Characterization of Evaporite Karst Features in the Southern Laramie Basin, Wyoming

Alan J. Ver Ploeg, Martin C. Larsen, and Karl G. Taboga

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Director and State Geologist Thomas A. Drean

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James R. Rodgers

Water filled collapse feature west of Lone Tree Creek sinkhole complex on Antelope Creek. Collapse is due to gypsum removal in the subsurface by both groundwater and surface water. *Photo by Alan Ver Ploeg, September 11, 2012.*

Cover photo: Alan Ver Ploeg with open sinkhole in the Lone Tree Creek sinkhole complex taken on the date of discovery, July 20, 2012. *Photo by field assistant Davin Bagdonas, 2012.*

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Alan J. Ver Ploeg, Martin C. Larsen, and Karl G. Taboga

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Table of Contents

List of Plates

(Paper copies contained in separate pocket)

List of Figures

INTRODUCTION

Karst topography is a landscape class typically marked by the presence of sinkholes, caves, disappearing streams, and springs (fig. 1). Karst geology and associated sinkholes are found throughout the world and in some instances can pose a threat to property and human safety. It is estimated that karst topography occurs over nearly 20 percent of the continental U.S. (USGS, 2013) and that geologic deposits capable of hosting karstic features are found in significant portions of the Western Great Plains and the Rocky Mountains (Johnson, 2008). Although these deposits underlie large areas of Wyoming, including the Laramie Basin, karst topography typically occurs in isolated areas because it develops only in the presence of specific hydrogeologic conditions. It is important to understand where these conditions exist, potentially creating geologic hazards and associated risk to people and infrastructure.

Johnson (2008) lists four requirements for the development of gypsum karst: 1) the presence of a gypsum deposit; 2) a water supply unsaturated with $CaSO_4$; 3) outlets that discharge the water-evaporite solution; and 4) energy, in this case a hydraulic gradient. Although much of Wyoming is underlain with evaporite deposits (Johnson, 1997), the area known to be affected by karstic features is much smaller because one or more of the three hydrologic conditions has been absent (See figure 1 in Johnson, 2008).

While completing geologic maps with funding from the U.S. Geological Survey (USGS) National Cooperative Geologic Mapping Program, Wyoming State Geological Survey (WSGS) geologists recognized the presence of evaporite karst features, including gypsite deposits and sinkholes, in and near the city of Laramie, as well as elsewhere in the southern Laramie Basin. A review of early aerial photography also documented the occurrence of sinkholes in some areas of Laramie where residential developments now exist. The recognition of existing karstic terrains and the realization that other areas within the basin have similar geologic conditions that favor sinkhole development indicated a need for a study describing and characterizing the identified karst features in the southern Laramie Basin (pl. 1).

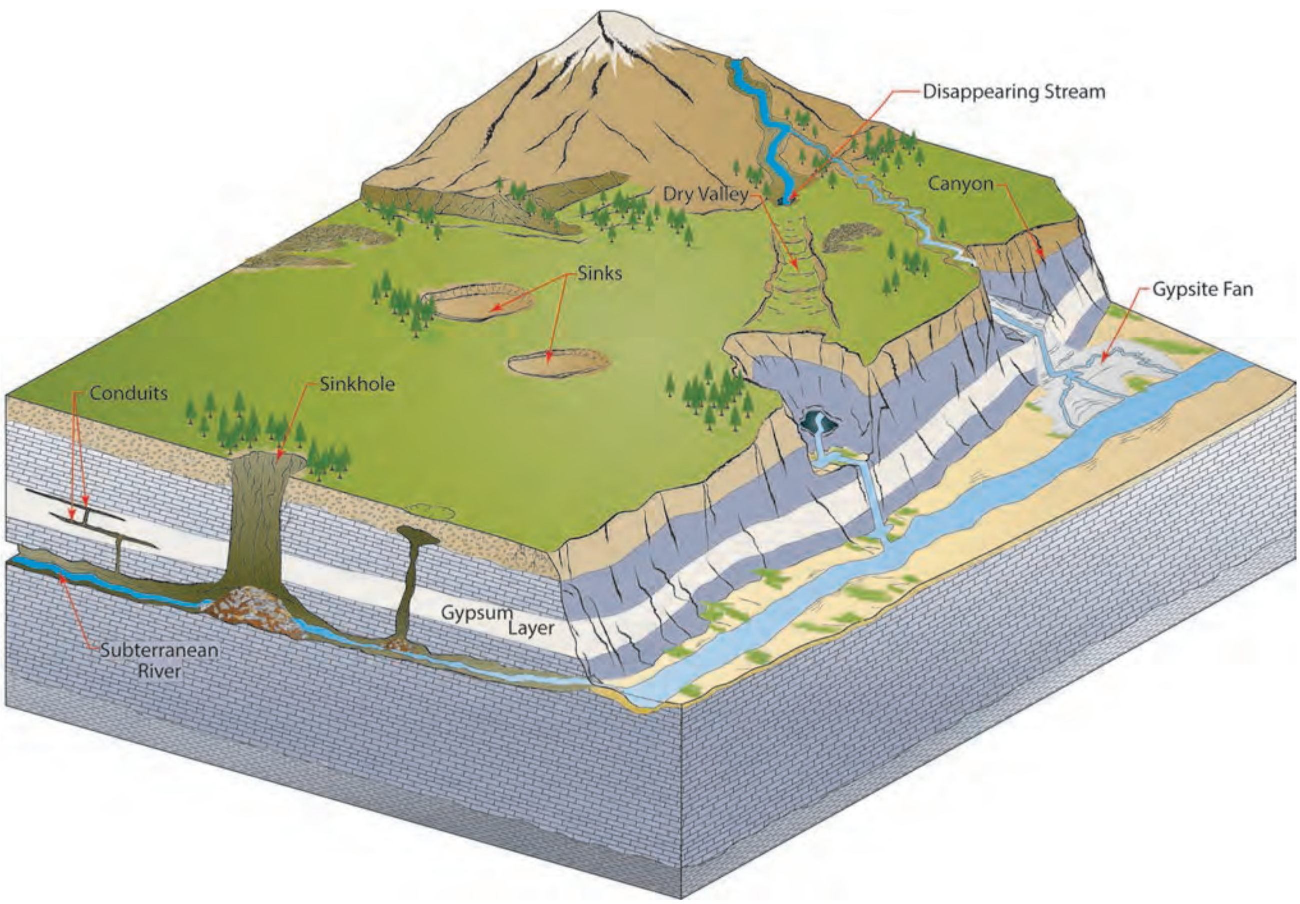

Figure 1. Block diagram illustrating various types of features associated with karst development.

BACKGROUND

The development of karst features requires the flow of naturally occurring mildly acidic groundwater through soluble rock materials such as limestone, dolomite, and evaporites. One way groundwater is made acidic is when infiltrating rainwater interacts with atmospheric carbon dioxide to form mild solutions of carbonic acid. Soluble rocks generally have low levels of intergranular porosity and groundwater preferentially flows through naturally occurring joints and fractures. Over time, the flowing groundwater enlarges the fracture opening, or aperture, by dissolving the adjacent rock. Concurrently, the magnitude of groundwater flow increases in the enlarged fracture, dissolution rates rise, and the affected fracture grows larger still. Eventually, the continual cycle of synchronous dissolution and increased circulation produces enhanced underground drainage systems composed of subterranean caves, piping, and solution-enlarged bedding planes and fractures. Commonly, structural failure occurs as overlying rock collapses into the subterranean caverns. Sinkholes develop when geo-material collapse continues to the land's surface.

Because karst formation requires the presence of flowing water, it is important to understand the source of the groundwater that forms the underground conduits and cavities that lead to sinkhole development. Karst features may have developed under current hydrogeologic and climatic conditions, or can simply reflect the wetter climate and the hydrogeological conditions of earlier times such as the Pleistocene and pre-Pleistocene epochs in Wyoming. In some cases, groundwater flows from its area of origin through rock fractures to form karst in soluble geologic formations several miles distant. Evaporite beds are sedimentary deposits that form as naturally occurring salts precipitate out of evaporating water including seawater. Over time and under the right conditions, evaporite minerals such as gypsum, halite, and anhydrite may form geospatially extensive beds that may be tens of feet thick. Widespread episodes of evaporite formation in the Laramie Basin took place on extensive, shallow marine platforms during the Permian and Triassic Periods, 300 to 200 million years ago.

Gypsum is a valued multipurpose mineral that is used in the manufacture of agricultural fertilizers and construction materials such as plaster, wallboard and Portland cement. However, high amounts of gypsum in the soil can inhibit plant growth and can react with untreated concrete causing disintegration. Two classes of gypsum have been identified in the southern Laramie Basin: gypsite and rock gypsum (Darton and Siebenthal, 1909). Both types have been quarried near Laramie. Rock gypsum is a grayish to white colored mineral that comes in various forms such as alabaster, satin spar, and selenite (fig. 2). In contrast, gypsite deposits contain an abundance of the mineral gypsum along with other trace elements that are commonly mixed with alluvial and eolian sediments. The uses of mined gypsite are similar to those for gypsum. Sonnenfeld (1984) developed a three part classification system for gypsite deposits based on methods of emplacement: 1) spring related deposits with gypsum saturated groundwater transported to the surface and precipitating out down gradient; 2) blanket deposits with downward leaching of gypsum in soils, eventually forming crusts within the soil; and 3) eolian deposits derived from eroding soil crusts or playa deposits to form gypsum dunes by prevailing winds. Another form of blanket deposit can occur when surface or near surface gypsum outcrops are broken down and distributed across the land by weathering or erosion. Gypsite deposits often result from a combination of these processes.

Due to their solubility, evaporite minerals have faster dissolution rates and lower mechanical strengths than carbonate rocks. Gypsum and gypsite are highly soluble in water making them exceptionally vulnerable for karst development. Once in solution, gypsum becomes mobile and can easily be transported by subsurface conduits (faults, fractures, piping, bedding planes and joints). In the subsurface, karstification proceeds slowly, driven by continuous geomorphic and hydrological processes. However, shallow evaporite deposits exposed to infiltrating surface water and precipitation are subject to accelerated dissolution and collapse, leading over time to karst development. Because evaporites are more soluble, evaporite karst environments are generally more sensitive to changes in local hydrologic conditions than carbonate karsts. Human activities that alter the natural flow of groundwater and surface water such as irrigation, groundwater extraction, wastewater management and stormwater drainage can trigger rapid changes in karst systems.

Karst systems can hinder human activity in manners that range in severity from minor easily mitigated occurrences to serious, life-threatening hazards. Sinkholes, for instance, can pose significant risk to property, people and infrastructure. The acute hazards associated with sinkhole development often appear suddenly and can be quite dramatic. Roads and buildings collapse abruptly, humans and animals are injured as seemingly solid ground gives way, and ponds and lakes drain into the ground without warning.

Other hazards associated with karst systems may appear gradually. Ground subsidence can cause sidewalks, streets, and curbs to heave, subside, and crack. Underground utilities such as electrical transmission and sewer lines can be ruptured. Pollutants can be conveyed quickly through aquifers by well-developed but previously unidentified karst systems. An environmental concern associated with karst terrain is the heightened potential that groundwater contamination from Underground Storage Tank (UST) releases can easily move through aquifers along horizontal conduits or piping within gypsum beds or gypsite deposits.

Figure 2. Examples of the forms of gypsum found in the southern Laramie Basin: a) alabaster-a fine granular form of gypsum commonly found in outcrop, b) gypsite-an erosional form of gypsum often mixed with clay, sand, and gravel, c) satin spar-crystalline form of gypsum (larger crystalline form is selenite).

Collapse features that appear relatively quickly can also be caused by sewer or water line leaks within evaporite units. Damage to sidewalks and roads, associated with underground piping and storm water infiltration in underlying or surface gypsite deposits, is not uncommon within the City of Laramie (Jarvis and Huntoon, 2003), (pl. 2). Many houses within the Laramie area that were constructed on gypsite deposits were built without basements because of alkali decay and bulking of the concrete foundations caused by the gypsite.

GEOLOGIC AND HYDROLOGIC SETTING

The Laramie Basin is a Laramide synclinal depression located in southeastern Wyoming. It is bounded on the west by the Medicine Bow Mountains, on the north by the Como Bluff anticline, and on the east by the Laramie Mountains (fig. 3). The syncline is asymmetrical with the steeper limb on the west side. Basin asymmetry resulted from east-verging movement on the Medicine Bow uplift, a reverse-faulted structure which overrode and folded the sedimentary rocks on the western flank of the basin. The eastern flank of the basin is characterized by shallower dips of the sediments on the western flank of the Laramie Mountains. Within the basin are several typical north to south trending Laramide-aged anticlinal structures that are mostly verging eastward out-of-the-basin, i.e., toward the east flank and commonly bounded on the east or steep limb with high angle reverse faults. In addition to this Laramide reverse or thrust faulting, faults with significant strike-slip components are present (Stone, 1995). The location and character of the structural features on the western flank of the Laramie Mountains and the southern part of the Laramie basin can be instrumental in predicting the presence of potential evaporate related karst geologic hazards in the Laramie area.

Sedimentary rocks within the Laramie Basin range from Pennsylvanian to Quaternary in age and include formations from the Pennsylvanian Fountain Formation to the Tertiary Wind River Formation (fig. 4). In the northern part of the basin, the total thickness of the sedimentary section is approximately 14,500 feet, including the Wind River Formation down to the base of the Casper/Fountain Formation. In the study area, the thickness of the sedimentary section is closer to 2,200 feet. The units of primary interest in this study due to their gypsum content are the Permian Satanka Shale, the Permian Forelle Limestone, and the Triassic/Permian Chugwater Formation as defined by Darton and Seibenthal (1909). These units are illustrated, including lithology, on the type-log (fig. 5).

The general hydrogeology of the Laramie basin is characteristic of other Laramide structural basins that occur widely throughout Wyoming (Huntoon, 1983). Typically,

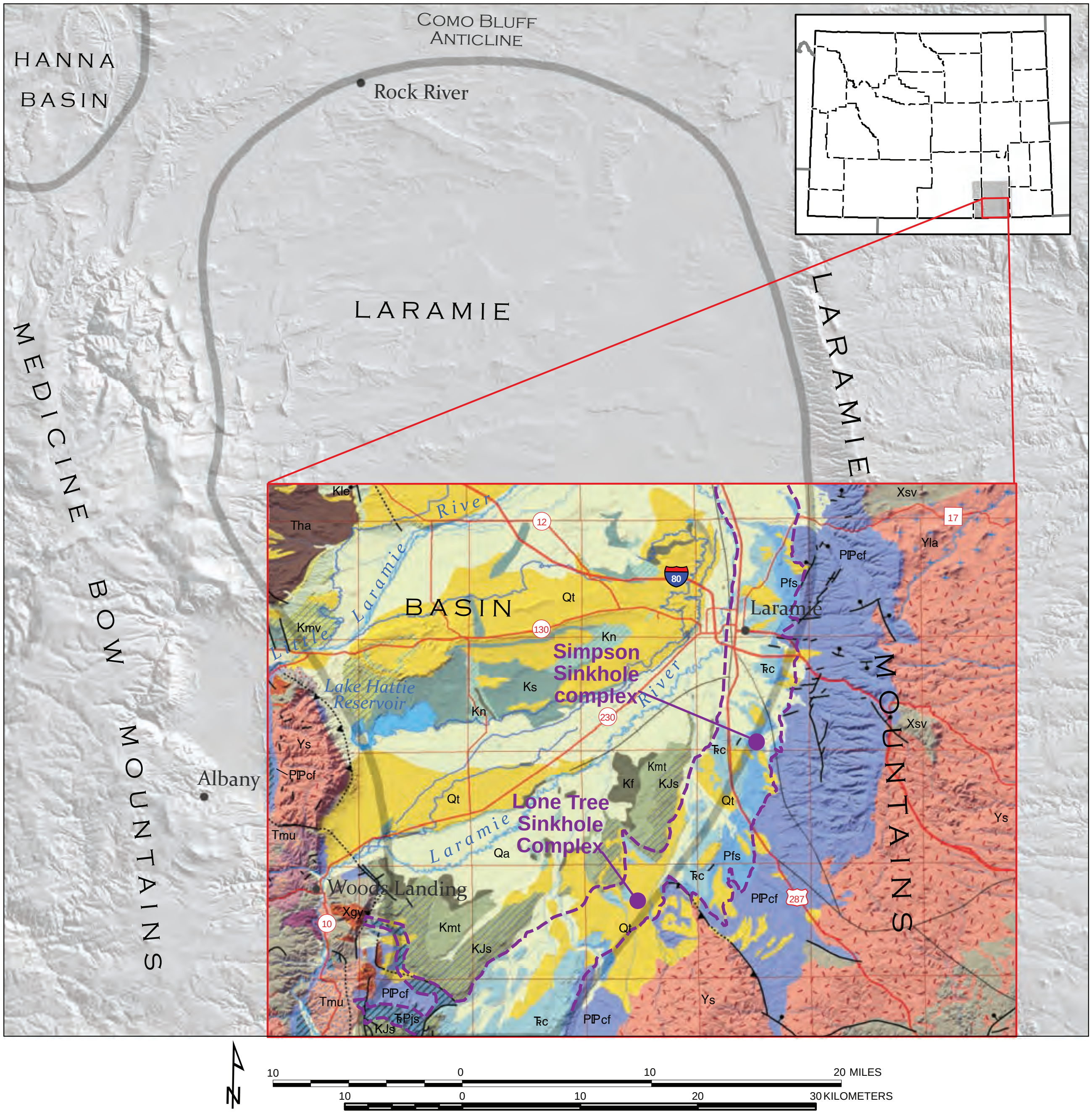

Figure 3. Location map showing southern Laramie Basin evaporite karst study area. Outcrops with gypsum occurrences and the observed sinkholes are delineated with the dashed purple lines.

groundwater in Laramide basin bedrock aquifers originates in the surrounding mountain ranges as infiltrating precipitation, or recharge, into Paleozoic and early Mesozoic sedimentary aquifers that outcrop along the mountain flanks and along the perimeters of the adjacent structural basin. Groundwater circulation, controlled by the basinward dip of these aquifers, is strongly influenced by geologic structures such as large displacement thrust faults, reverse-fault-cored anticlines, and associated fractures that developed during Laramide compressional deformation (Huntoon, 1993).

For a more detailed discussion of the stratigraphy, structure and hydrologic characterization of the southern Laramie basin, see Appendix A.

STRATIGRAPHIC NOMENCLATURE CHART OF THE HANNA AND LARAMIE BASINS, WYOMING

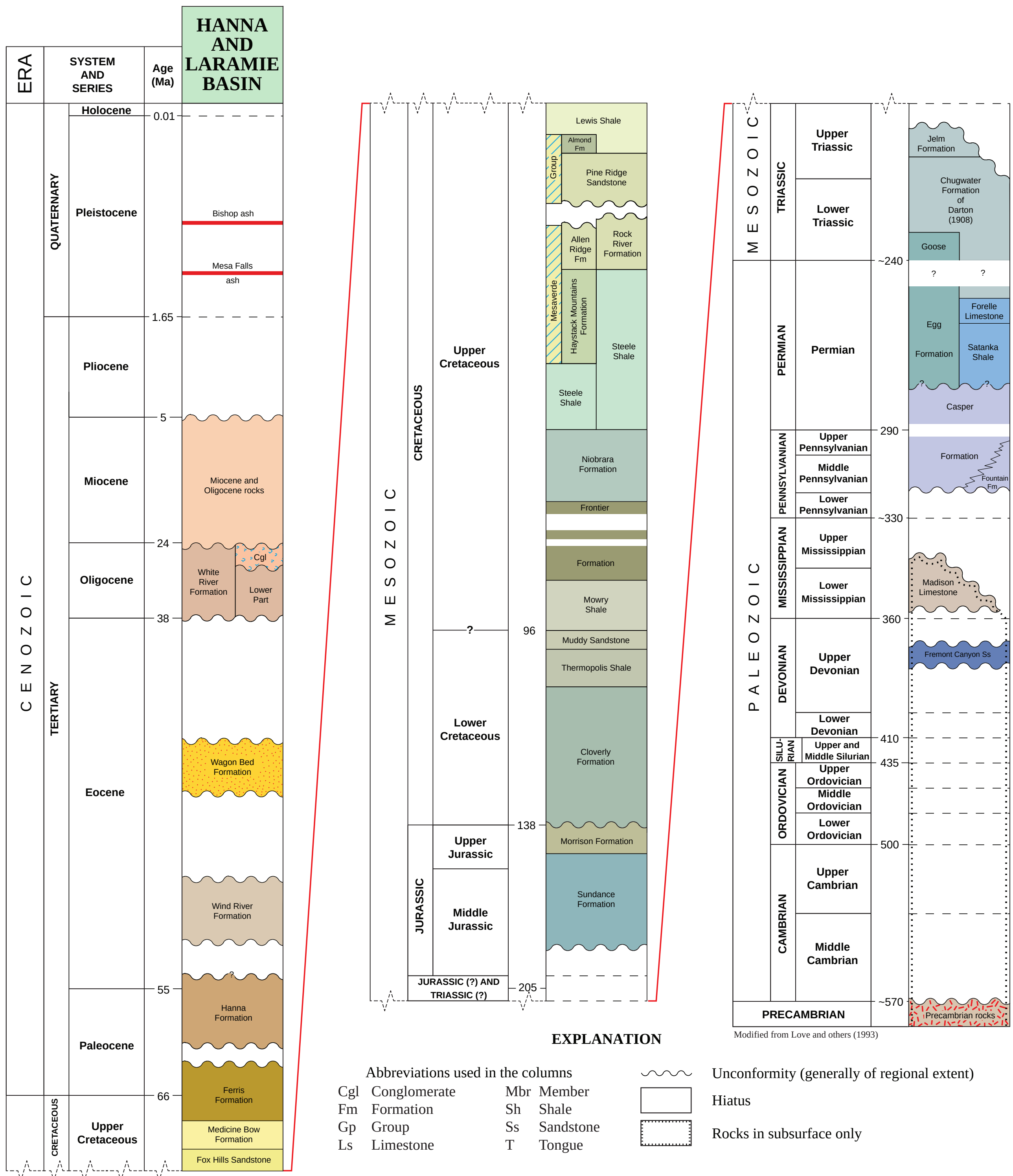

Figure 4. Stratigraphic nomenclature chart for Laramie and Hanna Basins.

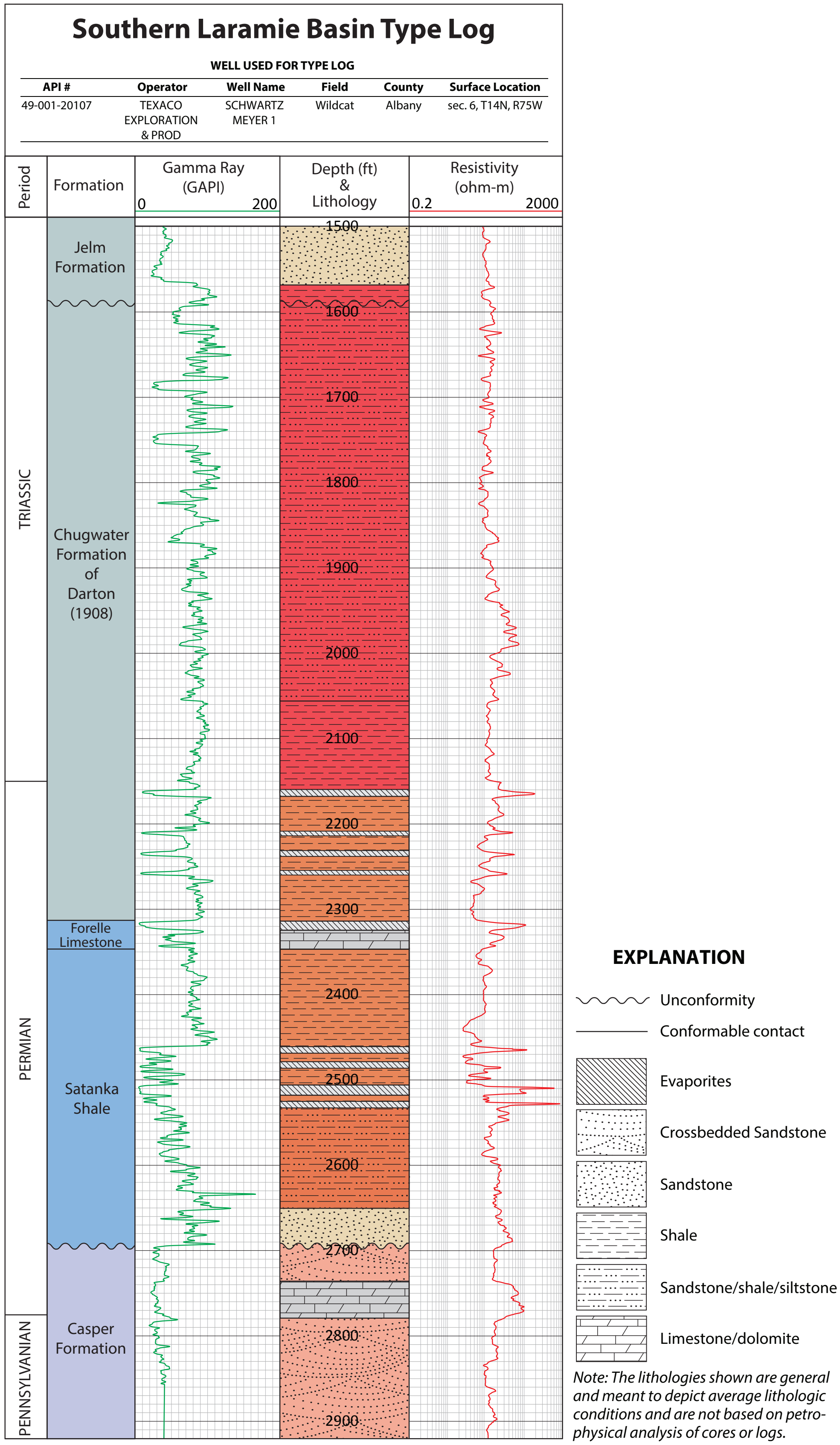

Figure 5. Type electric log showing log character and lithology for gypsum bearing formations in the southern Laramie Basin.

GYPSITE DEPOSITS

The WSGS has mapped numerous gypsite deposits (pl. 1) on the eastern and southern flanks of the Laramie basin. For the most part, these deposits are sourced by the gypsum beds in the lower Chugwater Formation. Gypsum beds in the lower Chugwater Formation are 10 feet or less in thickness (fig. 5); in areas where they have been exposed, these thin gypsum beds have been reworked by wind and water erosion to form gypsite fan deposits. These deposits are especially common in and around Laramie (pl. 2). Gypsite occurs in extensive fan deposits west of the Laramie fault which placed lower Chugwater gypsum beds near to the surface. Moreover, springs associated with the Laramie fault brought additional gypsum in solution to the surface; the dissolved gypsum then precipitated out down gradient and further enriched these fan deposits. The large gypsite deposit along the Spring Creek drainage in south Laramie (pl. 2) down gradient of the Laramie fault was probably deposited by a combination of spring discharge and erosion of near surface gypsum beds. Several springs still discharge in that area.

In addition to the Spring Creek area, WSGS has mapped other Chugwater-sourced gypsite fan deposits along much of the extent of the Laramie Fault trace. Extensive gypsite fans are found along the Soldier Creek drainage; in a large area of central Laramie that extends for one mile northward from the University of Wyoming campus that includes LaBonte Park and the Laramie High School; and in two rural areas, three miles and eight miles north of the city respectively. At each of these sites, the largest parts of these deposits are emplaced west of the Laramie fault (pl. 2). Portions of the gypsite deposits near the Spring Creek drainage and the area near the Laramie High School were mined as late as the 1940s (fig. 6). Housing and commercial developments now cover most of these gypsite deposits. LaBonte Lake, located in the central Laramie deposit, has been described by Jarvis and Huntoon (2003) as a evaporite karst collapse feature, with localized piping creating cavities and eventual collapse. Historical accounts from local residents indicate that the area around LaBonte Lake may have been mined for gypsum and 1947 aerial photography show stockpiles of quarried gypsum immediately northeast of LaBonte Lake, as well as an active gypsite quarry approximately a half mile to the east. The LaBonte Lake feature may be a result of both natural and man-made activity.

Recent construction excavations immediately north of the University campus exposed relatively pure gypsite deposits that started below a thin layer of surface soil and extended to the full depth of the excavation, 6-7 feet below ground surface (fig. 7). Descriptions of the south Laramie gypsite mining operation along Spring Creek (Slosson and Moudy, 1900) placed the thickness of the gypsite deposit at 9 feet. This is generally consistent with the observed thickness of the lower Chugwater gypsum beds proposed as the source for the gypsite deposits. The high solubility of the gypsum in these deposits makes them quite susceptible to the formation of cavities, piping and local resultant collapse features. The location of these gypsite deposits should be considered during future development planning within the areas of occurrence.

A number of the gypsite deposits along the basin's southern flank are sourced from gypsum layers in the upper Satanka Shale. The gypsite deposits mapped near the intersection of Sand Creek road and Sportsman Lake road (pl. 3) and southeast of Red Buttes Station (pl. 4) are typical examples of gypsite deposits sourced by Satanka gypsum beds.

OCCURRENCES AND COMMERCIAL DEVELOPMENT OF GYPSUM AND GYPSITE IN SOUTHERN LARAMIE BASIN

Based on correlation of well logs from the southwest corner of the basin to the Laramie area, gypsum beds identified in the Satanka, Forelle, and Chugwater formations are relatively continuous across the study area with some variations in thickness (fig. 8). A thick, massive gypsum unit interbedded with thin shale units described in the upper Satanka Shale, 50 to 100 feet below the Forelle Limestone, is traceable across the basin. Some thinning occurs from a maximum of 60 feet in the southwest corner of the study area near Red Mountain (fig. 9), to about 20 feet near Laramie, as shown in the well logs of the Airport and University wells in the Laramie area (fig. 8). The gypsum interbedded with the limestone in the Forelle is consistently present across the basin with little change in thickness. Three 10 foot gypsum beds in the lower Chugwater are identified in the same stratigraphic position and thicknesses across the basin.

Mining of rock gypsum and gypsite in the southern Laramie basin began in the late 1800s and continued into the early 1900s. Gypsum beds in the Satanka Shale are thick and pure enough for economic recovery. Mountain Cement Company is currently mining a massive 20 foot gypsum bed in the Red Buttes area (pls. 1 and 4), using the gypsum as an additive in cement production. Gypsum was originally mined in the Laramie area by Consolidated Plaster Company beginning in 1890 for the production of stucco and plaster (Darton and Siebenthal, 1909). Mountain Cement Company mined this same upper Satanka gypsum unit east of Red Mountain (fig. 9) in the late 20th century. The Red Mountain gypsum unit is massive (up to 60 feet thick) with thin red shale and limestone interbeds. The outcrop occurs approximately 50-60 feet below the overlying Forelle Limestone and represents the thickest occurrence of bedded gypsum in the southern Laramie basin. A stratigraphically equivalent Satanka gypsum bed, located 4 miles north of Laramie in the SW ¼ of Section 2, T. 16 N., R. 73 W., was mined for a short time in the early 1900s. The gypsum bed in this location is about 40-50 feet below the base of the Forelle Limestone and has a thickness of 10 feet.

South of the City of Laramie, the Standard Plaster Cement Company began mining gypsum rich gypsite deposits in 1896 and by 1900 were producing 2,500 tons per year (pl. 2 and fig. 6). The deposit is described as 9 feet thick with about 7 feet being over 90 percent pure and the lower 2 feet of gypsite is interbedded with clay and gravel (Slosson and Moudy, 1900). Evidence from 1947 aerial photography suggests that a deposit on the north side of Laramie was being mined at that time (fig. 6).

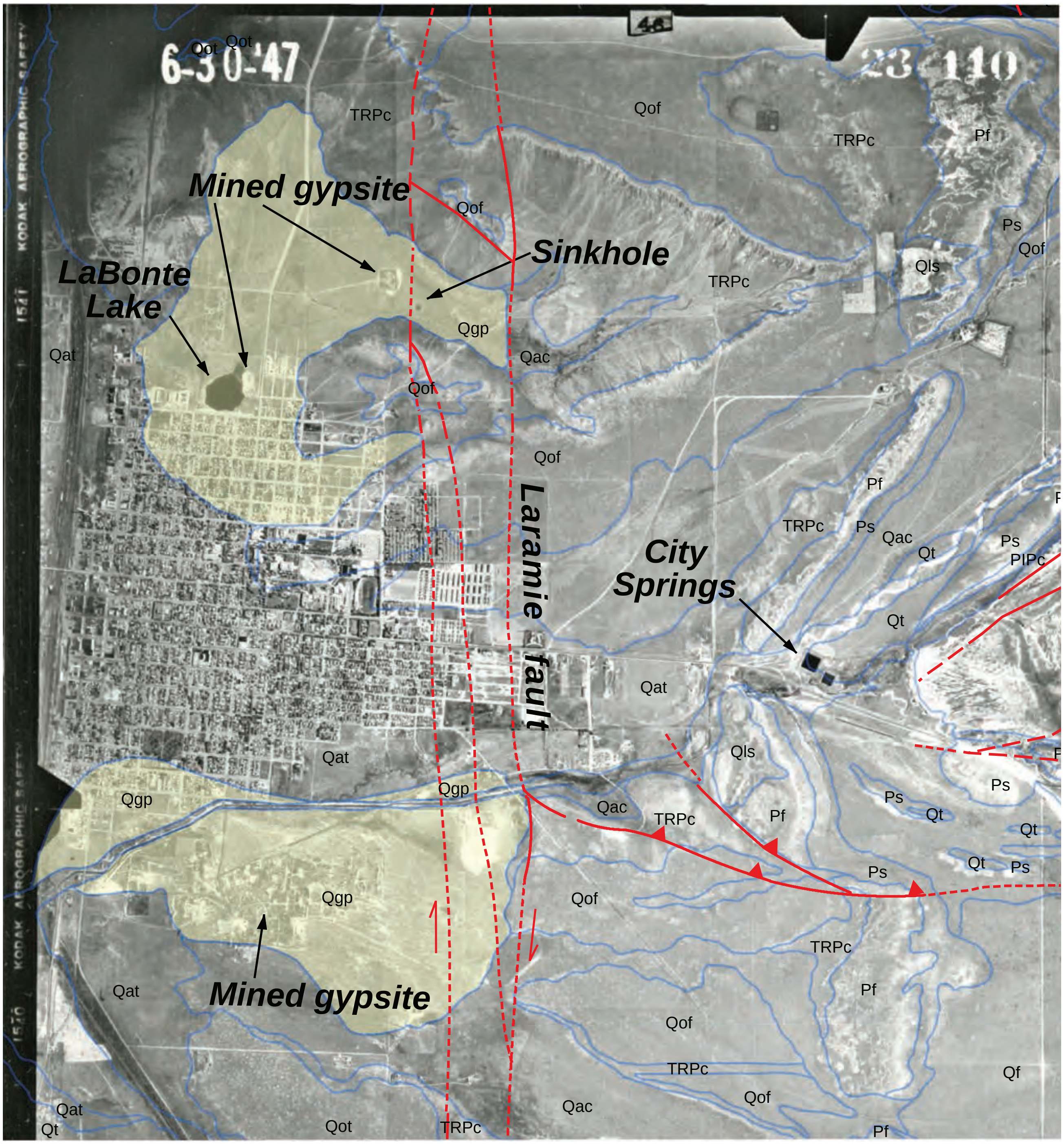

Figure 6. 1947 aerial photograph of the Laramie area showing the Laramie fault, geology, and gypsite related features.

Figure 7. Examples of street damage due to underlying gypsite and excavations showing gypsite deposits in the city of Laramie: a) excavation at intersection of 11th and Flint Streets showing gypsite with thin red clay interbeds to a depth of 6 feet, b) street damage north of UW campus due to underlying gypsite beds removed by surface water, c) excavation north of UW campus showing white gypsite deposit to the bottom of the trench 6-7 feet, d) street damage (asphalt collapse and hole) due to surface water removal of underlying gypsite, and e) broken water line near 10th and Flint Streets due to removal of gypsite and backfill with gravel after the repair.

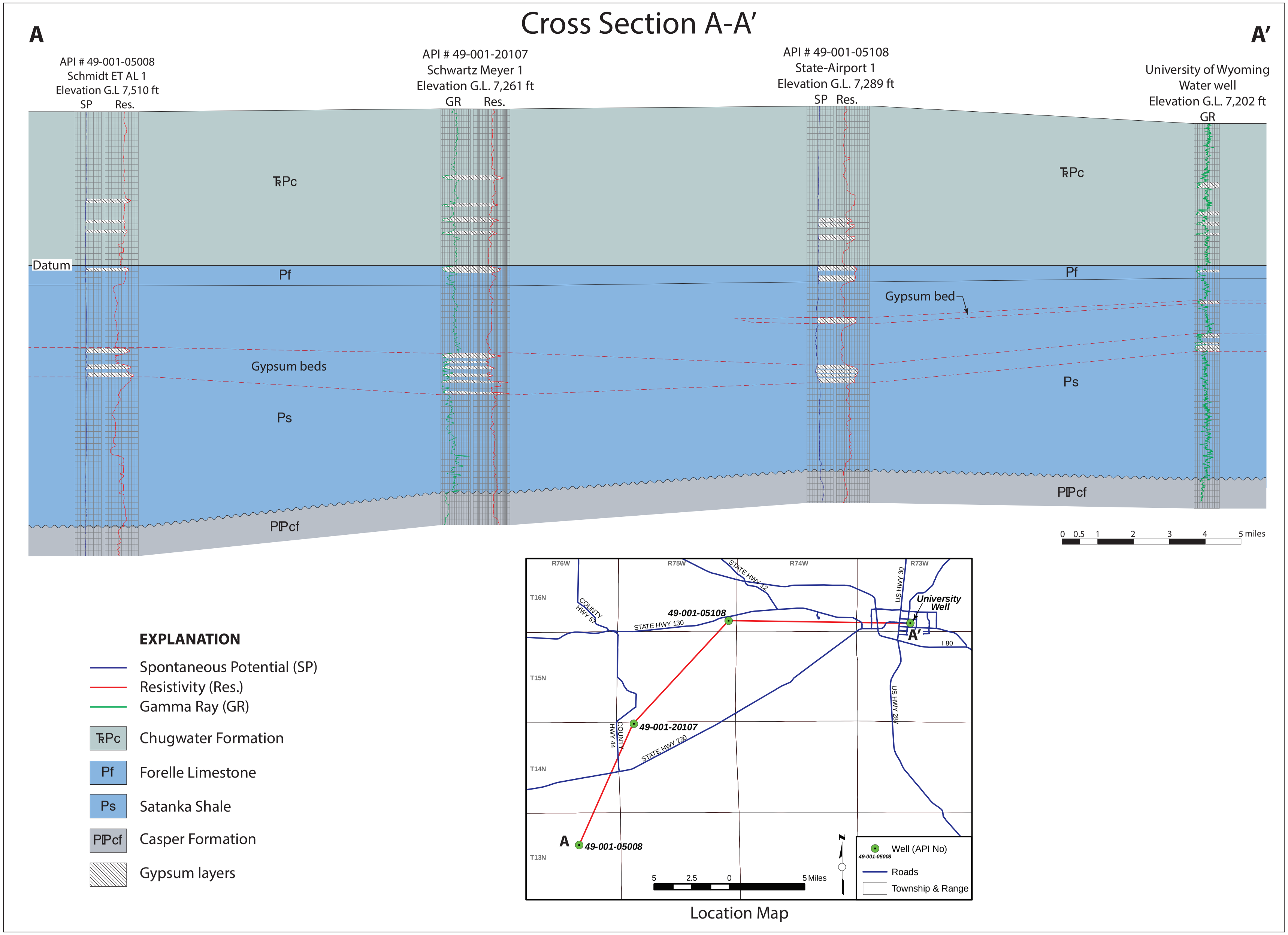

Figure 8. Electric log cross-section from the southwest corner of Laramie Basin to the University of Wyoming campus illustrating stratigraphic variation of gypsum bed occurrences across the study area.

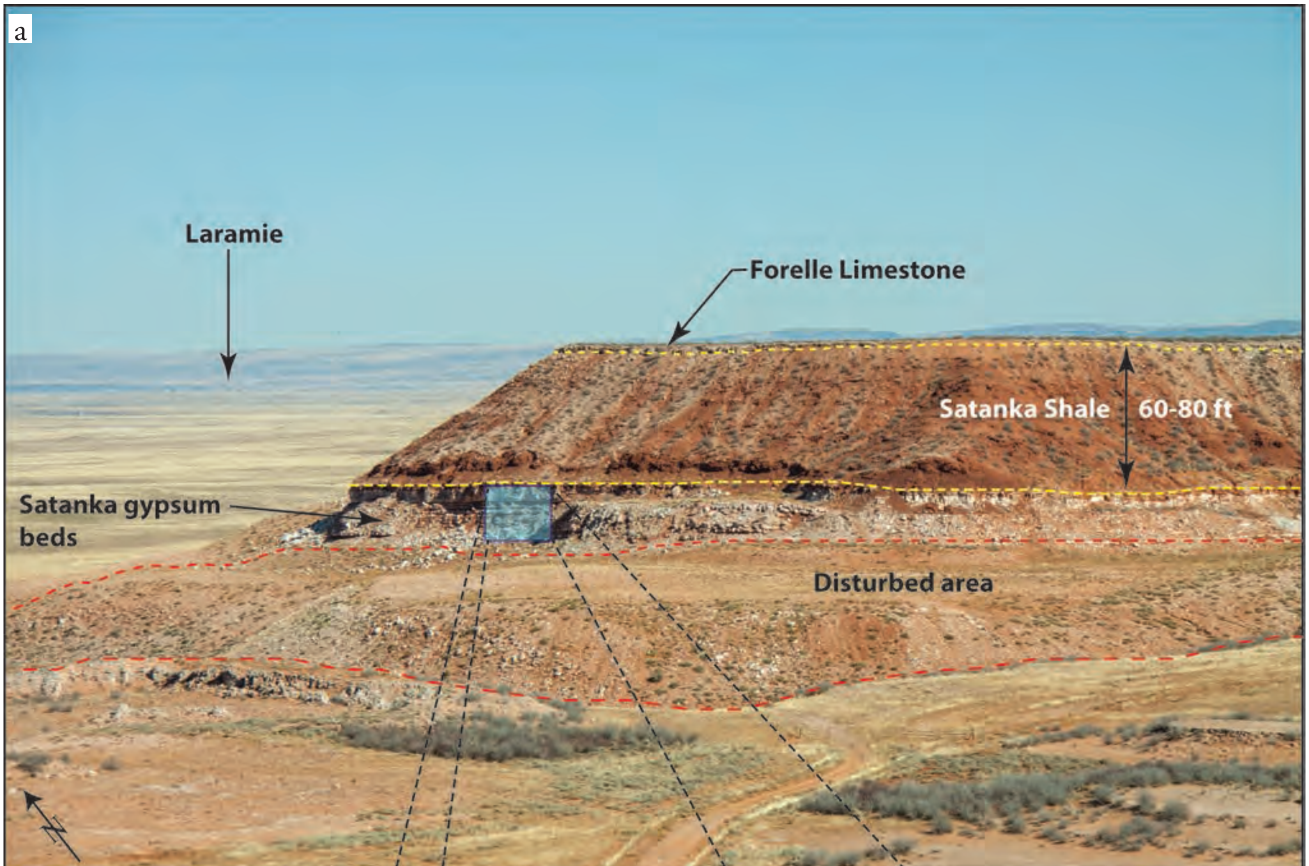

Figure 9. View of abandoned Red Mountain gypsum quarry, southwest corner of the Laramie Basin, showing Satanka Shale gysum beds in outcrop: a) overview of quarry with Satanka Shale gypsum outcrop, b) close-up of gypsum outcrop showing gypsum beds with thin shale interbeds, c) sample of alabaster form of gypsum from outcrop.

EVAPORITE KARST FEATURES IDENTIFIED IN THE SOUTHERN LARAMIE BASIN

WSGS geologists have identified sinkholes in various stages of development outside of the Laramie city limits in the southern Laramie basin. Gypsum layers within the Permian Satanka, Forelle, and lower Chugwater exposed at or near the surface and the known gypsite deposits within the southern Laramie basin may be prone to the development of karst features and the problems associated with them.

In 2012, while mapping the geology of the Johnson Ranch Quadrangle, the WSGS identified a significant sinkhole complex on state owned land about 16 miles southwest of Laramie (cover photo). Further investigation revealed that geologic and hydrogeologic conditions at this sinkhole are remarkably similar to those described at a sinkhole discovered in 1994 near Simpson Springs Creek, 5 miles southeast of Laramie. Western Water Consultants (WWC) of Laramie investigated the Simpson Springs sinkhole and provided a report of findings to the City of Laramie (Moody, 1994). The two sinkholes are nearly identical in character.They both appear in the same part of the geologic section, have similar dimensions, and occur near similar structural features that could focus the flow of groundwater required for karst formation.

Previous work in the southern Laramie basin has also focused on the distribution of gypsite deposits in the

Laramie area, and the physical and environmental hazards they pose. Jarvis and Huntoon (2003) used historical aerial photos, topographic maps, and subsurface shallow geophysical investigations to determine that LaBonte Lake (fig. 6 and pl. 2) in north Laramie originated as a subsidence feature formed by karstic piping and the subsequent dissolution of gypsite. Of more practical concern to Laramie residents in some parts of the city, is the damage to gutters, sidewalks, foundations and roads caused by the processes of freeze-thaw, swelling and dissolution of gypsite. Some smaller scale collapse features around Laramie have been caused by sewer and stormwater pipes leaking water directly into gypsite units. Jarvis and Huntoon (2003) determined that the extent and complexity of existing gypsite conduit networks may prevent the isolation and containment of shallow groundwater pollutants, should a contaminant release occur. They mapped the gypsite occurrences within the city of Laramie at a large-scale and attributed them to windblown (eolian) and spring water transport sources.

Sinkholes and related features

Sinkholes identified in the southern Laramie Basin typically progress in a four stage process of evolution (fig. 10). Sinkhole structure typically evolves from an early stoping stage where the cavity has not yet reached the surface (stage 1), to an open configuration when the cavity reaches the ground surface (stage 2), followed by a collapsed phase (stage 3), and finally deposition of erosional sediments and subsequent revegetation (stage 4). In stage 4, subsidence has ceased and the surface is relatively stable.

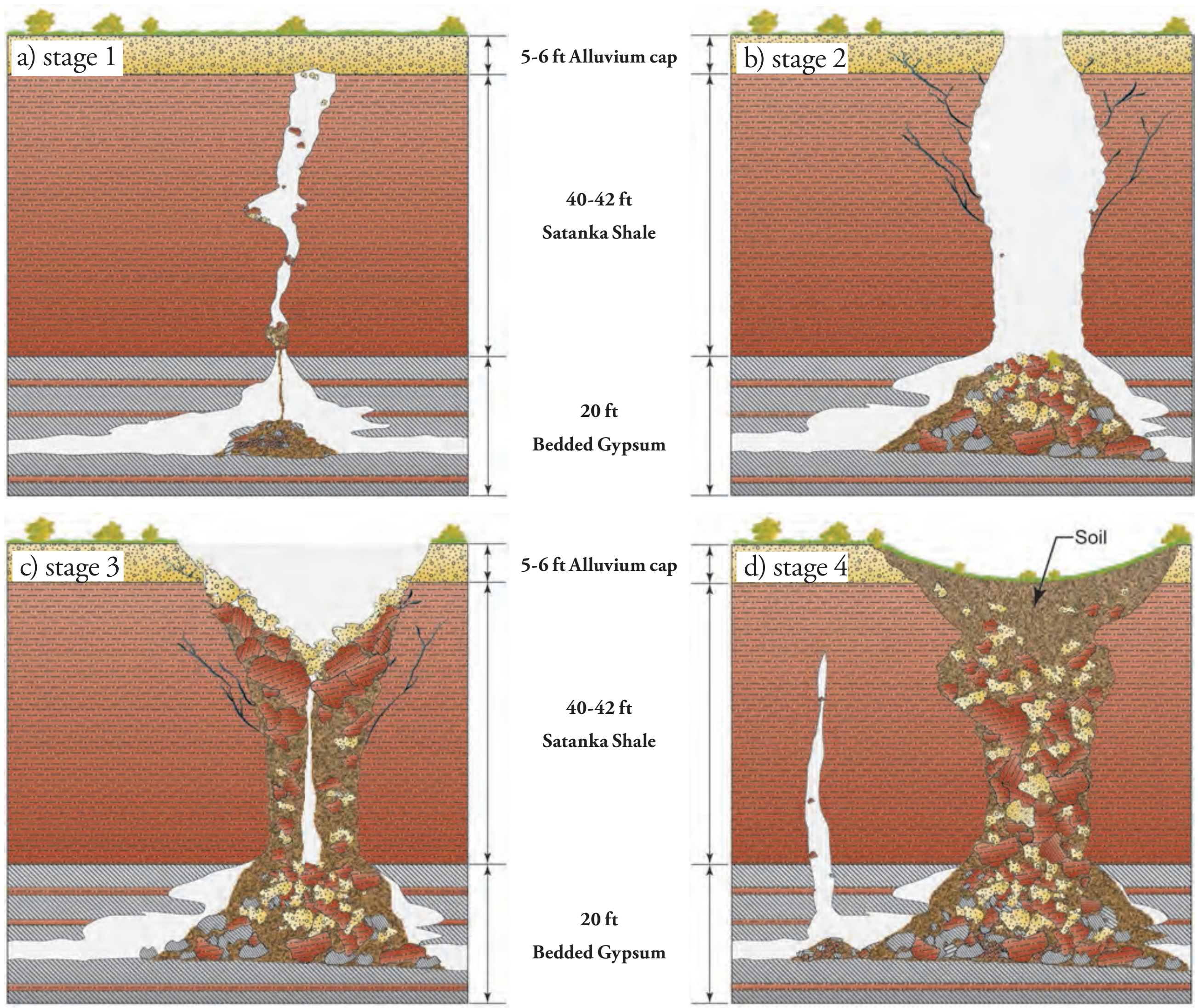

Figure 10. Four stages of sinkhole development based on observation at the Lone Tree sinkhole complex: a) early stage of development with gypsum removal and stoping shale toward the surface (stage 1), b) stoping breaks through at surface with open sinkhole (stage 2), c) sinkhole collapses on itself but is active with material filling the underlying void (stage 3), d) the sinkhole is filled, vegetated over, and currently inactive (stage 4).

The southern Laramie Basin is underlain and rimmed in part by the gypsiferous Permian Satanka Shale, Forelle Limestone and the lower Triassic Chugwater Formation, collectively designated as the Goose Egg Formation in areas adjacent to the southern Laramie Basin (fig. 4). However, sinkholes and other karstic features have been identified only along a small portion of the southeastern margin of the basin (fig. 3 and pl. 1). Furthermore, it is unlikely that sinkholes will develop in areas of the basin where these gypsum bearing formations are more deeply buried because overlying geologic units possess sufficient strength and thickness to resist collapse into the subterranean cavities formed by karstification. To date, the WSGS has identified two major sinkhole complexes within the southern Laramie basin, the Lone Tree Creek and Simpson Springs complexes are described below.

Lone Tree Creek sinkhole complex

In July of 2012, WSGS geologists encountered a previously undocumented open sinkhole (fig. 11a) in the NE1/4 of Section 16 of T.13N., R.74W., between the Lone Tree and Antelope Creek drainages (pl. 3) on the Johnson Ranch Quadrangle approximately 16 miles southwest of Laramie. The opening at the surface was approximately 5-6 feet across, circular in shape, and located on a gravel capped alluvial fan. Visual examination of the opening revealed a large roughly conical cavity that widens with depth. Initial measurements indicated that the cavity was 50-60 feet deep with the bottom sloping toward the east; the sinkhole contained groundwater to within 35 feet of the ground surface. A visual examination from the surface opening indicated that red siltstone debris and other collapsed material rested at the base of the cavity. Above that, the walls of the sinkhole exposed layers of competent Satanka red shale and siltstone that are capped at the surface by approximately 6 feet of gravel fan material.

Shortly after discovery of the Lone Tree Creek sinkhole complex, Davin Bagdonas (WSGS field assistant and co-author on the Johnson Ranch 24K geologic map) conducted a dimensional survey of the open cavity in August of 2012. At the time of measurement, total sinkhole volume was estimated at approximately 362 yd^3 (304.42m^3). In April of 2013, Davin, as part of a geology course project, conducted preliminary microgravity investigation (SCINTREX CG-5 Auto Grav System instrument) above the open sinkhole cavity. A survey line was measured at 207 feet (63 meters) with gravity measurements being taken every 23 feet (7 meters) directly west to east and centered over the sinkhole opening. The observed negative anomaly agreed well with the estimated volume and cavity location along the survey line. As a whole, the survey results were encouraging and this tool could be quite useful for future investigations in sinkhole prone areas, as well as modeling known areas (Bagdonas, 2013).

The sinkhole is located roughly in the center of an extensive area (~ 28 mi^2) of Quaternary alluvial fan deposits that is punctuated by outcrops of underlying bedrock at topographic high points. Roughly 100 feet to the northwest of the sinkhole, small exposures of Forelle Limestone crop out through the alluvial fan material. Rocks in this area strike approximately northeast to southwest and dip at about 5 degrees toward the northwest. Geological structure in the Johnson Ranch Quadrangle is dominated by numerous basement cored faults that are readily observable in bedrock outcrops but concealed by the alluvial fan deposits. The sinkhole lays in close proximity to the convergence of a northwest trending possible reverse/reactivated shear fault with a tear fault that trends southwest from the Boulder Ridge Anticline/Fault (pl. 3).

The sinkhole lies within a roughly circular depression nearly 10 acres in size that is about 15 - 20 feet lower in elevation than the surrounding land surface. The 10 acre depression, comprised of numerous smaller conical depressions that are filled with alluvial gravels, likely represent a complex of sinkholes that have collapsed over time (fig. 11b and fig. 10-stages 2, 3,and 4). Sinkholes in the second through fourth stages of development can be found in this complex and adjacent areas. The open sinkhole described above (stage 2) indicates that subterranean karst cavities (stage 1) are likely developing along the edge of the complex. One stage 3 sinkhole, seen along the northeast edge of the complex, has collapsed on itself and material is still flowing into the conical depression (fig. 11c). The greater part of the complex consists of older collapsed and revegetated sinkholes characteristic of the fourth stage of development. Moreover, two sinkholes on the northwest edge of the large depression appear to be in transition between stages three and four in that they have not yet been fully revegetated.

Other collapse features can be observed along the trace of the Satanka gypsum subcrop in the narrow depression (pl. 3), likely formed by gypsum dissolution from the penetration of surface water through the overlying gravel cap. This narrow depression follows the trace of the gypsum subcrop for over a mile and a half along strike and crosses Antelope Creek to the southwest. The area immediately west of Antelope Creek has collapsed forming a permanent pond of standing water, 800 feet long and 170 feet wide (fig. 11d). On the northwest edge of the ponded collapse feature, above the gypsum subcrop, two smaller sinkhole collapse features are noted. The westernmost sinkhole is in the early stage of revegetation (stage 4), while the sinkhole to the east is still in the third stage of development. It appears that surface water from precipitation and streamflow in Antelope Creek have led to the formation of the ponded feature and the associated sinkholes. Additional outcrop collapse features and weathered gypsum outcrops (gypsite) occur approximately a mile to the northwest. However, these features appear to be sourced by Chugwater gypsum beds. The pattern also appears to be offset by significant basement involved reverse faulting, parallel to and southwest of the Boulder Ridge reverse fault (pl. 3). Additional work is needed to accurately define the role of this faulting.

The recently identified Lone Tree Creek sinkhole likely developed from a subterranean void within a gypsum layer that is 20-30 feet thick in the upper Satanka Shale. WSGS has identified significant gypsum beds of this type in the upper Satanka Shale about 50-100 feet below the base of the Forelle Limestone from electric logs of oil and gas well tests elsewhere in the southern Laramie Basin (figs. 5 and 8). WSGS has mapped Satanka gypsum outcrops in the same stratigraphic interval to the southwest at Red Mountain and in a gypsum quarry operated by Mountain Cement Company, approximately 8 miles northeast of the sinkhole site. Based on the measured depth of the Lone Tree Creek sinkhole and the well log and outcrop analyses of the Satanka Shale, a gypsum unit with thin shale interbeds likely occurs at the bottom of the Lone Tree Creek sinkhole. Based on the change in relief of nearly 20 feet, it would appear that most of the gypsum bed within the 10 acre area near Lone Tree Creek has been removed by dissolution.

As noted earlier, the development of evaporite karst requires a source of moving water, unsaturated with respect to $CaSO_4$, to dissolve the gypsum and transport it away from the site of karst formation. WSGS calculated groundwater elevations for the potentiometric surface (fig. 12) from data obtained from the Wyoming State Engineer's Office (SEO)

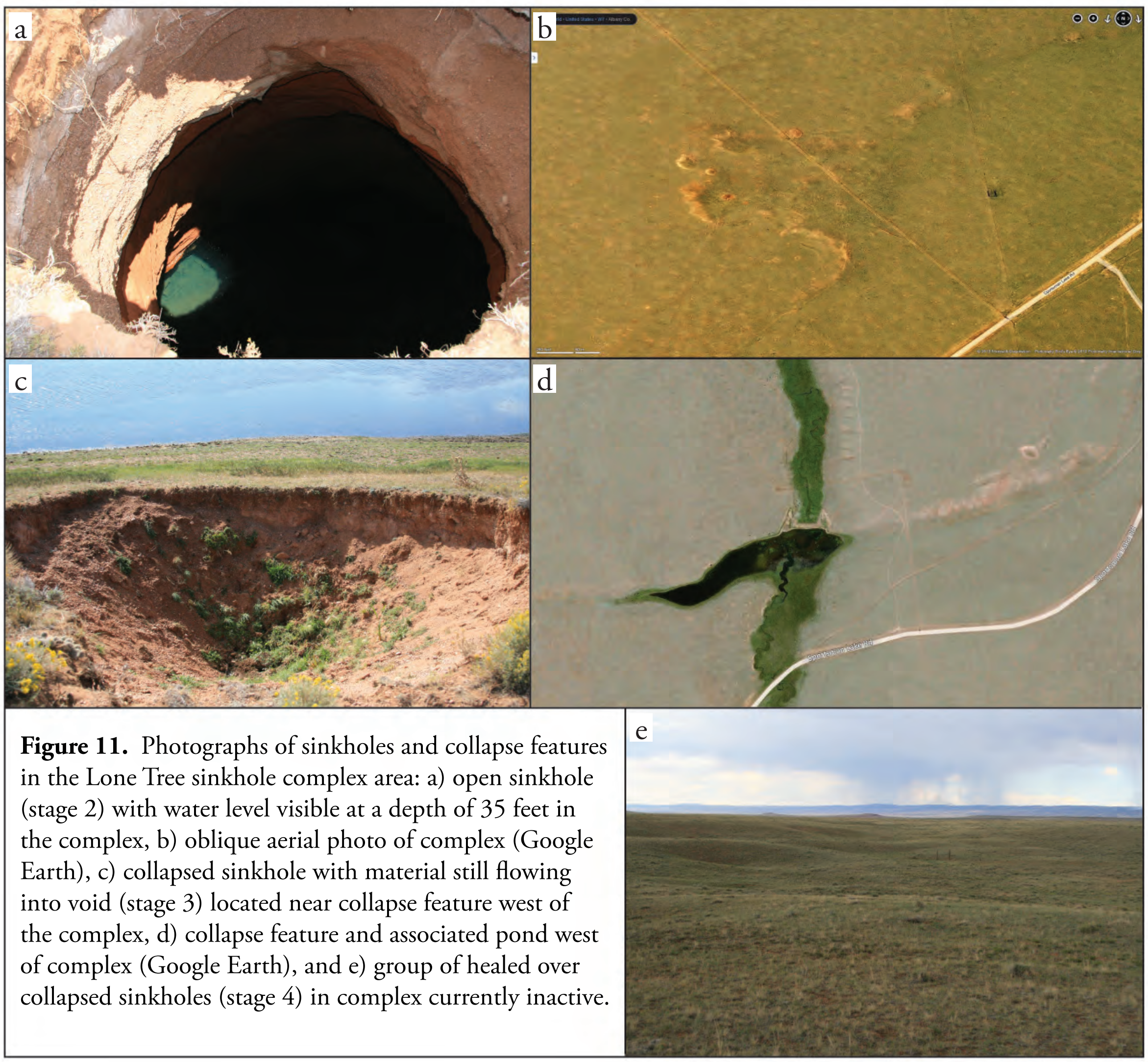

Figure 11. Photographs of sinkholes and collapse features in the Lone Tree sinkhole complex area: a) open sinkhole (stage 2) with water level visible at a depth of 35 feet in the complex, b) oblique aerial photo of complex (Google Earth), c) collapsed sinkhole with material still flowing into void (stage 3) located near collapse feature west of the complex, d) collapse feature and associated pond west of complex (Google Earth), and e) group of healed over collapsed sinkholes (stage 4) in complex currently inactive.

E-Permit Database (http://seoweb.wyo.gov/e-Permit/Common/Home.aspx) and photographic imagery from Google Earth (https://www.google.com /earth/). Although the SEO groundwater level data was collected over several decades, the potentiometric surface shown (fig. 12) generally corresponds with the observations made in previous hydrogeological studies in the vicinity of Laramie (Lundy, 1979; Moody, 2006; Taboga, 2006). Most shallow groundwater wells are completed in the first aquifer that produces sufficient quantities of good quality groundwater adequate to meet the intended use (Taboga and others, 2014a, b). Thus, figure 12 shows the potentiometric surface of "first encountered groundwater" irrespective of the hydrostratigraphic unit(s) wherein wells are completed.

The potentiometric surface of the Lone Tree Creek area suggests that groundwater recharges in the Fountain and Casper formations and in upland alluvial areas along Antelope and Lone Tree creeks just down gradient of the contact with the Precambrian Sherman Granite (pl. 3). Groundwater then flows to the northwest to discharge in sinkhole ponds, down gradient springs, and into the alluvium of the Laramie River. The large northwest and northeast striking faults and folds in the Lone Tree Creek area probably act as conduits for groundwater flow as evidenced by the parallel flow direction of groundwater. The close proximity of springs, seeps and lakes, and the shallow depths to groundwater in fault associated wells provides additional evidence of structural influence in the area. As in the eastern Laramie Basin, the vertical head gradient

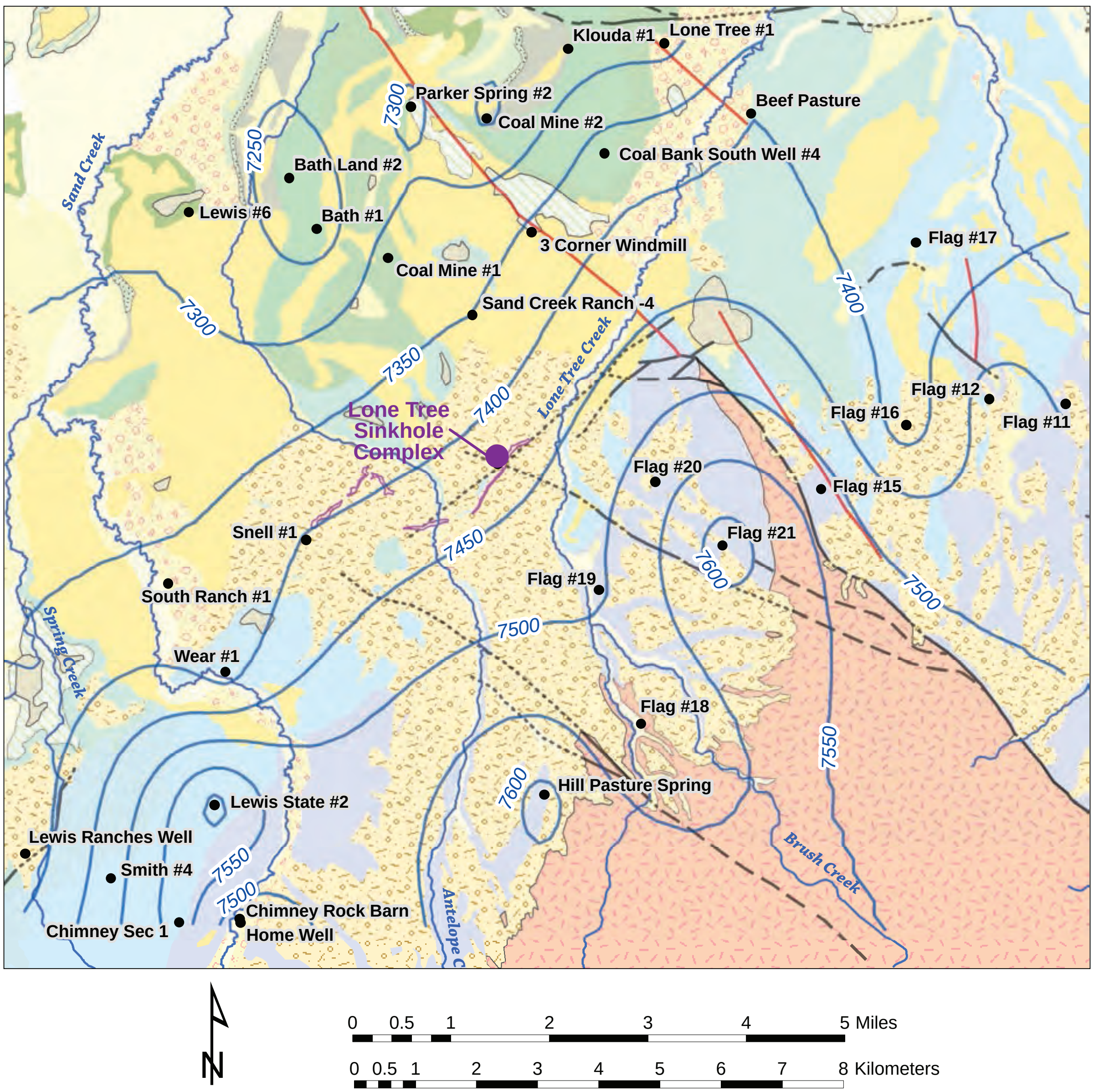

Figure 12. Potentiometric surface for the southern Laramie Basin in the vicinity of the Lone Tree sinkhole complex.

is upward and groundwater likely flows into the Satanka and Chugwater formations from the Fountain and Casper formations, especially through the fractures associated with these structures.

The WSGS sampled the standing water in the Lone Tree Creek sinkhole on June 30, 2015; the water chemistry analysis was completed by Wyoming Analytical Laboratories. The analysis (Appendix B) indicates that the sample has low concentrations of the major ions examined and a very low TDS concentration (257 mg/L) suggesting that the recharge area is in close proximity to the sinkhole site or that groundwater flows rapidly from the recharge area through high conductivity conduits, possibly the southeast to northwest trending faults shown on plate 3. Based on sulfate concentration, the Lone Tree Creek sinkhole water sample contains a maximum of 0.14 gm/L of gypsum, well under the saturation solubility level of 2.0 gm/L at 20° C.

Conditions in the Lone Tree Creek complex meet the four hydrologic factors (Johnson, 2008) required for the formation of evaporite karst: 1) a gypsum deposit, 2) a water supply unsaturated with $CaSO_4$, 3) outlets that discharge the water-evaporite solution, and 4) energy, in this case a hydraulic gradient. The springs and seeps observed in proximity to geological structure likely serve as discharge outlets for gypsum enriched water and the hydraulic gradient in the area of the sinkhole is approximately 0.01.

The sinkhole is located on State land and its presence was reported to the Office of Wyoming State Lands and Investments and the grazing leaseholder. The opening was fenced off by the leaseholder and signs were posted warning of the danger of sinkholes in the area.

Simpson Springs sinkhole complex

A sinkhole complex near Simpson Springs was identified by Western Water Consultants, Inc. (WWC), a Laramie engineering firm, in the summer of 1994. The Simpson Springs sinkhole complex is located 0.6 miles west of Simpson Springs and just south of Simpson Springs Creek (SW1/4, SW1/4, Section 34, T.15N., R.73W.) on the Monolith Ranch owned by the City of Laramie (pl. 4). Chris Moody, then an employee of WWC, investigated and described the open sinkhole and submitted a report with recommendations to the City of Laramie in December of 1994. The sinkhole was located east of a low ridge capped by Forelle Limestone and situated within the upper Satanka Shale. The area north and south of the sinkhole, along strike of the Satanka outcrop, exhibited numerous healed over and revegetated sinkholes in the fourth stage of development (fig. 10). Examinations of the pond to the north using Google Earth imagery and from the ground reveal several circular open cavities, possibly subaqueous sinkholes. In addition, several late stage sinkholes occur adjacent to the pond on the west side and immediately to the north of Simpson Springs Creek (fig. 13).

WWC investigated the site of the sinkhole in late August and September of 1994. Todd Kincaid, a scuba diver who has extensive experience working in karstic Floridian aquifer systems, examined and measured the feature. The sinkhole was described as 42 feet deep to the top of the collapsed Satanka Shale pile that lay at the bottom (Moody 1994). Groundwater filled the lower portion of the cavity to within 16 feet of ground surface. Five feet of wavy gypsum was noted in the side wall of the sinkhole immediately above the rubble pile with red shale, siltstone, and sandstone making up the remainder of the sidewall up to the surface. The sinkhole was shaped like an inverted cone, narrow at the top with a 3 foot diameter opening and wider at the bottom, representing stage 2 in development (fig. 10). The edge of the hole was not well supported due to undercutting. The sinkhole was fenced off to prevent livestock and human intrusion and has been recently backfilled.

The sinkhole likely formed from dissolution of the gypsum layer exposed in the sidewall and possibly underlying gypsum beds buried beneath the rubble zone. An upper Satanka gypsum seam, 20 feet thick, is mined at the Mountain Cement quarry, 3.5 miles to the southwest. Todd Kincaid, the diver, said that he did not see any indication that the sinkhole was part of an interconnected cavern system but that it could eventually coalesce into a larger system. It is important to note that this is similar to the model suggested for the Lone Tree Creek complex. Water samples were collected at the top and bottom of the water column in the sinkhole. Analysis of the samples indicated a water chemistry dominated by calcium and sulfate which is characteristic of gypsum dissolution. Complete water analysis reports are included in Appendix B. A mapped fault runs subparallel to the Satanka/Forelle outcrop in the area and fractures associated with the Simpson Springs anticline (pls. 1 and 4) probably focus the groundwater flow in quantities necessary to remove gypsum and create the sinkholes.

The potentiometric surface (fig. 14) shows that the Simpson sinkhole complex likely receives recharge from outcrops of the Casper Formation (pls. 1 and 4) exposed along the western flank of the Laramie Mountains (Taboga, 2006). From there, groundwater flows westward where a portion discharges at Simpson Springs located at the south of the nose of the Simpson Springs Anticline 0.3 mile west of the Casper-Satanka contact (Moody, 2006). The hydraulic gradient in the area of Simpson Springs is approximately 0.015.

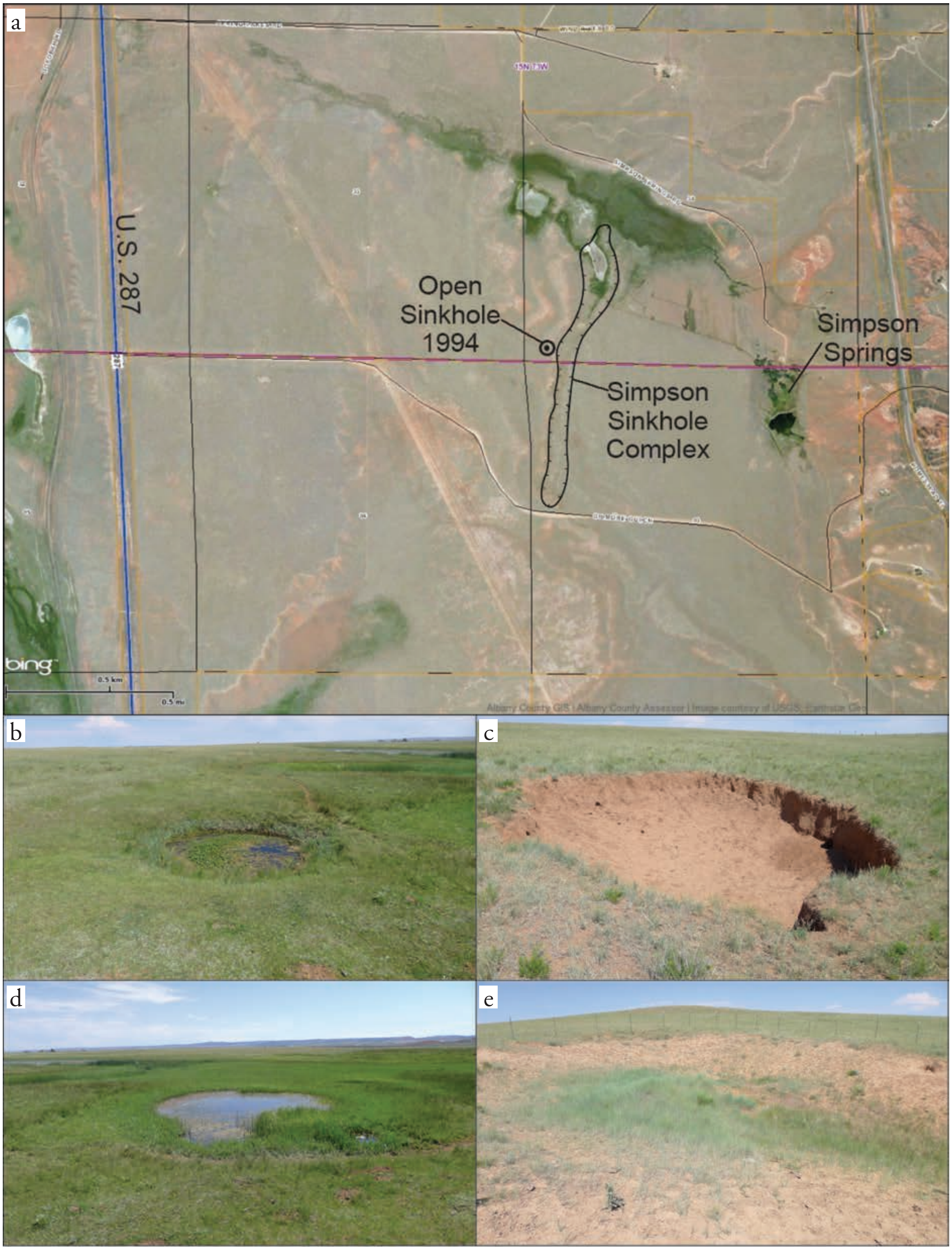

Figure 13. Photographs illustrating sinkhole and collapse features in the Simpson Springs sinkhole complex: a) aerial photo (Bing) of Simpson Springs sinkhole complex, b) open sinkhole (stage 2) on edge of collapsed area, c) small collapsed and partially healed over sinkhole (stage 3) south part of complex, d) circular opening of sinkhole with collapsed pond in open active state (stage 2), and e) site of open sinkhole identified in 1994 and recently backfilled.

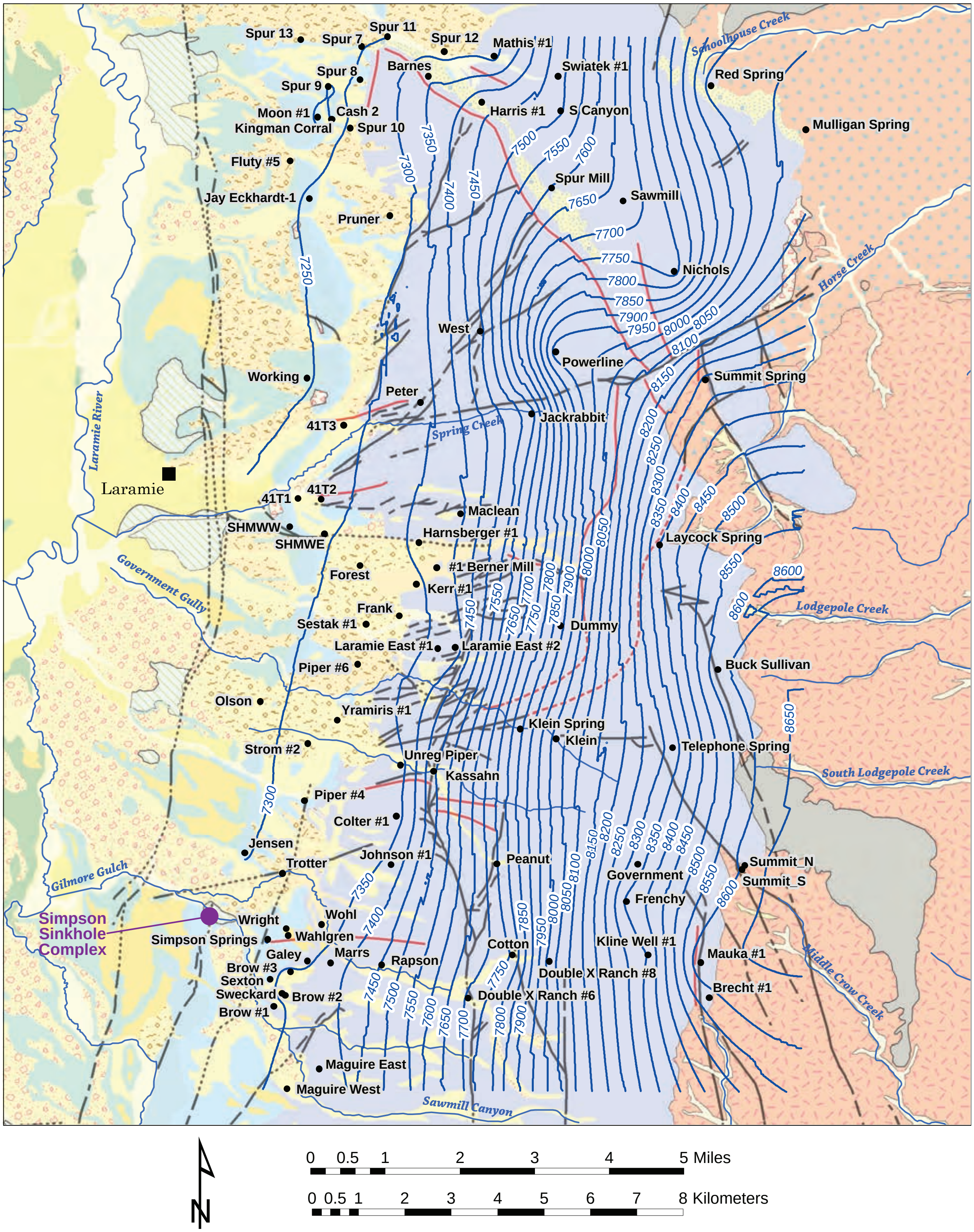

Figure 14. Potentiometric surface for the east flank of the southern Laramie Basin in the vicinity of the Simpson Springs sinkhole complex (Taboga, 2006).

A chemical analysis was conducted on a water sample obtained from the top of the standing water in the Simpson Springs sinkhole on September 14, 1994. The analysis (Appendix B) indicates that the Simpson Springs sample had major ion and TDS (1,100 mg/L) concentrations that were higher than those observed in the Lone Tree sample. This may be the result of groundwater contact with a layer of subaqueous gypsum exposed in the Simpson Springs sinkhole at the time that the water sample was obtained (Moody, 1994). Based on sulfate concentration (730 mg/L), the Simpson Springs water sample contains a maximum of 1.03 gm/L of gypsum, well under the saturation solubility level of 2.0 gm/L at 20° C.

SUMMARY AND CONCLUSIONS

This report is a description and characterization of identified gypsite deposits and modern karst features that occur in evaporite units in the southern Laramie basin. The intent is to inform the public, state and federal agencies, and local city and county planners of the presence of evaporite karst features and the geologic and hydrologic environments associated with their occurrence within the southern Laramie basin. Geologic mapping at a scale of 1:24,000 within the southern Laramie basin has enabled cursory identification and correlation of the occurrence of karst features including sinkholes, collapse features, and gypsite within bedrock outcrops containing gypsum beds in upper Satanka Shale, Forelle Limestone, and lower Chugwater formations.

Fault systems, fracture networks, and structural folds that extend into the Laramie basin from the Laramie Range and Boulder Ridge area, coupled with stratigraphic and lithological factors, appear to have a major influence on the concentration of groundwater flow necessary for the formation of the observed karst features. Two typical examples of karst development at the Lone Tree Creek and Simpson Springs sinkhole complexes are characterized by associated faulting, local folding, and abundant groundwater availability and flow concentration. Interaction with surface water appears to create collapse of surficial materials over subcrops of gypsum. Geologic evidence from identified and examined sinkhole features indicates that deep karst or sinkhole features developed approximately 40 to 60 feet below ground surface. These features are associated with the orientation of faults and fracture networks acting as major groundwater conduits flowing to the gypsum layers within primarily the thicker gypsum beds in the upper Satanka Shale.

Mapped gypsite deposits appear to be related to areas where faulting brings gypsum beds, primarily in the lower Chugwater Formation, to near ground surface. This allows associated springs and surface erosion to transport the gypsum down gradient forming the gypsite deposits in the Laramie area. Associated collapse features occurring in the city are both surface and groundwater related.

The hydrogeologic settings observed at the Lone Tree Creek and Simpson Springs sinkhole complexes are consistent with the four geologic conditions required for the development of karst (Johnson, 2008): 1) the presence of a gypsum deposit, 2) a water supply unsaturated with $CaSO_4$, 3) outlets that discharge the water-evaporite solution, and 4) a hydraulic gradient. Both sinkhole complexes are closely linked to geologic structures that likely conduct abundant quantities of low sulfate Casper Formation groundwater into overlying gypsiferous formations at hydraulic gradients of 0.01 or higher. In addition, the associated gypsum beds are less than 100 feet below the surface and structural features including faulting and fracturing are identified at both localities, satisfying the geologic conditions necessary for development of karst features.

While collapse and sinkhole hazards are possible within the mapped areas of Satanka Shale, Forelle Limestone, and the Chugwater Formation and associated gypsite deposits highlighted in plate 1, the risk is most likely greater in those areas with high densities of identified sinkholes and other collapse features. Sinkhole hazard risks may also be higher in areas where near surface gypsum bearing formations occur and hydrogeologic and structural conditions similar to those observed at the Lone Tree Creek and Simpson Spring sinkhole complexes exist.

Additional work is needed in order to fully understand the processes leading to sinkhole and collapse occurrences within these geological conditions and accurately identify potential areas for karst related hazards within the southern Laramie basin. Additional geologic structural and stratigraphic information, verification of existing structural interpretations, and a better understanding of the hydrologic model operating in the system is needed. Much of the structural geologic interpretation is based on analysis of early (1947 and 1966) aerial photography, with limited field investigation evidence in the area in and around the City of Laramie. Human activity over the last 150 years effectively masks the geology in the area. This additional research can be accomplished through more detailed structural and geologic mapping in identified and new areas; a detailed analysis of hydrologic data and associated modeling for the entire area of study is needed. Geophysical evaluation to determine geology and structure in the identified areas, masked areas, and new potential karst areas will also add to the understanding of the hazard. In addition, soil testing within the Laramie area would better define the boundaries of the gypsite deposits.

ACKNOWLEDGMENTS

Many thanks for the useful technical and editorial reviews of this report by Seth Wittke and Thomas Drean. Thanks to Chris Moody for the information including water analyses for the open sinkhole identified in 1994 in the Simpson Sinkhole Complex. Also, thanks for assistance from my mapping field assistant Davin Bagdonas with characterizing the Lone Tree sinkhole complex and discussions regarding the formation of the feature. The figures and plates were produced by Phyllis Ranz and James Rodgers. James Rodgers completed the layout of the report. Thanks to all for a job well done.

Appendix A: Geologic and hydrologic setting

Structural setting

The Laramie Basin is a Laramide synclinal depression located in southeastern Wyoming. It is bounded on the west by the Medicine Bow Mountains, on the north by the Como Bluff anticline, and on the east by the Laramie Mountains (fig. 3). The syncline is asymmetrical with the steeper limb on the west side. Basin asymmetry resulted from east-verging movement on the Medicine Bow uplift, a reverse-faulted structure which overrode and folded the sedimentary rocks on the western flank of the basin. The eastern flank of the basin is characterized by shallower dips of the sediments on the western flank of the Laramie Mountains. Within the basin are several typical north to south trending Laramide-aged anticlinal structures that are mostly verging eastward out-of-the-basin, i.e., toward the east flank and commonly bounded on the east or steep limb with high angle reverse faults. In addition to this Laramide reverse or thrust faulting, faults with significant strike-slip components are present (Stone, 1995). The location and character of the structural features on the western flank of the Laramie Mountains and the southern part of the Laramie basin can be instrumental in predicting the presence of potential evaporate related karst geologic hazards in the Laramie area.

Rock units in the Laramie area regionally dip 3-5 degrees westward from the Laramie Range, and strike nearly north to south. The regional trend is interrupted locally by faults and folds (pl. 1). The folds are mostly east-west trending anticlines and monoclines which plunge toward the west. The Quarry and Jack Rabbit anticlines and the lower hinge portion of Soldier monocline, southeast of the City of Laramie (pl. 2), are typical examples of these folds.

Faults, common along the east flank of the Laramie basin, appear to have occurred during two tectonic episodes. During the first event, which probably took place during the late Cretaceous, concurrent with the formation of the westward trending folds, the predominantly north to northeast trending faults were formed. Compressional stresses directed in a northeasterly direction probably created these features with the faults exhibiting strike-slip or horizontal motion in a right lateral sense, i.e., the west block of the fault moving toward the northeast relative to the east block, coupled with some vertical displacement. The Red Hills fault, located on the west flank of the Laramie Mountains (pls. 1 and 4), is an example of this type of fault. The offset on the Soldier monocline where it is cross-cut by the Red Hills fault is compelling evidence for right lateral movement on these types of faults (pl. 1).

A second, later episode of faulting is indicated by the east-west trending faults on the western flank of the Laramie Mountains. These faults developed as a result of relaxation of the earlier compressional stresses, creating the east-west trending normal faults which are for the most part downthrown to the south. These faults commonly offset the earlier strike-slip faults or are present on the southern flanks of east-west trending folds. The numerous east-west trending faults, downthrown to the south are present on the southeast-east corner of the Laramie area (pl. 1).

The Laramie fault trends primarily north-south in the study area, extending from Red Buttes northward through the city of Laramie (pls. 1, 2 and 4). Kinematic indicators on this fault are not readily observable at the surface because most of the fault trace is concealed by Quaternary deposits. However, unpublished data (personal communication from Chris Moody, then an employee of WWC) from water wells on both sides of the fault trace south of Laramie indicate that the fault is up-thrown on the western side. In addition, the presence of gypsum beds which source the gypsite deposits observed on the west side of the fault can only be explained by reverse movement on the fault. Although little observable evidence is recorded due to its poor exposure, it is probable that the Laramie fault had a component of right-lateral strike-slip motion. It is parallel to the Red Hills fault and likely created by the same north-northeast directed stresses. Locally, horizontal slickensides have been noted on both of these faults. The presence of gypsite deposits in the area around Laramie High School and immediately north of Laramie on trend with the Laramie fault suggest that it extends north through Laramie and beyond. The associated Sherman Hills fault oriented east-west and splaying into the Laramie fault on the south side of Laramie (pls. 1 and 2), is a reverse fault verging toward the south (based on shallow seismic evidence reported by Chris Moody). This type of motion is consistent with the effect of drag on the east block of a right-lateral strike-slip fault and is further evidence of shear motion on the Laramie fault. The west splay of the Laramie fault in north Laramie is marked by a collapsed sinkhole visible on 1947 aerial photography (fig. 6). The sinkhole, which was subsequently backfilled, was located at the intersection of East Reynolds and North Coughlin streets, immediately north of the current UniWyo Federal Credit Union. Additionally, spring activity immediately to the north of the collapsed and filled sinkhole marks the trace of the west splay of the Laramie fault (fig. 6). The occurrence of numerous springs along the Laramie fault trace has made it a prime target for shallow groundwater well tests.

In the southern Laramie basin, the major structural features include the Boulder Ridge reverse fault/anticline and the southern end of the Red Hills fault (pls. 1 and 3). The Boulder Ridge feature starts at the southeastern end of the basin and trends toward the northwest, plunging into the center of the basin. This structure is asymmetrical with the steep limb on the northeast flank and it is cored with a high angle reverse or thrust fault verging toward the northeast. This feature may have had its origin as a left-lateral strike-slip fault during Precambrian time (Sims, 2009) and was later reactivated during the Laramide event with southwest to northeast oriented principal horizontal stress forming the asymmetrical reverse faulted feature we see today. The Red Hills fault system may also have its origin as a fracture/fault system associated with the Boulder Ridge Precambrian strike-slip fault, formed and intruded with north-south trending diabase dikes during the Precambrian, and reactivated as a right-lateral strike-slip fault during the Laramide. The diabase dikes would have formed a zone of weakness along which the Laramide shearing could have taken place. The Laramie fault, parallel to and west of the Red Hills fault, has a potentially similar early history.

Numerous faults and major fractures trend toward the northwest, sub-parallel to the Boulder Ridge fault on the west flank of the Boulder Ridge anticline. As discussed in detail previously, these features serve as conduits for groundwater recharge in the southern part of the Laramie basin and probably redirect groundwater flow toward the northwest. The groundwater dissolved gypsum beds thus created voids and eventually, the sinkhole and collapse features west of Boulder Ridge, near Sportsman's Lake Road.

Stratigraphic setting

Sedimentary rocks within the Laramie basin range from Pennsylvanian to Quaternary in age and include formations from the Pennsylvanian Fountain Formation to the Tertiary Wind River Formation (fig.4). In the northern part of the basin, the total thickness of the sedimentary section is approximately 14,500 feet, including the Wind River Formation down to the base of the Casper/Fountain Formation. In the study area, the thickness of the sedimentary section is closer to 2,200 feet. The units of primary interest in this study due to their gypsum content are the Permian Satanka Shale, the Permian Forelle Limestone, and the Triassic/Permian Chugwater Formation as defined by Darton and Seibenthal (1909). These units are illustrated, including lithology, on the type-log in (fig. 5).

Satanka Shale

The Permian Satanka Shale crops out on the eastern and southern flanks of the Laramie basin in the study area (pls. 1, 2, 3, and 4). Buff to red, fine-grained sandstone with ripple marks, interbedded with thin white limestones and minor gypsum beds make up the lower 50-100 feet of the Satanka Shale. The upper part of the unit is characterized by brick red siltstone, friable red sandstone, and red shale which are commonly banded with white and ocher color zones. Gypsum beds are present in the upper part of the section, typically 50-100 feet from the top (fig. 5). A fossiliferous limestone unit about 1 foot thick occurs at the base of this gypsum unit at most localities (Darton and Seibenthal, 1909). Thickness ranges from 260 feet near Red Buttes (Nicoll, 1963) to nearly 350 feet in the subsurface further west in the basin. Well data indicates a 320-foot thickness in the Laramie area. The Satanka Shale is considered to be primarily marine with some evidence of continental deposition in the lower part of the unit. The contact with the underlying Casper Formation is disconformable (Nicoll, 1963).

Forelle Limestone

The Permian Forelle Limestone is a relatively thin, resistant limestone unit which forms a low ridge along the eastern and southern flanks of the Laramie basin (pls. 1, 2, 3, and 4). It is a gray to purple, thin bedded, sparsely fossiliferous limestone locally interbedded with red siltstone and thin gypsum laminations (figs. 5 and 8). Dissolution of the gypsum in the outcrop causes collapse of the limestone, producing wavy, broken outcrops resembling algal structures. Minor landslides are common on Forelle dip slopes east of Laramie, with the limestone unit detaching from the underlying Satanka Shale. Thickness ranges from 10 to 30 feet. In this portion of the Laramie basin the Forelle is interpreted (Nicoll, 1963) as a marine transgressive sequence. The contact with the underlying Satanka Shale is considered conformable.

Chugwater Formation

The Triassic/Permian Chugwater Formation (Darton, 1909) forms a prominent thick redbed unit along the eastern and southern flanks of the Laramie basin and underlies much of the city of Laramie (pls. 1 and 2). The Chugwater is composed of red shale and siltstone with interbedded red to salmon to buff, fine-grained sandstone. The lower portion of the formation contains red shale interbedded with thin to thick gypsum beds (figs. 5 and 8), local solution breccia, and banded, wavy, gypsiferous, thin limestone, sometimes mistaken for part of the Forelle Limestone (pls. 1, 2, 3, and 4). This portion of the Chugwater, along with the underlying Forelle Limestone and Satanka Shale, is mapped as the Goose Egg Formation west and north of the Laramie Basin.

The upper portion of the Chugwater, as defined by Darton, is equivalent to the Triassic Red Peak Member and is interpreted as shallow tidal marine and the lower portion (Permian upper Goose Egg equivalent) as marine (Picard, 1993), although few marine fossils have been recognized suggesting a tidal marine to littoral depositional environment. The contact with the underlying Forelle Limestone is considered conformable and the contact with the overlying fluvial Jelm Formation is unconformable (Picard, 1993). Thickness ranges from 620 to 800 feet in the Laramie basin and ranges between 620 to 680 feet within the study area, based on subsurface measurements from well logs.

Hydrogeologic setting

The general hydrogeology of the Laramie basin is characteristic of other Laramide structural basins that occur widely throughout Wyoming (Huntoon, 1983). Typically, groundwater in Laramide basin bedrock aquifers originates in the surrounding mountain ranges as infiltrating precipitation, or recharge, into Paleozoic and early Mesozoic sedimentary aquifers that outcrop along the mountain flanks and along the perimeters of the adjacent structural basin. Groundwater circulation, controlled by the basinward dip of these aquifers, is strongly influenced by geologic structures such as large displacement thrust faults, reverse-fault-cored anticlines, and associated fractures that developed during Laramide compressional deformation (Huntoon, 1993). Groundwater circulation commonly enhances the permeability of these structures by way of the dissolution mechanisms briefly described previously. Generally, enhanced circulation does not continue as these aquifers dip basinward below younger geologic units. Permeability in these units is reduced rapidly by geologic processes driven by the increased pressure and heat that result from progressively deeper burial. As a result of the rapid reduction in permeability, excess groundwater is discharged to springs usually located a few miles below the base of the highlands (mountains).

In Laramide structural basins, complex relationships between streamflows and groundwater are controlled by geologic structure, hydraulic properties of the streambed and adjacent aquifers, and climate. Faults and fractures associated with Laramide structures provide fluid migration pathways between surface water and groundwater along mountain flanks and basin perimeters. Headwater discharges from crystalline geologic units, such as granite, recharge downstream exposures of permeable sedimentary aquifers and alluvial deposits. If located near the mountain base where precipitation rates are lower, such surface water inflow, called mountain front recharge, may constitute the primary source of recharge for the receiving sedimentary and alluvial aquifers (Wilson and Guan, 2004). In contrast, farther into the basin, the same streams typically receive groundwater discharges from springs. Commonly, a stream has both gaining (receives groundwater inflows) and losing (contributes outflows to groundwater) reaches depending on the difference in water levels (heads) between the stream and adjacent aquifers. Climatic properties such as seasonal variations in precipitation, air temperatures and evaporation levels also affect the hydraulic exchanges between surface and groundwater.

The hydrologic settings of the areas examined in this report are consistent with the general Laramide basin conceptual model. Surface water flows and groundwater recharge along the rim of the Laramie Basin originate largely as precipitation that falls on the adjacent flanks of the Laramie Mountains. Due to the effects of elevation, annual precipitation levels in the mountains average about 26 inches compared to 11 inches in the basin interior. Further, a significant proportion of mountain precipitation falls in the form of snow and is stored as snowpack. Median measurements for 1981–2010 made at the SNOTEL precipitation monitoring site at Crow Creek in the Laramie Range, indicate that snowpack typically reaches peak levels of water content (7.0 inches) in the first week of April and then melts completely within three weeks (http://www.wcc.nrcs.usda.gov/snow/index.html). During that time, mountain vegetation is still in a quasi-dormant state, rates of evapotranspiration are relatively low, and soils have newly thawed, so much of the melted water infiltrates exposed rock outcrops or flows from mountain headwater streams to recharge alluvial deposits in the basin. In contrast to mountain flows, the reduced permeability of basin soils, lower precipitation rates, and the high efficiency with which semi-arid types of vegetation can utilize sporadic precipitation restrict the amount of water available for recharge in the basin interior.

Mountain precipitation is transported into the southern Laramie basin through two hydrostratigraphic units exposed along the mountain's flanks. The oldest and most massive unit is composed of uplifted and exposed Precambrian crystalline basement rocks that form the core of the Laramie Mountains. The Precambrian unit, composed primarily of Sherman Granite, outcrops at the southern end of the Laramie basin. Intergranular porosity (primary porosity) in the granite is negligible; groundwater storage and circulation are limited mainly to shallow fractures that discharge to springs that confluence into higher order streams. The second unit, the Paleozoic Casper aquifer, directly overlies the Precambrian rocks along the western and northern flanks of the Laramie Range. This second unit is composed of Fountain and Casper formations in the southern flanks of the basin. In contrast to the Precambrian rocks, the Casper/Fountain aquifer, a stratigraphically complex sequence of alternating sandstones and limestones, exhibits considerable levels of both intergranular and fracture porosity.

In the basin, the hydrogeology is made more complex by stratigraphy (fig. 4) and geologic structure. Basinward, the gross hydrostratigraphy of the southern perimeter of the Laramie basin consists of a succession of alternating Mesozoic shales and sandstones. Shale rich units such as the Satanka Shale, Chugwater Formation, Mowry and Thermopolis Shales, Niobrara Formation and Steele Shale act as aquitards. Formations dominated by sandstones such as the, Casper, Jelm, Sundance, Morrison, Cloverly, and Frontier formations serve as aquifers. In the basin, exposures of these bedrock units are largely covered by alluvial and colluvial deposits, most notably in proximity to the floodplain of the Laramie River. In addition, geologic structures such as strike-slip, thrust, and normal faults, reverse-fault-cored anticlines and monoclines of Laramide age and later, influence the quantity and direction of groundwater flows from mountain flank to basin interior.

To illustrate the differing potentials of the area's dominant mountain and basin geologic units to provide recharge to the gypsiferous formations discussed in this report, WSGS conducted a straightforward GIS analysis using a simplified water budget approach (Fetter, 2001). WSGS subtracted modeled average evapotranspiration rates (Sanford and Selnick, 2013) from average precipitation rates (PRISM, 2013) for Redbed and Casper formation exposures to estimate the remaining amount of annual precipitation available for recharge. The analysis indicates potential recharge in Casper and Fountain formation outcrops averages about 2.0 inches/year compared to 0.3 inches/year in Redbed exposures. Other factors such as surface water flows, water use and changes in groundwater and surface water storage are small and may reasonably be ignored.

The potentiometric surface constructed for the eastern Laramie basin (fig. 14) illustrates the hydrogeologic setting for the city of Laramie, gypsite deposit sites, and the Simpson sinkhole complex. The figure shows the potentiometric surface of "first encountered groundwater" irrespective of the hydrostratigraphic unit(s) of well completion. In Wyoming, most shallow groundwater wells are completed in the first aquifer that produces sufficient quantities of good quality groundwater adequate to meet the intended use (Taboga and others, 2014a, b). The potentiometric surface in figure 14 was generated from data obtained during November 2005 (Taboga, 2006).

Figure 14 shows that along the eastern margin of the Laramie structural basin, groundwater flows from topographic highs of the Laramie Mountains toward the basin interior. Groundwater recharges along outcrops of the heavily fractured Casper Formation (pls. 1 and 2) exposed along the western flank of the Laramie Mountains (Taboga, 2006) and then flows westward where a portion discharges at fault associated springs and seeps located at or a short distance west of the Casper-Satanka contact (Moody, 2006). More importantly, because groundwater head in the Casper aquifer is higher than in the overlying Redbed formations, a sizeable fraction of Casper aquifer groundwater discharges upward into the Satanka, Forelle and Chugwater formations through fractures associated with folds and faults (Moody, 2006). Those same faults and folds redirect downgradient groundwater flows also because of their enhanced conductivity (Huntoon and others, 1979).

Enhanced groundwater flows through the fractures associated with faults and anticlinal structures likely determine, in part, the occurrence and location of gypsite deposits west of the Laramie fault. The presence of actively discharging springs and seeps in proximity to high-grade gypsite fan deposits (pl. 1) strongly suggests that groundwater transports gypsum in solution from Satanka and Chugwater deposits to the surface to be reworked and scattered down gradient by wind and surface water erosion.

The hydrogeology of the southeastern basin margin can be summarized as follows. Recharge occurs primarily in the Casper Formation where it is exposed along the northern and western flanks of the Laramie Mountains (pl. 1), and, in the south, from high country streams that emerge from Sherman Granite outcrops and flow northward across alluvial deposits. From these recharge areas, groundwater flows basinward through the gypsiferous Satanka, Forelle and Chugwater formations to discharge to the Laramie River and nearby lakes, springs and tributary streams.

Appendix B: Water analyses from sinkholes

Water analysis from open sinkhole in the Lone Tree Creek sinkhole complex.

WYOMING ANALYTICAL LABORATORIES, INC.

1660 Harrison St.
Laramie, WY 82070
Wallaramie@wal-lab.com
(307) 742-7995
Fax: (307) 721-8956

Wyoming State Geologic Survey
Martin Larson
PO Box 1347

Laramie WY 82073

Request 34407

Group 1 Potability Report

Lab ID: P6313 **Client Id :** JR-Sinkhole-WSGS 6/30/15 1315 **Date** 7/2/2015

Calcium mg/L:	58	**Chloride mg/L:**	21
Magnesium mg/L:	14.9	**Sulfate mg/L:**	102
Sodium mg/L:	20	**Fluoride mg/L:**	1.5
Potassium mg/L:	1.6	**Nitrate mg/L:**	0.8
Iron mg/L:	0.04	**Nitrite mg/L:**	< 0.1
		Carbonate mg/L:	0
TDS mg/L:	257	**Bicarbonate mg/L:**	107
Conductivity umhos/cc:	487	**Hardness mg/L $CaCO_3$:**	206
pH standard units:	7.8	**Hardness grains/gallon:**	12.04

Approved Monte L. Ellis

Title Lab Manager

WAL, Inc. has an extensive QA/QC program where all analysis are analyzed using approved referenced procedures followed by checks and reviews by senior managers and quality assurance personnel. However, since the results are obtained from chemical measurements and thus cannot be guaranteed. WAL, Inc. assumes no liability for the use or interpretation of the results. Test results reported relate only to the samples as received by the laboratory. Although test results are generated under strict QA/QC protocols, any unsigned test reports, faxes, or emails are considered preliminary.

Thursday, July 02, 2015 *Page 1 of 1*

Water analysis from open sinkhole in the Simpson Springs sinkhole complex, sampled at the top of water surface.

WYOMING DEPARTMENT OF AGRICULTURE
ANALYTICAL SERVICES
1174 Snowy Range Road
Laramie, WY 82070
Telephone: (307) 742-2984

No. 4[illegible]

95-01551

SERVICE ANALYTICAL REPORT

SAMPLE: WATER
DATE COLLECTED: September 14, 1994
DATE RECEIVED: September 14, 1994
DATE COMPLETED: October 4, 1994

sinkhole – water surface @ 16'

INVOICE

LABORATORY FEE $ 25.00 [ ] PAID
[X] Payable on Receipt

Remit To: Wyoming Dept. of Agriculture
2219 Carey Avenue, Cheyenne, WY 82002-0100 (307) 777-6573

Western Water Consultants
P. O. Box 4128
Laramie, WY 82070
ATTN: Chris Moody
PHONE NO:

WESTERN WATER CONSULTANTS, INC.
RECEIVED
OCT 0 6 1994
LARAMIE, WY. 82070

Total alkalinity	200 mg/L
Calcium	210 mg/L
Chloride	16 mg/L
Carbonate alkalinity	0 mg/L
Specific conductance	1350 umhos/cm
Bicarbonate alkalinity	240 mg/L
Potassium	2.8 mg/L
Magnesium	55 mg/L
Sodium	18 mg/L
Nitrates + nitrites as N	0.7 mg/L
pH (units)	7.8
Sulfates	520 mg/L
Total dissolved solids	1100 mg/L
Total dissolved solids, calculated	943 mg/L

Sampled at top of water surface

jh

I hereby certify that the above was analyzed by myself or my assistant

SECTION SUPERVISOR DIRECTOR

White/Blue - Customer Yellow - Lab Pink - WDA

Water analysis from open sinkhole in the Simpson Springs sinkhole complex, sampled near the water/rubble interface.

DEPARTMENT OF AGRICULTURE
ANALYTICAL SERVICES
1174 Snowy Range Road
Laramie, WY 82070
Telephone: (307) 742-2984

No. 40761

95-03067

SERVICE ANALYTICAL REPORT

SAMPLE: WATER
DATE COLLECTED: November 30, 1994 1500
DATE RECEIVED: December 1, 1994
DATE COMPLETED: January 27, 1995

sinkhole -40'

Western Water Consultants
P. O. Box 4128
Laramie, WY 82070
Attn: Chris Moody
PHONE NO:

INVOICE

LABORATORY FEE $ 25.00 [ ] PAID
[x] Payable on Receipt

Remit To: Wyoming Dept. of Agriculture
2219 Carey Avenue, Cheyenne, WY 82002-0100 (307) 777-6573

Total alkalinity	190 mg/L
Calcium	280 mg/L
Chloride	15 mg/L
Carbonate alkalintiy	0 mg/L
Specific conductance	1550 umhos/cm
Bicarbonate alkalinity	230 mg/L
Potassium	3.0 mg/L
Magnesium	63 mg/L
Sodium	18 mg/L
pH (units)	7.7
Sulfates	730 mg/L
Total dissolved solids	1340 mg/L
TDS, calculated	1220 mg/L

Sampled at approximately 40' using the syringe sampler. Near water/rubble interface

WESTERN WATER CONSULTANTS, INC.
FEB 07 1995
LARAMIE, WY 82070

jh

CM

I hereby certify that the above was analyzed by myself or my assistant.

SECTION SUPERVISOR DIRECTOR

Yellow - Lab Pink - WDA

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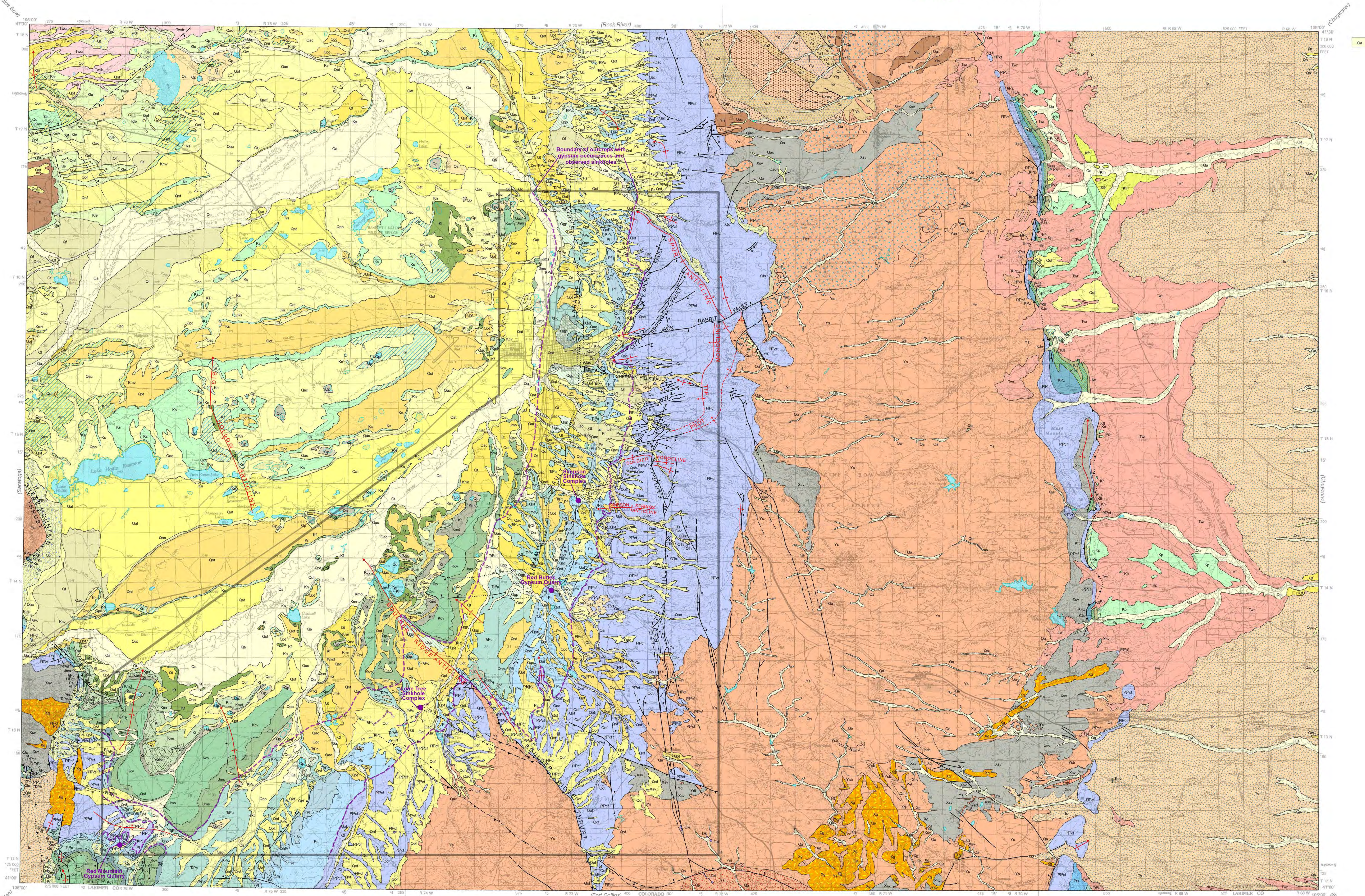
Interpreting the past , providing for the future

WYOMING STATE GEOLOGICAL SURVEY
Ronald C. Surdam, State Geologist
Laramie Wyoming

Geology - Interpreting the past to provide for the future

Prepared in cooperation with the
U.S. GEOLOGICAL SURVEY

CHARACTERIZATION OF EVAPORITE KARST FEATURES IN THE SOUTHERN LARAMIE BASIN, WYOMING, REPORT OF INVESTIGATIONS NO. 70 MODIFIED FROM MAP SERIES 77



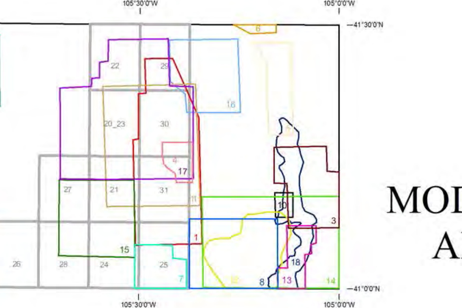
Base map from U.S. Geological Survey 1:100,000 - scale Metric topographic map of the Laramie, Wyoming 30' x 60' Quadrangle, 1981

Projection: Universal Transverse Mercator (UTM), zone 13
North American Datum of 1927 (NAD 27)
10,000-meter grid ticks: UTM, zone 13
50,000-foot grid ticks: Wyoming State Plane Coordinate System, East zone

SCALE 1:100,000
Contour interval 20 meters

UTM GRID CONVERGENCE (GN)
1981 MAGNETIC DECLINATION (MN) AT CENTER OF SHEET
DIAGRAM IS APPROXIMATE

DISCLAIMERS



INDEX TO GEOLOGIC MAPPING
(numbers are those listed in the sources of geologic data)

MODIFIED GEOLOGIC MAP OF THE LARAMIE 30' x 60' QUADRANGLE, ALBANY AND LARAMIE COUNTIES, SOUTHEASTERN WYOMING

mapped and compiled by
Alan J. Ver Ploeg and Cynthia S. Boyd
2016

KEY TO ABBREVIATIONS
Wyoming State Geological Survey maps: Map Series (MS), Open File Report (OFR), Hazards Section Digital Map (HSDM), and unpublished STATEMAP project (SMP).

INDEX TO 1:100,000-SCALE BEDROCK GEOLOGIC MAPS OF WYOMING

Prepared in cooperation with and research supported by the U.S. Geological Survey, National Cooperative Mapping Program, under Cooperative Agreements 98HQAG2071 and 06HQAG0049. The views and conclusions contained in this report are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Digital cartography by Abby L. Kirkaldie, Phyllis A. Ranz, and Robin W. Lyons
Editing and map design by Richard W. Jones

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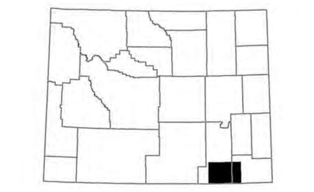
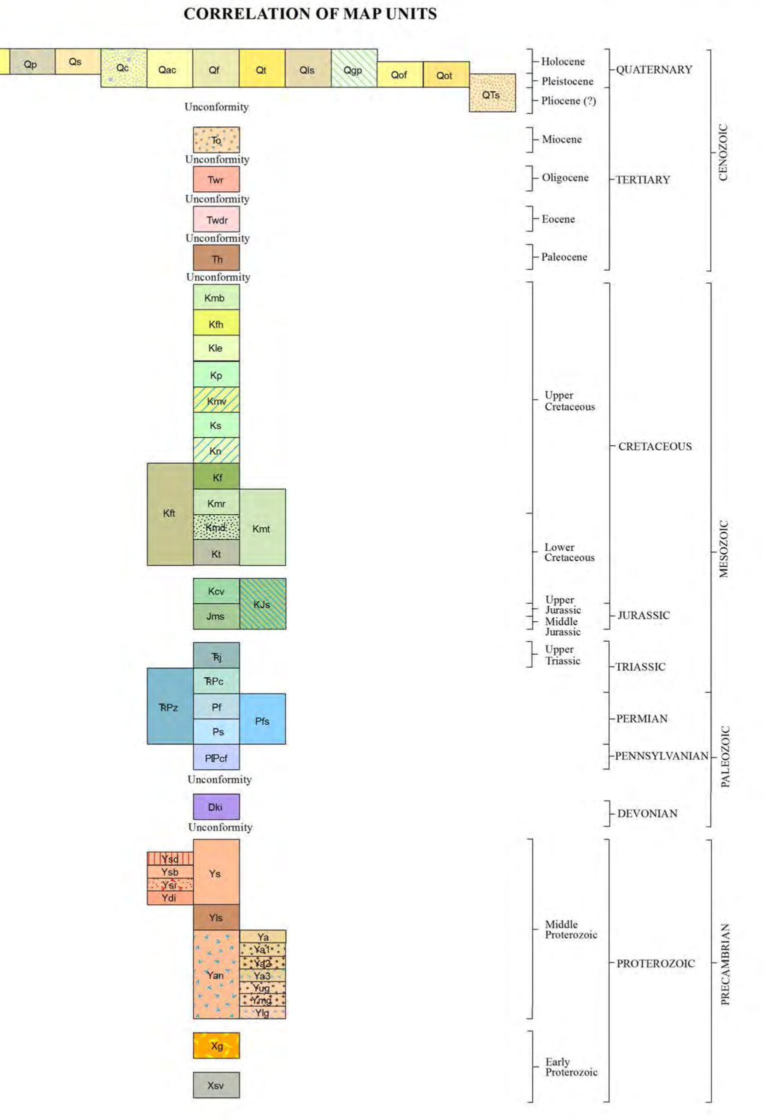


QUADRANGLE LOCATION

EXPLANATION

CORRELATION OF MAP UNITS



MAP SYMBOLS

Formation contact—dashed where approximately located

Fault—dashed where approximately located, dotted where concealed. Bar and ball on downthrown block; arrows indicate relative direction of oblique-slip movement. No indication on fault trace indicates undetermined motion

Reverse fault—Dashed where approximately located, dotted where concealed. Sawteeth on upthrown block

Monocline—Showing direction of plunge; dashed where approximately located; short arrow denotes steeper dipping limb

Anticline—Dashed where approximately located, dotted where concealed

MODIFICATIONS FOR REPORT OF INVESTIGATIONS NO. 70

Quarry or sinkhole complex location

Boundary of outcrop with gypsum occurrences and observed sinkholes

Southern Laramie Basin Study Area

DESCRIPTION OF MAP UNITS

Holocene surficial deposits

Qa **Alluvial deposits**—Unconsolidated and poorly consolidated clay, silt, sand, and gravel, mainly in floodplains and lowest stream terraces. Thickness approximately 0 to 50 feet (15 m)

Qat **Mixed alluvium and terrace deposits**—Unconsolidated and poorly consolidated clay, silt, sand, and gravel, representing a transition zone between alluvium and terrace deposits, mainly adjacent to the Laramie River. Thickness approximately 0 to 30 feet (9 m)

Qp **Playa lake deposits**—Clay- to silt-sized stratified lake bed deposits

Qs **Wind-blown deposits**—Clay- to silt-sized lake bed deposits occurring in dunes on the northeast or east (downwind) side of lakes and playa lakes. Also active and stabilized sand dunes east and south of Laramie, occurring in and sourced by Casper Formation sandstones. Thickness 0 to 50 feet (15 m)

Holocene and Pleistocene surficial deposits

Qc **Colluvium**—Unconsolidated masses of rock fragments and soil material on relatively steep slopes with thickest accumulations at the bases of slopes

Qac **Mixed alluvium and colluvium**—Sand, silt, clay, and gravel deposited mainly along intermittent streams; includes slope wash and smaller alluvial fan deposits that coalesce with alluvium. Thickness approximately 0 to 50 feet (15 m)

Qf **Alluvial fan deposits**—Poorly sorted clay, silt, and gravel; crudely bedded to nonbedded. Appear to be active, receiving sediments from intermittent streams flowing off the Laramie and Medicine Bow Mountains. May have some debris flow component. Grade into terrace deposits near the Laramie River. Locally grade into alluvium and colluvium. Thickness approximately 0 to 25 feet (8 m)

Qt **Terrace deposits**—Beds of coarse sand and gravel with occasional boulders and lenses of silt and clay. Includes fragments of weathered granite and limestone cobbles, whose predominance varies depending on source of feeding stream. Occur along present drainages, a few feet (0.6 m) to over 40 feet (12 m) above modern flood plains. Thickness approximately 0 to 10 feet (3 m)

Qls **Landslide deposits**—Blocks of bedrock or loose slope debris; arrows point in the inferred direction of movement. Many landslides occur in the Forelle Limestone, detaching at the contact with the underlying Satanka Shale

Qgp **Gypsite deposits**—Unconsolidated clay-sized gypsum interbedded with red clay, sand, gravel, and limestone cobbles. Many are located in stream valleys immediately west of the Laramie Basin, probably related to erosion of gypsum beds of the lower Chugwater Formation that were brought to the surface or near surface by the Laramie fault. These deposits were mined for cement plaster in the Laramie area near the turn of the century. Similar deposits occur in the southern and southeastern part of the Laramie Basin, also associated with faulting in the Chugwater Formation. Thickness 0 to 10 feet (3 m)

Qof **Older alluvial fan deposits**—Poorly sorted clay, silt, sand, and gravel; crudely bedded to nonbedded with some debris flow component. Limestone cobbles are common. Includes boulders and cobbles of quartzite and other Precambrian material on west side of map area. Currently inactive and dissected, often occurring as erosional remnants. Grade into older terrace deposits toward the Laramie River. Thickness 0 to 10 feet (3 m)

Qot **Older terrace deposits**—Beds of coarse sand and gravel with occasional boulders and lenses of silt and clay. Limestone cobbles are common on the east side of the Laramie Basin, while Precambrian rock predominates in those occurring on the west side of the basin. Often occur as erosional remnants ranging from 20 to 300 feet (6 to 91 m) above present stream flood plains. Some remnants may actually be older alluvial fan remnants. Thickness 0 to 10 feet (3 m)

Quaternary and Tertiary surficial deposits

QTs **Wind-blown deposits (lower Pleistocene/Pliocene?)**—Stabilized, eroded sand dune remnants perched on the sides of gulches located near the upper reaches of Gilmore Gulch, southeast of Laramie. These perched dune remnants, capped by cobble-sized lag gravels, are in and are sourced by Casper Formation sandstones. Thickness 0 to 100 feet (30 m)

Tertiary sedimentary rocks

To **Ogallala Formation (Miocene)**—Light-colored, sometimes tuffaceous, unconsolidated to well-cemented heterogeneous deposits of silt, sand, and gravel containing some cobbles and boulders, particularly near the Laramie Mountains. Restricted to the Denver Basin on this quadrangle. Thickness 0 to 350 feet (100 m)

Twr **White River Formation (Oligocene)**—White to pale pink blocky tuffaceous claystone and lenticular arkosic conglomerate in the Laramie Basin. In the Denver Basin, away from the Laramie Mountains, the formation is orange-gray claystone and siltstone with local and usually thin gray sandstone and conglomerate. Conglomerates and arkoses are particularly abundant near the Laramie Mountains on both sides of the range. Thickness 0 to 500 feet (152 m) in the Laramie Basin, 0 to 100 feet (30 m) in the Laramie Basin. Individual members described below could not be distinguished on this quadrangle but are included here because they are mapped separately in other parts of the Denver Basin.

Upper Conglomerate Member—Gray to brown to red, poorly to well-cemented conglomerate and sandstone with Paleozoic and Precambrian clasts, and matrix material of claystone, siltstone, and sandstone. The member becomes more conglomeratic toward the Laramie Mountains. Thickness 0 to 300 feet (91 m)

Brule Member—Pale pink to white argillaceous siltstone with local channel sandstone, limestone, claystone, and volcanic ash. Thickness 0 to 450 feet (137 m)

Chadron Member—Variegated tuffaceous and bentonitic claystone and siltstone, with channel sandstone and conglomerate. The lower part contains fluvial deposits. Thickness 0 to 700 feet (213 m)

Twdr **Wind River Formation (upper Eocene)**—Variegated claystone, shale, and arkosic sandstone with lenticular conglomerate. Upper part of the formation is a distinctive reddish maroon siltstone and claystone. Restricted to the Laramie Basin on this quadrangle. Thickness 400+ feet (122 m)

Th **Hanna Formation (Paleocene)**—Mostly brown to gray coarse-grained arkosic sandstone, with siltstones, dark carbonaceous shale, coal, and a basal conglomerate that contains giant quartzite boulders near the Medicine Bow Mountains. Restricted to the Laramie Basin on this quadrangle. Thickness approximately 800 feet (244 m)

Upper Cretaceous sedimentary rocks

Kmb **Medicine Bow Formation**—Light colored to gray to brown claystone, sandstone, and siltstone with coal and carbonaceous shale beds. Restricted to the Laramie Basin on this quadrangle. Thickness 0 to 400 feet (122 m)

Kfh **Fox Hills Sandstone**—Gray to yellow-brown sandstone that is sometimes interbedded with dark shale. The sandstone can be friable, silty, or pyrite-bearing and the lower part can be finer-grained, very limy, and green. Thickness 190 to 250 feet (58 to 76 m). Only mapped separately on the east side of the Laramie Mountains.

Kle **Lewis Shale**—Gray marine shale and siltstone with gray and brown lenticular sandstone beds; contains many concretions. Restricted to the Laramie Basin on this quadrangle. Thickness 2,200-2,600 feet (670 to 790 m)

Kp **Pierre Shale**—Dark gray shale with thin to moderately thick, sometimes persistent sandstone beds. Restricted to the Denver Basin on this quadrangle. Thickness about 5,700 feet (1,700 m)

Kmv **Mesaverde Formation**—Gray to tan sandstone and interbedded dark gray to black siltstone and sandy shale, with some coal beds and carbonaceous shale in the upper part. Capped by the Pine Ridge Sandstone Member. Restricted to the Laramie Basin on this quadrangle. Thickness up to1,600 feet (490 m)

Ks **Steele Shale**—Gray marine shale and siltstone, with numerous bentonite beds and thin lenticular sandstones, and some limestones. Restricted to the Laramie Basin on this quadrangle. Thickness 2,300 to 2,700 feet (700 to 820 m)

Kn **Niobrara Formation**—Black or gray to yellow speckled, calcareous shale, and light-colored limestone and chalk. Thickness approximately 325 to 700 feet (99 to 213 m). Thickest in the Laramie Basin

Kf **Frontier Formation**—Dark gray to black shale with interbedded thin, lenticular, tan to gray sandstones and thin bentonite beds. Persistent tan sandstone occurs at top of formation, locally referred to as the "Wall Creek Sandstone." Thickness approximately 550 feet (168 m)

Kmr **Mowry Shale**—Dark gray to black siliceous shale that weathers silver gray and contains thin bentonite beds and abundant fish scales. Thickness 80 to 150 feet (24 to 45 m). Thickest in the Laramie Basin

Upper and Lower Cretaceous sedimentary rocks

Kft **Frontier Formation, Mowry Shale, Muddy Sandstone, and Thermopolis Shale, undivided**

Kmt **Mowry Shale, Muddy Sandstone, and Thermopolis Shale, undivided**

Lower Cretaceous sedimentary rocks

Kmd **Muddy Sandstone**—Tan to gray sandstone that is 20 to 100 feet (6 to 30 m) thick. Thinnest in the Laramie Basin. A black shale sequence was mapped with the Muddy Sandstone by Vargas (1974) in the southwest corner of the map; elsewhere on the map, this sequence is mapped with the Mowry Shale

Kt **Thermopolis Shale**—Dark gray to black soft fissile shale that can contain thin partings of bentonite and sandstone. Ironstone concretions appear in the upper part of the formation. Fossil fish fragments occur locally in the upper thin sandstones. Selenite crystals are common in outcrop. Thickness 60 to 100 feet (18 to 30 m)

Kcv **Cloverly Formation**—Basal tan to white coarse-grained sandstone and chert pebble conglomerate, locally cross-bedded and overlain by varigated buff and purple claystones interbedded with thin black shale beds, and an upper gray to buff to brown, fine- to coarse-grained sandstone, cross-bedded in lower part. Thickness 100 to 140 feet (30 to 43 m)

Lower Cretaceous and Jurassic sedimentary rocks

KJs **Cloverly, Morrison, and Sundance formations, undivided**

Jurassic sedimentary rocks

Jms **Morrison and Sundance formations undivided**—Because the Sundance Formation is highly variable in thickness and may or may not be present over much of the quadrangle, it is mapped with the Morrison Formation where it is present. Total thickness 0 to 450 feet (137 m)

Morrison Formation (Upper Jurassic)—Pale-green, olive-green, blue-green to maroon, and chalky white variegated calcareous and bentonitic claystones interbedded with thin drab limestones and buff, non-resistant sandstones. Limestone locally contains orange to brown chert inclusions. Thickness 130 to 300 feet (40 to 91 m)

Sundance Formation (Upper and Middle Jurassic)—Variegated gray sandstone and siltstone, with greenish sandy shale in the lower part of the section. The formation is variably glauconitic, thins to less than 30 feet (9 m) on the south flank of the Laramie Basin, and may be very thin or absent in the eastern Laramie Basin. Mapped with the overlying Morrison Formation. Thickness 0 to 150 feet (46 m)

Triassic, Permian, and Pennsylvanian sedimentary rocks

Ʀj **Jelm Formation (Upper Triassic)**—Yellow to salmon pink massive sandstone, with large-scale cross-bedding, interbedded with thin partings of red siltstone, claystone, and shale. This unit was mapped separately by Vargas (1974) and is only represented on the southwest corner of the map. Combined with the Chugwater Formation in several areas of structural complexity on the west edge of the map and in areas where only thin sandstone erosional outliers occur. Thickness ranges up to 125 feet (38 m), thinning rapidly to the east and pinching out on the east side of the Laramie Basin

ƦPz **Chugwater Formation, Forelle Limestone, and Satanka Shale, undivided**

ƦPc **Chugwater Formation (Triassic and Permian)**—Red shale and siltstone with interbedded red to salmon to buff, fine-grained sandstone. Lower part of section contains red shale interbedded with thin to thick gypsum beds, local solution breccia, and banded wavy gypsiferous thin limestone sometimes mistaken for part of the Forelle Limestone. This part of the Chugwater along with the underlying Forelle Limestone and Satanka Shale would be mapped as Goose Egg Formation west of the Laramie Basin. Includes the Jelm Formation in several areas of structural complexity and where thin Jelm Formation sandstone erosional outliers occur. Thickness 650 to 800 feet (198 to 244 m)

Pfs **Forelle Limestone and Satanka Shale, undivided**—Mapped in area of structural complexity on north side of Jelm Mountain (western edge of quadrangle)

Pf **Forelle Limestone (Permian)**—Gray to purple, thin bedded, sparsely fossiliferous limestone locally interbedded with red siltstone and thin gypsum laminations. Wavy outcrops resembling algal structures common. Landslides are common on Forelle dip slopes with the unit detaching from the underlying Satanka Shale. Thickness 10 to 30 feet (3 to 9 m)

Ps **Satanka Shale (Permian)**—Red siltstone and shale (often banded with white and ocher color zones), soft sandstone, thin limestones, and local gypsum beds, especially near the top. Buff to orange to red, fine-grained sandstone with ripple marks common near base of unit. Gypsum beds in the Satanka are currently being mined in the Red Buttes area. Thickness 75 to 300 feet (23 to 91 m)

PPcf **Casper and Fountain formations, undivided**

Casper Formation (Permian and Pennsylvanian)—Buff to reddish, calcareous to quartzitic, very fine- to coarse-grained, well-cemented subarkosic sandstone interbedded with buff to purplish-gray limestone and dolomite beds, usually micritic and locally fossiliferous. Sandstone often exhibits large-scale festoon cross-bedding, increasing toward the south. As many as 10 different limestone or dolomite beds, which are locally quarried for cement or gravel uses, have been identified in the Laramie area. The Casper Formation serves as the prime aquifer in the Laramie area. Thickness 150 to 800 feet (46 to 244 m)

Fountain Formation (Pennsylvanian)—Coarse-grained pink to red to purple sandstone and arkose, with some conglomerates, siltstones, and shales. Interfingers with and underlies Casper Formation, thinning to the north and pinching out near the north edge of the map. Thickness 0 to 500 feet (152 m)

Devonian kimberlitic intrusive rocks

Dki **Kimberlitic diatremes**—Porphyritic, brecciated, kimberlitic intrusive masses and dikes that sometimes contain diamonds. Xenoliths of Silurian and Orodovician limestone and dolomite, Precambrian crystalline rocks, peridotite, and eclogite are present in the diatremes

Middle Proterozoic crystalline rocks

Ys **Sherman Granite**—Pink to orange, medium- to coarse-grained, biotite hornblende granite, syenogranite, quartz monzonite, and granodiorite. The Sherman Granite is gradational with or interfingers with the Laramie Mountains hornblende and pyroxene syenite. The Sherman Granite has been dated at 1,430 ±20 Ma (million years before present) by a Rb-Sr whole rock isochron (Zielinski and others, 1981)

Ysd **Sherman Granite and basalt mixed**

Ysb **Sherman Granite border facies**—Medium- and fine-grained porphyritic facies of the Sherman Granite. Mapped separately only in the southeastern part of the quadrangle

Ysi **Sherman Granite inner cap rock phase**—Pinkish-gray, porphyritic, biotite monzogranite (granite with equal amounts of alkali feldspar and plagioclase). Foliation defined by oriented, tabular, microcline phenocrysts; biotite-rich streaks; and oriented, tabular inclusions. Mapped in the southern part of the quadrangle as part of the Virginia Dale ring structure

Ydi **Dioritic rocks of the Virginia Dale ring structure**—Black to gray, medium-grained subophitic, ophitic, or hypidiomorphic-granular diorite; composed of andesine, hornblende, biotite, quartz, and opaque minerals. Mapped in the southern part of the quadrangle as part of the Virginia Dale ring structure

Yls **Laramie Mountains hornblende and pyroxene syenite**—Brown to black, coarse-grained, hornblende biotite syenite, quartz syenite, and monzonite. These rocks grade by occurrence of pyroxene into light brown to black, coarse grained, hornblende pyroxene syenite. The syenite is gradational with the Laramie anorthosite. Zircons from both major phases of the syenite define a single chord on a U-Pb concordia plot, indicating an age of 1,435±15 Ma. This syenite is part of what some geologists call the Laramie Anorthosite Complex

Ya **Laramie Mountains anorthosite and norite**—White to light-bluish gray, medium- to coarse-grained, generally leucocratic anorthosite that is massive to layered to brecciated. A minor gray mafic anorthosite or norite commonly forms a gradational phase between syenites and the leucocratic anorthosite, or forms less resistant, more mafic layers in layered anorthosite. This unit commonly occurs as sharply bounded angular inclusions in the syenite, but as noted above is gradational into the syenite. This anorthosite is the bulk of what some geologists call the Laramie Anorthosite Complex. On the north end of the Laramie Mountains, this complex has been subdivided into several units listed below, based on unpublished mapping by D.H. Lindsley of the State University of New York at Stony Brook

Ya **Chugwater Anorthosite**

Ya1 **Chugwater Anorthosite (An 1)**

Ya2 **Chugwater Anorthosite (An 2)**

Ya3 **King Mountain Anorthosite (An 3)**

Yug **Upper Gabbroic Anorthosite**

Ymg **Middle Gabbroic Anorthosite**

Ylg **Lower Gabbroic Anorthosite**

Early Proterozoic crystalline and metasedimentary rocks

Xg **Granitic rocks**—Pink, medium- to coarse-grained granite. Very similar in composition to the Sherman Granite, although composed of a higher percentage of calcic plagioclase and lower percentage of potassium feldspar. Restricted to small exposures in the Medicine Bow Mountains (southwest corner of quadrangle) and Laramie Mountains. Other similar rocks have been dated at about 1,740 Ma in the Medicine Bow Mountains and 1,700 to 1,750 Ma in the Laramie Mountains (granite of the Duck Creek area)

Xsv **Metasedimentary and metavolcanic rocks**

Laramie Mountains—Pelitic schist, marble, granite gneiss, layered amphibolite, and felsic gneiss. The Granite Village area in the southeastern Laramie Mountains area is mapped in much greater detail by Houston and Marlatt (1997)

Medicine Bow Mountains—Granitic gneiss, felsic gneiss, amphibolite, hornblende gneiss, and amphibolite in southwest corner of the quadrangle

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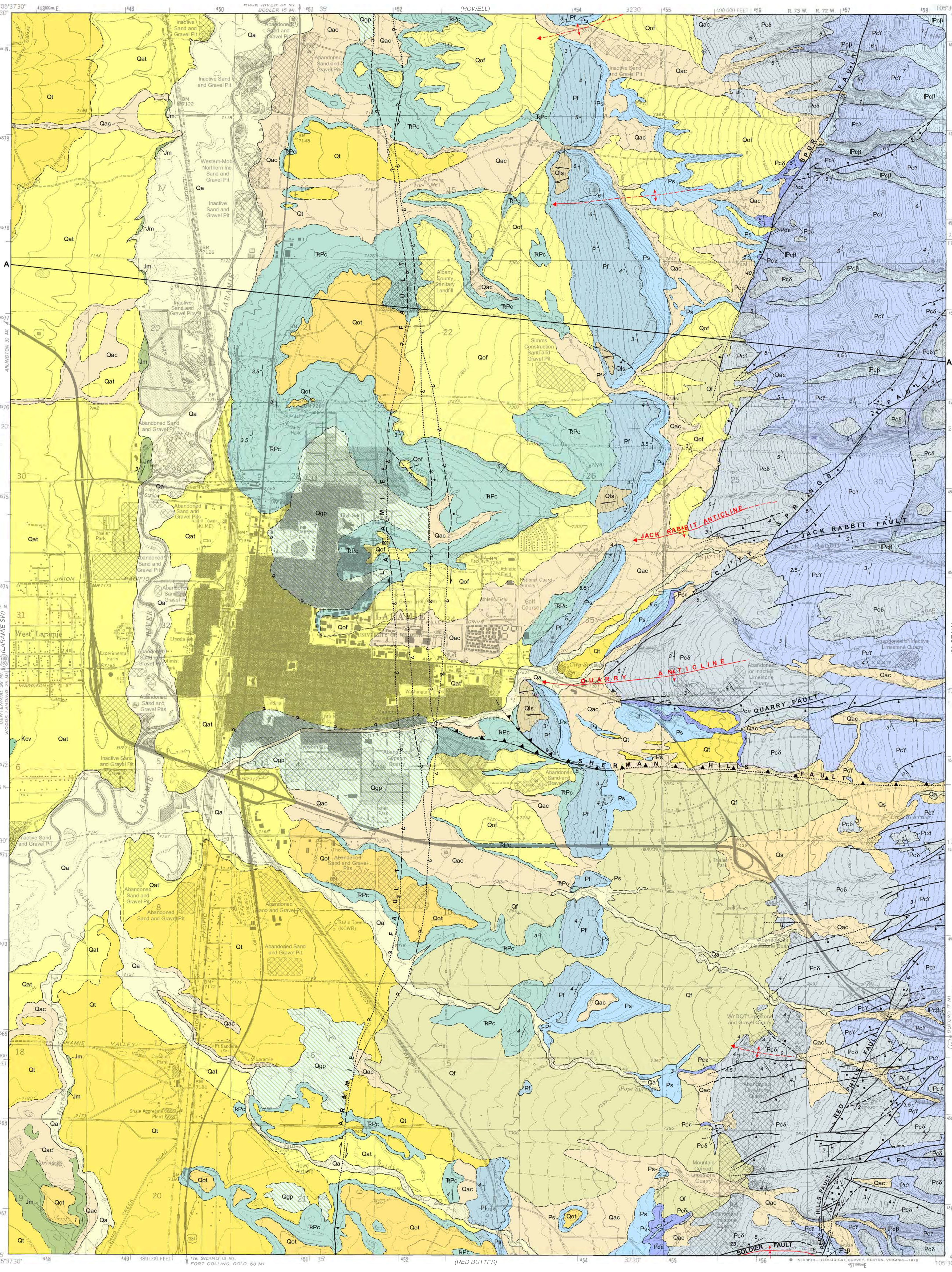
WYOMING STATE GEOLOGICAL SURVEY
Ronald C. Surdam, State Geologist
Laramie, Wyoming

Geology - Interpreting the past to provide for the future

Prepared in cooperation with the
U.S. GEOLOGICAL SURVEY

CHARACTERIZATION OF EVAPORITE KARST FEATURES IN THE SOUTHERN LARAMIE BASIN, WYOMING, REPORT OF INVESTIGATIONS NO. 70 REPRINTED FROM MAP SERIES 50



Base map from U.S. Geological Survey 1:24,000-scale topographic map of the Laramie, Wyoming Quadrangle, 1963, photorevised 1978.

Base hillshade derived from USDA/NRCS – National Cartography & Geospatial Center 10-meter Digital Elevation Model (DEM), 2000; azimuth 125º, sun angle 45º, vertical exaggeration 2

Projection: Universal Transverse Mercator (UTM), zone 13
North American Datum of 1927 (NAD 27)
1,000-meter grid ticks: UTM, zone 13
10,000-foot grid ticks: Wyoming State Plane Coordinate System, east zone

A digital version of this map is also available on CD-ROM.

GN MN
0°22' 7 MILS
13° 231 MILS

UTM GRID AND 1978 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

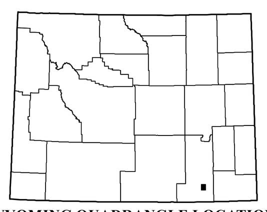
SCALE 1:24,000

1 0.5 0 1 Miles

2,000 1,000 0 2,000 4,000 6,000 Feet

1 0.5 0 1 Kilometers

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

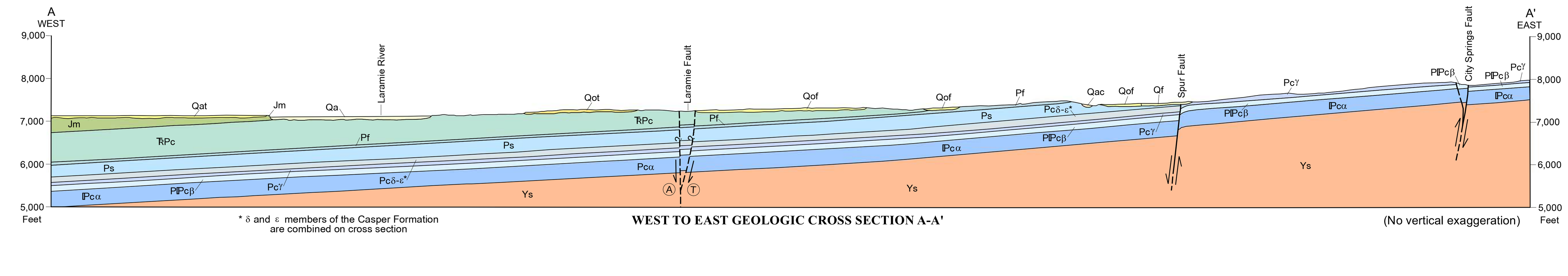


WYOMING QUADRANGLE LOCATION

Geology mapped in 1993; revised and published in digital format in 1998; members of the Casper Formation were mapped indepentantly using Lundy's (1978) classification scheme (Figure 1) and map as a guide in 2008-09.

Digital cartography by Phyllis A. Ranz, Thomas E. Ver Ploeg, J. Fred McLaughlin, and Robin W. Lyons

Prepared in cooperation with and research supported by the U.S. Geological Survey, National Cooperative Mapping Program, under STATEMAP Award No. 1434-94-A-1262 and Cooperative Agreement 08HQAG0083. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.



* δ and ε members of the Casper Formation are combined on cross section

WEST TO EAST GEOLOGIC CROSS SECTION A-A'

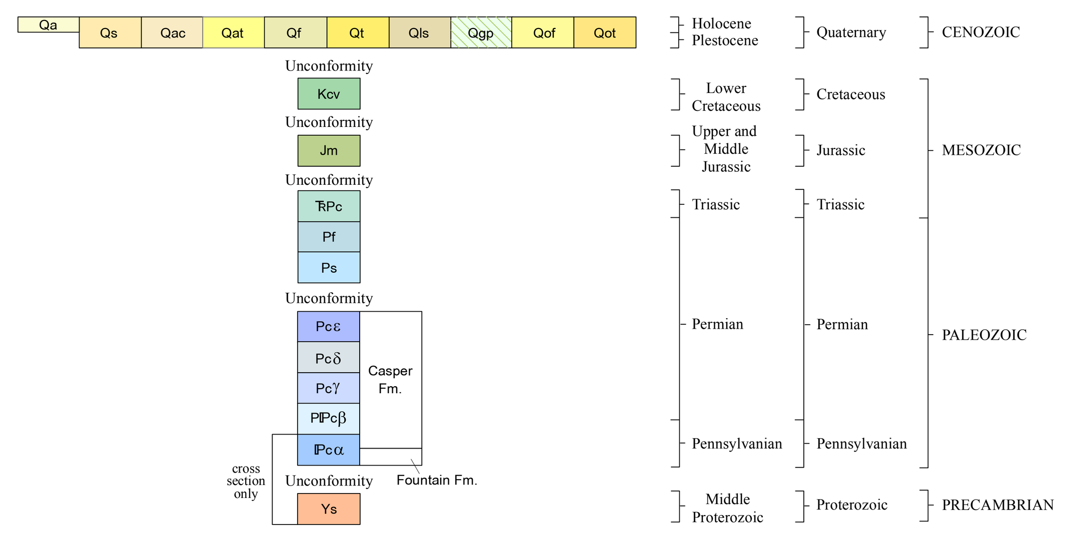
(No vertical exaggeration)

REVISED GEOLOGIC MAP OF THE LARAMIE QUADRANGLE, ALBANY COUNTY, WYOMING

by
Alan J. Ver Ploeg
2009

EXPLANATION

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

Quaternary surficial deposits

Qa — **Alluvial deposits (Holocene)**—Unconsolidated and poorly consolidated clay, silt, sand, and gravel, mainly in flood plains and lowest stream terraces. Thickness approximately 0 to 25 feet (0 to 7.6 m)

Qs — **Windblown sand deposits (Holocene/Pleistocene)**—Active and stabilized dunes, made up of very fine-to fine-grained sand. Although numerous unmapped small-scale examples occur within the map area, the only mapped example occurs in the south portion of the Sherman Hills development east of Laramie. Thickness approximately 0 to 15 feet (0 to 4.6 m)

Qac — **Mixed alluvium and colluvium (Holocene/Pleistocene)**—Sand, silt, clay, and gravel deposited mainly along intermittent streams; includes slope wash and smaller alluvial fan deposits that coalesce with alluvium. Locally, includes unmapped gypsite deposits in the north Laramie area near the high school and junior high school. Thickness approximately 0 to 20 feet (0 to 6 m)

Qat — **Mixed alluvium and terrace deposits (Holocene/Pleistocene)**—Unconsolidated and poorly consolidated clay, silt, sand, and gravel, representing a transition zone between alluvium and terrace deposits, mainly adjacent to the Laramie River. Thickness approximately 0 to 30 feet (0 to 9 m)

Qf — **Alluvial fan deposits (Holocene/Pleistocene)**—Poorly sorted clay, silt, and gravel; crudely bedded to non-bedded. Appear to be active, receiving sediments from intermittent streams flowing off the Laramie Mountains. May have some debris flow component. Grade into terrace deposits toward west, approaching the Laramie River. Locally, grade into alluvium and colluvium. Thickness 0 to 25 feet (0 to 7.6 m)

Qt — **Terrace deposits (Holocene/Pleistocene)**—Beds of coarse sand and gravel with occasional boulders and lenses of silt and clay. Includes fragments of weathered granite and limestone cobbles, predominance varies depending on feeding stream source. Occur along present drainages, a few feet (0.6 m) to over 35 feet (11 m) above modern floodplains. Thickness approximately 0 to 10 feet (0 to 3 m)

Qls — **Landslide deposits (Holocene/Pleistocene)**—Blocks of bedrock or loose slope debris; arrows on the map point in the inferred direction of movement. Occur in the Forelle Limestone, detaching at the contact with the underlying Satanka Shale

Qgp — **Gypsite deposits (Holocene/Pleistocene)**—Unconsolidated clay-sized gypsum interbedded with red clay, sand, gravel, and limestone cobbles. Located in stream valleys immediately west of the Laramie Fault, probably related to erosion of gypsum beds of the lower Chugwater Formation and upper Satanka Shale which were brought to the surface or near surface by the Laramie Fault and associated springs. Thickness approximately 0 to 20 feet (0 to 6 m)

Qof — **Older alluvial fan deposits (Holocene/Pleistocene)**—Poorly sorted clay, silt, sand, and gravel; crudely bedded to non-bedded with some debris flow component. Limestone cobbles are common. Currently inactive and dissected, often occurring as erosional remnants. Grade into older terrace deposits toward the west, in the northern part of the map area. Thickness 0 to 10 feet (0 to 3 m)

Qot — **Older terrace deposits (Holocene/Pleistocene)**—Beds of coarse sand and gravel with occasional boulders and lenses of silt and clay. Limestone cobbles are common. Often occur as erosional remnants ranging from 20 to 100 feet above present stream flood plains. Some remnants may actually be older alluvial fan remnants. Thickness 0 to 10 feet (0 to 3 m)

Mesozoic and Paleozoic sedimentary rocks

Kcv — **Cloverly Formation (Lower Cretaceous)**—Basal tan to white coarse-grained sandstone and chert-pebble conglomerate, locally cross-bedded and overlain by variegated buff and purple claystones interbedded with thin black shale beds, and an upper gray to buff to brown, fine- to coarse-grained sandstone, cross-bedded in lower part. Thickness 100 to 120 feet (30 to 37 m)

Jm — **Morrison Formation (Upper and Middle Jurassic)**—Pale-green, olive-green, blue-green to maroon, and chalky white variegated calcareous and bentonitic claystones interbedded with thin drab limestones and buff, non-resistant sandstones. Limestone locally contains orange to brown chert inclusions. A thin section of Sundance Formation may exist in the area, but due to few and poor exposures, it is mapped with the Morrison. Thickness 300 to 375 feet (91 to 114 m)

TRPc — **Chugwater Formation (Triassic and Permian)**—Red shale and siltstone with interbedded red to salmon to buff, fine-grained sandstone. Lower part of section contains red shale interbedded with thin to thick gypsum beds and banded, wavy, gypsiferous thin limestone sometimes mistaken for part of the Forelle Limestone. This part of the Chugwater along with the underlying Forelle Limestone and Satanka Shale would be mapped as Goose Egg Formation west of the Laramie Basin. Locally, some possible thin erosional outliers of Jelm Formation sandstone may occur, but due to their lack of persistence, they are mapped with the Chugwater. Thickness 650 to 800 feet (200 to 240 m)

Pf — **Forelle Limestone (Permian)**—Gray to purple, thin bedded, sparsely fossiliferous limestone locally interbedded with red siltstone and thin gypsum laminations. Wavy outcrops resembling algal structures common. Landslides are common on Forelle dip slopes with the unit detaching from the underlying Satanka Shale. Thickness 10 to 30 feet (3 to 9 m)

Ps — **Satanka Shale (Permian)**—Red siltstone and shale (often banded with white and ocher zones), soft sandstone, thin limestone beds, and local gypsum beds, especially near the top. Buff to orange to red, fine-grained sandstone with ripple marks common near base of unit. Gypsum beds in the Satanka are currently being mined in the Red Buttes area to the south of this map. Thickness 250 to 300 feet (76 to 91 m)

Casper and Fountain formations, undivided (Permian and Pennsylvanian)—Combined unit not mapped on this quadrangle; see detailed descriptions below. Buff to reddish, calcareous to quartzitic, very fine- to coarse-grained, well-cemented subarkosic sandstone interbedded with buff to purplish-gray limestone and dolomite beds, usually micritic and locally fossiliferous. Sandstone often exhibits large-scale festoon cross-bedding, increasing toward the south. As many as 10 distinct limestone or dolomite beds, which are locally quarried for cement or gravel uses, have been identified in the Casper in the Laramie area (Benniran, 1970). The Casper Formation serves as the prime aquifer for the city of Laramie. Thickness 600 to 700 feet (180 to 210 m) (Benniran, 1970, and Kirn, 1972)

Casper/Fountain subdivisions—Benniran (1970) subdivided the formation into separate informal members based on 10 distinct limestone units (limestone 10 is the highest stratigraphically and the youngest, limestone 1 is the lowest stratigraphically and the oldest) that are separated by sandstones (**Figure 1**). The sandstone units act as local aquifers. Lundy (1978) combined the limestone units into five informal members (epsilon, delta, gamma, beta, and alpha) based upon local, confined aquifer packages (**Figure 1**)

Pcε — **Epsilon member (Permian)**—The youngest Casper Formation member; capped by limestone 10 (occurs south of the mapped area) and a sandstone unit that grades into the overlying Satanka Shale. Consists of red to pink, medium- to fine-grained sandstone, mostly covered in the Laramie area. Overall thickness of this member 22 to 30 feet (6.7 to 9.1 m)

Pcδ — **Delta member (Permian)**—Includes limestones 9 and 8 and two separate sandstone units. Limestone 9 is an 8- to 10-foot (2.4- to 3.0-m)-thick, white-gray to pink, massive, fractured limestone that caps the member. A reddish-brown to buff, thinly laminated, thick sandstone separates the two limestones of the delta member. Limestone 8 is a pink to light-gray, massive, fractured 12-foot (3.7-m)-thick limestone that crops out mostly at the base of the Laramie Mountains. A light-tan to red, calcareous, cross-laminated, porous sandstone 40 to 55 feet (12 to 17 m) thick lies beneath limestone 8. Overall thickness of delta member is 80 to 112 feet (24.4 to 34.1 m)

Pcγ — **Gamma member (Permian)**—Includes limestones 7 and 6 and two separate sandstone units. Limestone 7 is an extensive unit, 17 to 18 feet (5.2 to 5.5 m) thick, that forms prominent ridges and the main dip slope of the western Laramie Mountains, as well as caps the gamma member. It has a tan to buff, dolomitic base overlain by a sandy grayish limestone. Limestone 6 is a dense, fossiliferous limestone, 6 to 8 feet (1.8 to 2.4 m) thick, that is only present in the northern part of the Pilot Hill map area. A pink to red, fine- to medium-grained, friable, calcareous sandstone, 50 to 60 feet (15 to 18 m) thick, extends from the base of limestone 7 to the top of limestone 5 except where it is divided by limestone 6. Overall thickness of gamma member 73 to 86 feet (22 to 26 m)

PIPcβ — **Beta member (Permian and Pennsylvanian)**—Includes limestones 5 and 4 and two separate sandstone units. Limestone 5 is a finely crystalline, purple to pink, dense, highly fractured limestone, 8 to 12 feet (2.4 to 3.7 m) thick, that weathers to dark gray and caps this member. A light-brown to tan-red, calcareous, fine-grained, friable, 25- to 30-foot (7.6- to 9.1-m)-thick sandstone separates limestones 5 and 4. Limestone 4 has a buff to tan dolomitic base that grades upward into light-gray to purple, dense, ridge-forming limestone, 18 to 26 feet (5.5 to 7.9 m) thick. Below limestone 4, a thick [90 feet (30 m)], red to buff, moderately resistive, extremely calcareous, thick, moderately sorted sandstone layer forms the base of the beta member. North of Rogers Canyon (on adjacent quadrangles) entire member is Permian in age. Overall thickness of this member 141 to 158 feet (43.0 to 48.2 m)

IPcα — **Alpha member (Pennsylvanian)**—Shown on cross section only; does no crop out in the Laramie 1:24,000 quadrangle, but the member is mapped in the Pilot Hill quadrangle to the east. The oldest member of the Casper Formation includes limestones 3, 2, and 1 and three separate sandstone units, the lowest of which grades into the underlying Fountain Formation, which which forms the base of this member. Limestone 3 at the top of the Alpha member is one of the more prominent limestones in this section of the Casper Formation. The base of the 29- to 40-foot (8.8- to 12-m)-thick limestone 3 is light-tan to brown sandy dolomite, fining upwards into a purple-pink carbonate that weathers gray and forms ridges. A light-brown to reddish-brown, poorly sorted, fine-grained sandstone unit, 75 to 80 feet (23 to 24 m) thick, separates limestone 3 from limestone 2. Limestone 2 is a thin [8 to 12 feet (2.4 to 3.7 m)], pink to purple, sandy unit that is mostly covered in the map area. A pink to brown, calcareous, cross-laminated, medium-sorted, fine-grained sandstone, 65 to 80 feet (20 to 24 m) thick, separates limestones 2 and 1. Limestone 1 is a purple to pink, massive, fossiliferous, sandy unit, 9 to 13 feet (2.7 to 4.0 m) thick. The unit below limestone 1 is a tan, pink, and red, cross-bedded, medium-grained sandstone that interfingers with thin [up to 1 inch (3 cm)] thick, sandy limestones. The basal sandstone unit, 80 to 150 feet (24 to 46 m) thick, is slightly arkosic; more so as it grades into the Fountain Formation. Overall thickness of the Alpha member 266 to 375 feet (81.1 to 114 m)

Fountain Formation (Pennsylvanian)--Coarse-grained pink to red to purple sandstone and arkose, with some conglomerates, siltstones and shales. Interfingers with and underlies Casper Formation, thinning to the north and pinching out near Rogers Canyon northeast of the Laramie quadrangle. For mapping purposes, the Fountain Formation was included with the alpha member, which is entirely in the subsurface on the quadrangle. The Fountain Formation lies unconformably on top of Precambrian basement rock. Possibly deposited by an alluvial plain or a series of coalescing fans at the base of the Ancestral Rockies. Approximately 30 feet (9 m) thick at Pilot Hill (Benniran, 1970)

Middle Proterozoic granitic and metamorphic rocks

Ys — **Sherman Granite**—Shown on cross section only. Where it crops out east of the map area, it is medium- to coarse-grained, pink to orange, biotite hornblende granite, syenogranite, quartz monzonite, and granodiorite. The Sherman Granite has been dated at 1,430 ±20 Ma (Mega-annum or million years before present) by a Rb-Sr whole rock isochron (Zielinski and others, 1981)

MAP SYMBOLS

Formation contact—Dashed where approximately located

Fault—Dashed where approximately located, dotted where concealed. Bar and ball on downthrown block; arrows indicate relative direction of oblique-slip movement

Reverse fault—Dashed where approximately located, dotted where concealed. Sawteeth on upthrown block

Anticline—Trace of axial plane and direction of plunge determined by field dip measurements and by photo interpretation, dashed where approximately located

Monocline—Trace of axial plane as determined by field measurements and by photo interpretation; dashed where approximately located; short arrow denotes steeper dipping limb

1 **Strike and dip of beds**—showing angle of dip

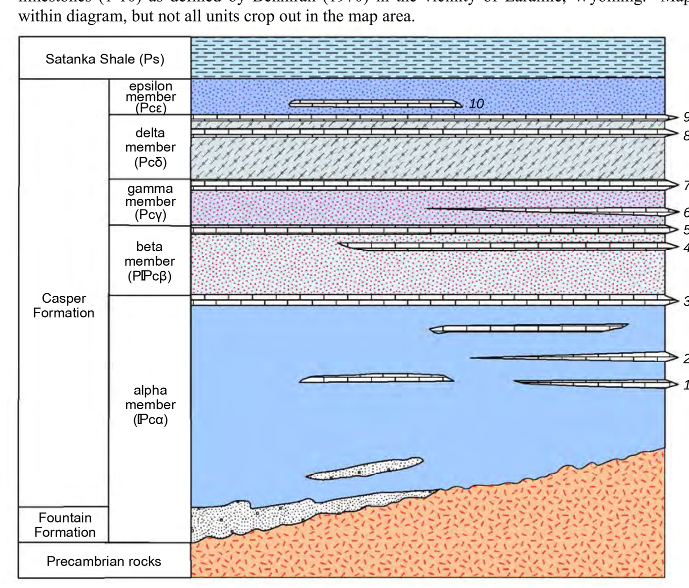
4 **Strike and dip measurements from Lundy (1978)**

A A' **Cross section location**—Line of section; Ys, Sherman Granite (Middle Proterozoic), is shown on the cross section only as it does not crop out in map area; circled letters next to faults indicate strike-slip component of movement, T is toward observer and A is away from observer

Surface mines and quarries—Outline of quarry or pit where bedrock has been disturbed, removed, or reclaimed as of June 1998. Solid boundary indicates active operation, dashed line indicates inactive or abandoned operation. Includes company name (for active operations) and commodity mined

FIGURE 1

Schematic relationship between Lundy's (1978) informal members of the Casper Formation and the Casper limestones (1-10) as defined by Benniran (1970) in the vicinity of Laramie, Wyoming. Map area falls within diagram, but not all units crop out in the map area.



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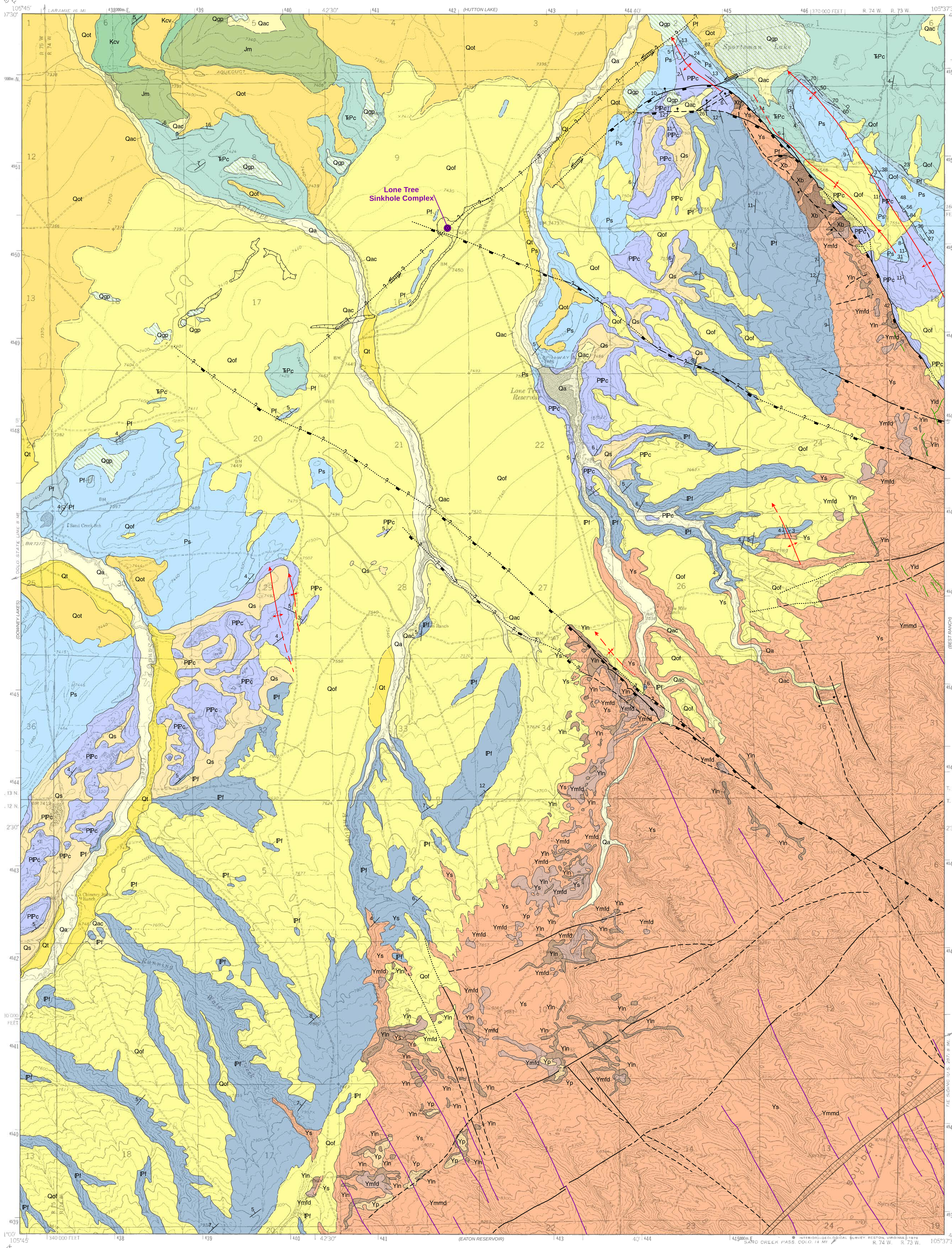
WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean, Director and State Geologist
Laramie, Wyoming

Geology - Interpreting the past - providing for the future

Prepared in cooperation with the
U.S. GEOLOGICAL SURVEY

Plate III

CHARACTERIZATION OF EVAPORITE KARST FEATURES IN THE SOUTHERN LARAMIE BASIN, WYOMING, REPORT OF INVESTIGATIONS NO. 70 MODIFIED FROM OPEN FILE REPORT 12-3

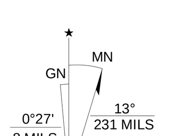


Base map from U.S. Geological Survey 1:24,000 - scale topographic map of the Johnson Ranch, Wyoming Quadrangle, 1963, Photorevised 1978

Projection: Universal Transverse Mercator (UTM), zone 13
North American Datum of 1927 (NAD 27)
1,000-meter grid ticks: UTM, zone 13
10,000-foot grid ticks: Wyoming State Plane Coordinate System, east zone

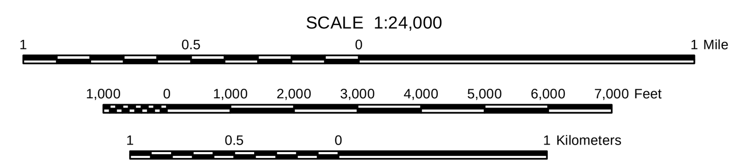
Wyoming State Geological Survey
P.O. Box 1347 - Laramie, WY 82073-1347
Phone: (307) 766-2286 - Fax: (307) 766-2605
Email: wsgs.sales@wyo.gov

A digital version of this map is also available on CD-ROM

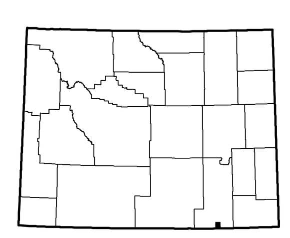


UTM GRID AND 1978 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24,000



CONTOUR INTERVAL 20 FEET
DOTTED LINES REPRESENT 10-FOOT CONTOURS
NATIONAL GEODETIC VERTICAL DATUM OF 1929



WYOMING QUADRANGLE LOCATION

Digital cartography by Tom Ver Ploeg, Robin W. Lyons, and Kristen C. Klaphake
Map edited by Suzanne C. Luhr

Prepared in cooperation with and research supported by the U.S. Geological Survey, National Cooperative Geologic Mapping Program, under USGS award number G11AC20493. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

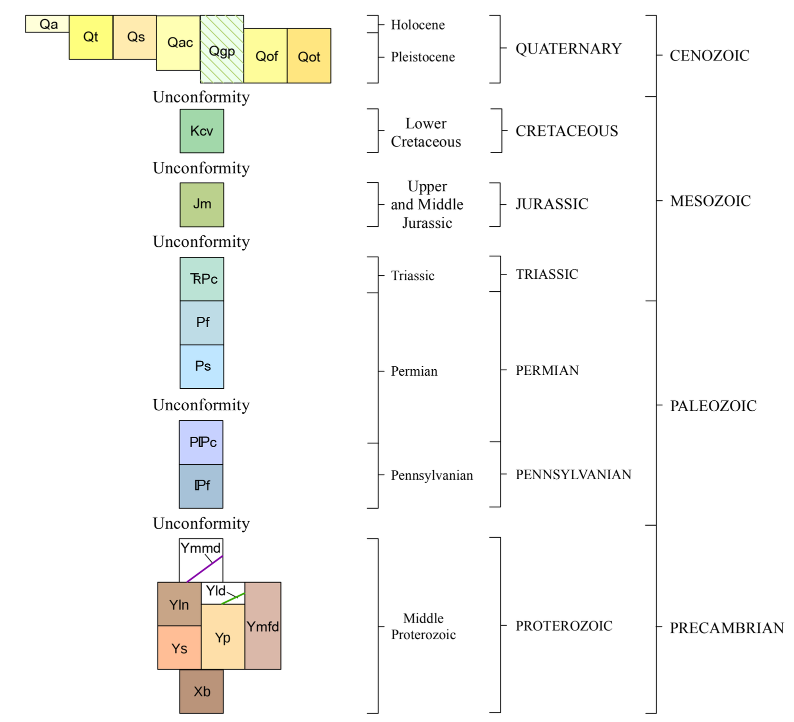
MODIFIED PRELIMINARY GEOLOGIC MAP OF THE JOHNSON RANCH QUADRANGLE, ALBANY COUNTY, WYOMING

by

Alan J. Ver Ploeg, Davin A. Bagdonas, and J. Fred McLaughlin

2016

CORRELATION OF MAP UNITS



MAP SYMBOLS

Formation contact—Dashed where approximately located

Fault—Dashed where approximately located; dotted where concealed; block on hanging wall of reverse fault; bar and ball on downthrown block of normal fault; arrows indicate direction of oblique-slip movement

Fracture or possible fault—Dashed where approximately located, dotted where concealed

Fault zone—Characterized by brittle deformation; fault breccia, cataclastic material, and alteration is common

Anticline—Dashed where approximately located; arrow on end indicates direction of plunge; shorter arrow on asymmetrical structure indicates steeper limb, as determined by field measurements and aerial photo interpretation

Syncline—Dashed where approximately located, dotted where concealed; arrow on end or along axis indicates direction of plunge

Collapse structure

Sinkhole

26 **Strike and dip of inclined bedding**

82 **Strike and dip of overturned bedding**

MODIFICATIONS FOR REPORT OF INVESTIGATIONS NO. 70

Quarry or sinkhole complex location

DESCRIPTION OF MAP UNITS

Quaternary surficial deposits

Qa **Alluvial deposits (Holocene)**—Unconsolidated to poorly consolidated clay, silt, sand, and gravel, mainly in flood plains and lower stream terraces. Alluvial material is derived from all local geological units. Thickness approximately 0 to 50 feet (15 m) (Nicoll, 1963)

Qt **Terrace deposits (Holocene and Pleistocene)**—Beds of coarse sand and gravel with occasional boulders and lenses of silt and clay. Include fragments of weathered granite and limestone cobbles, predominance varies depending on feeding stream source. Occur along present drainages, a few feet (0.6 m) to over 35 feet (11 m) above modern floodplains. Thickness approximately 0 to 10 feet (3 m)

Qs **Windblown sand deposits (Holocene)**—Active and stabilized dunes, made up of very fine to fine-grained sand sourced by Casper Formation and Fountain Formation sandstones. Buff to gray to reddish, locally covered with patchy vegetation. Dunes are primarily deposited around vegetation, bedrock outcrops, and in small washes and topographic lows. Thickness 0 to 15 feet (5 m) (Nicoll, 1963)

Qac **Mixed alluvium and colluvium (Holocene and Pleistocene)**—Sand, silt, clay, and gravel deposited along intermittent streams; includes slope wash and smaller alluvial fan deposits that coalesce with alluvium. Thickness 0 to 50 feet (15 m) (Nicoll, 1963)

Qgp **Gypsite deposits (Holocene and Pleistocene)**—Unconsolidated clay-sized gypsum interbedded with red clay, sand, gravel, and limestone cobbles. Located in proximity to faults, probably related to fluid movement and erosion of gypsum beds of the lower Chugwater Formation and Satanka Formation. Thickness approximately 0 to 9 feet (2 m)

Qof **Older alluvial fan deposits (Pleistocene)**—Poorly sorted clay, silt, sand, and gravel; crudely bedded to non-bedded with some component of debris flow. Include boulders and cobbles of local geologic units. Currently inactive and dissected, often occurring as erosional remnants. Thickness 0 to 10 feet (3 m) (Nicoll, 1963)

Qot **Older terrace deposits (Pleistocene)**—Beds of course sand and gravel with occasional boulders and lenses of silt and clay. Resistant limestone and granite material occur as rounded, well-weathered boulders and gravels. Often occur as erosional remnants ranging from 20 to 300 feet (6 to 91 m) above present stream flood plains. Some remnants may actually be older alluvial fan remnants. Thickness 0 to 10 feet (3 m) (Nicoll, 1963)

Lower Cretaceous sedimentary rocks

Kcv **Cloverly Formation (Lower Cretaceous)**—Basal tan to white coarse-grained sandstone and chert pebble conglomerate, locally crossbedded and overlain by variegated buff and purple claystones interbedded with thin black shale beds, and an upper gray to buff to brown, fine- to coarse-grained sandstone, crossbedded in lower part of the formation. Thickness 100 feet (30 m) (Ver Ploeg and Boyd, 2007)

Jurassic sedimentary rocks

Jm **Morrison Formation (Upper and Middle Jurassic)**—Pale-green, olive-green, blue-green to maroon, and chalky white variegated calcareous and bentonitic claystones interbedded with thin drab limestones and buff, non-resistant sandstones. Limestone locally contains orange to brown chert inclusions. Includes about 50 feet (15 m) of Sundance Formation at the base; olive-drab, glauconitic sandstone and shale not mapable due to poor exposures. Thickness 350 feet (107 m) (Ver Ploeg and Boyd, 2007)

Triassic, Permian, and Pennsylvanian sedimentary rocks

TRPc **Chugwater Formation (Triassic and Permian)**—Red shale and siltstone with interbedded red to salmon to buff, fine-grained sandstone in upper part. Lower part of section contains red shale and calcareous siltstone, interbedded with thin to thick gypsum beds, local solution breccia, and banded wavy gypsiferous limestone sometimes mistaken as part of the Forelle Limestone. Includes approximately 150 feet (46 m) of Jelm Formation in upper section as a yellow to salmon-pink massive sandstone, with large-scale crossbedding, interbedded with thin partings of red siltstone, claystone, and shale. This unit was mapped separately by Vargas (1974). The lower part of the Chugwater Formation, along with the underlying Forelle Limestone and Satanka Shale, are mapped as Goose Egg Formation west of the Laramie Basin. Thickness 800 feet (244 m) (Ver Ploeg and Boyd, 2007)

Pf **Forelle Limestone (Permian)**—Gray to purple, thin-bedded, sparsely fossiliferous, resistant limestone locally interbedded with red siltstone and thin gypsum beds. Wavy outcrops of algal dome structure and more crinkly contorted bedding common (Nicoll, 1963). Crops out as low, broken, small ridges and highly fractured beds. Thickness 4 to 20 feet (1 to 6 m) (Nicoll, 1963)

Ps **Satanka Formation (Permian)**—Red siltstone and shale that is often banded with white and ocher color zones, and buff to orange to red fine-grained soft sandstone with distinct ripple marks common near the base of the unit. Gypsum occurs in the Satanka Formation as lenticular beds occurring as thick as 17 feet (5 m) (Darton and Siebenthal, 1909). Karst/sinkhole erosional structures associated with fluid flow in faults occur in the Satanka Formation on the northern portion of the map. Unconformably overlies the Casper Formation. Contact with Casper Formation can be difficult to discern though changes in grain angularity and the occurrence of ripple marks in the Satanka indicate the contact boundary. Thickness up to 260 feet (79 m) (Nicoll, 1963; Ver Ploeg and Boyd, 2007)

PPc **Casper Formation (Permian and Pennsylvanian)**—Buff to reddish, calcareous to quartzitic, very fine to course-grained, well-cemented sandstone interbedded with thin buff to purplish-gray limestone and dolomite beds, usually micritic and locally fossiliferous. Sandstone often exhibits large-scale festoon cross-bedding with siliceous fracture fill associated with faulting and local stresses. Within the map area siliceous-filled Casper Formation crops out as distinct resistant ridges, anchoring abundant vegetation and thick brush. Thickness is highly variable within the Laramie Basin, thinning toward the southwest. Within the map area thickness is 120 to 200 feet (37 to 61 m) (Maughan and Wilson, 1963)

EXPLANATION

IPf **Fountain Formation (Pennsylvanian)**—Coarse-grained pink to red to purple sandstone and arkose, with some conglomerates, fossiliferous limey sandstones, siltstones, shales, and thin limestone lenses. Blotchy pink-red iron staining is common on arkosic, resistant, ridge-forming portions of the formation. Conformably underlies Casper Formation within map area. Thickness is variable within the Laramie Basin, thickening toward the southwest. Within the map area thickness is 400 to 500 feet (122 to 152 m) (Nicoll, 1963)

Middle Proterozoic granitic and metamorphic rocks

Ymmd **Monzodiorite dike (Mg-rich)**—Fine-grained, brown to purple-black, highly fractured and weathered monzodiorite dikes that crop out linearly for several hundred feet to several miles (hundreds of meters to several kilometers) through the Sherman batholith. Dikes are predominately sub-vertical, which can be easily seen in the field as vertical to near vertical jointing within the dike. Monzodiorite dikes contain megacrystic alkali feldspars that display thin rims of plagioclase. Plagioclase xenocrysts associated with small, round quartz grains and hornblende are seen in random locations in the field (Frost and others, 1999). Two varieties of monzodiorite dikes have been recognized within the Sherman batholith that include an Fe-rich commingled body and an Mg-rich body that has less interaction with local country rock (Edwards, 1993). Mg-rich dikes are common within the map area. Monzodiorite dikes on the map area contain xenocrysts as described above, in addition to plagioclase and perthite that show obvious compositional zoning. Abundant, very small, needle-shaped apatite are pervasive throughout the sample and can be seen in thin section.

Major phases include plagioclase (some as myrmekite), perthite, microcline, biotite (sometimes altered to chlorite), hornblende, quartz, and orthoclase.
Minor phases include apatite, epidote, ilmenite, magnetite, and titanite.

The monzodiorite dikes have not been dated using modern isotope concordia methods. However, monzodiorite dikes cross cut Sherman Granite, Lincoln Granite enclaves and dikes, and porphyritic granite, indicating a post-Sherman batholith emplacement history.

Yld **Leucocratic dike**—Fine- to coarse-grained, sub-round to angular crystal structures of quartz, plagioclase and microcline with small amounts of mafic minerals. Some outcrops show localized mafic mineral concentrations along grain boundaries of primary quartz and plagioclase crystals. Leucocratic dikes range from fine to-small grained, pink-red, granitic, late stage batholith injections to coarse-grained, mature inner-grown crystal structures that consist of large quartz and alkali feldspar grains. Hydrothermal fluid alteration is evident in the larger crystal structure dikes as hematite staining and epidote. Alteration can also be seen as secondary, subgrain quartz growth within the larger crystal structure and especially along fractures within crystal faces

Major phases are plagioclase, quartz, microcline, perthite, and biotite
Minor phases are apatite, zircon, hornblende, ilmenite, and fluorite (Frost and others, 1999)

The age of the Leucocratic dikes is similar to that of the Lincoln Granite and in many cases the two are compositionally similar. The age of the fine-grained leucocratic dikes is assumed to be similar to the Lincoln Granite at 1,430 ± 2.6 Ma (Mega-annum or million years before present) by U-Pb dating (Frost and others, 1999). The age of the larger grained Leucocratic dikes is unknown, but field relationships suggest late stage batholith emplacement as a partially differentiated end member of the Sherman batholith

Yln **Lincoln Granite**—Medium- to fine-grained, equigranular, orange-red to orange-gray, biotite granite that crops out in horizontal sheets with resistant caps that create hills, domes, and high ridges that tend to outcrop above Sherman Granite. Some Lincoln Granite occurs as dikes and small inclusions/enclaves in the adjacent Sherman Granite. Lincoln Granite is generally less abundant than Sherman Granite. Lincoln Granite is a more evolved phase of the Sherman batholith with greater silica and less iron enrichment. The Lincoln Granite is classified as a ferroan alkali-calcic peraluminous granitoid (Frost and Frost, 2010). Contacts with the Sherman Granite are generally sharp. Contacts with the porphyritic granite are mingled to sharp. The Lincoln Granite was named after the Lincoln Monument that is present on the summit of the old Lincoln Highway and Interstate 80 (Edwards, 1993).

Major phases are quartz, plagioclase, microcline, perthite, biotite, hornblende, and ilmenite.
Minor phases are apatite, zircon, myrmekite.

Locally along fractures and faults the Lincoln Granite includes very small needle-like apatite along with titanite, epidote, and minor hematite and chlorite as alteration products. Some samples include isolated alkali feldspar megacrysts that make up less than 1% of the rock (Frost and others, 1999). The Lincoln Granite has been dated at 1,430 ± 2.6 Ma by U-Pb dating (Frost and others, 1999)

Ymfd **Mafic bodies, pods, and dikes (Fe-rich)**—Fe-rich mafic bodies, pods, and dikes occur throughout the map area within the Sherman batholith. They are strongly commingled with local porphyritic granite and Lincoln Granite and are generally emplaced as enclave-like dike features. Some field samples contain small inclusions of Sherman Granite as well as megacrystic plagioclase. In thin section the megacrystic plagioclase appear to be xenocrysts. Field relationships suggest dike/pod emplacement during batholith cooling.

Major phases include plagioclase, perthite, biotite, quartz, and orthoclase.
Minor phases are titanite, apatite, ilmenite, magnetite and zircon.

The mafic bodies, pods, and dikes have not been directly dated using modern isotope methods. Field relationships as described above suggest a later intrusive age to the Sherman Granite and similar age to Lincoln and porphyritic granites in the range of 1,430 to 1,433 Ma (Edwards, 1993)

Yp **Porphyritic granite**—Medium-grained, orange-gray to brown biotite hornblende granite with ½ to 1½ inch (1 to 4 cm), orange-pink and pink-gray perthitic microcline, and some plagioclase phenocrysts that show rapakivi-texture of plagioclase and quartz rims. Some outcrops of porphyritic granite show orientation of phenocrysts in a single stress direction that relates to local emplacement deformation. The porphyritic granite (named by Edwards, 1993) is considered a modal composition end member between the Sherman and Lincoln Granites (Frost and others, 1999). Hydrothermally altered outcrops have rapakivi texture where perthitic cores have altered to very fine grained, feathery masses of sericite. Epidote and minor chlorite are also seen as alteration products. Biotite exhibits moderate to heavy chloritic alteration with fine-grained, secondary quartz growth that de-laminates cleavage planes. Hematite-rich fluid is evident on crystal faces within the rock and is associated with cross-cutting quartz veins.

Major phases of the porphyritic granite are perthitic microcline, plagioclase, quartz, biotite, hornblende, and in hydrothermally altered samples, epidote and chlorite.
Minor phases include ilmenite, apatite, zircon, titanite, pigeonite, and in hydrothermally altered samples, sericite, hematite, and hydrothermally associated secondary quartz.

The porphyritic granite has been dated at 1,430 to 1,433 Ma by modal composition association between the Lincoln and Sherman Granites respectively (Frost and others, 1999)

Ys **Sherman Granite**—Medium- to coarse-grained, pink to reddish-orange, biotite hornblende granite that crops out in rounded to craggy mounds and more commonly a thick weathered grus. The Sherman Granite has a subporphyritic granular texture, exhibiting megacrystic microcline rimmed in plagioclase resulting in rapakivi texture in some locations. Sherman Granite is the most common phase of the Sherman batholith. It is the less evolved phase of the Sherman batholith with lower silica and greater iron concentrations. The Sherman Granite is classified as a ferroan alkali-calcic metaluminous granitoid (Frost and Frost, 1997). Contacts with both the Lincoln Granite and the porphyritic granite tend to be sharp.

Major phases are microcline, plagioclase, quartz, hornblende, biotite, and ilmenite.
Minor phases include zircon and apatite, and in some locations augite, pigeonite, and fayalite.

The Sherman Granite has been dated at 1,433 ± 1.5 Ma by U-Pb dating (Frost and others, 1999)

Xb **Garnet-biotite felsic gneiss**—Black to grayish-pink, fine-grained, feet (m)-scale folded, garnet-biotite felsic gneiss and biotite felsic gneiss. Composed of quartz, plagioclase, biotite, garnet, alkali feldspar, cordierite, and minor zircon, sphene, and chlorite. Very fine-grained biotite is interlayered with felsic bands rich in plagioclase, microcline, and quartz. Fine-grained biotite grains in mica-domains orient similar to elongate xenomorphic garnet. Garnet is common as poikioblasts in leucosome and quartzofeldspathic layers. Compositional banding parallels internal foliation of biotite. Banding forms isoclinal to tight folds with feet (m)-scale amplitude. Few inch (cm) parasitic folds on fold limbs are present. Unit is intruded by Sherman Granite and pigmatitic dikes related to late-stage Sherman batholith emplacement. Granitic intrusive material parallels banding and folding, parasitizing gneissic structure within the contact margin of the unit. Unit is interpreted as meta sedimentary rock syndepositional with metavolcanic gneisses described in relative proximity to unit and therefore of similar depositional age. Biotite felsic gneiss and garnet-biotite felsic gneiss have not been directly dated using modern isotope methods. Field relationship and comparative interpretation suggest an age ~1,743 to 1,610 Ma with the younger age preferred for metamorphic age (Jones, and others, 2010; Premo and Fanning, 2000)

Black to pinkish-gray to reddish, fine- to medium-coarse-grained biotite-hornblende felsic gneiss and biotite-hornblende augen gneiss occur as feet (m) scale lenses in garnet-biotite felsic gneiss and biotite felsic gneiss. Composed of quartz, plag0ioclase, alkali feldspar, biotite, and hornblende. Hornblende and biotite occur on rims of ¼ to ¾ inch (0.5 to 2 cm) quartz-feldspar porphyroclasts as augen and in very thinly banded mm-scale foliation layers. Based on outcrop study of fabric orientation, unit is most likely a metaigneous rock deformed at a similar age to garnet-biotite felsic gneiss and biotite felsic gneiss with a similar comparative age of ~1,743 to 1,610 Ma. It is unknown if this unit relates to younger deformed 1,433 Ma Sherman Granite that may have deformed during batholith emplacement

DISCLAIMERS

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NOTICE TO USERS OF INFORMATION FROM THE WYOMING STATE GEOLOGICAL SURVEY

NOTICE FOR OPEN FILE REPORTS PUBLISHED BY THE WSGS

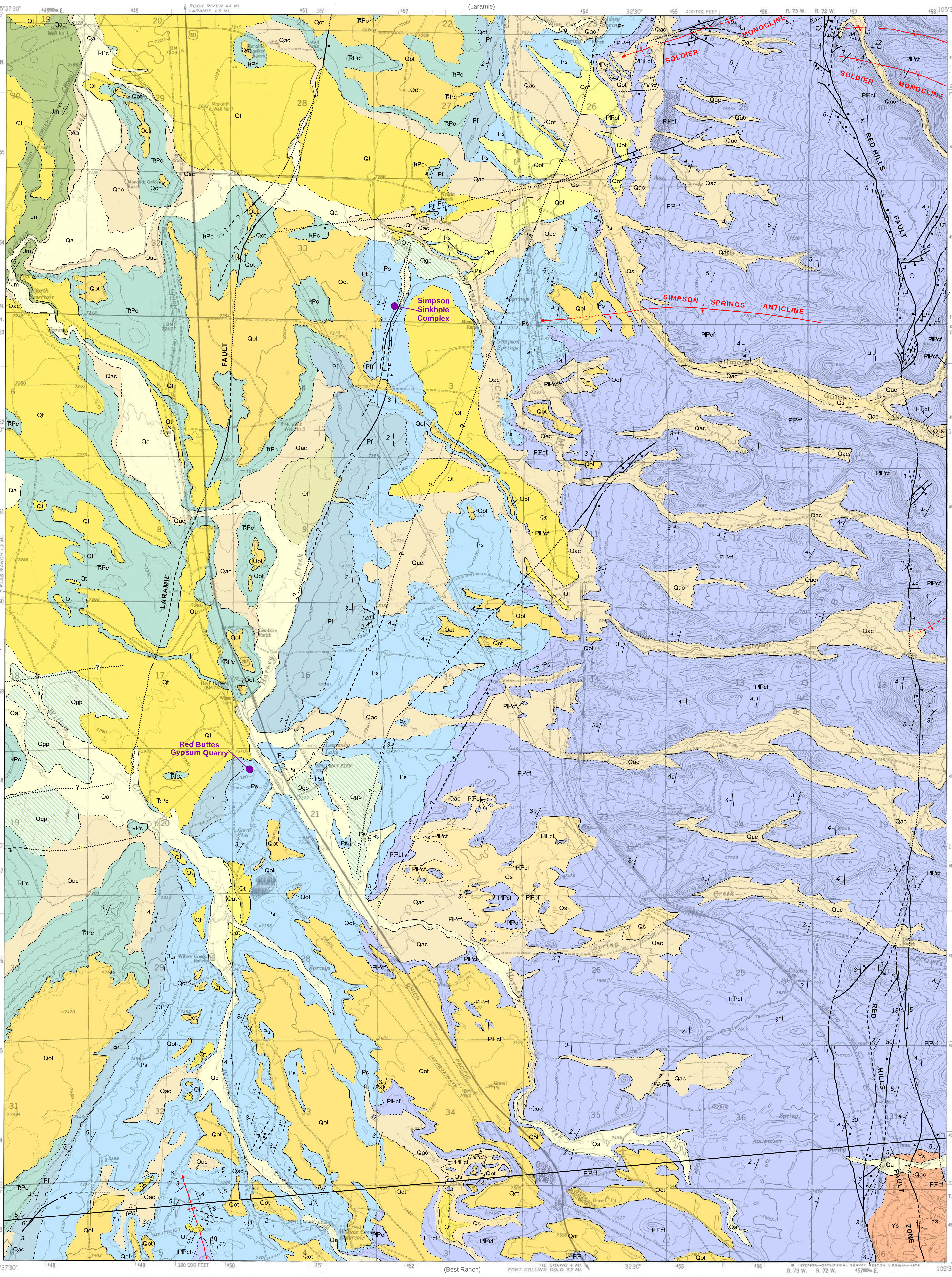
Plate IV

WYOMING STATE GEOLOGICAL SURVEY
Ronald C. Surdam, State Geologist
Laramie, Wyoming

Geology - Interpreting the past to provide for the future

Prepared in cooperation with the U.S. GEOLOGICAL SURVEY

CHARACTERIZATION OF EVAPORITE KARST FEATURES IN THE SOUTHERN LARAMIE BASIN, WYOMING, REPORT OF INVESTIGATIONS NO. 70 MODIFIED FROM MAP SERIES 76



Base map from U.S. Geological Survey 1:24,000-scale topographic map of the Red Buttes, Wyoming Quadrangle, 1963 (revised 1978)

Projection: Universal Transverse Mercator (UTM), zone 13
North American Datum of 1927 (NAD 27), 1,000-meter UTM grid ticks
10,000-foot grid based on Wyoming State Plane Coordinate System, East zone

Wyoming State Geological Survey
P.O. Box 1347 - Laramie, WY 82073-1347
Phone: (307) 766-2286 - Fax: (307) 766-2605
Email: sales-wsgs@uwyo.edu

A digital version of this map is also available on CD-ROM.

0°22' 7 MILS
13° 231 MILS

UTM GRID CONVERGENCE (GN)
1978 MAGNETIC DECLINATION (MN) AT CENTER OF SHEET
DIAGRAM IS APPROXIMATE

SCALE 1:24,000

1 0.5 0 1 Mile

1,000 0 1,000 2,000 3,000 4,000 5,000 6,000 7,000 Feet

1 0.5 0 1 Kilometer

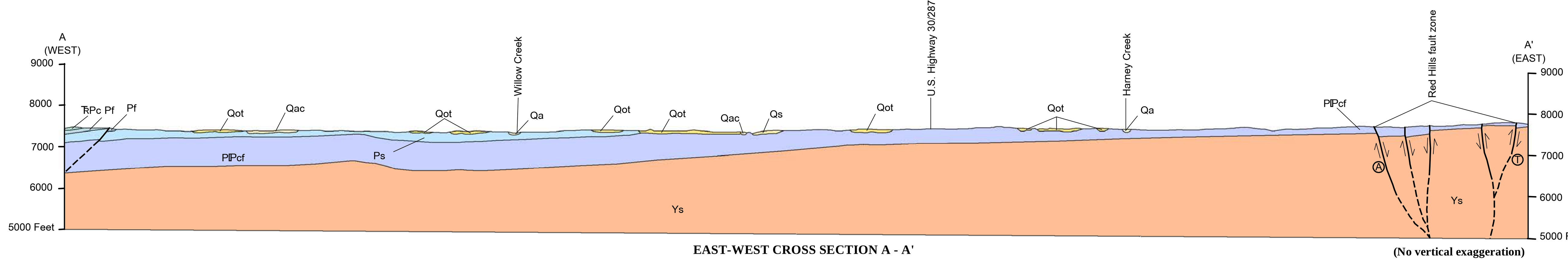
CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Prepared in cooperation with the U.S. Geological Survey, National Cooperative Mapping Program, under STATEMAP Award No. 1434-94-A-1262 and Cooperative Agreement Number 06HQAG0049.The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Geology mapped in 1994, revised 2007.

Digital cartography by Alice J. Vogelmann, David W. Lucke, and Robin W. Lyons.

People with disabilities who require an alternative form of communication in order to use this publication should contact the Editor, Wyoming State Geological Survey. TTY Relay Operator 1 (800) 877-9975f.

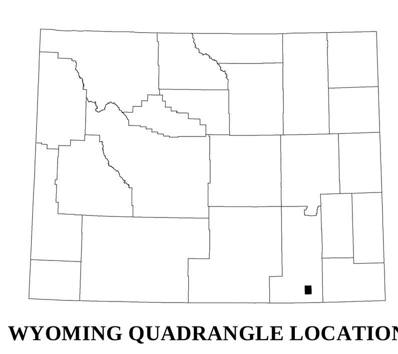


EAST-WEST CROSS SECTION A - A'

(No vertical exaggeration)

MODIFIED GEOLOGIC MAP OF THE RED BUTTES QUADRANGLE, ALBANY COUNTY, WYOMING

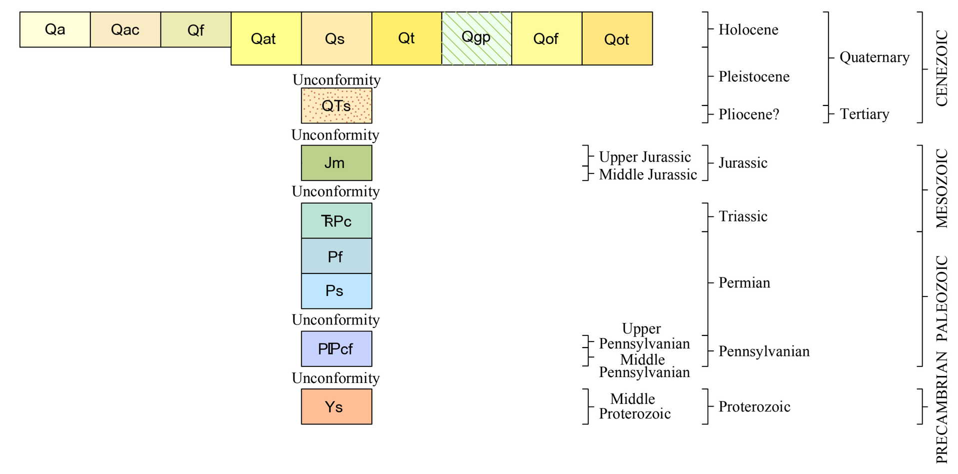
by
Alan J. Ver Ploeg
2016



WYOMING QUADRANGLE LOCATION

EXPLANATION

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

Holocene surficial deposits

Qa — **Alluvial deposits**—Unconsolidated and poorly consolidated clay, silt, sand, and gravel, mainly in floodplains and lowest stream terraces; thickness 0 to 20 feet (0 to 6 m)

Qac — **Mixed alluvium and colluvium**—Sand, silt, clay, and gravel deposited mainly along intermittent streams; includes slope wash and smaller alluvial fan deposits that coalesce with alluvium; thickness approximately 0 to 20 feet (0 to 6 m)

Qf — **Alluvial fan deposits**—Poorly sorted clay, silt, and gravel; crudely bedded to nonbedded. Appear to be active, receiving sediments from intermittent stream; may have some debris flow component. Only occurrence is northeast of Red Buttes; thickness 0 to 30 feet (0 to 9 m)

Holocene and Pleistocene surficial deposits

Qat — **Mixed alluvium and terrace deposits**—Unconsolidated and poorly consolidated clay, silt, sand, and gravel, representing a transition zone between alluvium and terrace deposits. Restricted to a small occurrence along Willow Creek, in the southern part of the map. Thickness approximately 0 to 15 feet (0 to 4.6 m)

Qs — **Windblown sand deposits**—Active and stabilized dunes, made up of very fine to fine-grained sand. Although numerous unmapped small-scale examples occur within the map area, mapped examples occur at the mouth of Gilmore Gulch and southeast of Red Buttes in the Red Buttes housing development. Thickness approximately 0 to 15 feet

Qt — **Terrace deposits**—Beds of coarse sand and gravel with occasional boulders and lenses of silt and clay. Includes fragments of weathered granite and limestone cobbles, their predominance varies depending on source of feeding stream. Occur along present drainages, a few feet (0.6 m) to over 15 feet (4.6 m) above modern flood plains; thickness approximately 0 to 10 feet (0 to 3 m)

Qgp — **Gypsite deposits**—Unconsolidated clay-sized gypsum interbedded with red clay, sand, gravel, and limestone cobbles. Mostly located in stream valleys immediately west of the Laramie fault, probably sourced by solution and erosion of gypsum beds in the upper Satanka and lower Chugwater formations which were brought to the surface or near surface by faulting. Thickness approximately 0 to 20 feet (0 to 6 m)

Qof — **Older alluvial fan deposits**—Poorly sorted clay, silt, sand, and gravel; crudely bedded to nonbedded with some debris flow component; limestone cobbles are common. Currently inactive and dissected, often occurring as erosional remnants. Grade into older terrace deposits toward the west, in the northern part of the map area. Thickness 0 to 20 feet (0 to 6 m)

Qot — **Older terrace deposits**—Beds of coarse sand and gravel with occasional boulders and lenses of silt and clay; limestone cobbles are common. Often occur as erosional remnants ranging from 20 to 40 feet (6 to 12 m) above present stream floodplains. Some remnants may actually be older alluvial fan remnants. Thickness 0 to 10 feet (0 to 3 m)

QTs — **Older windblown sand (Pleistocene/Pliocene?)**—Mostly unconsolidated light-gray sand and silt interbedded with lenses of gravel and cobbles composed of limestone and sandstone eroded from outcrops of Casper Formation, as well as igneous and metamorphic cobbles from the Precambrian outcrops to the east. Crops out in Gilmore Gulch on the east edge of the map. Additional work is required to definitively establish the age of these deposits. Thickness 0 to nearly 100 feet (0 to nearly 30 m)

Mesozoic and Paleozoic sedimentary rocks

Jm — **Morrison Formation (Upper and Middle Jurassic)**—Pale-green, olive-green, blue-green to maroon and chalky white variegated calcareous and bentonitic claystones interbedded with thin drab limestones and buff, non-resistant sandstones. Limestone locally contains orange to brown chert inclusions. A thin section of Sundance Formation may exist in the area, but due to few and poor exposures and questionable identification, it is mapped with the Morrison. Thickness 300 to 400 feet (91 to 122 m)

ŦPc — **Chugwater Formation (Triassic and Permian)**—Red shale and siltstone with interbedded red to salmon to buff, fine-grained sandstone. Lower part of section contains red shale interbedded with thin to thick gypsum beds, local solution breccia, and banded wavy gypsiferous thin limestone sometimes mistaken for part of the Forelle Limestone. This part of the Chugwater along with the underlying Forelle Limestone and Satanka Shale are mapped as Goose Egg Formation west of the Laramie Basin. Locally, some sandstone erosional outliers of possible Jelm Formation may occur, but due to their lack of persistence and questionable identification, they are mapped with the Chugwater. One example of possible Jelm Formation occurs east of Harney Creek in sec. 29, T. 15 N., R. 73 W. Thickness 650 to 800 feet (198 to 244 m)

Pf — **Forelle Limestone (Permian)**—Gray to purple, thin bedded, sparsely fossiliferous limestone locally interbedded with red siltstone and thin gypsum laminations and associated solution breccia; wavy outcrops resembling algal structures common; thickness 10 to 30 feet (3 to 9 m)

Ps — **Satanka Shale (Permian)**—Red siltstone and shale (often banded with white- and ocher-colored zones), soft sandstone, thin limestones, and local gypsum beds, especially near the top. Buff to orange to red, fine-grained sandstone with ripple marks common near base of unit. Gypsum beds in the Satanka are currently being mined south of Red Buttes. Thickness 140 to 200 feet (43 to 61 m)

PIPcf — **Casper and Fountain formations undivided**—Mapped together due to the transitional nature of the contact between the Casper and the Fountain; total combined thickness 600 to 800 feet (183 to 244 m)

Casper Formation (Permian and Upper and Middle Pennsylvanian)—Buff to reddish, calcareous to quartzitic, very fine- to coarse-grained, well-cemented subarkosic sandstone interbedded with buff to purplish-gray limestone and dolomite beds, usually micritic and locally fossiliferous. Sandstone often exhibits large-scale festoon cross-bedding, increasing toward the south. The limestone beds are quite thin and less numerous than in the Laramie area and are for the most part absent in the southern part of the map area. Intertongues with underlying Fountain Formation. The Casper Formation serves as the prime aquifer in the map area

Fountain Formation (Pennsylvanian)—Primarily maroon arkosic cross-bedded fine to coarse sandstone and conglomerate interbedded locally with shales and thin limestones; up to 400 feet (122 m) thick

Precambrian crystalline rocks

Ys — **Sherman Granite (Middle Proterozoic)**—Coarsely crystalline pink granite ranging in age from 1,414 to 1,435 Ma (Mega-annum or millions of years before present). Crops out in the southeast corner of the map area

MAP SYMBOLS

Formation contact—Dashed where approximately located

Fault—Dashed where approximately located, queried where inferred, and dotted where concealed; ball and bar on downthrown block; arrows indicate relative horizontal movement where known

Anticline—Dashed where approximately located, dotted where concealed; trace of axial plane and direction of plunge determined by field dip measurements and air photo interpretation; shorter arrow indicates apparent dip of steeper limb of asymmetric anticline

Monocline—Showing direction of plunge; dashed where approximately located, dotted where concealed; trace of axial plane determined by field dip measurements and air photo interpretation (note: axial plane is oblique to dip on several monoclines in northeastern corner of map due to strike-slip faulting); shorter arrow denotes steeper dipping limb

60 **Strike and dip of beds**—Showing angle of dip; formation symbol in parentheses indicates attitude measured for bedding in an exposure that was too small to depict at the present map scale

45 **Strike and dip of beds**—Showing angle of dip; measurements from Lundy (1978) and Nicoll (1963)

Horizontal beds

A — A' **Line of cross section**—Circled letters next to faults indicate strike-slip component of movement, T is movement toward observer, A is movement away from observer

Collapse structure

MODIFICATIONS FOR REPORT OF INVESTIGATIONS NO. 70

Quarry or sinkhole complex location

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