for phlogopite growth in lower greenschist-facies metamorphic conditions (~300-350°C) together with incomplete resetting of step-heated detrital muscovite, indicate that the UV laser-probe ⁴⁰Ar/³⁹Ar ages reflect growth and hence deformation ages, not cooling ages (Wells and others, 2008).

Thermochronological results from within and beneath the D₆ shear zone in the parautochthon contrast markedly with the Late Cretaceous muscovite ages from the lower allochthon (Wells and others, 1990, 2000a). Late early to early late Miocene cooling ages (⁴⁰Ar/³⁹Ar from muscovite, biotite, and potassium feldspar; fission track in apatite) (Wells and others, 2000) collectively indicate rapid cooling during the Miocene, during footwall unroofing related to extensional displacement.

Samples collected from Ten Mile Creek canyon constrain the cooling history of the lower plate to the Raft River detachment fault (Wells and others, 2000). Muscovite from mylonitic Elba Quartzite yielded total-gas ages of 14.66 ± 0.09 Ma (RR91-6) and 14.57 ± 0.1 Ma (MWRR100-89) from quartzite and a muscovite-schist interbed, respectively (table 2). Biotite from the older schist unit yielded a well-defined plateau age of 13.76 ± 0.15 Ma (RR91-13). The discordance of these ages is consistent with closure temperatures for muscovite and biotite—approximately 350° and 300°C ± 25°C, respectively (McDougall and Harrison, 1999). Detrital potassium feldspar from the Elba Quartzite was analyzed following the multiple-diffusion-domain analysis methods of Lovera and others (1989, 1991) (see Wells and others, 2000, for details). The potassium feldspar is affected by excess argon and yielded a saddle-shaped age spectrum, with an age gradient from 10.58 ± 0.40 Ma at 10.3 percent ³⁹Ar release, to 70.23 ± 0.27 Ma. The low-temperature portion of the age spectrum was modeled to determine a cooling history (figure 5), which is cautiously interpreted as a minimum cooling rate due to the potential complication of excess argon in this portion of the gas release. The fission-track age of detrital zircon from the Elba Quartzite is 9.4 ± 0.73 Ma. At average geologic cooling rates, zircon has a closure temperature of approximately 210°C ± 20°C (Zaun and Wagner, 1985). Apatite from the metamorphosed adamellite unit, collected on the eastern side of Indian Creek canyon (1.5 miles [2.2 km] to the east of the Ten Mile Creek canyon locality) records a cooling age of 7.42 ± 0.99 Ma. At geologic cooling rates (1-100°C/m.y.), fission-track annealing in apatite occurs between approximately 60° and 120°C (for example, Gleadow and Duddy, 1981; Gleadow and others, 1983). The muscovite, biotite, and potassium feldspar ⁴⁰Ar/³⁹Ar ages and the apatite and zircon fission-track ages detail a cooling curve for the lower plate to the Raft River detachment fault (figure 5).

The D₆ mylonite zone was previously interpreted as a Mesozoic thrust-sense (Malavieille and Cobb, 1986; Snoke and Miller, 1988) and Cenozoic normal-sense shear zone (Malavieille, 1987a; Wells, 1992, 1997). Plastic shearing

Table 2. Geochronologic data from the Kelton Pass quadrangle area, eastern Raft River Mountains; all age reported at 1-sigma analytical uncertainty. ⁴⁰Ar/³⁹Ar analyses from Lower Allochthon (Ordovician strata and unit IPot) were performed in the laboratory of R.D. Dallmeyer at the University of Georgia (Wells and others, 1990). ⁴⁰Ar/³⁹Ar analyses from Parautochthon (Precambrian rocks) were done at the U.S. Geological Survey in Denver, Colorado (Wells and others, 2000). Plateau ages marked with an asterisk (*) are not true plateau ages, but rather are weighted mean ages (preferred ages) of selected contiguous gas increments, and most likely represent the cooling age. Fission track analyses were performed by A.E. Blythe at University of Southern California. NA=Not applicable, sample from just outside quadrangle.

PARAUTOCHTHON

Map #	Sample Number	Sample site Latitude	Sample site Longitude	Mineral	Unit Symbol	Total Gas Age (Ma)	Plateau Age (Ma)	Fission Track Age (Ma)
1	MWRR100-89	41° 54' 46"	113° 14' 22"	Muscovite	Pe	14.57 ± 0.10	14.88 ± 0.8*	
2	RR91-6	41° 54' 28"	113° 13' 38"	Muscovite	Pe	14.66 ± 0.09	15.05 ± 0.18*	
2	RR91-6	41° 54' 28"	113° 13' 38"	Zircon	Pe			9.4 ± 0.73
2	RR91-137	41° 54' 28"	113° 13' 38"	K-feldspar	Pe	46.35 ± 0.44	13.15 ± 0.16*	
3	RR91-13	41° 54' 19"	113° 13' 33"	Biotite	Aos	13.44 ± 0.06	13.76 ± 0.15	
NA	RR91-82	41° 53' 57"	113° 15' 13"	Apatite	Aad			7.42 ± 0.99
4	MWRR80-89	41° 56' 01"	113° 14' 33"	Hornblende	Ami	192.69 ± 0.54		
5	MWRR82-89	41° 54' 14"	113° 13' 43"	Hornblende	Ami	134.94 ± 1.38		

LOWER ALLOCHTHON

Map #	Sample Number	Sample site Latitude	Sample site Longitude	Mineral	Unit Symbol	Total Gas Age (Ma)	Plateau Age (Ma)	Fission Track Age (Ma)
6	MWRR12-89	41° 55' 44"	113° 10' 55"	Muscovite	IPot	88.0 ± 0.3	88.5 ± 0.3	
7	MWRR40-88	41° 54' 48"	113° 11' 25"	Muscovite	Ogc	88.7 ± 0.3	90.4 ± 0.3	
8	MWRR41-88	41° 54' 18"	113° 12' 21"	Muscovite	Ogc	87.1 ± 0.4	87.8 ± 0.3	
9	MWRR59-88	41° 54' 03"	113° 12' 07"	Muscovite	Ogc	81.3 ± 0.2		
10	MWRR58-88	41° 56' 15"	113° 10' 08"	Whole Rock	Ock	65.0 ± 0.6		
11	MWRR92-89	41° 53' 8"	113° 12' 35"	Muscovite	Pe	66.04 ± 0.29		
12	MWRR93-89	41° 53' 09"	113° 12' 48"	Muscovite	Pe	56.05 ± 0.13		

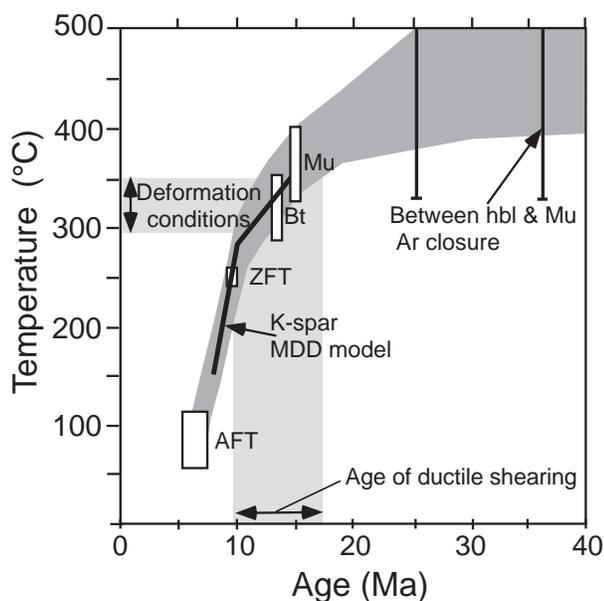


Figure 5. Time-temperature plot derived from thermochronometric data for the Ten Mile Creek canyon locality. Darker shaded area represents cooling path envelope (envelope bounding permissible cooling paths); boxes indicate cooling ages with range of closure temperature and 1-sigma errors in age; vertical bars indicate temperature conditions bracketed between thermochronometers. The apatite fission-track age is projected from age-versus-distance regression of Wells and others (2000). The approximate deformation conditions for late plastic (ductile) shearing in quartz are indicated by lighter shaded area. Note that the D₆ extensional shearing took place during rapid cooling, indicating a Miocene age for shearing. Letter symbols on figure are: AFT, apatite fission track; ZFT, zircon fission track; Bt, biotite ⁴⁰Ar/³⁹Ar; Mu, muscovite ⁴⁰Ar/³⁹Ar; Hbl, hornblende ⁴⁰Ar/³⁹Ar; Kspar MDD model, multiple diffusion domain thermal model for potassium feldspar.

occurred within the temperature window spanned by Miocene rapid cooling, as indicated by the deformation conditions recorded in microstructures (Wells and others, 2000), and confirms a Miocene age. Rapid cooling during the Miocene probably resulted from footwall uplift related to both displacement along the Raft River detachment fault and extension of the upper plate.

ECONOMIC GEOLOGY

Metals

No mining prospects were observed within the Kelton Pass 7.5' quadrangle. However, in the nearby Black Pine Mountains, five separate "Carlin type" gold ore bodies have been identified and produced gold (Brady, 1984; Willden and Adair, 1984; Hefner and others, 1991). Gold deposits in the Black Pine mining district are generally hosted within the Oquirrh Formation. These rocks are of similar metamorphic grade, and are probably in an equivalent structural position to the Oquirrh Formation in the middle allochthon in the eastern Raft River Mountains (Wells and others, 1990; Wells and Allmendinger, 1990). Two detachment faults may localize mineralization in the Raft River Mountains: the Raft River detachment and the middle detachment. The carbonate rocks above the Raft River detachment, including Ordovician and Permian-Pennsylvanian rocks, may be hosts for detachment-related mineralization, such as the well-documented examples in the lower Colorado River extensional corridor (for example, Spencer and Welty, 1982). Locally, extensive iron-oxide and pyrite mineralization is related to both high-angle faults above the Raft River detachment and the Raft River detachment fault. About 1.6 miles (2.5 km) west of the quadrangle, in the Clear Creek mining district (principally section 12, T. 14 N., R. 13 W.), several adits and numerous surface pits indicate mining activity for copper, silver, and lead (Doelling, 1980).

Sand and Gravel

Deposits of well-sorted gravel and subordinate sand are found in lacustrine beach and barrier bar deposits along the eastern edge of the quadrangle. The principal accumulations of gravel are mapped as lacustrine gravel (Qlg), but many other small shoreline gravel deposits exist. Some gravel accumulations close to State Highway 42 were previously inventoried by the Utah State Department of Highways, including accumulations at locations SE $\frac{1}{4}$ SE $\frac{1}{4}$ section 1, T. 14 N., R. 12 W. (Qlg); SW $\frac{1}{4}$ NW $\frac{1}{4}$ section 6, T. 14 N., R. 11 W. (Qlg); and NE $\frac{1}{4}$ SE $\frac{1}{4}$ section 6 and NE $\frac{1}{4}$ SW $\frac{1}{4}$ section 5, T. 14 N., R. 11 W. (Qla) (Utah Department of Highways, 1965). Deposits of sand are also found along the eastern edge of the quadrangle. Lacustrine sand is present as sand sheets (Qls) and also beneath gravel barrier beaches, and fine sand and silt occurs in relatively thin eolian deposits (Qe).

Building Stone (Flagstone)

Ornamental flagstone is quarried at many localities within the Raft River, Grouse Creek, and Albion Mountains, and

represents an important and well-established industry. This flagstone industry has been studied and described by Tripp (1994). The quality of flagstone in the region is primarily a function of mica content in quartzite and magnitude of deformation related to Tertiary extensional shear zones. Principally, mylonitic quartzite is quarried; the mylonitic foliation, along which mica is commonly concentrated, acts as prominent folia along which the quartzite is split. The quartzite of Clarks Basin, quartzite of Yost, and Elba Quartzite are the principal rock units in the region that are currently quarried, and these units have the greatest potential for economic flagstone.

Within the Kelton Pass 7.5' quadrangle, the quartzite of Yost is not present, and the quartzite of Clarks Basin is not well-enough foliated and generally too jointed and fractured to be of economic interest for flagstone. The low quality of the quartzite of Clarks Basin as flagstone (in the quadrangle) is due in part to its position in the upper plate of the Raft River detachment fault and resultant brittle deformation (indicated by common closely spaced joints and fractures). Additionally, the quartzite of Clarks Basin in the quadrangle has not experienced Tertiary (foliation-producing) mylonitization, in contrast to quarried localities in the Grouse Creek and western Raft River Mountains described by Tripp (1994). There, the quartzite of Clarks Basin crops out within an Eocene-Oligocene top-to-the-west shear zone (Wells and others, 1997, 2000a). The Elba Quartzite has potential for flagstone, but its quality is not as high, due to jointing and fracturing, as in areas to the west along the south flank of the range that are currently quarried.

Broken or Crushed Stone

Highly fractured rocks of the Eureka Quartzite have been mined at the head of Emigrant Spring Canyon (NE $\frac{1}{4}$ NE $\frac{1}{4}$ section 23, T. 13 N., R. 12 W.) for fire insulation material or possibly for road or railroad gravel. No other localities with easy access to fractured quartzite are present.

Water Resources

The principal uses for groundwater in the quadrangle are for livestock and limited agricultural use. Given that the ranching industry in the area is relatively well established, and no commercial or residential development is currently taking place, no significantly large demands on groundwater are foreseeable in the near future. Published reports on the water resources of this region include Baker (1974) and Batty and others (1993).

Two distinct groundwater flow systems are present within the quadrangle. The first is within Cenozoic deposits in the Raft River Valley; the second lies in westernmost Curlew Valley and was referred to as the Kelton flow system by Baker (1974). The two flow systems are separated by a bedrock ridge of nearly continuous outcrops of Oquirrh Formation that connects the southern Black Pine Mountains to the northeastern Raft River Mountains.

The eastern boundary of the Kelton flow system, as indicated by gravity studies (Baker, 1974), is a ridge of locally exposed Oquirrh Formation and volcanic rocks associated with the Wildcat Hills (approximately 5 miles [8 km] east of

the quadrangle) that more typically is shallowly buried by Cenozoic deposits. This bedrock ridge probably marks the trace of a high-angle fault with east-side-up displacement. Water that enters the Curlew Valley from the eastern Raft River and southern Black Pine Mountains probably flows to the south, between the Raft River Mountains and the bedrock ridge to the east (Baker, 1974). The Cenozoic deposits in the Kelton Pass 7.5' quadrangle, as estimated from gravity studies, are as much as 2000 feet (600 m) thick in the southeastern part of the quadrangle, but are greater than 3000 feet (900 m) thick east of the quadrangle (Baker, 1974).

No test wells have been reported in the quadrangle, although two sites nearby do have groundwater monitoring wells (Baker, 1973; Batty and others, 1993). Monitoring of wells near Kelton (9 miles [14.4 km] south of the southeast corner of the quadrangle) shows a slow decline in water table depths between 1935 and 1982 (about 7 feet [2.1 m] of withdrawal), a rapid increase of about 4 feet (1.2 m) between 1982 and 1985, and a steady rapid decline of 6 to 7 feet (1.8-2.1 m) between 1985 and 1993. A well about 2 miles (3.2 km) southeast of the southeast corner of the quadrangle, for which data is limited, recorded up to 2 feet (0.6 m) of groundwater-depth increase from 1963 to 1993 (Batty and others, 1993).

GEOLOGIC HAZARDS

Earthquakes

Surficial geologic mapping shows no Quaternary fault scarps in the Kelton Pass 7.5' quadrangle. The only mapped Quaternary faults in northwesternmost Utah are: (1) a single 1-mile (1.6-km) long fault mapped by Compton (1975) about 3 miles (5 km) to the west of the northwest corner of the quadrangle, interpreted by Hecker (1993) as cutting middle to late Pleistocene deposits; and (2) a N-S trending belt of inferred faults along the eastern margin of the Grouse Creek Mountains, interpreted by Hecker (1993) to be of middle to late Pleistocene age. No range-bounding faults have been identified along the northern, southern, and eastern margins of the Raft River Mountains, and the range morphology probably results from doming rather than block-faulting typical of other ranges in the Basin and Range Province. However, this part of northwestern Utah lies near the Intermountain seismic belt, a north-south zone of historic earthquake activity that bisects Utah (Smith and Arabasz, 1991). Historic earthquakes such as that in Hansel Valley in 1934 show that a significant seismic potential exists in the region (Smith and Arabasz, 1991). Possible earthquake hazards include surface fault rupture, ground shaking (causing rockfalls and slope failures within steep-walled canyons), and liquefaction within the unconsolidated basinal sediments where shallow groundwater is present.

Flooding

Flooding is a potential hazard within the narrow canyons that cut into the Raft River Mountains, and flooding, debris flows, and seasonal high-energy deposition may occur on active alluvial fans near the flanks of the mountain range. These hazards are mostly restricted to areas underlain by map units Qal and Qaf₁.

Gullying

Gullying has occurred in many areas underlain by Tertiary tuffaceous deposits (part of Ts) and finer grained Quaternary lacustrine deposits. Gullying is especially pronounced within washes crossing the Cedar Creek Road.

Landsliding

Landsliding is a potential hazard along the canyons that dissect the Precambrian basement, and along the steeper dipslopes to the range-scale anticline defined by Precambrian lithologies. The canyons are typically steep-walled within Archean rocks due to the high resistance to erosion of the overlying Elba Quartzite. Landslides are mapped on plate 1 as Qms.

ACKNOWLEDGMENTS

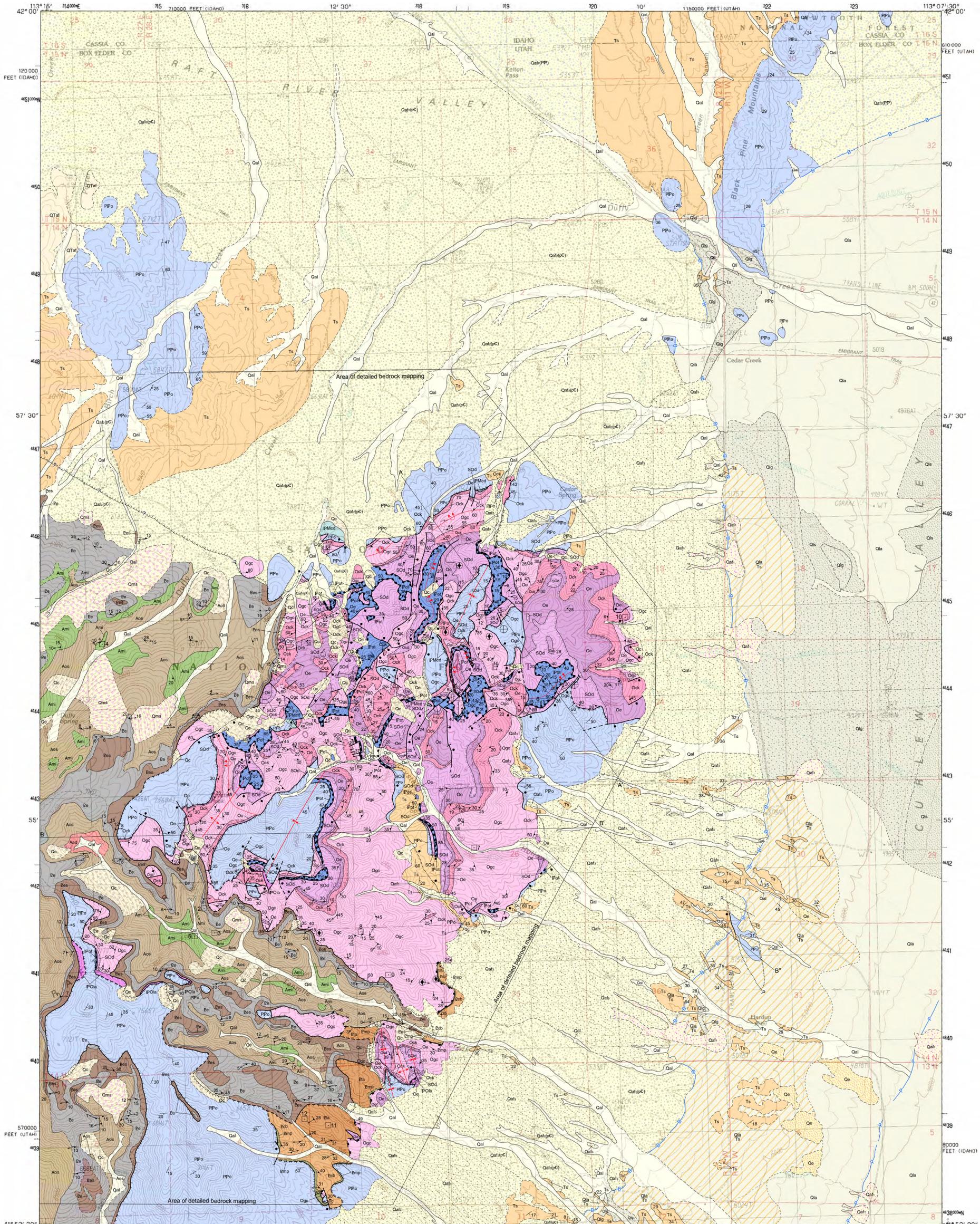
K. Tilman, K.M. Merchant, and T.T. Cladouhos provided invaluable field assistance. R.W. Allmendinger and D.M. Miller provided continuing interest and support throughout this project. This work was principally supported by National Science Foundation Grant EAR-8720952 to R.W. Allmendinger and M.L. Wells, and a National Research Council Postdoctoral Fellowship at the Branch of Western Regional Geology, U.S. Geological Survey (USGS). Additional support was provided by the Utah Geological Survey (UGS). Much of this map area is private land; I thank the local ranchers and landowners for granting access and for their hospitality, especially R. Bronson, J. Flinders, L. Kempton and family, R. Morris, D. Dorius, and Ten Mile ranch foreman W. Pugsley. J.E. Repetski (USGS) is gratefully acknowledged for conodont identification and color-alteration indexing. R.D. Dallmeyer (University of Georgia) provided the ⁴⁰Ar/³⁹Ar geochronological analyses from Ordovician rocks. L.W. Snee is thanked for access to the USGS ⁴⁰Ar/³⁹Ar facility in Denver, Colorado, and for interpretive assistance, and A.E. Blythe (University of Southern California) performed the fission-track analyses. Constructive reviews by D.M. Miller and R. Tosdal (USGS), and B. Black, R. Biek, J.K. King, D. Sprinkel, and G. Willis (UGS) greatly improved the geologic report.

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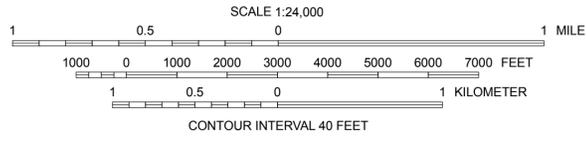
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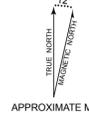
For use at 1:24,000 scale only. The Utah Geological Survey (UGS) does not guarantee accuracy or completeness of data.



Base from USGS Kelton Pass 7.5' Quadrangle (1990)
 Projection: UTM Zone 12
 Datum: NAD 1983
 Spheroid: Clarke 1886

Project Manager: Jon King
 GIS and Cartography: J. Buck Eher, Darryl Greer and Angela Wadman

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GEOLOGIC MAP OF THE KELTON PASS QUADRANGLE, BOX ELDER COUNTY, UTAH, AND CASSIA COUNTY, IDAHO

by
Michael L. Wells
 Department of Geoscience, University of Nevada, Las Vegas
 4505 S. Maryland Parkway, Las Vegas, NV 89154-4010

2009

1	2	3	1. Naf
4	5	6	2. Strevell
7	8	7	3. Black Pine Peak
		8	4. Roseview Point
			5. Curlew Junction
			6. Park Valley
			7. Black Butte
			8. Kelton Pass SE

ADJOINING 7.5' QUADRANGLE NAMES

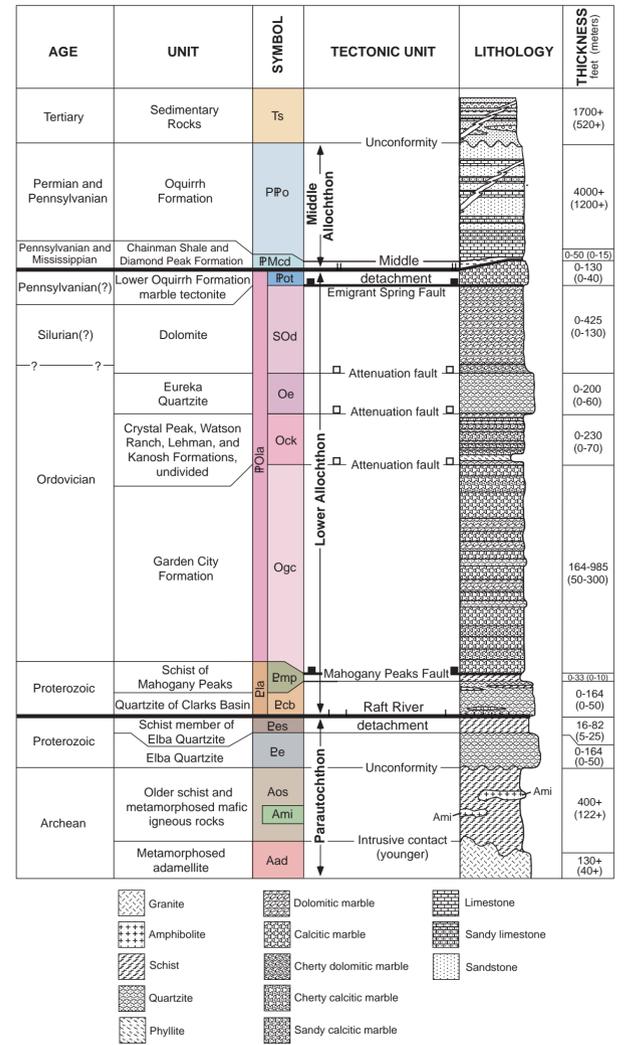
DESCRIPTION OF MAP UNITS

- Qe** **Eolian sand and silt** (Holocene) - Unconsolidated light-gray to light-brown sand and silt deposited as small dunes and sheets.
 - Qaf₁** **Younger alluvial-fan deposits** (Holocene) - Unconsolidated gravel, sand, and silt in small alluvial fans that breach Lake Bonneville shorelines and overlie Lake Bonneville deposits.
 - Qal** **Stream alluvium** (Holocene and latest Pleistocene) - Unconsolidated poorly sorted gravel, sand, silt, and clay deposited in active ephemeral stream beds and washes. Includes local colluvial deposits, particularly in mountain valleys.
 - Qms** **Mass-movement deposits** (Holocene and latest Pleistocene) - Landslide and slump deposits.
 - Qc** **Colluvium** (Holocene and latest Pleistocene) - Unconsolidated gravel and sand on steep slopes.
 - Qla** **Lacustrine and alluvial deposits, undivided** (Holocene and Pleistocene) - Unconsolidated intermingled deposits of lacustrine and alluvial origin. In most places, consists of thin sheets of fine-grained alluvium on erratically exposed lacustrine marl, silt, and fine sand.
 - Qla/Ts** **Lacustrine and alluvial deposits that overlie Tertiary rocks** - Undivided deposits of lacustrine and alluvial origin (Qla) that thinly mantle a pediment on Tertiary sedimentary rocks (Ts).
 - Qlg** **Lacustrine gravel** (latest Pleistocene) - Unconsolidated, well-sorted, moderately to well-sorted, cobble and pebble gravel and subordinate sand deposited in Lake Bonneville; forms prominent barrier beaches.
 - Qls** **Lacustrine sand** (latest Pleistocene) - Unconsolidated fine to coarse sand and minor gravel deposited in Lake Bonneville.
 - Qll** **Lacustrine lagoonal deposits** (latest Pleistocene) - Unconsolidated buff-white to tan, silty marl, and calcareous silt and fine sand deposited in Lake Bonneville.
 - Qaf₂(pC)** **Old alluvial-fan deposits** (Pleistocene) - Unconsolidated, poorly sorted boulders, gravel, sand, and silt forming broad fans along the north flank of the eastern Raft River Mountains and south end of the Black Pine Mountains; older than Lake Bonneville. Letters in () denote predominant clast lithology; pC = Precambrian quartzite, schist, and amphibolite; PP = Permian and Pennsylvanian Oquirrh Formation limestone and sandstone.
 - Qaf₃(PP)** **Older alluvial-fan deposits** (Pleistocene) - Unconsolidated, poorly sorted boulders, gravel, sand, and silt forming broad fans along the eastern flank of the Raft River Mountains; more dissected (older) than Qaf₂; predominant clast lithology is metamorphosed Paleozoic marble, quartzite, and phyllite.
 - QTaf** **Oldest alluvial-fan deposits** (Pleistocene and Pliocene) - Unconsolidated deposits of boulders, gravel, sand, and silt, forming hills in northwestern part of quadrangle; predominant clast lithology is Precambrian quartzite, schist, and amphibolite.
 - Ts** **Sedimentary rocks** (Miocene) - Moderately lithified, interbedded sandstone, siltstone, mudstone, conglomerate, and limestone; fine-grained detrital rocks are commonly tuffaceous, and typically white, yellow, and tan in color. Thickness poorly constrained; minimum 1700 feet (520 m).
- MIDDLE ALLOCHTHON**
- PPo** **Oquirrh Formation** (Permian and Pennsylvanian) - From top to base: light- to medium-gray weathering, tan to brown sandstone and calcareous sandstone, locally containing fusulinids, is most common exposed lithology; platy, tan-, maroon-, and gray-weathering, sandy to silty limestone and subordinate calcareous sandstone; dark-blue-gray fossiliferous limestone with sandy interbeds; thickness poorly constrained, estimate 4000 feet (1200 m).
 - PMcd** **Chainman Shale and Diamond Peak Formation, undivided** (Lower Pennsylvanian and Upper Mississippian) - Poorly exposed, black, quartz-rich slate and interbeds of black quartzite; thickness 0 to 50 feet (0-15 m).
- LOWER ALLOCHTHON**
- POla** **Paleozoic, undivided** (Pennsylvanian?, Silurian?, and Ordovician) - Undivided marble, quartzite, and phyllite from highly attenuated Paleozoic units listed below.
 - Pot** **Lower Oquirrh Formation marble tectonite** (Pennsylvanian?) - Banded, blue-gray and light-gray, crinoid-rich marble; highly deformed; typical thickness 65 to 130 feet (20-40 m).
 - SOd** **Dolomite** (Silurian?) and Ordovician) - Dark-gray to buff, fine-grained, finely laminated to massive, dolomitic marble; thickness 0 to 425 feet (0-130 m).
 - Oe** **Eureka Quartzite** (Ordovician) - Resistant, vitreous, white, well-sorted, medium-grained quartzite; thickness 0 to 200 feet (0-60 m).
 - Ock** **Crystal Peak, Watson Ranch, Lehman and Kanosh Formations, undivided** (Ordovician) - From top to base: dolomitic marble, interbedded quartzite and sandy calcitic marble of two middle units, and brownish quartzite and muscovite phyllite; thickness 0 to 230 feet (0-70 m).
 - Ogc** **Garden City Formation** (Ordovician) - Calcitic marble with subordinate dolomitic marble, sandy marble and quartzite; commonly chert-rich in upper beds; typical thickness 164 to 985 feet (50-300 m).
 - Ela** **Schist of Mahogany Peaks and quartzite of Clarks Basin, undivided** (Proterozoic) - Interlayered pelitic schist, quartzite, and lesser marble in lower allochthon.
 - Emp** **Schist of Mahogany Peaks** (Proterozoic) - Staurolite-garnet-biotite schist and biotite schist; thickness 0 to 33 feet (0-10 m).
 - Ecb** **Quartzite of Clarks Basin** (Proterozoic) - Flaggy, white, muscovite-bearing quartzite, lesser muscovite schist, and minor marble; 164 feet (50 m) maximum thickness.
- PARAUTOCHTHON**
- Bes** **Schist member of Elba Quartzite** (Proterozoic) - Dark-brown to dark-gray, quartz-mica-feldspar schist and foliated cataclastite; 16 to 82 feet (5-25 m) thick.
 - Be** **Elba Quartzite** (Proterozoic) - White, muscovite quartzite and muscovite schist, locally conglomeratic near base; 0 to 164 feet (0-50 m) thick.
- Green Creek Complex of Armstrong (1968)** (Archean) - Divided into units of Compton (1972):
- Aad** **Metamorphosed adamellite** (Archean) - Gneissic to massive, medium- to coarse-grained, granular to porphyritic, biotite-muscovite monzogranite; intrudes older schist (Aos); at least 130 feet (40 m) exposed.
 - Ami** **Metamorphosed mafic igneous rocks** (Archean) - Dark-green to dark-gray to black, medium-grained gneissic amphibolite, hornblende schist, and hornblende metagabbro; intrudes older schist (Aos).
 - Aos** **Older schist** (Archean) - Fine-grained, mica-feldspar-quartz schist and schistose phyllite; 400 feet (122 m) minimum thickness.

MAP AND CROSS-SECTION SYMBOLS

- Contact - Dashed where located approximately, dotted where covered, short dashed where gradational, teeth where scratch
- Bedding form line on cross sections
- High-angle fault - Dashed where located approximately, dotted where covered; bar and ball on downthrown side; arrow and number shows dip on fault; on cross sections arrows show offset and queried where uncertain existence
- Middle detachment fault - Dashed where located approximately, dotted where covered; double hachures on hanging wall
- Emigrant Spring and Mahogany Peaks low-angle faults - Dashed where located approximately, dotted where covered; where space available, solid boxes on hanging wall
- Attenuation (low-angle) faults - Dashed where located approximately, dotted where covered; where space available, open boxes on hanging wall
- Raft River detachment fault - Dashed where located approximately, dotted where covered; hachures on hanging wall; queried where location uncertain
- Fault of uncertain geometry - Dashed where located approximately, dotted where covered
- Boxes and hachures only shown on faults where space permits
- Fold axial trace
- D₂ Anticline, located approximately
- D₂ Syncline, located approximately
- D₂ Overturned anticline, located approximately
- D₂ Overturned syncline, located approximately
- D₂ Recumbent fold (on cross sections)
- Bedding attitudes
- 43° inclined
- ⊕ horizontal
- ⊖ vertical
- Foliation attitudes
- 30° inclined
- ⊕ horizontal
- ⊖ vertical
- 80° overturned
- Mineralogic lineations
- 20° inclined
- ↔ horizontal
- Geochronology sampling site - see table 2
- Trace of lake shoreline
- B Bonneville shoreline
- P Provo shoreline
- A—A' Line of cross section

LITHOLOGIC COLUMN



CORRELATION OF MAP UNITS

