GEOLOGIC MAP OF THE WILLOW SPRINGS QUADRANGLE, SEVIER AND EMERY COUNTIES, UTAH

BY HELLMUT H. DOELLING , PAUL A. KUEHNE, AND JAMES I. KIRKLAND

Map 237
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2009

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GEOLOGIC MAP OF THE WILLOW SPRINGS QUADRANGLE, SEVIER AND EMERY COUNTIES, UTAH

By Hellmut H. Doelling, Paul A. Kuehne, and James I. Kirkland

ABSTRACT

The Willow Springs quadrangle lies along the west edge of the Colorado Plateau physiographic province and the east edge of the High Plateaus, a transition zone between the Colorado Plateau to the east and the Basin and Range Province to the west, and is in the Colorado River drainage basin.

Exposed bedrock ranges from Middle Jurassic to Late Cretaceous in age and includes (in ascending order) the Entrada Sandstone, Curtis Formation, Summerville Formation, Morrison Formation, Cedar Mountain Formation, Dakota Formation, and Mancos Shale, and is more than 3800 feet (1160 m) thick. The rocks of the quadrangle dip gently northwestward from the large San Rafael Swell anticline into the Fish Lake Plateau syncline. This pattern is interrupted by two folds that are parallel and plunge northwestward—the Salvation Creek syncline and the Last Chance anticline. The strata dip northeastward and northward on the shared limb of these two folds in the southern third of the quadrangle, mostly from 10 to 20 degrees. A Pliocene tephrite dike cuts Jurassic strata in the southwest part of the quadrangle.

Quaternary surficial deposits of Holocene to Pleistocene age include varieties of alluvium, mass-movement deposits, mixed pediment-mantle and colluvial deposits, and mixed eolian and alluvial deposits. These deposits cover extensive areas in the northwest quadrant, Blue Flats, and Last Chance Desert parts of the quadrangle. Some of these deposits are associated with landslide and debris-flow hazards.

The Dakota Formation and Ferron Sandstone Member of the Mancos Shale contain coal deposits, and bentonite mud is mined in the quadrangle from the Brushy Basin Member of the Morrison Formation. Morrison Formation outcrops are generally littered with chert (agate and jasper). The Cedar Mountain Formation has yielded important vertebrate fauna including dinosaurs, the earliest North American snakes, frogs, early mammals, and the earliest North American marsupial. Even though exploration wells drilled into the Last Chance anticline were dry, oil and gas possibilities in the quadrangle are classified as favorable.

INTRODUCTION

The Willow Springs quadrangle is located along the north-south boundary of Sevier and Emery Counties in central Utah. The north boundary of the quadrangle is 0.5 to 4 miles (0.8-6.4 km) south of Interstate Highway 70 (I-70), and 11 miles (18 km) south of the town of Emery. The quadrangle is named after Willow Springs, which flows into Willow Springs Wash in the northern third of the quadrangle. The map area is along the west edge of the Colorado Plateau physiographic province; the High Plateaus, a transition zone between the Colorado Plateau and Basin and Range Province to the west, is present in the Johns Peak quadrangle to the west.

Elevations rise along flats, slopes, and cliffs from less than 5800 feet (1770 m) in the east part to more than 8200 feet (2500 m) along the west edge of the quadrangle, where the rocks dip very gradually west and northwestward. In the southern third of the quadrangle, the rock formations form a steep shared limb (monocline) of two folds that trend about N. 50°W. (northeast flank of Last Chance anticline). The limb is expressed as a series of hogbacks.

The principal access is a well-maintained dirt road that extends south from Exit 89 on I-70 (about 35 miles [56 km] east of Salina, Utah) that passes generally down the middle of the quadrangle; only a few roads extend east and west from this principal roadway.

Previous mapping of the quadrangle is limited. It was first mapped geologically by Lupton (1916) at a scale of 1:62,500 as part of the U.S. Geological Survey coal-mapping program. With some modification, this map was used in the first geologic map of Utah at a scale of 1:250,000 (Hintze and Stokes, 1963). Doelling (1972) mapped part of the quadrangle at 1:33,500 scale as part of a study of the Emery coal field, and Doelling (2004) remapped the quadrangle as part of a 1:100,000-scale mapping project. The present project expands upon the 1:100,000-scale mapping.

STRATIGRAPHY

Sedimentary strata exposed in the Willow Springs quadrangle range in age from Middle Jurassic to Late Cretaceous, and have a total thickness of about 3800 feet (1160 m). Additionally, a Tertiary igneous dike cuts across the southwest part of the quadrangle. Several Quaternary units have been differentiated, including alluvial, mixed alluvial and eolian, and mass-movement deposits.

Subsurface Rock Units

Nearby drill holes have penetrated a normal stratigraphic sequence of formations below the oldest exposed units of the quadrangle. The Mountain Fuel Supply Desert Wash 1A well, NW¼SE¼ section 14, T. 25 S., R. 5 E. (Sevier County), was drilled in 1966 to a total depth of 4590 feet (1400 m) in the Cedar Mesa Sandstone under the Last Chance Desert. Reported thicknesses are: Carmel Formation, 1034 ft (315 m); Glen Canyon Group, 1486 ft (452 m); Chinle Formation, 235 ft (72 m); Moenkopi Formation, 1220 ft (372 m); Kaibab Formation, 162 ft (49 m) (Utah Division of Oil, Gas and Mining, 2008).

The American Liberty Oil Co. #1 well, SW¼SW¼ section 13, T. 25 S., R. 5 E. (Sevier County), was drilled in 1948 to a total depth of 4493 feet (1369 m) in the Cedar Mesa Sandstone under the Last Chance Desert. Reported thicknesses are: Carmel Formation, 284 feet (87 m); Glen Canyon Group, 2113 feet (644 m); Chinle Formation, 227 feet (69 m); Moenkopi Formation, 1245 feet (379 m); Kaibab Limestone, 130 feet (40 m); and from the picked top of the Cedar Mesa Sandstone to total depth, 2379 feet (725 m) (Utah Division of Oil, Gas and Mining, 2008). The reported thickness of the Cedar Mesa Sandstone must include underlying strata. The reported thickness of the Carmel Formation in the hole is suspect; from a section measured by the senior author at East Cedar Mountain, SE¼ section 24, T. 25 S., R. 7 E., 9 miles (15 km) directly east of the southeast corner of the quadrangle, the Carmel Formation is 607 feet (185 m) thick and thickens westward. Therefore, since the well spudded near the top of the Carmel, the reported 284-foot (87-m) section in the drill hole is either in error, or is in fact the thickness from the Carmel top down to the top of the thick gypsum unit in the Winsor Member of the Carmel Formation.

About 6 miles (9.5 km) southeast of the southeast corner of the quadrangle, in the NW¼NW¼ section 19, T. 26 S., R. 7 E., the Shell #1 well spudded in the Carmel Formation and was drilled to a total depth of 6704 feet (2043 m), penetrating Cambrian rocks at the bottom of the hole. Deduced thicknesses as calculated from reported formational tops are as follows (names given by drillers, local formation names in parentheses): Glen Canyon Group, 1519 feet (463 m); Chinle Formation, 383 feet (117 m); Moenkopi Formation, 930 feet (283 m); Kaibab Limestone, 120 feet (36 m); Toroweap Formation, 222 feet (68 m); Cedar Mesa Sandstone, 160 feet (49 m); other Wolfcampian-age rocks (Elephant Canyon Formation and/or lower Cutler Group), 698 feet (213 m); Supai Formation, 580 feet (177 m); Redwall Limestone, 904 feet (276 m); Ouray Limestone, 314 feet (96 m); Elbert Sandstone, 452 feet (138 m); and Cambrian rocks (partial section of Lynch Dolomite? or Maxfield Limestone), 32 feet (10 m).

Jurassic Rocks

Entrada Sandstone (Je, Jem)

The Entrada Sandstone is the oldest formation exposed in the Willow Springs quadrangle. The upper part of the formation is exposed in an arcuate outcrop along the base of the escarpment that makes up the north flank of the Last Chance anticline. We measured a partial section of 530 feet (160 m) in section 14, T. 25 S., R. 5 E. The nearby American Liberty Oil Co. #1 well reached the underlying Carmel Formation at a depth of 326 feet (99 m), showing the Entrada is about 850 feet (260 m) thick. Craig and Dickey (1956) indicated the Entrada is at least 850 feet (260 m) thick on the west flank of the San Rafael Swell in the Willow Springs quadrangle. Others (Hintze, 1988; Morris and others, 2000) showed the Entrada is 400 to 900 feet (120–270 m) thick between Price and Cathedral Valley. Witkind (1988) stated that the Entrada is only 200 to 300 feet (60–90 m) thick in the Huntington 30' x 60' quadrangle, only 18 miles (29 km) north of the Willow Springs quadrangle, and indicated that the unit thins northward. Some of the differences in thickness may be explained by the presence of the J-3 unconformity at the top and the amount of erosion that took place prior to deposition of the overlying Curtis Formation.

The Entrada Sandstone is mostly fine-grained sandstone with a few medium-grained lenses and siltstone partings. Scattered throughout the fine-grained rock are medium and coarse grains. It is mainly light brown or orange brown. Siltstone partings are generally darker brown. At irregular intervals, light-gray sandstone ledges divide units in the Entrada. The sand is cemented with calcium carbonate; toward the base of the exposed section secondary gypsum veinlets are locally present.

The Entrada in the San Rafael Swell area can be divided into three informal members (not mapped separately in the Willow Springs quadrangle). The middle and upper members are exposed in the Willow Springs quadrangle and are separated by a distinctive marker bed (Jem). The lower 300 feet (90 m) of the exposed Entrada (middle member) forms slight ledges with a platy weathering habit in steep slopes. The sandstone beds locally exhibit low-angle cross-stratification. The upper 65 to 70 feet (20–21 m) of the middle member forms a vertical cliff of thin to thick beds. These upper light-gray and light-brown alternating sandstone beds are commonly lumpy and are divided by partings of dark-brown siltstone. Some of the light-gray beds exhibit wavy cross-stratification.

Above the middle member is a local marker bed (Jem) that is as much as 5 feet (1.5 m) thick. It is a light-green-gray, thin to medium irregularly bedded, hard, calcareous sandstone ledge that interrupts the normal light-brown or orange-brown sequence. Above the marker bed is a 160- to 165-foot (50 m) cliff (upper member) of mostly light-brown sandstone. It consists of two parts separated by a purple siltstone parting. The lower 85 feet (26 m) forms a smooth vertical cliff that is structureless; the upper 75 feet (23 m) also forms a vertical cliff, but is thin to massively bedded. The beds are generally separated by thin, dark-brown siltstone partings. These partings, along with a few light-gray beds, increase in number toward the top.

The Entrada Sandstone is considered Middle Jurassic (Callovian) in age (Anderson and Lucas, 1994). No fossils or other age indicators were found in the Entrada in the Willow Springs quadrangle, but it is between the underlying Carmel Formation that contains palynomorphs of Callovian age near the top, and the overlying Curtis Formation, which has yielded a few marine late Middle Jurassic invertebrate fossils in the San Rafael Swell (Anderson and Lucas, 1994). A regional unconformity (J-3 unconformity) separates the Entrada from the overlying Curtis Formation; Pipiringos and O'Sullivan (1978) estimated the elapsed time between uplift and erosion of the Entrada and the onset of burial beneath the Curtis sediments to be less than 1 million years. The Entrada Sandstone correlates with the Preuss Sandstone in the central Wasatch Range and part of the Twist Gulch Formation in central Utah (Sprinkel, 1994).

Although the Entrada Sandstone clearly contains eolian-deposited sandstone in eastern and parts of southern Utah, the formation on the west flank of the San Rafael Swell (including the Willow Springs quadrangle) is different and undoubtedly water-lain. Morris and others (2000) indicated the unit is the product of tidal-flat deposition. Discussing its deposition in the area of Capitol Reef National Park (outcrops are similar to the Willow Springs quadrangle), Smith and others (1963) judged that the Entrada Sandstone was deposited in quiet water, and cited Baker and others (1936) and Craig and others (1955), who considered the deposition to have been largely subaqueous.

Curtis Formation (Jct)

The Curtis Formation overlies the Entrada Sandstone and is exposed in the arcuate northeast- to west-dipping outcrops along the escarpment of the north flank of the Last Chance anticline in the southern part of the quadrangle. We measured the Curtis in section 1, T. 25 S., R. 5 E., where the formation is about 205 feet (62 m) thick. Craig and Dickey (1956) reported that the Curtis is 250 feet (76 m) thick in the northern part of the San Rafael Swell, but that it thins to the south and east. To the south, in the Capitol Reef area, it pinches out a few miles south of the Wayne-Garfield County line.

In the Willow Springs quadrangle, the Curtis is mostly silty sandstone with lesser amounts of siltstone. At the base, it has a poorly sorted pebble conglomerate as much as 0.5 feet (0.2 m) thick, with gray pebbles ranging from coarse grit to 4 inches (10 cm) across, that are contained in a matrix of fine- to coarse-grained sandstone. The sandstone above is light gray, light greenish gray, or light tan gray, moderately to poorly sorted and muddy, and mostly calcareous. Most units are planar bedded; a few exhibit faint cross-stratification. A few units, especially near the bottom, contain scattered pebbles. Siltstone is medium gray wherever present.

The Curtis Formation consists of two unmapped parts: a lower cliffy unit about 130 feet (40 m) thick, and an upper slope former about 70 feet (21 m) thick. In the lower cliffy unit, the Curtis becomes more ledgy toward the top. Overall, it is less cliffy upward, and the upper slope former becomes gentler upward. The Curtis is one of the easiest formations to identify in the quadrangle, as it forms a distinctive light-colored interval between the brown Entrada below and Summerville above.

The age of the Curtis Formation is early Late Jurassic. The Curtis has been considered to be Callovian in age (see Hintze, 1988, p. 47), but recent palynological work by Wilcox and Currie (2006) showed that it is early Oxfordian (earliest Late Jurassic; ~166 to 155 Ma). The Curtis Formation and its correlatives were probably deposited in a single transgressive-regressive sequence recording the final pulse of the Jurassic interior seaway. The Curtis Formation correlates with the Stump Sandstone of northern Utah. The Curtis in the Willow Springs quadrangle is conformably overlain by the Summerville Formation.

The Curtis sediments were deposited in a shallow-water marine environment (Craig and Dickey, 1956), and some of the sandstone is glauconitic. Glauconite is a cementing mineral that forms only in marine environments where sedimentation rates are relatively low. However, the moderate to poor sorting in the lower part of the Curtis Formation of the Willow Springs quadrangle might indicate some wave action.

Summerville Formation (Js)

The Summerville Formation overlies the Curtis Formation with a conformable, gradational contact in the Willow Springs quadrangle. Along with the Curtis and Entrada, it is exposed in the arcuate northeast- to west-dipping outcrop along the escarpment of the north flank of the Last Chance anticline in the southern third of the quadrangle. We measured it in section 1, T. 25 S., R. 5 E., just north of the main roadway to Cathedral Valley, where it is about 215 to 220 feet (66–67 m) thick. We also measured it in Last Chance Canyon where it is 260 feet (80 m) thick. The Summerville Formation was defined by Gilluly and Reeside (1928) at Summerville Point in the northern San Rafael Swell where it has a thickness of about 165 feet (50 m). In the San Rafael Swell, the upper boundary with the Morrison Formation is the J-5 unconformity, and the Summerville Formation varies considerably in thickness due to gentle folding and erosion prior to deposition of the Morrison. Although such synclines and anticlines are not persistent throughout the San Rafael Swell area, beveling of the formation beneath the unconformity probably accounts for differences in thickness of the Summerville. Trimble and Doelling (1978) reported that the

Summerville thickness in the San Rafael River mining area, on the east side of the San Rafael Swell, varies from 105 to 400 feet (32–122 m) because of small-amplitude folds in the unit.

The Summerville Formation ordinarily forms a steep, convex slope punctuated by a few ledges. In the Willow Springs quadrangle, it consists of very fine grained silty sandstone interbedded with siltstone in thin beds. It is generally evenly bedded, but not as evenly bedded as in the eastern part of the San Rafael Swell (Doelling, 2004). The bedding ranges from laminar (a few millimeters) to medium (as much as 2 feet [0.6 m]). The thickest beds generally form ledges. Light- to medium-brown beds dominate (80%), although the thinnest and thickest beds are very light gray (20%). A few thin beds of gray limestone are also present, and the Summerville is generally calcareous.

The age of the Summerville Formation, like the Curtis Formation, is either late Middle Jurassic or early Late Jurassic. The Summerville Formation has been considered to be Callovian (see Hintze, 1988, p. 47), but recent palynological work by Wilcox and Currie (2006) showed that the unit is early Oxfordian (earliest Late Jurassic; ~166 to 155 Ma). The Summerville was probably deposited in shallow quiet waters as might occur under tidal-flat conditions (Craig and Dickey, 1956). Common features associated with the Summerville beds are mud cracks and ripple marks.

The Summerville Formation in the Willow Springs quadrangle is overlain by the Tidwell Member of the Morrison Formation, and the contact appears gradational. The contact is where the light- to medium-brown overall color of the Summerville changes to the conspicuously red-brown coloration of the Tidwell Member. Pipiringos and O'Sullivan (1978) indicated that the contact is a regional unconformity (J-5 unconformity), with a hiatus of about 2 million years; however, in the area between Cathedral Valley and the Moore Road that crosses the west flank of the San Rafael Swell, this unconformity is not obviously displayed.

Morrison Formation (Jm)

The Morrison Formation is generally divisible into three members in the San Rafael Swell and Castle Valley areas: in ascending order, the Tidwell, Salt Wash, and Brushy Basin Members. The Morrison is about 290 to 360 feet (88–110 m) thick in the Willow Springs quadrangle, and is the uppermost Jurassic unit.

Salt Wash and Tidwell Members (Jmst): We mapped the Salt Wash and Tidwell Members of the Morrison Formation as one unit because they are difficult to separate in the quadrangle. The combined unit crops out along the north flank of the Last Chance anticline where it is 175 to 200 feet (50–60 m) thick. It consists of ledges and slopes, as does the underlying Summerville Formation, but the ledges are commonly thicker and more lenticular and the overall color is reddish brown rather than light brown. These strata are more resistant than those of the underlying Summerville Formation. The lower part (Tidwell) consists mostly of siltstone and very fine grained sandstone in thin, even beds. Upward, the sandstone ledges coarsen, thicken, and are commonly ripple marked, contorted, and cross-bedded (Tidwell–Salt Wash transition). In the uppermost part, conglomeratic sandstone and conglomerate are present (Salt Wash). These upper beds are channeled into those below and locally display trough cross-stratification. Gradually, the sorting deteriorates upward, but this pattern is not everywhere evident. Conglomerate is locally absent in the upper part of the section. For example, in section 1, T. 25 S., R. 5 E., the unit contains conglomeratic sandstone as low as 90 feet (27 m) below the contact with the overlying Brushy Basin Member, whereas in Last Chance Canyon only the uppermost 7 feet (2 m) is pebbly.

Tidwell and Salt Wash Members are fluvial and lacustrine and are normally assigned to the Late Jurassic (Kimmeridgian) (Hintze, 1988; Demko and others, 2004). The upper conformable contact is placed where the ledgy Jmst unit is replaced by smooth, slope-forming bentonitic mudstone or shale of the Brushy Basin Member. Commonly, gray, yellow, brown, and red cherty beds are present in the Brushy Basin Member just above the contact. In a differing opinion, Demko and others (2004) indicated that the Tidwell–Salt Wash unit in Last Chance Canyon is the upper member of the Summerville Formation. However, fluvial channel deposits and crinkly bedding typical of the Tidwell and Salt Wash Members are present in the quadrangle, and we mapped this interval as such.

Brushy Basin Member (Jmb): The Brushy Basin Member is a smooth, rounded, slope-forming unit above the Salt Wash Member along the arcuate outcrop belt on the north flank of the Last Chance anticline. Also, near the east edge of the map, exposures extend northward from the southeast corner of the map to Mussentuchit Wash. The Brushy Basin ranges from 90 to 180 feet (27–55 m) thick; variations in thickness are due to channeling of the overlying Cedar Mountain Formation.

The Brushy Basin Member forms a steep, smooth, rounded slope that is normally very light gray, light pink gray, or light purple. It is mostly bentonitic mudstone made up of clay, silt, and fine-grained sandstone. The unit contains scattered horizons of brown limestone nodules and thin, white sandstone and conglomeratic beds. Where the Buckhorn Conglomerate Member of the Cedar Mountain Formation has channeled into the Brushy Basin Member, the upper contact is easily discernible; however, where mudstone of the Cedar Mountain Formation overlies the Brushy Basin, the contact is difficult to map. Large quantities of chalcedonic chert (jasper-agate) are common near the base of the Cedar Mountain Formation.

The Brushy Basin Member was deposited in a fluvial and flood-plain environment with smaller and fewer channel deposits than the Salt Wash Member and is Late Jurassic (Kimmeridgian-Tithonian) in age (Hintze, 1988; Demko and others, 2004; Greenhalgh and Britt, 2007; Kowallis and others, 2007).

Cretaceous Rocks

Cedar Mountain Formation

The Cedar Mountain Formation forms mostly light-gray or light-greenish-gray, smooth, rounded slopes above the Brushy Basin Member of the Morrison Formation and beneath the yellowish-gray sandstone of the Dakota Formation. We recognize three members in the Willow Springs quadrangle (in ascending order): the Buckhorn Conglomerate, Ruby Ranch Member, and Mussentuchit Member.

Buckhorn Conglomerate Member (Kcb): The Buckhorn Conglomerate Member is locally present at the base of the Cedar Mountain Formation. This lower member is lenticular in the Willow Springs quadrangle, and is not differentiated from the Ruby Ranch Member where it is thin and discontinuous. The Buckhorn crops out along the north flank of the Last Chance anticline in the southern third of the quadrangle, and along the east edge of the map as far north as the Mussentuchit Wash area. The Buckhorn is channeled into the Brushy Basin Member of the Morrison Formation, reducing the underlying strata thickness. The Buckhorn is generally 35 feet (11 m) thick or less, and it is not present in some places.

The Buckhorn Conglomerate Member is composed of sandstone, conglomeratic sandstone, conglomerate, and mudstone with an overall gray-brown color, and generally forms rubbly, cliffy ledges and benches. These beds are lenticular, poorly to moderately sorted, and have trough cross-stratification. Generally, the pebble and cobble clasts are subangular to subrounded chert. Some beds are clast supported while others are matrix supported. The matrix is mostly medium to coarse-grained sandstone. The subordinate mudstone units are present as partings and beds between the coarser-grained units. The mudstone is light- to dark-gray, argillaceous, locally carbonaceous and sandy, and indistinctly bedded, and forms recesses and slopes between ledges. The Buckhorn Conglomerate Member appears conformable with the overlying Ruby Ranch Member. Lenticular sandstone beds are generally present in the Ruby Ranch Member directly above the Buckhorn channels.

The Buckhorn Conglomerate Member is Early Cretaceous in age. Greenhalgh and Britt (2007) considered the Buckhorn to be Barremian-Aptian (late Early Cretaceous) in age, but noted that no diagnostic fossils have been found within it. Some workers used a regional calcrete bed that is near the base of the Cretaceous, but locally above the Buckhorn, to place the Buckhorn in the Jurassic (Aubrey 1996, 1998; Currie, 1997). However, Kirkland and Madsen (2007) showed that there are several unrelated calcrete beds and that they are post-depositional and cut across bedding. We follow Greenhalgh and Britt (2007) and Kirkland and Madsen (2007) and place the Buckhorn in the late Early Cretaceous as the basal unit of the Cedar Mountain Formation. In this quadrangle the upper Buckhorn Conglomerate interfingers with the basal Ruby Ranch. The Buckhorn is discontinuous throughout the Colorado Plateau region beneath the other members of the Cedar Mountain Formation. It may interfinger with the Yellowcat (Greenhalgh and Britt, 2007), and is overlain by the Poison Strip, Ruby Ranch, and Mussentuchit Members (Kirkland and others, 1997).

Ruby Ranch Member (Kcr): The Ruby Ranch Member, which forms a continuous outcrop belt in the quadrangle, varies from 60 to 100 feet (18–30 m) thick. Kirkland and others (1999) indicated that it is separated from the overlying Mussentuchit Member by an unconformity, which may explain the variation in thickness.

The Ruby Ranch Member is mainly clayey and silty mudstone, but locally has accumulations of lenticular sandy mudstone and ledgy sandstone that are more common above the Buckhorn Conglomerate channels. The fresh unweathered mudstone is generally dark gray to dark purplish gray and is darker in color than on the weathered slopes. Commonly, the mudstone contains layers of medium-brown or medium-brown-gray limestone nodules. These nodular layers break up on weathering, and where abundant, nodules cover much of the slope surface. The sandstone, where present, is mostly poorly sorted and ranges from fine grained to pebbly. Where fresh, the mudstone breaks conchoidally into small to large, angular, equidimensional fragments.

The Ruby Ranch Member generally forms smooth-weathering, light-gray to light-greenish-gray slopes with abundant carbonate nodules littering the slopes. Where the Buckhorn Conglomerate Member is not present, light-hued, medium to thick mudstone beds that vary in resistance and steepness form a continuous slope from the top of the combined Tidwell-Salt Wash unit to the base of the Mussentuchit Member. The Ruby Ranch Member is recognized by "bumpy" rounded slopes with abundant brownish limestone nodules that in some areas nearly cover the slope, and a slightly less variegated and duller overall color. The Brushy Basin Member slopes are generally smoother than the Ruby Ranch Member mudstones. Subtle color banding indicative of variations in the mudstone bedding is more common in the Ruby Ranch Member.

The age of the Ruby Ranch Member is Early Cretaceous (Aptian-Albian) according to fossil evidence and radiometric and stratigraphic relations (Kirkland and others, 1999; Kirkland and Madsen, 2007). The Ruby Ranch Member is generally present everywhere the Cedar Mountain Formation is exposed throughout the Colorado Plateau region, but is missing in southwestern Utah (Kirkland and others, 1999; Jim Kirkland, Utah Geological Survey, verbal communication, 2008).

Mussentuchit Member (Kcm): The Mussentuchit Member unconformably overlies the Ruby Ranch Member and is continuous across the quadrangle, ranging from 60 to 80 feet (18–24 m) thick. The basal contact is marked by minor relief of about 2 feet (0.6 m), the basal beds contain chert and quartzite pebbles, and lignite (not coal) is present just above the basal beds in some areas. Outside this quadrangle, the basal part is locally marked by thick conglomerate units such as the conglomerate of Short Canyon (Doelling and Kuehne, in preparation; Gary Hunt, Utah Geological Survey, verbal communication, 2008). The Mussentuchit differs from the Ruby Ranch by the lack of the nodular limestone layers, and by a marked increased in volcanic ash in the mudstone. The type section of this member was designated by Kirkland and others (1997) at a location on the south side of Mussentuchit Wash in the Willow Springs quadrangle. The upper contact with the Dakota Formation is an unconformity with about 2 feet (0.6 m) of relief. The basal Dakota beds are marked by chert and quartzite pebbles, local conglomerate, and increases in carbonaceous material, and they include coal.

The mudstone of the Mussentuchit Member generally weathers into light-gray, white, and light-green-gray colors. The mudstone is smectitic, sandy, and/or silty. Locally, the member has a few ledges of medium-green-gray, fine- to medium-grained sandstone. Like the Ruby Ranch, differences in resistance to weathering and erosion create "bumpy" slopes with changes in slope angle. Locally, some dark lignitic horizons are present, especially near the base and top of the unit.

The Mussentuchit Member has yielded a rich vertebrate fauna (Kirkland, 1997; Cifelli and others, 1997). It is above the Albian-Cenomanian boundary, as confirmed by a radiometric age of 98.39 ± 0.07 Ma (Cifelli and others, 1997). Thus, this member is early Late Cretaceous (early Cenomanian) in age based on the international geologic time scale (Gradstein and others, 2004). The member crops out mostly along the west flank of the San Rafael Swell and extends into southwest Utah (Biek and others, 2003; Biek and others, 2007), but is not present in many parts of the Colorado Plateau region.

Dakota Formation (Kd)

The Dakota Formation is also locally known as the Dakota Sandstone. Inasmuch as the Dakota is mostly shale in the Willow Springs quadrangle, we use "formation." In its full development in the quadrangle, the Dakota consists of a lower slope, a lower sandstone ledge or cliff, a middle slope, an upper sandstone ledge or cliff, and a thin pebbly upper slope containing *Pycnodonte newberryi* (oyster shell fossils). The five divisions are not developed everywhere in the quadrangle—in many areas the upper sandstone ledge is thin or missing, and in other areas the lower sandstone ledge is thin or missing. The lower boundary is an unconformity. The upper boundary is mapped where overlying deeper marine (shale) deposits first occur. In some areas of the San Rafael Swell, a local unconformity has been identified near the base of the upper slope that contains pebbles and *Pycnodonte newberryi* fossils (Eaton and others, 1990; Jim Kirkland, Utah Geological Survey, verbal communication, 2008). However, for mapping purposes we have included the thin slope in the Dakota Formation following Lawyer (1972) and Peterson and others (1980). The Dakota is 50 to 120 feet (15–37 m) thick in the quadrangle.

The Dakota Formation generally forms a ridge and slope at the top of the arcuate stack of strata along the north flank of the Last Chance anticline in the southern third of the quadrangle. Along the east margin of the south half of the quadrangle the strata flatten out and the Dakota forms a ledge and slope.

The Dakota Formation consists of interbedded sandstone, shale, carbonaceous shale, coal, conglomeratic sandstone, and conglomerate. The sandstone ledges or cliffs consist of thin to thick lenticular beds of sandstone and conglomerate. The sandstone beds are generally light-hued, including yellow, orange gray, light tan gray, and very light brown. They are commonly fine to medium grained, but locally contain pebbles and cobbles that grade into gray conglomerate; most are well to moderately sorted. Partings in the ledges and cliffs consist of carbonaceous shale or gray shale. The conglomerate and sandstone commonly exhibit trough cross-beds. Bioturbation is common, and burrows and plant imprints are locally common. The carbonaceous shale partings commonly contain plant debris. The rock is moderately cemented with calcite. Locally, the sandstone contains pyrite nodules, but most of the pyrite has altered to brown limonite.

The slopes contain irregularly bedded mudstone, siltstone, sandy shale, gray shale, carbonaceous shale, coal, muddy sandstone, and brown sandstone. Except for the brown sandstone, the strata weather into slopes and recesses. The most common colors are shades of gray or gray brown. Thin, discontinuous coal beds are present, especially in outcrops in the southeastern quarter of the quadrangle. The thickest bed encountered is 4 feet (1.2 m) thick. Coal is generally accompanied by dull black boney coal and carbonaceous shale. The carbonaceous shale beds generally contain carbonized twigs and other macerated plant debris. Except for the brown variety, most sandstone beds are friable and fine grained. The brown variety of sandstone is typically thin bedded and cemented with calcite. The Dakota Formation is Late Cretaceous (Cenomanian) in the Willow Springs quadrangle (Eaton and others, 1990; Molenaar and Cobban, 1991).

Mancos Shale

The Mancos Shale is divided into five parts in the vicinity of the Willow Springs quadrangle. These include (ascending order) the Tununk Member, Ferron Sandstone Member, lower Blue Gate Member, Emery Sandstone Member, and upper Blue Gate Member. The lower three parts have been identified in the quadrangle, but because the upper part of the Mancos Shale has experienced much landsliding, the contacts of the upper two parts cannot be mapped. Parts of the Emery Sandstone Member, and possibly the upper Blue Gate, are probably incorporated in many of the slumps and landslides in the quadrangle. The Mancos Shale was deposited during the Late Cretaceous in the Western Interior Seaway.

Tununk Member (Kmt): The Tununk is the oldest of the Mancos Shale members and represents the westernmost incursion of the Western Interior Seaway. In the quadrangle, it is present beneath the Limestone Cliffs (not actually limestone) in a southwest-to-northeast band as a steep concave slope, and locally as a vertical cliff. We measured the Tununk Member in the NE¼ section 3, T. 25 S., R. 5 E., where it is 750 feet (230 m) thick.

The Tununk Member is composed of marine mudstone and shale that is medium to dark brown or gray and locally black, and that breaks into equidimensional fragments when excavated. The unit is soft, silty, and sandy (fine grained) near the bottom and top. Bedding is mostly indistinct to thin and laminated. The Tununk contains secondary gypsum veinlets and is mostly calcareous. In the upper 50 feet (15 m), the shale is interbedded with thin, brown to gray, very fine grained sandstone beds that are about 1 foot (0.3 m) apart. The upper contact is mapped at the base of the first medium or thick sandstone bed of the conformably overlying Ferron Sandstone Member.

The Tununk Member overlies the Dakota Sandstone at most locations in the Colorado Plateau region. It correlates with the Tropic Shale in southwestern Utah (Hintze, 1988). Fossils indicate it is Late Cretaceous (Cenomanian) in age (Molenaar and Cobban, 1991).

Ferron Sandstone Member (Kmf): This member of the Mancos Shale generally forms a series of sandstone cliffs (misnamed the Limestone Cliffs) above the steep slope of the Tununk Member and is 450 to 600 feet (140–180 m) thick in the quadrangle, thinning to the northeast. Commonly, a bench has developed on top of the Ferron. The Ferron can be divided into a lower cliff, lower slope, middle ledgy zone, upper slope, and upper cliff (not mapped separately). However, the thicknesses of these subunits vary considerably. We measured the Ferron in several places: the lower cliff varies from 30 to 75 feet (10–20 m), the lower slope from 95 to 150 feet (30–50 m), the middle ledgy zone from 100 to 200 feet (30–60 m), the upper slope from 50 to 120 feet (15–40 m), and the upper cliff from 40 to 170 feet (10–50 m).

The Ferron Sandstone Member consists of interbedded yellow-gray, light-brown, and white sandstone, gray sandy shale, dark-gray carbonaceous shale, and dark-gray to black coal. The sandstone is mostly fine to medium grained, mostly calcareous, thin to massive lenticularly bedded, cross-stratified, rippled, bioturbated, contorted, and contains limonitic nodules (some still have pyritic cores). The thicker gray sandy shale, gray shale, and carbonaceous shale units are best developed in the upper and lower slopes. However, they are common in the cliff-forming units as thin beds or partings. The member contains several lenticular coal beds, especially in the lower and upper slopes. Locally, the coals have burned along the outcrop leaving reddish coal bloom (clinker) as evidence. A more detailed account of the coal beds and resources is given in the section on coal.

The Ferron Sandstone conformably overlies the Tununk Member. Within the quadrangle, it was deposited in fluvial, deltaic, and lagoonal environments. It correlates with the Tibbett Canyon and Smoky Hollow Members of the Straight Cliffs Formation in the Kaiparowits Plateau in south-central Utah. It is present near the Henry Mountains to the southeast, where it is thinner. It surrounds the northern half of the San Rafael Swell, but thins northward and eastward, eventually losing its cliff-forming habit. Fossils indicate it is Late Cretaceous (Cenomanian-Turonian) in age (Molenaar and Cobban, 1991).

Lower Blue Gate and Emery Sandstone Members (Kmb and Qms [Kme?]): The Blue Gate consists of two slope-forming parts, separated by the Emery Sandstone Member, within the quadrangle. The lower Blue Gate is exposed in place, whereas the Emery and upper Blue Gate occur only in slide masses. Like the Tununk Member, the lower Blue Gate Member of the Mancos Shale forms steep, earthy slopes. It is present above the Limestone Cliffs (Ferron Member), in most cases eroded back at least 50 feet (15 m) from the cliff edges. It differs from the Tununk Member in being a lighter shade of gray, and exhibiting more laminated and thin beds. Because its outcrop is in the higher parts of the northwest quadrant of the quadrangle, it generally receives a greater amount of precipitation, especially in the form of snow. Therefore, it is commonly mantled with mass-movement deposits (Qmv and Qms). The Blue Gate Member and the inclusive Emery Sandstone Member have a cumulative exposed thickness of about 1000 feet (300 m) in the quadrangle, but in the surrounding area are at least 2500 feet (760 m) and possibly as much as 3000 feet (900 m) thick (Doelling, 2004). The thickness of the Emery Sandstone Member and upper Blue Gate is indeterminable in the quadrangle due to the thick cover of mass-movement deposits.

The lower Blue Gate Member is mostly evenly bedded, pale-blue-gray, marine shale that is irregularly interbedded with siltstone and several yellow-gray sandstone beds, which are slightly more resistant and most common in the upper part. It is overlain by the Emery Sandstone in neighboring areas (which divides the Blue Gate Member into upper and lower parts) and may also be overlain by the Emery Sandstone in this quadrangle, but such outcrops are either poorly exposed or present as landslide blocks and slumps.

The Emery is yellow-gray, fine- to medium-grained, thin- to thick-bedded, friable sandstone that forms a cliff where it is not involved in landslides. Where incorporated into landslide material, it is commonly poorly cemented—these outcrops are labeled as Qms (Kme?) on the map.

The Blue Gate Member is present below the Book Cliffs in the Colorado Plateau region and in the Henry Mountains basin. It correlates with the John Henry Member of the Straight Cliffs Formation in the Kaiparowits Plateau area (Peterson, 1969). Santonian-age (Late Cretaceous) fossils are present in the lower Blue Gate Member and Emery Sandstone (Peterson and others, 1980).

Tertiary Rocks

Tephritic Dike (Td)

A tephritic dike trends about N. 20° W. and is approximately 5 feet (1.5 m) thick in sections 2, 11, and 12, T. 25 S., R. 5 E.

Similar dikes and accompanying sills are common to the south in the Cathedral Valley area and to the east around Cedar Mountain (Gartner, 1986; Doelling, 2004). The dike in the Willow Springs quadrangle is nearly vertical and locally flanked by three or four 3-foot-thick (1 m) parallel dikes. Where parallel dikes are present, the thickness of the main dike is approximately 4.5 feet (1.4 m). Locally, the Entrada Sandstone, into which the dike has intruded, is baked and bleached. This baked zone extends as much as 25 feet (8 m) on each side of the dike; the sandstone is bleached to a light gray and is more resistant than unbleached bedrock. The baked edges of sandstone are hard and may stand vertically 50 feet (15 m) above unbaked sandstone. The dike also intrudes the Curtis, Summerville, and Morrison Formations.

Generally, the dike is more resistant than the baked sandstone. It is dark gray to black, somewhat vesicular, and displays calcite-filled vugs and small phenocrysts of biotite and plagioclase. Smith and others (1963) indicated the presence of plagioclase, pyroxene, and calcite in the dikes in the southern San Rafael Swell. Williams and Hackman (1971) described these dikes as diabase, but Gartner (1986) classified them as tephrite and phonotephrite. They are dark colored and contain phenocrysts of olivine and feldspar in a dense greenish-black groundmass. Gartner (1986) stated that labradorite is the main feldspar present, with secondary augite, analcite, biotite, thomsonite, anorthoclase, olivine, and natrolite throughout the dike rocks.

Gartner (1986) reported K-Ar ages of the dikes in the region ranging from 3.8 to 6.4 Ma. Nelson (1989) obtained three K-Ar ages ranging from 3.8 to 5.4 Ma in the nearby Geyser Peak quadrangle, and Doelling (2004) reported $^{40}Ar/^{39}Ar$ ages of 4.35 ± 0.04 and 4.49 ± 0.08 Ma on likely related sills in the Mussentuchit Flat and Ireland Mesa quadrangles to the east.

Quaternary Deposits

Alluvial Deposits

Stream alluvium (Qal, Qal1, Qal2): Clay- to boulder-size clasts are common along the courses of modern washes and stream channels. They are unconsolidated, poorly to moderately sorted, and consist of interlayered coarse and fine lenses. We mapped higher levels (older alluvium) where persistent. Although most clasts that make up the alluvium have local sources, some have been carried considerable distances downstream. Volcanic materials are ubiquitous in the alluvium, and because of their resistance to weathering and erosion, have been carried the greatest distance from their source to the west.

Younger alluvium (Qal1) has a maximum thickness of 10 feet (3 m). Older alluvium (Qal2) is locally as much as 50 feet (15 m) thick and suggests a lengthy period of canyon or valley filling. Young alluvial deposits are in the active downcutting washes, whereas the older deposits form fill beneath flat or slightly sloping surfaces between canyon walls. The unit generally includes some young alluvium along small active channels that is impractical to map separately. The sloping surfaces are currently being gradually dissected and deeply gullied by active washes.

Higher and older alluvial deposits are rare except where supported by resistant clasts. These higher deposits contain volcanic materials and are discussed with the mixed alluvial and colluvial deposits (Qapcv). The Qal1 deposits are entirely Holocene in age, whereas the Qal2 deposits are probably Holocene and late Pleistocene in age.

Alluvial mud (Qam): Light-gray mud, mostly derived from Mancos Shale members, has been deposited as valley fill, slope wash, and fans. It consists dominantly of unconsolidated clay, silt, and sand particles in deposits that are mostly structureless, laminated, or crudely stratified. These deposits generally interfinger with modern alluvium in lower parts. Many of these deposits have been deeply incised by floods that accompany local torrential rainfall; the walls of the incised channels are commonly vertical or nearly vertical.

This mud has generally accumulated in small ephemeral basins with bedrock thresholds. The Ferron Sandstone Member forms the threshold for deposits originating from the Blue Gate Member, whereas the Dakota Formation forms the threshold for deposits originating from the Tununk Member. Below these thresholds stream gradients increase, valleys narrow and commonly become canyon-like, and deposits contain coarser constituents.

These deposits are locally as much as 50 feet (15 m) thick and correspond in age to Qal2 deposits (Holocene to late Pleistocene). During late summer torrential rains, muddy weathered bedrock washes out and spreads as sheet-wash fans across the fill.

Alluvial-fan deposits (Qaf): These generally consist of unconsolidated silt to cobble-size particles that are carried from surrounding bedrock outcrops by torrential rainfall and are deposited where washes experience a reduction in gradient, forming fan-shaped deposits. Alluvial-fan deposits are much like the alluvial mud deposits in that they are derived from local sources; however, they contain less mud. Like the alluvial mud deposits, they commonly funnel and interfinger into the alluvium of larger drainages and are currently being gullied. These fan deposits are less than 15 feet (5 m) thick, generally cover bedrock, and are Holocene in age.

Pediment-mantle deposits (Qap): These deposits consist of unconsolidated silt to gravel-size material with local accumulations of sandstone boulders, and are most common below the Limestone Cliffs (actually Ferron Sandstone). Most of the material is locally derived; deposits immediately below the cliffs are mostly derived from the Ferron Sandstone. Elsewhere, deposits contain angular to rounded pebbles and cobbles from the Dakota Formation, Buckhorn Conglomerate and other ledges in the Cedar Mountain Formation, Salt Wash Member of the Morrison Formation, and a small amount of andesite and basalt. The deposits are crudely stratified and are mostly matrix supported. The pediment-mantle deposits are as much as 20 feet (6 m) thick, but average 15 feet (5 m). These deposits are much like the mixed pediment-mantle and colluvial deposits with volcanic clasts (Qapcv), except associated colluvium is not prominent and volcanics do not constitute an appreciable amount of the deposits. They are considered mostly Holocene to late Pleistocene in age.

Mass-Movement Deposits

Landslide deposits (Qms): Landslides are common in the Blue Gate Member of the Mancos Shale in the northwestern part of the quadrangle. Several large scarps arc across the landscape, some for more than 1 mile (1.6 km). Deposits exposed on the surface of more recent mass movements are the Blue Gate Member (labeled Kmb), and boulder deposits (labeled Qmv) that commonly mantle the Blue Gate shale. These areas are high elevation (6000 to 8000 feet [1830–2440 m]) and commonly covered with snow in winter. Snowmelt percolates into the muddy shales, causing them and more resistant units to progressively fail. Areas mapped as Qms (Kme?) are yellowish gray and are probable slump blocks of the Emery Sandstone Member of the Mancos Shale. Large slump blocks of the Ferron Sandstone Member of the Mancos Shale are common below and parallel to the Limestone Cliffs, and are back-tilted toward the cliffs or scattered randomly. Many smaller landslides (not mapped) are present on bedrock units that consist of weak shale or are strongly jointed. Most landslide deposits in the quadrangle are Holocene to Pleistocene in age.

Talus and rock-fall deposits (Qmt): This unit consists of deposits of rock debris that have accumulated on slopes below cliffs or ledges. Large blocks that have broken off and fallen from a ledge or cliff are ubiquitous in the quadrangle; only the larger deposits are mapped. Talus deposits rarely exceed 5 feet (1.5 m) in thickness and consist of poorly sorted angular fragments. They are Holocene to Pleistocene in age.

Boulder deposits (Qmv): Boulder deposits form hummocky surfaces on the Blue Gate Member of the Mancos Shale in high areas above the Limestone Cliffs. Some of these deposits have slumped and slid on top of the Blue Gate Member and are mapped separately as Qms (Qmv) (see discussion of landsliding under "Landslide deposits"). The remainder form bouldery mantles on the Blue Gate Member. The boulder deposits are much more resistant to weathering and erosion than the underlying shale, so as the underlying shale is eroded, the colluvial boulders creep downslope.

The boulder deposits consist of andesitic basalt boulders in a matrix of mud, silt, sand, granules, pebbles, and cobbles. The matrix consists of varying amounts of volcanic rock, quartzite, sandstone, and chert that is angular to rounded, poorly sorted, and unconsolidated. The boulders are generally subrounded to rounded, and range up to several feet across. The thickness of the boulder deposits is variable—as much as 20 feet (6 m) over more level areas and thinner on the slopes. The deposits are Holocene to Pleistocene in age.

Mixed-Environment Deposits

Mixed eolian and alluvial deposits (Qea): Scattered deposits of mixed eolian and alluvial sediment are present above the Limestone Cliffs, in hollows on the boulder (Qmv) deposits, and on the Ferron Sandstone Member of the Mancos Shale. Those on the Qmv deposits contain silt to fine-grained sand and volcanic material derived from the Qmv unit and mud derived from the Blue Gate Member of the Mancos Shale. The silt was probably carried into the hollows by the wind. Sheetwash and debris flows have also contributed to the deposits. Some contain much fine-grained sand, probably derived from the Emery Sandstone Member of the Mancos Shale. Those developed on Ferron Sandstone outcrops are a mixture of wind-blown sand and erosional debris from the Ferron, including mud. The thickness of the deposits is variable, but generally less than 15 feet (5 m). They are Holocene to middle Pleistocene in age.

Mixed alluvial pediment-mantle and colluvial deposits with volcanic boulders (Qapcv): These deposits consist of andesitic and basaltic boulders in a matrix of clay to cobbles. The matrix consists of varying amounts of angular to rounded, poorly sorted, unconsolidated andesite, basalt, quartzite, sandstone, and chert. The boulders are generally subrounded to rounded and range up to several feet across. These deposits are similar to the boulder deposits (Qmv) mapped above the Limestone Cliffs but are at a different elevation, farther from the source, and contain a larger alluvial component. They are mostly present below the Limestone Cliffs and commonly form planar surfaces that slope gently eastward. These pediment-mantle deposits appear to have been chiefly washed down two drainages, Willow Springs Wash and an ancient drainage that flowed between Mussentuchit Wash and the north flank ridge of the Last Chance anticline. The outcrop of these deposits is narrow immediately below the Limestone Cliffs and widens to the east, and caps pediment surfaces (benches) at several levels above the modern drainages. The andesitic and basaltic material is much more resistant to weathering than the bedrock units over which it is deposited; therefore, the slopes below the edges of the pediment remnants are commonly covered with colluvium of the same material (included in map unit), masking the edges of the pediment-mantle deposits.

The pediment-mantle deposits average 10 to 15 feet (3–5 m) thick, but locally may be as much as 25 feet (8 m) thick. The colluvial aprons are generally thinner. The highest pediment-mantle deposits contain boulders that have white, secondary calcium-carbonate coatings on their undersides. The pediment-mantle deposits are probably Pleistocene in age, whereas the colluvial drape is mostly Holocene.

STRUCTURAL GEOLOGY

Regional Structural Setting

The Willow Springs quadrangle is located on the east edge of the High Plateaus, a transition zone between the Colorado Plateau and the Basin and Range Province to the west. Structurally, the High Plateaus area is a basin as reflected by regional strikes and dips of strata, that is cut by generally north-south-trending faults. Structure contours show the strikes in the Willow Springs quadrangle range from N. 30° E. to N. 70° E., and dips range between 2 and 6 degrees to the northwest (into the basin). Locally, the Last Chance anticline and Salvation Creek syncline have a northwest trend and alter regional bedding attitudes. Two faults are present in the Willow Springs quadrangle and have northwest to northeast trends.

Last Chance Anticline

The axis of the Last Chance anticline crosses the quadrangle at about N. 50° W. and plunges northwestward near the west edge of the quadrangle. The strike is north-south on the western flank, and about N. 45° W. on the eastern flank. Beds on the plunging nose dip 10° to 20° northward. The anticlinal axis is mostly covered by unconsolidated Quaternary deposits and cannot be precisely plotted. Hager (1954) divided the Last Chance anticline into two parts, north and south, and showed the anticline extending southeast out of the quadrangle towards Caineville.

Salvation Creek Syncline

The Salvation Creek synclinal axis trends N. 20° to 30° W. in the southeast part of the quadrangle. It is a very shallow structure and plunges northwestward into the Limestone Cliffs. The Salvation Creek syncline extends southeast out of the quadrangle.

Faults

Only two normal faults are evident in the quadrangle. One cuts the strata in sections 1 and 12, T. 25 S., R. 5 E., trends about N. 25° E., is nearly vertical, and displaces strata about 40 feet (12 m). The fault becomes a monocline before it dies out to the north. The displacement appears to increase southward and is greatest where last observable before becoming concealed beneath Quaternary deposits.

The second fault is located in section 21, T. 24 S., R. 5 E. where it cuts map unit Kme?. This fault is largely buried by boulder deposits (Qmv) and may actually be an old landslide scarp. The fault trends N. 35° W. and the amount of displacement cannot be determined.

ECONOMIC GEOLOGY

Petroleum and Gas Possibilities

Four holes have been drilled in the northern Last Chance anticline in the Willow Springs quadrangle. One had a show of oil in the upper Kaibab, and another had weak gas shows in the Chinle. The other two wells had no shows. Hager (1954) reported that a “minor high” (anticline), the northern Last Chance anticline, is in T. 25 S., R. 5 E. The Last Chance anticline continues to the southeast where natural gas was discovered in 1934 in the Sinbad Limestone Member of the Moenkopi Formation. Hager noted a “saddle” (syncline) between the southern and northern parts of the Last Chance structure. He also reported that heavy oil was encountered in the Cedar Mesa Sandstone. At least six wells were drilled in the southern Last Chance anticline structure south of the quadrangle, some recording 840 Btu per cubic foot gas and most recording the heavy oil in the Cedar Mesa Sandstone. The gas and oil were not commercially produced because of a lack of infrastructure.

The oil and gas possibilities of the quadrangle remain favorable based on the structures. As far as we know, no other Paleozoic formations have been adequately tested.

Coal

Coal is present in the Ferron Sandstone Member of the Mancos Shale and in the Dakota Formation. The area is part of the Emery coalfield. The Ferron Sandstone coals were originally evaluated by Lupton (1916) and additional work was done by Doelling (1972). Lupton indicated the presence of 13 coal beds in the Ferron which he labeled A to M; coal bed A is the lowest and M is the highest. The Ferron is generally divisible into cliffs and slopes in the quadrangle. Starting at the Tununk Member upper contact, the overlying Ferron consists of a cliff, a slope, a series of ledges, another slope, and an upper cliff. Beds A to E are in the lower slope, beds F and G are in the middle ledges, and beds H to M are in the upper slope.

The coal beds are lenticular, and only coal beds A, C, I, and J are thick enough to be economically interesting. Bed A is the most valuable in the quadrangle, as it is as much as 14 feet (4 m) thick. Bed A is split, thin, and bony in the far north, but is at least 4 feet (1.2 m) thick from the south half of section 7, T. 24 S., R. 6 E. southwestward along the outcrop to section 9, T. 25 S., R. 5 E. Bed A has locally burned along the outcrop, which has created a reddish coal bloom. Bed C is 4 feet (1.2 m) thick in the salient just north of Willow Springs Wash in section 18, T. 24 S., R. 6 E. Elsewhere, Bed C is thin and split. All other beds are poorly developed in the quadrangle. Bed M locally thickens north of Willow Springs Wash, but is commonly split or is significantly bony.

Coal in the Dakota Formation is generally thin or absent, but locally the exposed bed is as much as 4 feet (1.2 m) thick. It is present in the dip slope along the north flank of the Last Chance anticline in sections 1 and 2, T. 25 S., R. 5 E.

The only known coal mine in the quadrangle is the Willow Springs mine in Willow Springs Wash, in the SE¼NW¼ section 13, T. 24 S., R. 5 E., which may have been active (or under development) between 1932 and 1946. At present the site is abandoned and the adit has caved. Doelling (1972) indicated the mine produced only 16,000 short tons.

The quality of the coal has not been adequately tested in the quadrangle, but probably will approximate that found in other locations in the Emery coalfield. The coal is classified as high-volatile C bituminous (Doelling, 1972), and in the southeast corner subituminous A (Quick and others, 2004). Lupton (1916) estimated the presence of about 200 million short tons of in-place reserves for the quadrangle. Doelling (1972) estimated the presence of 130 million short tons of in-place reserves, and an additional 50 million short tons in inferred in-place reserves.

Bentonite Mud

The only active mine in the quadrangle is for bentonite mud. It is located in NW¼ section 8, T. 25 S., R. 6 E. and is operated by the Western Clay Company of Aurora, Utah. The pay zone is near the top of the Brushy Basin Member of the Morrison Formation. The mine advanced a trench about 5 to 10 feet (2–3 m) wide and 530 feet (160 m) long along strike. The operation is intermittent and dependent on demand. The material is used as a foundry sand binding agent, livestock and poultry feed cube and pellet binder, drilling mud, newspaper filler, adsorbent for radioactive materials, water catchment or small reservoir sealant, and related applications. The pay zone consists of blocky light-gray mudstone that is probably devitrified volcanic ash. The pit was opened in 1991 and has produced about 83,500 short tons at an average rate of 5500 tons per year (as of 2006). One unpublished Western Clay Company report listed the deposit as 88% montmorillonite, 5% quartz, and 7% feldspar; this material is classified as sodium bentonite.

Other Resources

Chalcedony is abundant near the Salt Wash-Brushy Basin contact in the Morrison Formation. The red (jasper), yellow (citrine), and gray (flint) chalcedony could be worked into semiprecious jewelry. Collectors might also find the abundant *Pycnodonte newberryi* oyster shell fossils interesting, as found at the top of the Dakota Formation. Various types of chert and limestone nodules are present at many localities, which might interest rock hounds.

Water Resources

The Willow Springs quadrangle is located on the edge of a middle-latitude desert at the southeast margin of the Fish Lake Plateau. Annual precipitation ranges from 6 to 10 inches (15–25 cm), the higher amount falling in the higher elevations (Richardson and others, 1981). Elevations range from a low of about 5720 feet (1740 m) (where Last Chance Wash exits the quadrangle in the southeast corner) to a high of about 8200 feet (2500 m) above Clay Flats along the west-central margin of the quadrangle. All drainages are ephemeral, generally draining the area from west to east. However, Willow Springs Wash and Last Chance Creek commonly have flowing water in their channels for short distances most of the year. Willow Springs are located along Willow Springs Wash in section 13, T. 24 S., R. 5 E., and a small amount of water flows in the wash channel downstream for about 0.8 mile (1.3 km). A similar spring in the SE¼ section 9, T. 25 S., R. 5 E. (not shown on the topographic map) provides water that flows in the canyon of Last Chance Creek, also for about 0.8 mile (1.3 km). In times of drought, both springs are dry.

The Willow Springs quadrangle provides winter grazing for cattle, and water catchments have been constructed across the quadrangle. Most of these catchments collect flow in small washes, which channel water for a short time after a brief rainfall or snowfall. Every few years a torrential summer rainfall causes flash floods in many of the washes, destroying the catchment dams. These catchments are quickly repaired for the winter grazing season.

GEOLOGIC HAZARDS

Landslides

Many landslides (Qms) were mapped along the Mancos Shale outcrops in the Willow Springs quadrangle. The quadrangle contains little development; presently, only roads would be affected by landsliding. They would be most affected in the area above the Limestone Cliffs, where the Blue Gate Member is present. Landsliding in these areas is more likely to occur during prolonged periods of increased precipitation, as occurred in 1983–1984. Translational sliding is common, but movement in the Blue Gate Member can occur by block tilting and rotation.

Rock Falls

Rock falls occur sporadically in the Willow Springs quadrangle. They are most evident at the base of the Limestone Cliffs, but can occur below any cliff-forming unit. Rock-fall debris may travel great distances downslope by rolling, bouncing, and sliding. Large angular boulders in Qmt deposits attest to previous rock-fall events. Because the quadrangle is uninhabited by humans, a hazard exists primarily where roads or trails pass near cliffs.

Debris Flows and Flooding

Flooding-induced erosion and deposition are the most active and potentially damaging hazards in the quadrangle, especially in areas of mapped young alluvial deposits. The sparsely vegetated slopes, benches, and deep, narrow washes are subject to rapid erosion from waters generated by cloudburst rainstorms. Debris flows and floods generally remain confined to stream channels in high-relief areas, but may exit channels and deposit debris where slope gradients decrease or channels are shallow along their travel paths. Debris flows and stream floods regularly damage the few roads in the Willow Springs quadrangle. These hazards are directly related to torrential rainfall, which is more likely to occur in the late summer season, although long, steady rains in the spring and snow melt in the spring can also cause damage. Because the roads are not surfaced or paved, those crossing the shale members of the Mancos can become so muddy that travel over them is impossible.

Problem Soils

The clay-bearing bedrock units and unconsolidated deposits, fine-grained rocks associated with some of the cliff-forming formations, and soils derived from them are susceptible to collapse, shrink-swell, piping, and dissolution. Essentially, problem soils are expected to develop on all formations stratigraphically above the Salt Wash Member of the Morrison Formation.

Earthquakes

The quadrangle is in a low-risk zone, having a 30% probability of an earthquake greater than magnitude 5.0 within the next 100 years (U.S. Geological Survey, 2007). Because the area is uninhabited by humans, potential for damage is low.

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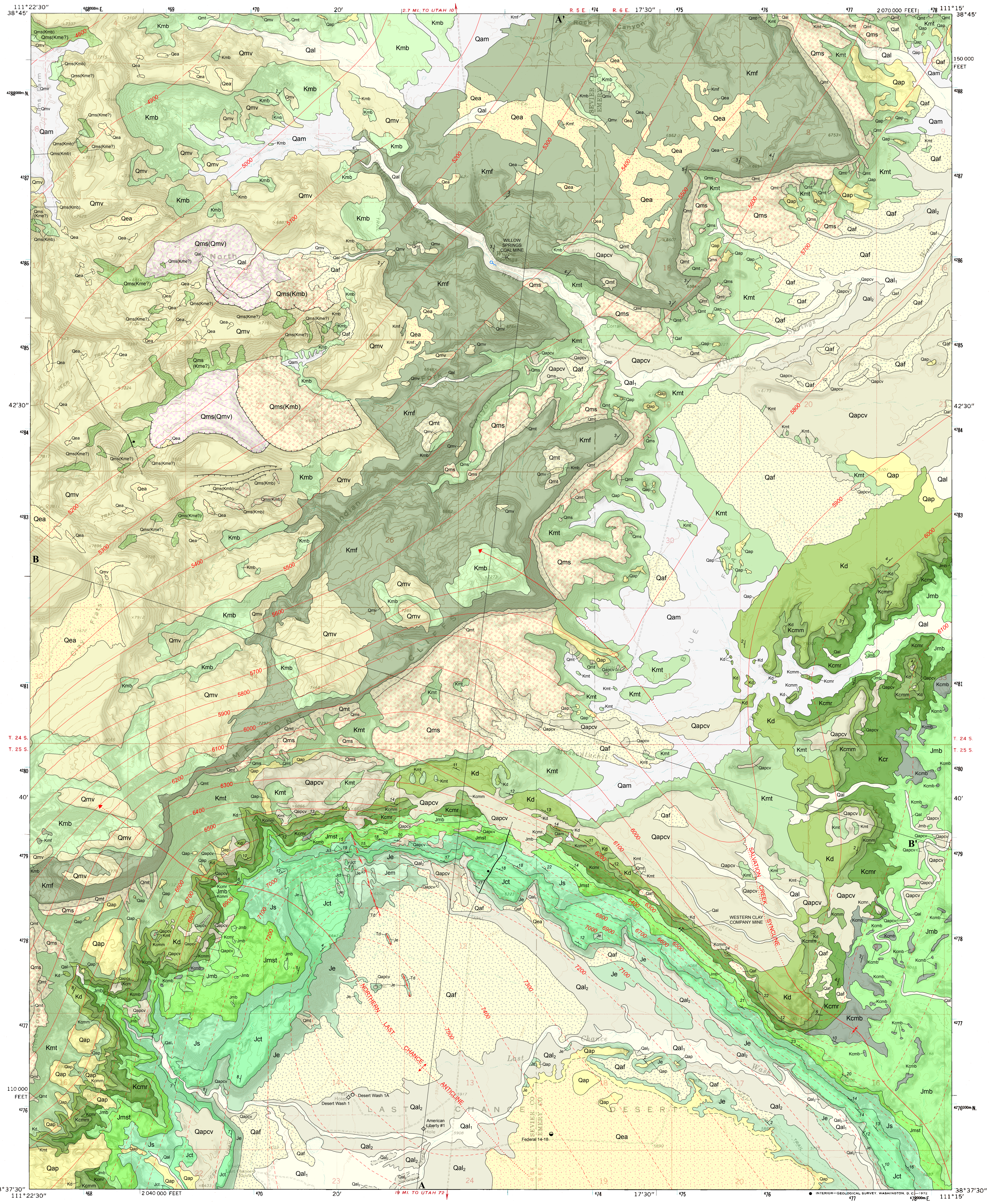

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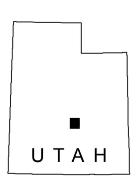

QUADRANGLE LOCATION

SCALE 1:24,000

1 0.5 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 0.5 0 1 KILOMETER

TOPOGRAPHIC CONTOUR INTERVAL 40 FEET

GEOLOGIC MAP OF THE WILLOW SPRINGS QUADRANGLE, SEVIER AND EMERY COUNTIES, UTAH

by

Hellmut H. Doelling, Paul A. Kuehne, and James I. Kirkland

2009

11°15'
TRUE NORTH
MAGNETIC NORTH

APPROXIMATE MEAN DECLINATION, 2009

Base from U.S. Geological Survey, Willow Springs 7.5' Quadrangle, (1968)
Shaded relief generated from 10 meter National Elevation Data
Projection: UTM Zone 12
Datum: NAD 1927
Spheroid: Clarke 1886

Project Managers: Donald L. Clark and Grant C. Willis
GIS and Cartography: Kent D. Brown, Paul A.Kuehne and Lori J.Douglas
ISBN 1-55791-814-7

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1	2	3
4		5
6	7	8

1. Old Woman Plateau
2. Walker Flat
3. Mesa Butte
4. Johns Peak
5. Mussentuchit Flat
6. Geyser Peak
7. Solomons Temple
8. Salvation Creek

ADJOINING 7.5' QUADRANGLE NAMES

UTAH GEOLOGICAL SURVEY
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DESCRIPTION OF MAP UNITS

Qal1 / Qal2 / Qal — **Stream alluvium** (Holocene to late Pleistocene) – Unconsolidated deposits of poorly to moderately sorted clay, silt, sand, granules, gravel lenses, and volcanic boulders; Qal_1 represents alluvium in active larger channels and floodplains; Qal_2 deposits are 6-50 feet (2-15 m) above the active channels and are characterized by weak soil development; Qal is shown where Qal_1 and Qal_2 are not differentiated on map; Qal_1 is a maximum of 10 feet (3m) thick, Qal_2 is a maximum of 50 feet (15 m) thick.

Qam — **Alluvial mud** (Holocene to late Pleistocene) – Mostly unconsolidated clay, silt, and sand, deposited as fans and mudflows from Mancos Shale outcrops; form valley fill and muddy alluvial fans; correspond to Qal_2 deposits with which they interfinger; locally deeply incised by erosion; unstratified and nearly structureless; as much as 50 feet (15 m) thick.

Qaf — **Alluvial-fan deposits** (Holocene) – Unconsolidated deposits of poorly sorted, generally unstratified, muddy silt, sand, and gravel; gravel ranges from pebbles to boulders; deposits are locally derived and reflect the source materials. As much as 15 feet (5 m) thick.

Qap — **Pediment-mantle deposits** (Holocene to late Pleistocene) – Mostly unconsolidated sand and gravel, but locally silty and bouldery; deposits are mostly locally derived and contain angular to rounded pebbles and cobbles from the Ferron Sandstone, Dakota Formation, Buckhorn Conglomerate and other ledges in the Cedar Mountain Formation, Salt Wash Member of the Morrison Formation, and andesitic and basaltic units; crudely stratified, mostly matrix supported; as much as 20 feet (6 m) thick, but average 15 feet (5 m) in thickness.

Qms — **Landslide deposits** (Holocene to Pleistocene) – Large coherent blocks to fragmented masses of bedrock and surficial debris transported downslope by mass movement; more recent masses have hummocky surfaces and scarps along their upper boundaries; above the Limestone Cliffs, dominant involved unit is indicated - Qmv (boulder deposits), Kme? (Emery Sandstone Member), Kmb (Blue Gate Member), mostly coherent blocks are shown with bedrock color; Qms deposits line the base of the Limestone Cliffs (cliffs formed by the Ferron Sandstone Member of the Mancos Shale) where they consist of hummocky-surfaced, jumbled masses of angular sandstone blocks; thicknesses variable and unknown.

Qmt — **Talus and rock-fall deposits** (Holocene to Pleistocene) – Generally angular rock-fall blocks, boulders, and small fragments deposited as veneers on slopes below ledges and cliffs; colluvium contains additional slope-wash debris of poorly sorted rock fragments in a sandy matrix; only larger or covering deposits are mapped; thicknesses vary, but average less than 5 feet (1.5 m).

Qmv — **Boulder deposits** (Holocene to Pleistocene) – Andesitic and basaltic boulders derived from lava flows of Fish Lake Plateau; boulders to 6 feet (2 m) across in a matrix of sand, granules, and cobbles of andesitic basalt, sandstone, quartzite, and siliceous limestone; mostly matrix supported; volcanic boulders are commonly porphyritic and vesicular; deposits form resistant veneers (as old pediment, outwash-gravel, colluvial, landslide, and fan deposits) on top of much softer sedimentary rocks and are presently washed downstream by the more vigorous floods; thicknesses vary, but average less than 15 feet (5 m).

Qapcv — **Mixed alluvial pediment-mantle and colluvial deposits with volcanic boulders** (Pleistocene) – Pediment-mantle deposits containing boulder-, cobble-, granule-, and sand-size clasts of andesitic basalt mixed with varying amounts of cobble-, granule-, and sand-size clasts of sandstone, quartzite, and siltstone; include associated colluvial deposits formed as the pediment flanks erode; occur at varying levels above modern stream channels; pediment-mantle deposits are relatively flat on top, slope away from the cliffs (eastward), and are developed along the ancestral Willow Springs Wash and along an ancestral stream that once flowed south of Mussentuchit Wash and north of the north flank of the Last Chance anticline; pediment-mantle deposits grade imperceptibly upslope into colluvium of the same composition as the pediment-mantle deposits; as much as 25 feet (8 m) thick, but typically 15 feet (5 m); flanking colluvium is generally thinner.

Qea — **Mixed eolian and alluvial deposits** (Holocene to Pleistocene) – Unconsolidated accumulations of mostly silt and sand that fill depressions formed by tilted landslide blocks; mostly found above the Limestone Cliffs; mostly derived from local Blue Gate Member slope wash coupled with silt and sand blown in from more distant sources; also some derived from the finer constituents of the Qmv deposits; large area of Qea in the Last Chance Desert is made up mostly of windblown and slope-wash sand derived from the Entrada Sandstone and lies above a pediment-mantle surface; as much as 20 feet (6 m) thick.

Td — **Tephritic dike** (Pliocene) – Dark-gray to dark-green-gray dike consisting chiefly of labradorite, augite, analcite, biotite, thomsonite, anorthoclase, olivine, and natrolite (diabase dike of Williams and Hackman, 1971); nearly vertical and intruded into the Entrada Sandstone, Curtis Formation, and Summerville Formation in sections 2, 11, and 12, T. 25 S., R. 5 E.; trends about N. 20° W., and up to 5 feet (1.5 m) in thickness; locally breaks up into three or four parallel dikes; Nelson (1989) obtained three K-Ar ages ranging from 3.8 to 5.4 Ma in the Geyser Peak quadrangle, and Doelling (2004) reported two $^{40}Ar/^{39}Ar$ ages from related sills to the east in the Mussentuchit Flat and Ireland Mesa quadrangles of 4.35±0.04 Ma and 4.49±0.08 Ma.

Km — **Mancos Shale**-- Undivided on cross sections only.

Kme? — **Emery Sandstone Member?** (Upper Cretaceous, Santonian) – Yellow-gray, friable, fine- to medium-grained sandstone; normally present in middle of Blue Gate Member; probably broken up, displaced by landsliding (see Qms), and not exposed in place in the Willow Springs quadrangle; thickness indeterminable.

Kmb — **Blue Gate Member** (Upper Cretaceous, Campanian-Santonian) – Mostly pale-blue-gray marine shale, nodular and irregularly bedded mudstone, and siltstone with several yellow-gray, slightly more resistant, sandy beds; mostly a slope former, with sandy beds more common in the lower and upper parts; only lower part is exposed in quadrangle; more than 1000 feet (300 m) is exposed.

Kmf — **Ferron Sandstone Member** (Upper Cretaceous, Turonian-Cenomanian) – Alternating yellow-gray, light-brown, and white sandstone, gray sandy shale, gray and carbonaceous shale, and coal; mostly fine- to medium-grained sandstone, commonly calcareous; lenticular to thin to massive beds; can be divided into a lower cliff, lower slope, middle ledgy zone, upper slope, and upper cliff; contains several lenticular coal beds, especially in lower and upper slopes; 450 to 600 feet (140-180 m) thick, thinning northward.

Kmt — **Tununk Member** (Upper Cretaceous, Cenomanian) – Medium- to dark-gray marine shale; forms steep slope under Ferron Sandstone cliff; becomes increasingly sandy toward top; about 750 feet (230 m) thick.

Kd — **Dakota Formation** (Upper Cretaceous, Cenomanian) – Variable assemblages of yellow-gray sandstone, conglomerate, light-brown shale, and coal; sandstone is generally fine to coarse grained, cross-bedded, thick bedded, and lenticular; conglomerate contains gray quartzite and black chert pebbles up to 2-3 inches (5-8 cm) across; coal beds, where present, are generally less than 2 feet (60 cm) thick, but locally are up to 4 feet (1.2 m) thick; forms ledges and slopes; 50-120 feet (15-37 m) thick.

Kcm — **Cedar Mountain Formation** – Undivided on cross sections only. Members are designated from Kirkland and others (1997).

Kcmm — **Mussentuchit Member** (Upper to Lower Cretaceous, Cenomanian -Albian) – Mostly gray, silty, smectitic mudstone, containing a few thin, green-gray, lenticular sandstone beds and some lignitic zones near the top; forms smooth, rounded slopes; 60 to 80 feet (18-24 m) thick.

Kcmr — **Ruby Ranch Member** (Lower Cretaceous, Albian-Aptian) – Mostly green-gray, light-gray, and purple, silty mudstone that contains nodular brown limestone beds; also has a basal muddy sandstone bed; locally contains a few lenticular ledges of fine-grained, locally pebbly sandstone, especially at the base; brown limestone ledges commonly break up and litter the smooth slopes; 60 to 100 feet (18-30 m) thick.

Kcmb — **Buckhorn Conglomerate Member** (Lower Cretaceous, Aptian?) – Gray-brown conglomerate, conglomeratic sandstone, and sandstone; contains pebble- and cobble-sized clasts of quartzite, chert, and black siliceous limestone in a matrix of poorly sorted, fine- to coarse-grained sandstone interbedded with gray-green silty and sandy shale; sandstone is trough cross-bedded, lenticular, and discontinuous; forms ledges and benches that are channeled into the underlying Brushy Basin Member of the Morrison Formation; mapped only where the outcrops form benches and is included with the Ruby Ranch Member (Kcr) where thin or less well developed; 0 to 35 feet (0-11 m) thick.

Jm — **Morrison Formation** – Undivided on cross sections only.

Jmb — **Brushy Basin Member** (Upper Jurassic, Tithonian) – Very light gray, light-pink-gray to light-purple, locally variegated, bentonitic, silty shale; contains interbedded zones of brown limestone nodules, thin white sandstone, and conglomerate beds; forms rounded slopes and hills or a steep slope beneath lower cliffy portion of Cedar Mountain Formation; where the Cedar Mountain Formation has no basal cliffy part, the shale of the Cedar Mountain forms one continuous slope with the Brushy Basin Member; commonly contains abundant chalcedony (jasper-agate) at the base, either in thin to medium beds or as fragmentary angular pieces; also contains scattered thin rubble zones of limestone and siliceous chert; 90 to 180 feet (27-55 m) thick.

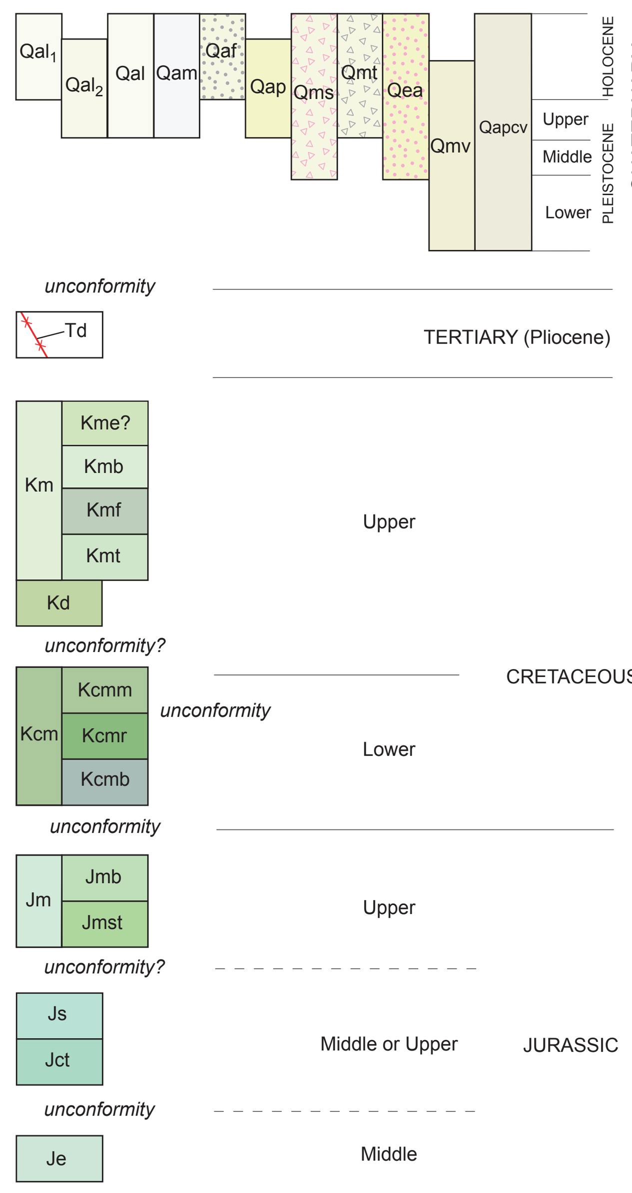
Jmst — **Salt Wash and Tidwell Members, undifferentiated** (Upper Jurassic, Kimmeridgian) – Red and red-brown shale, siltstone, and sandstone (Tidwell Member) overlain by discontinuous channels of gray, brown, and white sandstone, conglomeratic sandstone, and conglomerate (Salt Wash Member); sandstone is very fine grained to fine grained at base, and coarsens upward, locally becoming gritty and pebbly; forms slopes and ledges with the ledges becoming more lenticular toward the top; lower contact marked by change from red to light brown and medium brown of the Summerville Formation; 175 to 200 feet (50-60 m) thick.

Js — **Summerville Formation** (Upper Jurassic, Oxfordian) – Brown sandstone and siltstone interbedded with subordinate, thin white beds of fine-grained, thin- to medium-bedded sandstone; forms steep slopes; about 210 to 260 feet (64-80 m) thick.

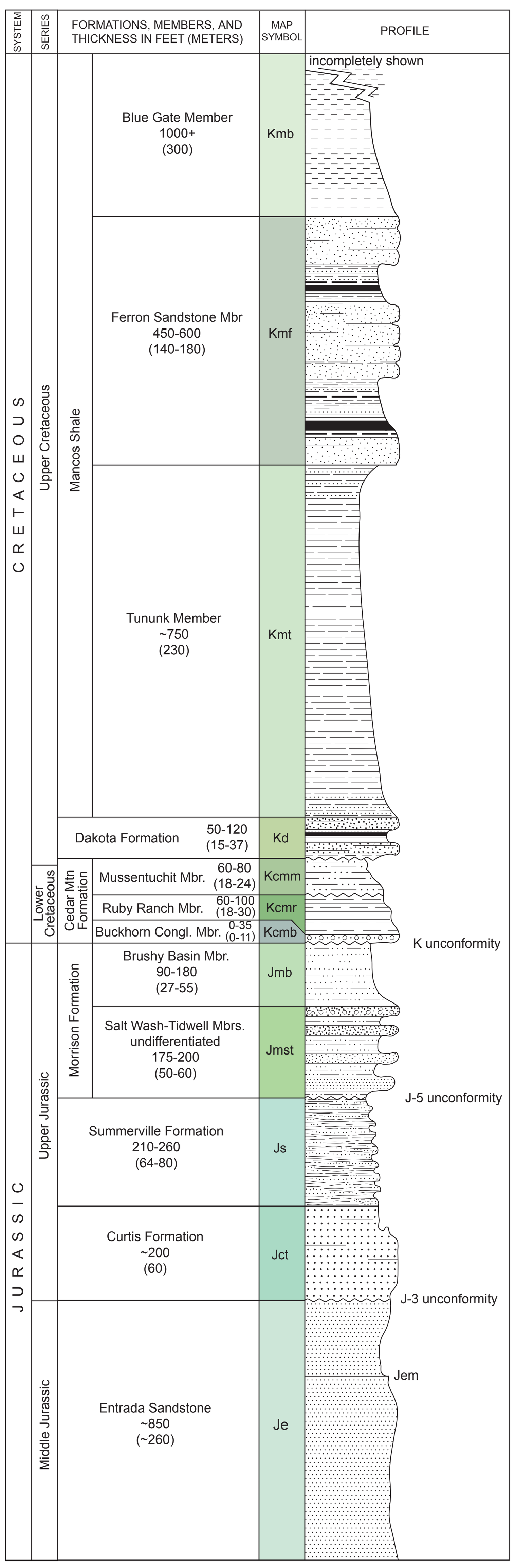
Jct — **Curtis Formation** (Upper Jurassic, Oxfordian) – Light-gray to light-green-gray glauconitic sandstone, siltstone, and rare basal conglomerate; fine to coarse grained, fining upward; poorly to well sorted and becomes mostly well sorted toward top; upper 70 feet (20 m) less resistant, forms ledgy, steep slope; lower 130 feet (40 m) more resistant and forms cliff; about 200 feet (60 m) thick.

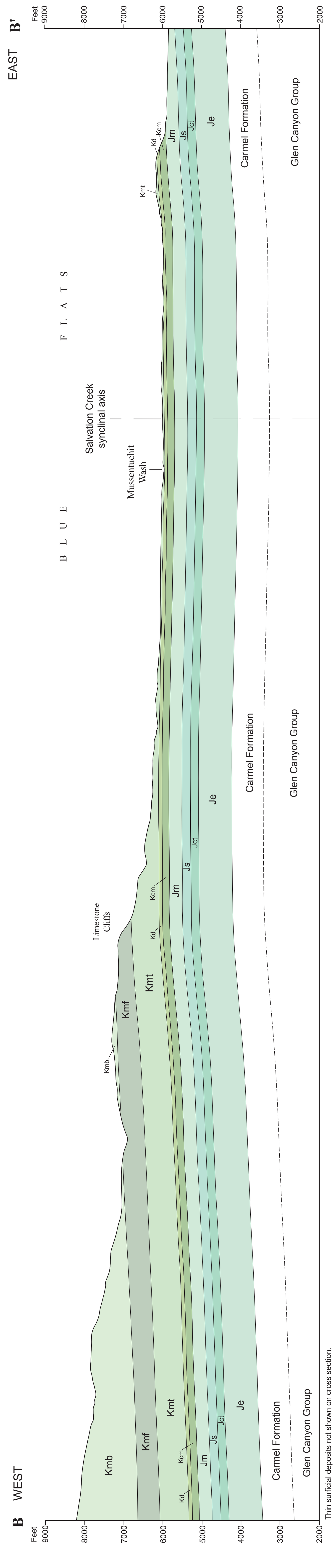
Je / Jem — **Entrada Sandstone** (Middle Jurassic, Callovian) – Orange-brown to brown, silty sandstone and subordinate siltstone, very fine to fine grained with scattered medium or coarse grains; thin bedded to massive; weathers into cliffs or rounded, ledgy slopes; contains a white, fine-grained sandstone marker bed (Jem) about 160 feet (50 m) below top of formation; incompletely exposed in quadrangle; 530 feet (160 m) measured, but complete thickness is about 850 feet (260 m).

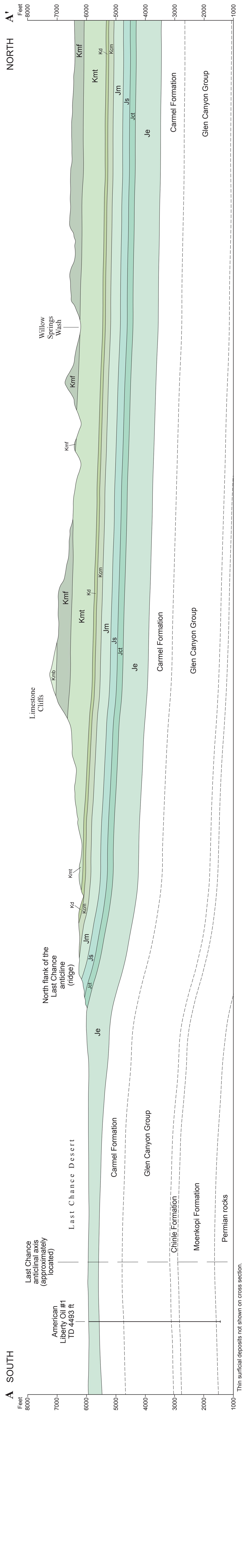
CORRELATION OF MAP UNITS



LITHOLOGIC COLUMN

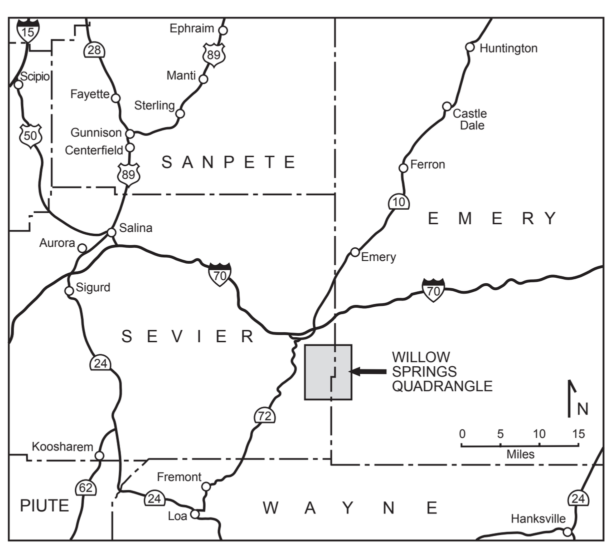






MAP SYMBOLS

- Contact – dashed where approximately located
- Normal fault – bar and ball on downthrown side; dotted where concealed
- Mass-movement scarp – hachures on downdropped side; dashed where approximately located
- Structure contour – contour interval 100 feet (30 m), drawn on base of Dakota Formation; short dash where contour is projected above ground surface; long dash where approximate
- Axial trace of anticline – showing plunge; dotted where concealed
- Axial trace of syncline – showing plunge; dotted where concealed
- A —— A' Line of cross section
- 12 Strike and dip of bedding
- Dry hole – oil and gas exploration well
- Show of oil
- Show of gas
- Mine
- Abandoned mine adit



Location of the Willow Springs quadrangle in central Utah.