Geologic Map and Geohazard Assessment of Silver Bow County, Montana

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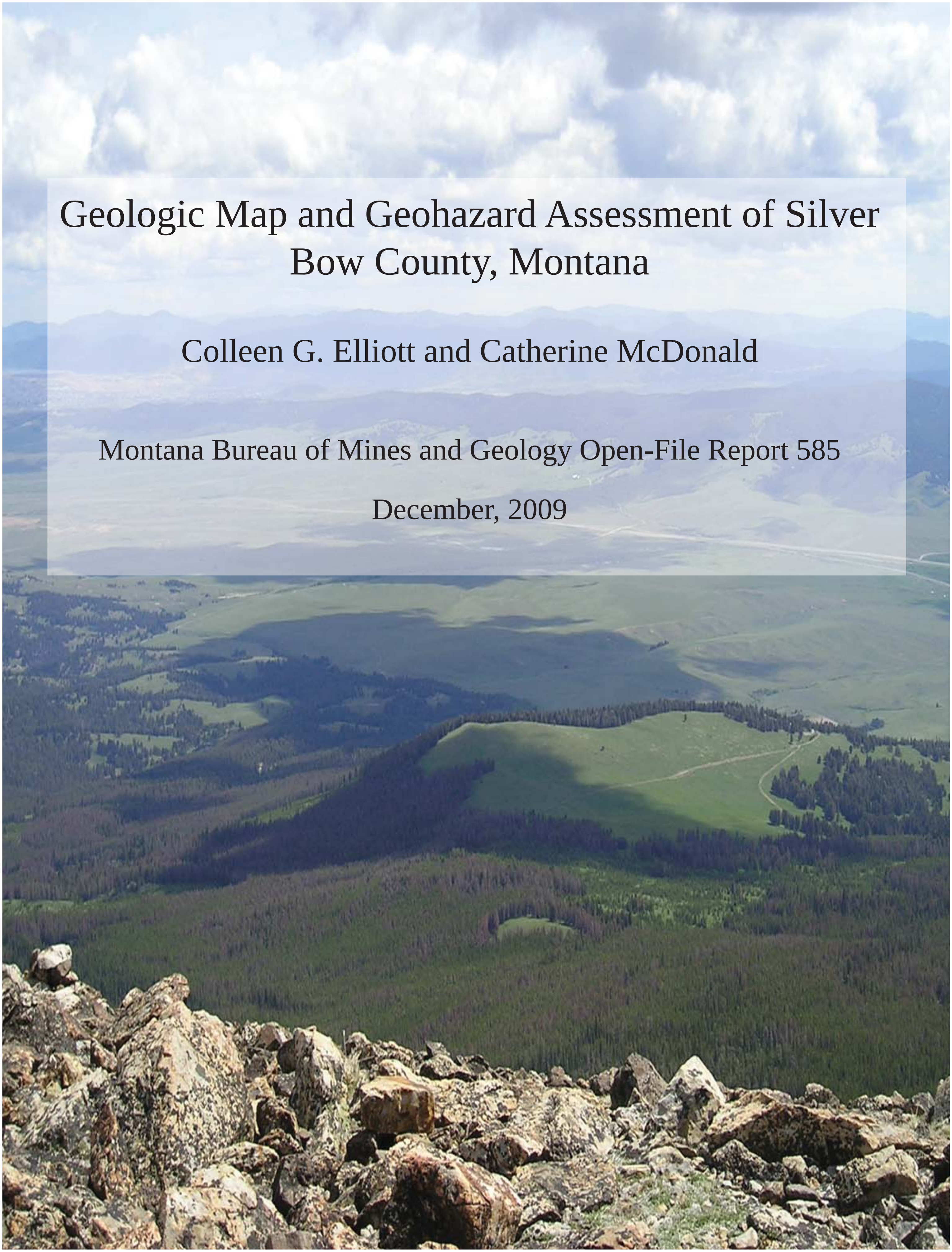

Front photo by Colleen Elliott, MBMG.

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1. EXECUTIVE SUMMARY

The 2004 Hazard Mitigation Plan for Silver Bow County, Montana, identified earthquakes and landslides as hazards of concern, leading to the FEMA-funded study described in this report. Earthquake and landslide data were compiled from existing data, then enhanced by aerial photograph analysis and field investigations. The final product consists of digital data in GIS format at a scale of 1:50,000 for use in general planning. GIS layers represent county geology in traditional format, rock and sediment type, fault locations and probable ages, and size and settings of landslides and related deposits. This report describes how geologic data were collected and interpreted, and offers conclusions that can be drawn, as summarized below.

The geology of Silver Bow County is influenced by a number of regional tectonic features and can be divided into five basic geologic domains underlying different parts of the county: Precambrian metamorphic rocks, Paleozoic and Mesozoic sedimentary and metasedimentary rocks, the Boulder batholith, the Lowland Creek volcanic rocks, and Cenozoic valley sediments.

All of these domains contain faults, some that have not moved for hundreds of millions of years, and some that have moved in geologically recent times. The oldest faults do not present an earthquake hazard. Some younger faults can be inferred to have produced earthquakes larger than magnitude 6.5 within the past 1.8 million years, and may generate earthquakes in the future. Not all potential sources of earthquakes can be identified since moderate-sized earthquakes in southwest Montana typically originate on faults that are not recognized at the surface.

The Continental Fault is one of a linked set that is more than 1.9 miles wide and as much as 33.5 miles long. The Continental Fault proper has had over 3,500 feet of offset and has very likely moved in the past 1.8 million years. The Rocker Fault is segmented and has a cumulative length of more than 30 miles. Segments of the Rocker Fault have moved within the past 1.8 million years. Both the Rocker Fault and the Continental Fault set have been offset by small motions on northeast-trending faults that may be acting as transfer faults to accommodate motion on the larger faults. Existing east–west extensional stresses in the crust are capable of causing seismicity near Butte, and may cause movement on the Continental and Rocker Faults.

Silver Bow County lies near the western edge of a zone of elevated seismicity. There is a 2% chance that during the next 50 years it will experience seismic shaking greater than 0.12 g, which is strong enough to damage buildings, especially older unreinforced masonry buildings (Wong and others, 2005).

Landslides are a smaller hazard, even though there are more than 300 identified landslide occurrences within the county. They cover less than 1% of the surface of the county and are most common where slopes are steep. They are clustered within the volcanic rocks in the northern part of the county and the sedimentary rocks in the southern part. Landslides are primarily a hazard for structures built in canyon bottoms, stream channels, outlets of canyons, and on modified steeper slopes. Damage caused by landslides can be avoided by performing site-specific studies.

Recommendations arising from this study include trenching and radiometric dating studies along the Continental and Rocker Faults to detail their movement histories. It is also recommended that hazards be reevaluated in the event of large-scale loss of vegetation, changes in headwater hydrology, or alteration of precipitation and melting patterns as predicted by global climate change.

2. INTRODUCTION

2.1. Background and Purpose

The purpose of this report is to evaluate natural geologic hazards in Silver Bow County as part of an effort by Silver Bow County to update and improve their 2004 Hazard Mitigation Plan (Butte–Silver Bow, 2004). The 2004 plan identified earthquakes and landslides as hazards of concern and ranked earthquakes as the hazard to which the county is most vulnerable. Landslide hazard was ranked low in terms of vulnerability, but the 2004 plan recognized that very limited data on existing or potential landslide hazards were available. In January 2007, Butte–Silver Bow City/County submitted a Pre-Disaster Mitigation Program Planning grant application to the Federal Emergency Management Agency (FEMA) proposing a detailed county-wide study of earthquake and landslide hazards in collaboration with the Montana Bureau of Mines and Geology (MBMG). The grant was awarded in August 2007 with the primary goal of identifying and mapping geologic hazards and incorporating the new data into the updated hazard mitigation plan.

2.2. Scope

The MBMG evaluated earthquake and landslide hazards by compiling existing geologic and hazard data,

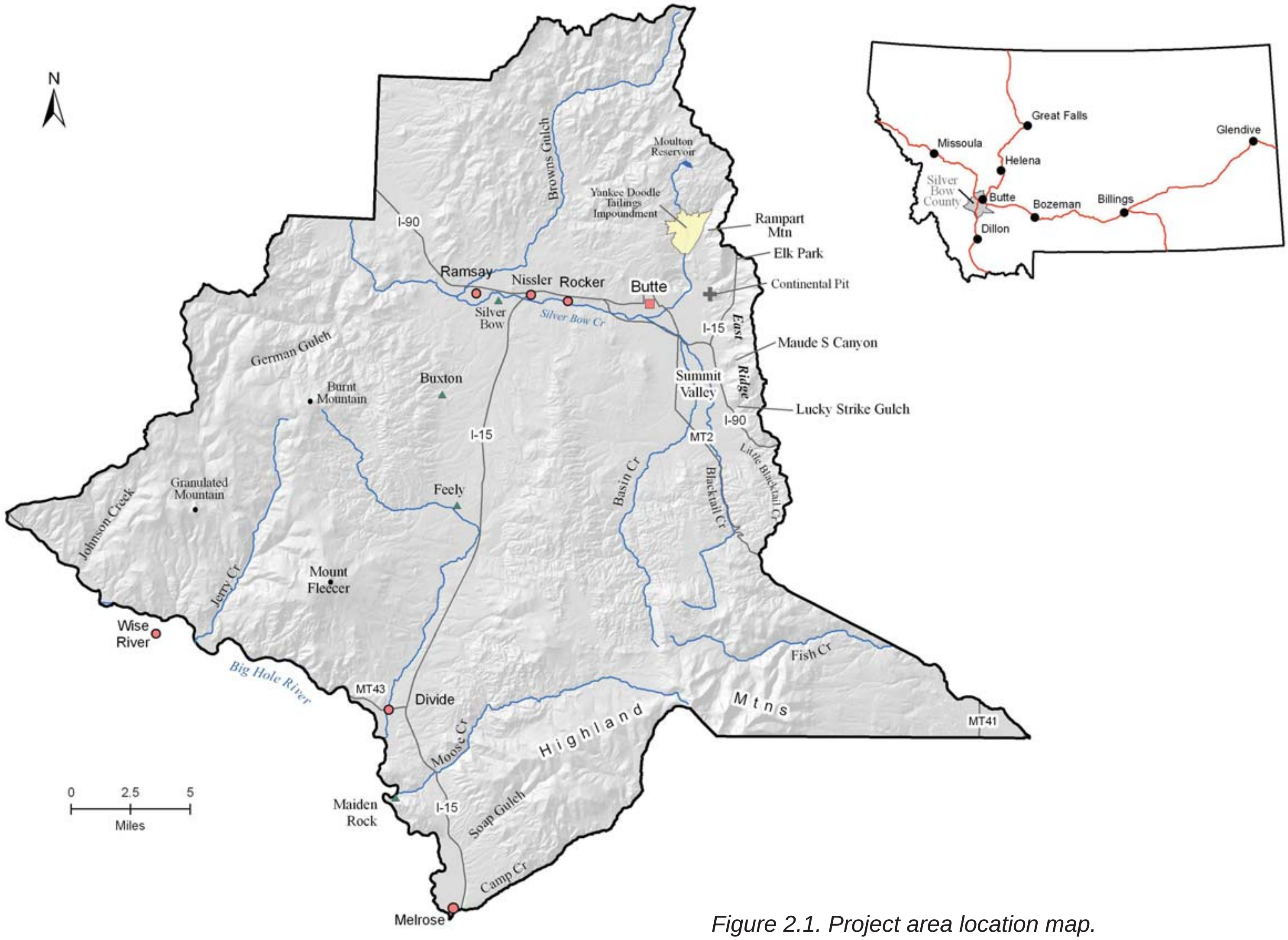

Figure 2.1. Project area location map.

collecting new field data, and summarizing results in a final report. The study area encompasses Silver Bow County (fig. 2.1). We placed top priority on developing a better understanding of earthquake hazards through in-depth fault study and field mapping. Landslide hazards were analyzed through aerial photograph interpretation and field mapping. Although earthquake hazards are a county-wide concern, landslides, debris flows, and various related types of downslope movement of earth materials are site-specific and need to be accurately identified and mapped for further hazard analysis.

The primary product of this hazard assessment is digital geologic data at 1:50,000 scale (GIS format) to be used by county planners for hazard mitigation. We began by compiling available geologic information. While previously existing geologic maps covered most of Silver Bow County, they were prepared at different scales by different geologists using different nomenclature, and none was prepared for the specific purpose of hazard assessment. Compilation therefore involved correlating geological units across map boundaries and fitting them into a unified stratigraphy. Geologic faults were correlated across the county where agreement was good between previous maps. Faults that did not trace across previous maps and those that were identified as possibly having recent movement and potentially contributing to earthquake hazards were tagged for closer study.

Compilation of geologic data and previous maps was followed by field mapping to improve areas of poor coverage and resolve disagreement between previous maps. The Continental and Rocker Faults were studied in detail in order to locate them as precisely as possible and to assess their movement histories.

The final product is a 1:50,000 scale digital geologic map of Silver Bow County consisting of several GIS layers:

1. Geology presented in traditional format, identifying geologic units by age and established stratigraphy,

2. Geologic units identified solely by rock and sediment type,

3. Locations and approximate ages of faults in the county, and

4. Locations, sizes, and geologic settings of landslides and related deposits.

Along with geological data collection, this project included geophysical investigation of the two largest faults in the county, the Continental Fault and the Rocker Fault. The usefulness of ground-penetrating radar was tested as a non-intrusive tool for locating fault planes covered by shallow alluvium. Unpublished gravity data collected over the years by Montana Tech students and staff were compiled and modeled to add clarity to the geometries of fault planes and the associated Summit Valley and Rocker Valley sediment basins. Faculty in the Department of Geophysical Engineering at Montana Tech performed the studies.

2.3. Report Organization

This report begins with a general overview of the regional geologic setting of Silver Bow County and broad descriptions of the major geologic domains within the county. The general description of the nature of earthquake and landslide hazards that follows gives context for more detailed and specific assessments of earthquake and landslide hazards that make up the bulk of this report. The discussion is necessarily technical to clarify the complex reasoning behind geologic interpretations of where, how often, and when earthquakes and landslides occur.

The significant interpretations and conclusions reached in the technical sections are summarized in the final section in a format anticipated to be most useful to those completing the pre-disaster mitigation planning. The final recommendations include suggested further studies that can fill ongoing knowledge gaps and provide additional relevant data for effective hazard mitigation.

Plates included in this report are the geologic map of Silver Bow County and geologic cross sections of the Summit, Rocker, and Buxton Valleys (pl. 1). Plate 2 is a map showing only faults and their classification based on age of last movement as verified by observed overprinting relationships. Plate 3 shows the locations, class, and size of mapped landslides and related deposits and their geologic setting.

Appendix 1 is a detailed description of each stratigraphic unit mapped in Silver Bow County with names, ages, and symbols that correspond directly to the 1:50,000 geologic map and cross sections of plate 1. An index map showing sources of geologic data is included as figure A-1.

Appendix 2 contains explanations of the new and unpublished geophysical data to which the main text refers.

In this report we define "geologically recent" as between the beginning of the Quaternary Period 1.8 million years ago and today. This usage is consistent with the Definitions of Fault Activity for the Basin and Range Province adopted by the Western States Seismic Policy Council (WSSPC) in 2008. These definitions are included as appendix 3. Appendix 4 is the Geologic Time Scale endorsed by the Geological Society of America in 1999, included for reference. Numeric ages given in this report for geologic features and events are based on the radiometric calibrations of this time scale.

3. GEOLOGIC SETTING

The principal illustration for this report is the updated geologic map shown in plate 1. This map combines previous mapping from many authors (fig. A-1, appendix 1) and includes new detail where coverage was lacking. New information gleaned from compilation of previous work and from new mapping is described in detail in the following sections and appendices. This section provides a broad overview of the geology of southwest Montana and a general description of Silver Bow County geology to provide background for subsequent sections.

3.1. Regional Setting

Silver Bow County lies within the Rocky Mountains of the Cordillera or "backbone" of the North American continent. Tectonic zones and features that have an influence on the local geology include the following (fig. 3.1):

1. The Basin and Range Province: a broad zone of crustal extension west of the Rocky Mountains that extends into southwestern Montana and western Idaho and runs south into Mexico. While broad scale extension in the Basin and Range is east–west, in Montana the extension direction is east–northeast to west–southwest. In southwest Montana, the Basin and Range began to form about 17 million years ago (Fritz and Sears, 1993).

2. The Great Falls Tectonic Zone: a broad northeast-trending belt from Salmon, Idaho, to Great Falls, Montana, and Saskatchewan (O'Neill and Lopez,

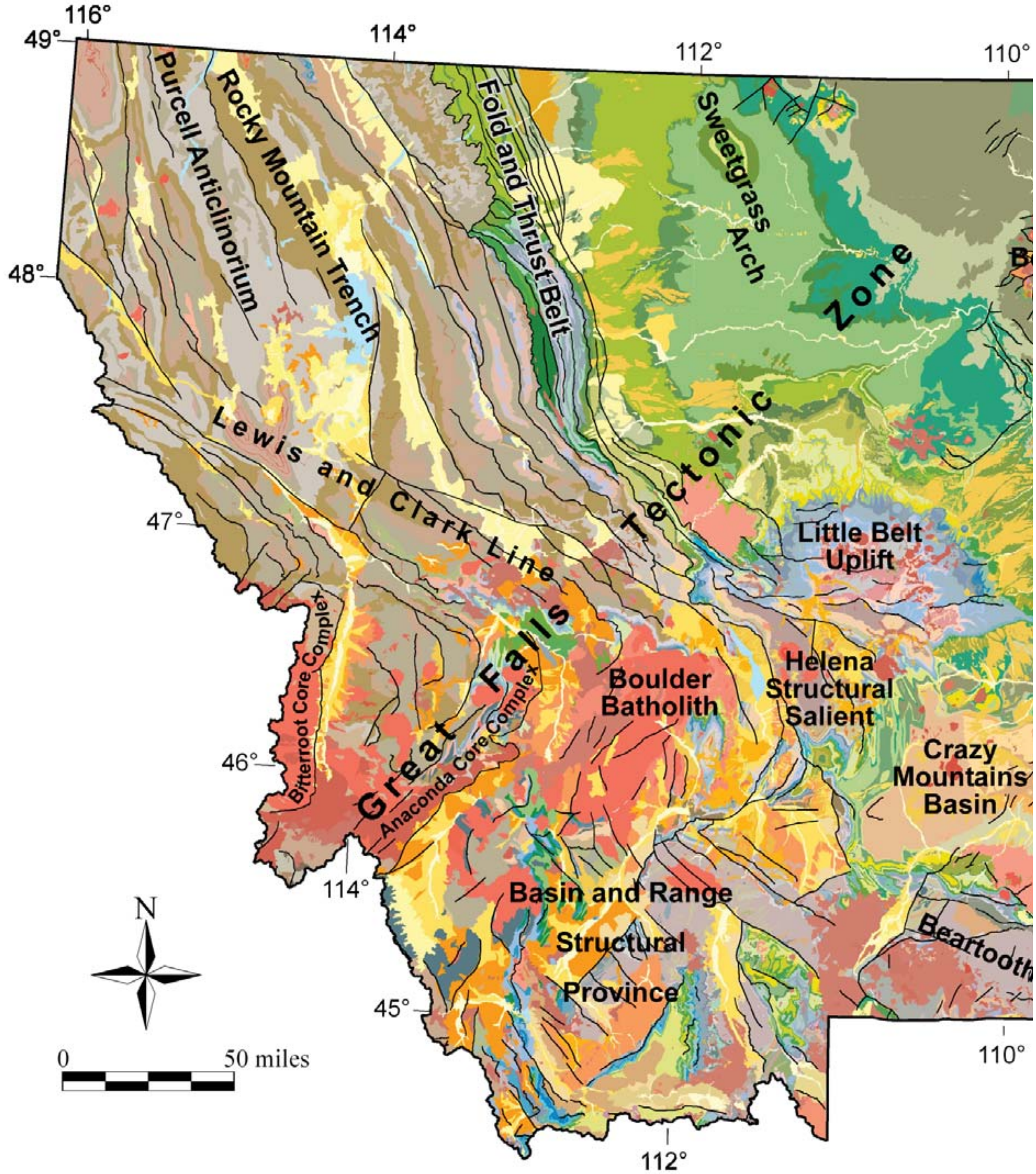

Figure 3.1. Tectonic zones of western Montana. The following features are discussed in the text: Basin and Range, Great Falls Tectonic Zone, Helena Salient, Boulder batholith, and Lewis and Clark Line.

1985; O'Neill, 1998). It overlies a Paleoproterozoic geologic boundary and is marked by a zone of distinctive igneous rocks and by northeast-trending faults. Some faults in this zone have moved as recently as the Quaternary Period (Vuke, 2004).

3. Helena Salient: this is a bulge of Front Range-style folding and thrust faulting that protrudes eastward into the Rocky Mountain Foreland (Robinson, 1963; Schmidt and others, 1988). The southern edge of the Helena Salient is the South Montana Transverse Zone or Perry Line that crosses Silver Bow County through the Highland Mountains (McMannis, 1963; Ross and Villeneuve, 2003; O'Neill and others, 2004; Vuke, 2004; Sears, 2006).

4. Boulder batholith: a large Cretaceous granitic mass that is described below.

5. Lewis and Clark Line: a topographic and geologic lineament that extends over 500 miles from northeastern Washington through central Montana, passing just north of Silver Bow County. It is a zone of folds and faults that date back at least to Mesoproterozoic time (Harrison and others, 1974; Reynolds, 1979; Winston, 1986; Wallace and others, 1990; Sears and Hendrix, 2004).

6. Intermountain Seismic Belt: a zone of elevated seismicity that encompasses much of western Montana. This belt is discussed in Section 5.

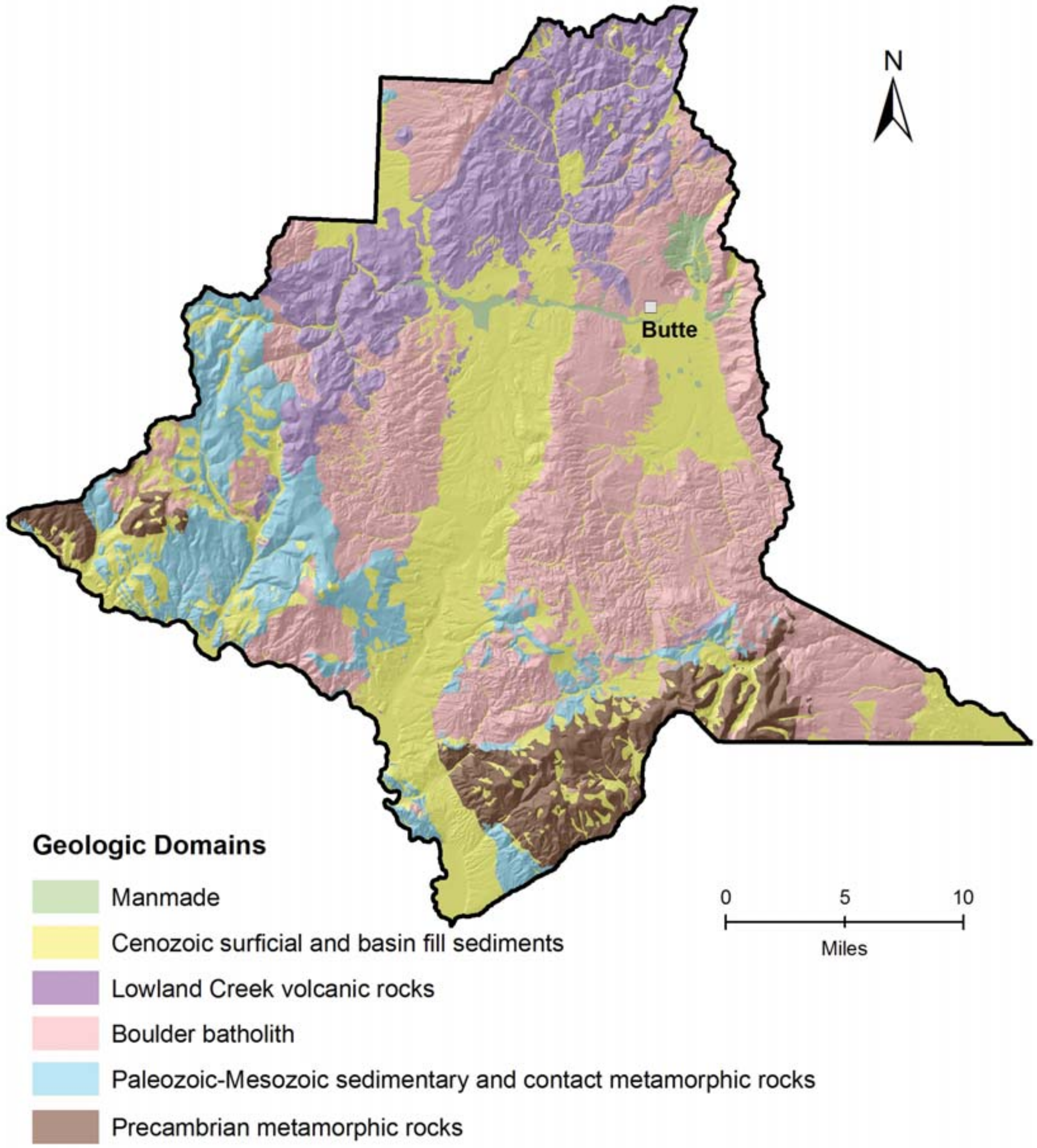

Figure 3.2. Rock type and age domains of Silver Bow County.

3.2. Silver Bow County Geology

The geology of Silver Bow County is both diverse and distinctive. It is diverse in the variety of rock types and geologic structures, and distinctive in its location at the intersection of the numerous geologic provinces described above, in the nearly complete stratigraphic section representing more than 2.5 billion years of geologic history, and, of course, in the presence of the world-class Butte ore bodies.

In Figure 3.2, the county is divided into five geologic domains based on rock type and age, which can also be loosely tied to mechanical properties:

1. Precambrian metamorphic rocks;
2. Paleozoic and Mesozoic sedimentary rocks and contact metamorphic rocks;
3. Boulder batholith;
4. Lowland Creek volcanic rocks; and
5. Cenozoic valley sediments.

Each of these is briefly described below.

3.2.1. Precambrian Metamorphic Rocks

The oldest rocks are Archean gneisses that were derived from sediments and volcanic rocks deposited more than 2.5 billion years ago and metamorphosed to gneiss between 1.8 and 1.7 billion years ago during a continental collision (Harms and others, 2004).

Archean rocks are well exposed along Camp Creek in the southern Highland Mountains, where they are in unconformable contact with younger Cambrian age sedimentary rocks (from 490 to 540 million years old) and fault contact with younger Precambrian rocks of the Belt Supergroup (approximately 1350 to 1450 million years old).

Belt Supergroup metasedimentary rocks make up a significant portion of the Highland Mountains south of Butte. They are also found near the western border of the county. Between 1350 and 1450 million years ago, dominantly fine-grained sedimentary rocks were deposited in a quiet sea, part of whose margin is thought to have run east–west through what are now the Highland Mountains (Winston, 1986). Low-grade metamorphism of the sediments to slates and quartzites occurred during regional mountain building between 80 and 60 million years ago.

The mechanical and erosional properties of Precambrian rocks in Silver Bow County vary. The Archean gneisses are very hard and resistant; the Belt Supergroup metasedimentary rocks are less resistant, but because they have undergone some metamorphism are well indurated and rigid compared to some of the younger rocks. Slaty cleavage in Belt Supergroup rocks locally forms planes of weakness along which failure may occur. Precambrian rocks and Cretaceous igneous rocks (see below) support the highest elevations in the county and tend to resist erosion relative to other rock types.

3.2.2. Paleozoic and Mesozoic Sedimentary Rocks and Contact Metamorphic Rocks

The south-central and western parts of Silver Bow County are underlain by a wide variety of sedimentary rocks that range in age from about 540 to 85 million years old. Rock types include conglomerate, sandstone, siltstone, mudstone, shale, limestone, dolomite and their contact-metamorphic equivalents (primarily quartzite, hornfels, and marble). The oldest of these rocks are quartz sandstones and quartzites of the Cambrian Flathead Formation.

The mechanical properties of the Paleozoic and Mesozoic rocks vary widely. The weakest units are shales and mudstones that occur in the Silver Hill, Park, Three Forks, Morrison, Kootenai, and Blackleaf Formations. Sandstone and limestone beds from throughout the stratigraphic section are more resistant and form steep slopes and ridges along the Big Hole River and in the Highland Mountains.

3.2.3. Boulder Batholith

The granitic Boulder batholith dominates Silver Bow County and hosts the world-class Butte metal deposits. It is composed of a number of plutons, the largest of which is the Butte Granite, which is 74 to 76 million years old (see detailed review in du Bray and others, 2009), and includes a number of smaller bodies that vary in age between 73.7 and 80.7 million years old. The Boulder batholith is coeval and probably cogenetic with the Elkhorn Mountain volcanics, and intruded into the base of that volcanic pile. After intrusion of the main plutons of the Boulder batholith, a suite of stocks and dikes was emplaced and accompanied by formation of what are known to the mining community as "pre-Main Stage" copper and molybdenum deposits of the Butte mining district. The rich "Main Stage" ore veins were formed sometime between 61 and 50 million years ago (Lund and others, 2002).

Intrusion of the multiple plutons that form the batholith was part of the tectonic event that built the Rocky Mountains and caused the low-grade metamorphism that produced quartzite, marble, and hornfels bodies where granitic magma heated sedimentary rocks.

Boulder batholith rocks are mechanically homogeneous where intact, but jointing has created dominant planes of weakness that control rock behavior near the surface. The dominant joint sets are vertical and north–south-trending, but other orientations exist, creating the potential for wedge failure as well as toppling and sliding failure.

3.2.4. Lowland Creek Volcanic Rocks

Along ridge tops in the northern and western parts of the county, a thick pile of silica-rich volcanic rocks caps the Boulder batholith. Over 2,000 feet (610 m) of Lowland Creek Volcanics was deposited in a northeast-trending belt during the Eocene Epoch, between 48 and 52 million years ago (Baadsgaard and others, 1961; Smedes and Thomas, 1965; Ispolatov and others, 1996). Volcanism was related to southeast–northwest extension of the crust that followed contractional mountain building (O'Neill and Lageson, 2003; Kalakay and others, 2003; O'Neill and others, 2004; Foster and others, 2007).

Mechanical strength and erosional resistance of the

Lowland Creek Volcanics vary widely. Lava flows and densely welded ash-flow tuffs will generally be resistant and form caps on hills. Poorly indurated ash beds within the Lowland Creek Volcanics fail readily, especially when wet, and commonly undermine more resistant overlying rocks, resulting in significant sliding. Steep hillsides in the Moulton Reservoir area, for example, are scattered with small slump masses within volcanic rocks.

3.2.5. Cenozoic Surficial and Basin-Fill Sediments

The broad valleys of Silver Bow County were formed by extension along steep faults that moved intermittently from mid-Eocene times onward. The wide variety of sediments deposited in the valleys are represented on the geologic map (pl. 1) by 28 mappable sedimentary units that range from fine-grained lake and swamp deposits to coarse stream deposits and bouldery debris flows. Most of the sediments contain ash from volcanic eruptions in Montana, Idaho, Wyoming, and as far west as Oregon and Washington. Coarse clasts in the sediments generally have compositions similar to nearby bedrock, though there is evidence that clasts in some beds were transported from the Anaconda Range located west of the county (Thomas, 1995).

Deposition in the valleys and faulting within the valleys and along their margins occurred at the same time, and the close relationship between faults and deformed sediments suggests earthquake shaking.

In Silver Bow County, the history of block faulting and valley sedimentation occurred in at least four stages. Faulting between 50 and 60 million years ago created the northeast trends that dominate the hills north of Butte. Subsequent east–west extension created the north–south faults bounding the Summit Valley and Buxton-Rocker Valley, followed by northeast–southwest extension, which created or reactivated southeast-trending faults like those bounding the Melrose valley. Current block faulting is related to east–west crustal extension (Stickney, 2007).

Valley-fill sediments are dominantly poorly compacted and easily eroded. Some muddy horizons contain swelling clays that are prone to sliding. Surface sediments in the Summit and Buxton Valleys and across the East Ridge are dominated by granite detritus, or "grus," which tends to be porous, well-drained, and less prone to sliding. Sediment accumulation in valleys continues into the present day.

4. OVERVIEW OF POTENTIAL HAZARDS

Geologic phenomena that may be of concern to government can be described as hazards (potentially life-threatening) and adverse construction conditions (non-life-threatening).

Hazards include flooding, earthquakes, and landslides. Hazards, or phenomena that may cause harm, are distinct from risk, which is the likelihood of harm on exposure to a hazard. The level of risk depends on the probability the hazard will occur over a given period and its potential to affect human populations and structures. The focus of this project is primarily earthquake and landslide hazards.

4.1. Earthquakes

Earthquake hazard is defined as any physical phenomenon associated with an earthquake that may produce adverse effects on human activities. This includes surface faulting, ground shaking, landslides, liquefaction, tectonic deformation, tsunami, and seiche and their effects on land use, manmade structures, and socioeconomic systems. Earthquake hazard is commonly quantified as the probability of occurrence of a specified level of ground shaking during a specified period. Probabilistic earthquake hazard analyses incorporate the potential effects of active faults within and surrounding the region of interest, and "background seismicity," which includes earthquakes that are large enough to be potentially damaging.

Earthquake risk is the expected (or probable) life loss, injury, or building damage and associated economic impact that will happen given the probability that some earthquake hazard occurs. Although earthquake risk and earthquake hazard are occasionally used interchangeably, this report identifies earthquake hazards. These hazards would be a fundamental component of earthquake risk analyses.

Hazards associated with continental earthquakes include:

- Shaking and ground rupture: these can damage and destabilize human structures. The severity of damage depends on earthquake magnitude, distance from the fault rupture, duration of shaking, and nature of ground materials. Unconsolidated materials can amplify seismic waves relative to bedrock.
- Landslides: earthquakes can trigger earth movements and destabilize soils and hillsides.

• Fires: shaking can break power and gas lines and cause fires, a major cause of property damage associated with earthquakes. Broken water lines can hamper firefighting efforts.

• Soil liquefaction: some unconsolidated earth materials will lose their strength and behave like a liquid when shaken. The most susceptible materials are water-saturated silty sands, sands, and fine gravels. Bedrock is not susceptible to liquefaction.

• Seiche and floods: earthquake shaking can cause water bodies to slosh like water in a bathtub, creating standing waves that may damage structures. Earthquakes can cause flooding by breaking dams or by triggering landslides that displace water from lakes and ponds, causing them to top their banks. Earthquake-generated landslides may dam rivers, causing immediate upstream flooding and later downstream flooding when the river breaches the landslide dam.

• Public health effects: disease and hardship caused by lack of sanitation, potable water, and medical care are important aftereffects of destructive earthquakes.

4.2. Landslides

Landslides cover a number of kinds of surface movements under the umbrella of mass wasting, which is the downhill movement of soil and rock under the force of gravity. Mass wasting classifications vary, but generally incorporate:

- Type of material: rock, earth (fine-grained material), and debris (coarse-grained material);
- Type of movement: falling, topping, sliding (motion on a failure plane), flow (motion within the failing mass), creep; and
- Rate of movement: varies between rapid (e.g., rockfall) and very slow (e.g. soil creep).

Cruden and Varnes (1996) present an exhaustive landslide classification that is widely used today.

Mass wasting occurs when the gravitational force acting on a slope exceeds the resisting force or shear strength. This can be caused by:

- Change in slope angle, perhaps by undercutting or by the addition of slope material from the top;
- Decrease in shear strength by increasing water content, by shaking, by chemical weathering, by removal of vegetation; or
- Combinations of changes in slope and changes in shear strength.

Many contributing factors may play a role in causing any one mass movement. For instance, a slope may have been undercut by the natural meandering of a stream at the same time that it is overloaded by building near the top of the slope and water content is increased by lawn watering. Any given mass movement, however, is triggered by a single event. The two most common triggers are earthquakes and heavy rainfall.

A detailed, but not exhaustive, list of the most common factors that cause mass movements includes:

- Weak or sensitive materials;
- Unfavorably oriented planes of weakness;
- Slope undercutting (stream erosion, wave erosion, glacial ice, subterranean erosion, human excavations);
- Slope steepening (tectonic uplift, sediment deposition by water, wind or glacial ice, human slope loading);
- Increase in water content (rainfall, snowmelt, irrigation, reservoir filling, reservoir leaking);
- Ground vibration (earthquake, pounding of storm waves, heavy traffic, mine blast);
- Freeze–thaw cycles;
- Shrink–swell cycles;
- Devegetation;
- Volcanic activity; and
- Rapid drawdown of rivers or water reservoirs.

Mass wasting is the most pervasive geologic hazard and one of the most expensive. It encompasses slow downslope movements as well as the more spectacular landslides and debris flows. Knowledge of bedrock geology and topography is crucial for anticipating where destructive slope failure may occur over time.

5. FAULTS AND EARTHQUAKES

The fault inventory prepared for this study (pl. 2, fig. 5.1) is an amalgamation of faults compiled from preexisting maps and those discovered or remapped during this study. The digital product accompanying this report contains all fault and earthquake data available to date.

The presence of a fault does not imply that there will be future earthquakes along the fault, nor does the absence of a fault guarantee that there will be no earthquakes. First, faults that formed during a past geologic event may have been inactive for tens or hundreds of millions of years. Examples of inactive faults include

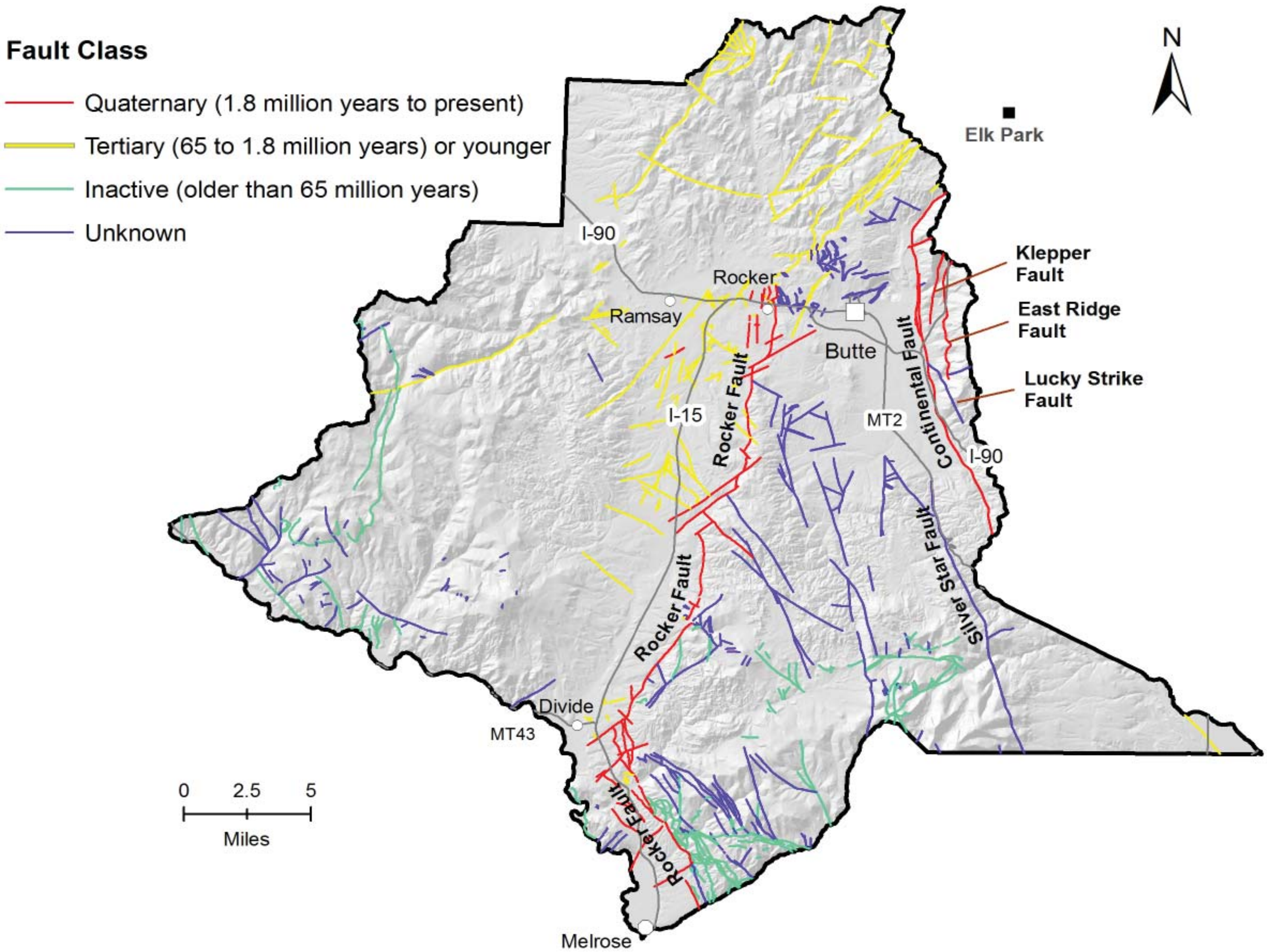

Figure 5.1. Faults in Silver Bow County identified by demonstrated age of last motion. Quaternary faults are those that are known to cut Quaternary sediments or structures. Tertiary or younger faults are those that cut Tertiary rocks. Some of these faults may have had Quaternary motion, but no conclusive overprinting relationships have been observed. Inactive faults have had no recognizable movement after Cretaceous times (65 million years). Because of their orientations and generally sinuous traces, these faults are unlikely to be reactivated in the future. Unknown faults are those for which overprinting relationships are inconclusive.

those in the Highlands that now have a folded or sinuous trace (pl. 2, fig. 5.1).

Second, many recent earthquakes in Montana originate from focal points that do not lie on mapped faults (Stickney, 2007). Not all existing faults have been found and mapped, and not all faults reach the surface of the earth. In the western United States, earthquakes with magnitudes lower than 6.5 commonly do not breach the surface (dePolo and Slemmons, 1990; dePolo, 1994). The 1925 Clarkston earthquake, the 1935 Helena earthquakes, the 1949 Virginia City earthquake, and the 2005 Dillon earthquake are all examples of damaging earthquakes that occurred on faults that did not breach the surface.

Fieldwork done for this report focused largely on identifying the framework that controls faults in Silver Bow County, and on interpreting the movement history of faults. Basic mapping and field observations in Silver Bow County provide data that place rough constraints on the timing of fault movement. Timing is bracketed by identifying and dating geologic features that are cut by the fault and those that formed after the fault moved.

In this report, faults are categorized as "geologically recent" and potentially hazardous if movement in the past 1,800,000 (1.8 million) years has been large enough to break the ground surface. In the Basin and Range province, earthquake faults have recurrence intervals from hundreds to hundreds of thousands of years long, and all major historical earthquakes have occurred on faults that showed evidence of Quaternary activity (appendix 3; WSSPC, 2008). It is geologically impractical in Silver Bow County to distinguish faults hundreds or thousands of years old from those that are a million years old without radiometric dating, which is outside the scope of this study. Therefore, the units cut by faults can only be dated by index fossils or by correlation with dated units elsewhere. In this county, the boundary between Tertiary and Quaternary, 1.8 million years, is a reasonable datum based on stratigraphy and radiometric ages (Hanneman, 1989) and can be recognized in the field with some certainty.

See appendix 3 for a more detailed discussion of the classification of potentially hazardous faults in the Basin and Range province.

What follows is a general description of faults in Silver Bow County, with more detailed discussion of the two most prominent faults in the county, the Continental Fault and the Rocker Fault. This is followed by an overview of earthquake history in Silver Bow County and a review of seismic hazard estimates.

5.1. Geology and Faults

Silver Bow County is riddled with geologic faults, some of which date back more than 1.7 billion years. Many are locked up and have not moved for hundreds of millions of years. A few have moved much more recently and must be considered to have the potential for future movement. It is impossible to say with certainty exactly when or how large the latest fault movement was, but there is significant evidence that faulting did occur in geologically recent times. The faults that have demonstrably moved most recently trend northeast and displace Quaternary sediments in the Melrose valley (Vuke, 2004) and in lower Sheep Gulch east of Buxton (figs. 5.1,5.2). These faults and others with the same orientation also overprint the Rocker Fault and possibly the Continental Fault north of the Continental Mine, based on relationships observed outside the county in Elk Park. Northeast-trending faults in Silver Bow County belong to a broad northeast–southwest belt of faults, Mesozoic and Tertiary igneous bodies, and geophysical anomalies called the Great Falls Tectonic Zone (O'Neill and Lopez, 1985). This zone is thought to represent a region of crustal weakness created almost 2 billion years ago and periodically reactivated up to the present. There is no evidence that any of the faults in the Great Falls Tectonic Zone have large displacements.

Overprinting of the Continental and Rocker Faults by the northeast faults does not necessarily mean that the former are now inactive. The northeast faults are appropriately oriented to act as transfer faults that accommodate movement on offset segments of the larger Continental and Rocker Faults.

Fault planes are exposed in Tertiary and some Quaternary outcrops (fig. 5.2), as are sediment disruption structures commonly caused by ground shaking (fig. 5.2). Evidence of faulting within Tertiary sediments is common, especially in the Buxton, Divide, and Melrose valleys. Erosional surfaces between layers of Tertiary sediments (fig. 5.3) show that faulting, valley formation, and sediment deposition occurred concurrently. These processes began before 15 million years ago and continued after 5 million years ago, based on fossil assemblage ages for sediments near Feely and Rocker (A. Tabrum, Carnegie Museum, written communication, 2003). Total seismicity in the past 15 million years must have

Figure 5.2a. Quaternary gravel (right side) faulted against Tertiary silt, lower Sheep Gulch east of Buxton. Arrows indicate sense of movement. Compass is 4 inches long.

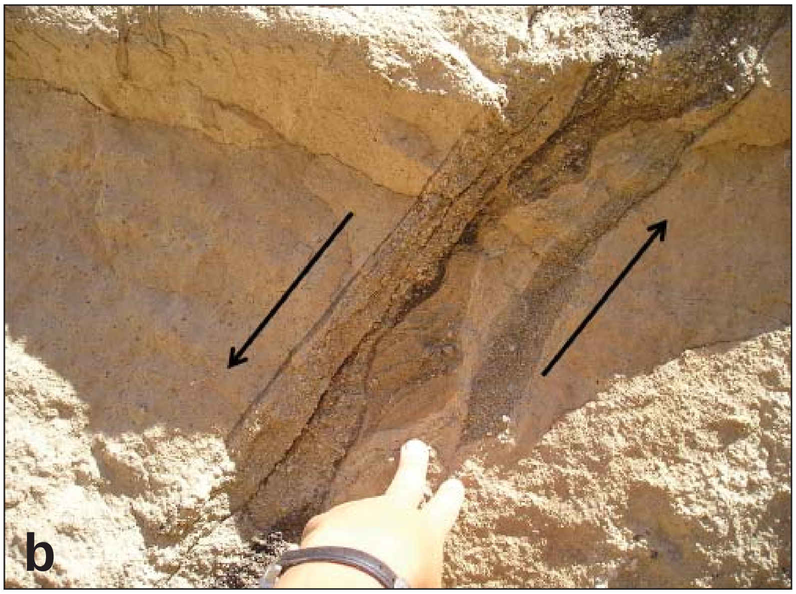

Figure 5.2. Faults and related structures in unconsolidated sediments, Silver Bow County.

(a) See facing page.

(b) Normal fault zone in Tertiary silt and sand east of I-15 near Silver Bow. The sediments on the left moved down with respect to those on the right, as indicated by arrows.

(c) Poorly sorted gravel that has sagged into fine sand and silt while wet. Photo taken near photo b. Pencil is 6 inches long.

(d) Poorly sorted Quaternary gravel that has been contorted and injected by white ashy silt while wet. Photo taken in foundation area of building under construction west of Silver Bow. Hammer is 12 inches long.

(e) Fine Quaternary gravels (darker color) that have sagged into Tertiary silt while wet. Photo taken in foundation area of house under construction near Buxton. Pack is 20 inches high.

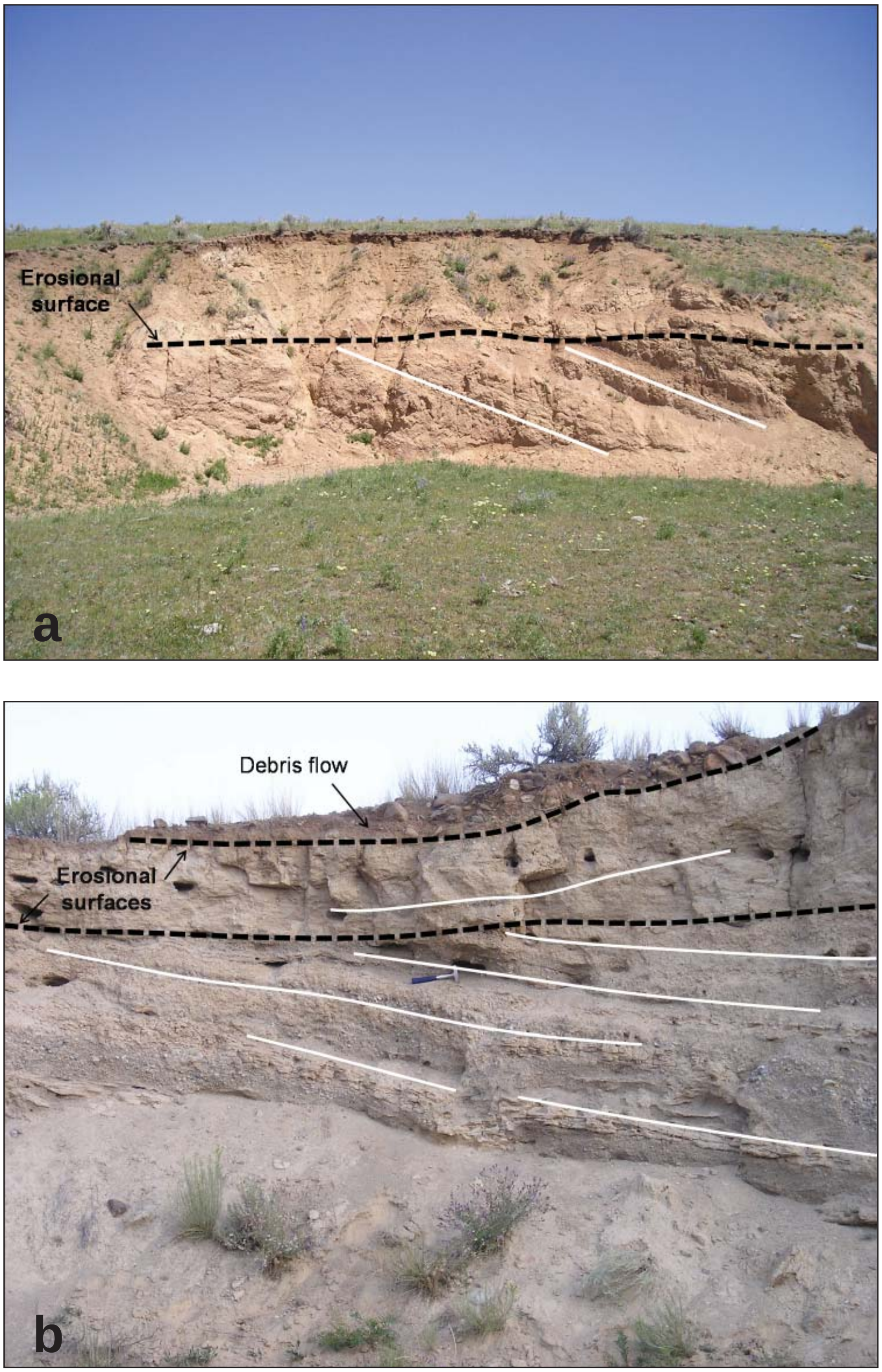

Figure 5.3. Erosional surfaces within valley fill sediments. (a) Tertiary Divide map unit silts and sands in Slab Gulch, northwest of Feely. After they had been deposited, the sediment beds at the bottom of this outcrop were tilted more than 20° to the east (right) and the package was eroded flat. A new set of almost identical beds was then deposited on top. Tilting of beds is caused by movement on faults. The outcrop is approximately 13 feet high. (b) Tertiary Divide map unit sands and gravels in gully approximately 1 mile south of Rocker. In this exposure, the lower, east-tilted beds are locally deformed and overlain by subhorizontal sand beds, which are in turn planed off and overlain by a thin remnant of Quaternary-Tertiary debris flow deposits (map unit QTdf).

been significant, since the minimum magnitude associated with surface faulting is 6.5 (dePolo, 1994).

5.2. Continental Fault and Related Structures

5.2.1. Previous Studies

The first published description of the Continental Fault (Weed, 1912) describes the East Ridge as a network of fault strands with measurably offset markers and local breccias and slickensides. Weed (1912) observed broken gas and water lines, cracked walls, and fissures in the streets of uptown Butte and concluded that the cause was active faulting. Detailed topographic surveys in 1896, 1899, 1904, and 1906 showed that benchmarks on the Butte Hill subsided as much as 0.218 feet each year with respect to a benchmark at the Butte Reduction Works (located where Montana Street now crosses Silver Bow Creek).

Weed (1912) argued that Bison Creek in Elk Park once flowed into the Summit Valley and had its flow reversed by movement on the valley-bounding faults. Other geologists agreed (Pardee, 1950; Alt and Hyndman, 1986), adding that the Elk Park valley, like others in the region, is too big to have formed in our current dry climate and must have formed in Miocene times when the climate was wetter. Tributaries that join the main branch of Bison Creek and the Boulder River point upstream rather than downstream ("barbed tributaries"), indicating that there was once southwesterly flow.

Meinzer (1914) and Atwood (1916) noted that the bedrock floor of the Summit Valley deepens eastward from Rocker, supporting the idea that the valley is fault-bounded. They argued that faulting was recent, but their conclusions appear to hinge on a now discredited model for stream erosion and landscape development proposed by William Morris Davis in the late 1800s. Corry (1931) outlined a local geologic history based on models of mountain building that became obsolete with the advent of plate tectonic theory. He argued that the latest motions along the Continental Fault were very recent because the fault scarp does not bear evidence of glaciation, but neither this study nor other recent studies (Houston, 2001; Berg and Hargrave, 2004) have found any evidence that any part of the Summit Valley has been glaciated, so Corry's argument is not applicable.

Meyer and others (1968) recognized that the Continental Fault system cuts, and is therefore younger than, quartz porphyry dikes that we now know are 66 million years old (Lund and others, 2002). McClave (1973) claimed that the Continental Fault last moved after Pliocene time (thus making it a Quaternary fault), displacing young alluvial fill in the upper Silver Bow basin as well as the enrichment zone of the Butte ore system. In a compilation of Quaternary Faults in western Montana, Haller and others (2000) cited the Weed (1912), Meinzer (1914), and Pardee (1950) studies in support of their conclusion that the Continental Fault is less than 1.8 million years old. Haller and others (2000) concede that while none of these studies categorically demonstrates young movement on the Continental Fault, young movement is suggested by the angular nature of the fault scarp and by the apparent reversal of the Elk Park drainage discussed above.

A regional tectonic synthesis by Sears and Ryan (2003) has the Continental Fault active during middle Miocene times, but overprinted in Late Miocene and younger times by northwest-trending cross-faults that dissect northeasterly drainage patterns.

The length, orientation, and sense of motion on the Continental fault were first described in detail by Corry (1931), who was able to examine the Continental and related faults where they cut various mine workings. Corry's maps (Corry, 1931, pls. VII and XII) show a Continental Fault that is about 9.3 miles (15 km) long, and a fault zone about 15 miles (24 km) long.

Pardee (1950) described exposures and fault planes in the Continental Fault Zone in detail, noting that the fault zone varies between 200 and 1,000 feet (61–305 m) wide and dips 75° W. on average. He concluded that movement on the fault was several hundred feet left-lateral and 1,500 feet (457 m) downdip, though in a mine on the East Ridge, fault striations indicate right-lateral oblique offset. He also estimated 1,330 feet (405 m) of vertical displacement across Elk Park pass based on the difference in elevation between Elk Park and the depth to bedrock beneath the Summit Valley.

Czehura and Zeihen (1997) and Czehura (2006) estimated 3,500 feet (1,080 m) of down-dip displacement on the Continental Fault based on diamond drilling data that indicated offsets in mineralization zoning (a copper–molybdenum dome) and on displacement of a 58.8-million-year-old dike. Czehura and Zeihen (1997) reported that the fault dips between 78° and 84° W., though some related strands dip as little as 65° W.

Houston (2001) summarized previous work on the Continental and other faults in the Butte mining district and provided detailed descriptions of fault sequence and rotations in the Butte area. He reported that the Continental Fault dips 80° W., and has 3,600–4,590 feet (1,100–1,400 m) downdip offset in the Continental Pit area, increasing to the south. The Klepper Fault, which parallels and is related to the Continental Fault, dips 85° E. and has 2,360 feet (720 m) of right-lateral separation, based on offset rock units, and 3,600 feet (1,100 m) of dip slip, based on hornblende chronology reported by Dilles and others (1999). Total right-oblique slip on the Klepper Fault works out to about 1.3 miles (2.1 km). The East Ridge Fault, another related fault, dips 60° W., with 164 feet (50 m) right separation based on offset lithologies, and an unknown amount of dip separation.

5.2.2. This Study

The faults that created Rampart Mountain, Elk Park, and the East Ridge form a linked fault zone, as defined by Wong and others (2005), that is more than 1.9 miles (3 km) wide and as much as 33.5 miles (54 km) long, striking between 160° and 198° (pl. 2, fig. 5.1). The main faults are:

1. The Klepper Fault, bounding the west side of Elk Park (mostly outside of Silver Bow County);

2. The Continental Fault, which extends from the Yankee Doodle tailings pond through the Continental Mine, along the base of the East Ridge beneath an apron of granitic alluvium, and south through Little Blacktail Creek;

3. The East Ridge Fault, which trends parallel to the East Ridge and lies midway up the slope;

4. A fault here named the Lucky Strike Fault that trends southeast and cuts a notch along the slope of the East Ridge; and

5. The Silver Star Fault (O'Neill and others, 1996), which trends parallel to the Continental Fault. It has been mapped to extend from upper Blacktail Creek to Fish Creek (Smedes and others, 1988), or from Basin Creek in south Butte, southeast to the Jefferson Valley (Ruppel and others, 1993).

All of the faults in the zone are normal faults, dipping between 80° E. (Klepper Fault) and 65° W. One possible exception is the Lucky Strike Fault, which may have had reverse movement based on its topographic style and on small-scale structures observed near the fault that show west-side-up displacement.

The faults in the zone have clear topographic expression, but are poorly exposed in outcrop. Ground-penetrating radar surveys across the Continental Fault described by Speece in appendix 2 did not reveal conclusive evidence of near-surface fault planes. This is at least partly because of the deep weathering of the granite bedrock and the lack of lithologic contrast across the faults. Differential alteration of minerals in granite causes it to weather into equigranular sand and fine gravel or "grus" that is easily erodible and tends to subdue topography. Formation of grus is enhanced by tectonic fracturing, resulting in deeper weathering over faulted rocks. Some researchers suggest that the presence of deep grus mantles indicates the rapid relief differentiation that accompanies faulting (Migo and Thomas, 2002), but this is difficult to quantify.

We were able to examine part of the Continental Fault Zone where it is exposed in the north wall of the Continental Pit (fig. 5.4). We looked specifically for evidence of faulting in overlying sediments and for fossils that show the age of the sediments. We observed a series of sub-parallel strands within altered granite and between granite and the overlying alluvium. Where it is faulted, the clay-rich alluvium is sheared, indicating that it was deposited before fault displacement. The age of the alluvium is uncertain due to lack of index fossils. We were not able to observe whether the Continental Fault reaches the surface and do not know if it has ruptured recent soils. Modern ground squirrel bones found at more than 3 feet deep and not within obvious burrows in alluvium west of the Continental Pit suggest that the sediments are young, but it is unclear whether the fault cuts those particular sediments.

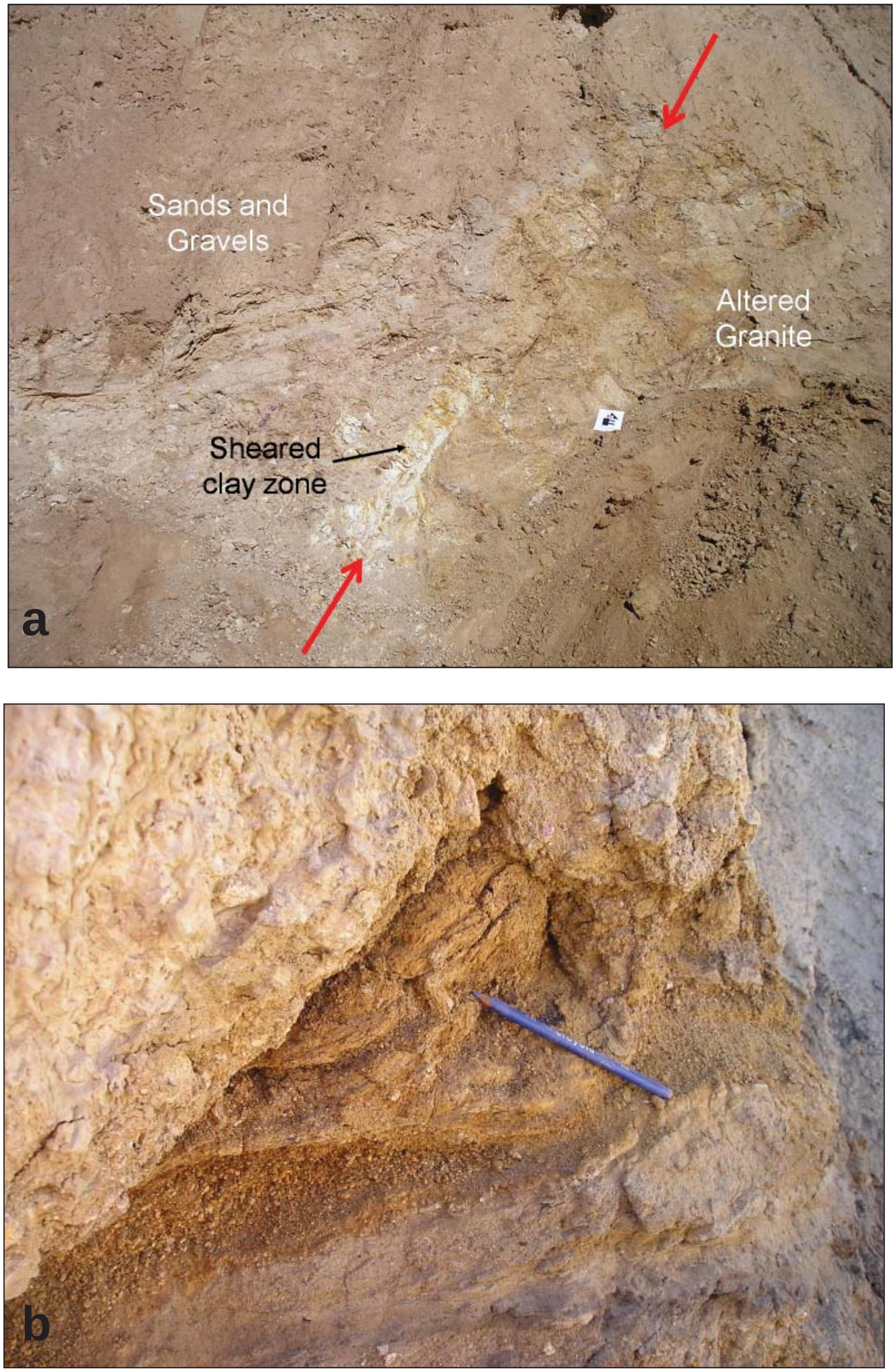

Figure 5.4 Continental Fault in the Continental Mine. (a) West-dipping fault plane between altered granite (right) and sands and gravels (left). The light-colored zone between the sediments and the granite is sheared clay. Scale is 3 inches wide. (b) Sand and gravel approximately 1,000 feet west of the Continental Fault that was deposited before movement on the fault, and later deformed. Pencil points to deformed sediment.

The timing of movement on the Continental Fault is constrained only by the youngest dated geologic unit known to predate movement, which is the 58.8-million-year-old dike reported by Czehura and Zeihen (1997) and Czehura (2006). Because the fault cuts alluvium in the Continental Mine Pit and because no dikes are known to intrude the alluvium, we know it moved more recently than 58.8 million years but not how recently. If the possible fault displacements reported by Weed (1912) for uptown Butte had continued from 1906 to today, more than 23 feet (7 m) of movement would have accumulated. Given that modern surveying has not shown similar displacements (Reilinger and others, 1977; Reilinger, 1985) and that local subsidence can be tied to underground mine workings, Weed's argument for ongoing, continuous fault motion is weak.

Hummocky debris flows in Maude S Canyon are suggestive of young movement on the East Ridge Fault. At least two identified debris flows cross the trace of the fault, one of which appears to have been offset along a fault scarp. Such a scarp would not last long in the easily weathered granite of the East Ridge, but might have a better chance of preservation in a debris flow. In future studies, trenches across the trace of the East Ridge Fault are recommended as a possible means of obtaining better data for the age of last motion and recurrence rate of the Continental and related faults.

The abrupt topographic relief of the East Ridge also supports recent, or Quaternary, movement on the Continental Fault. Similar prominent escarpments characterize active faults throughout the Basin and Range province. Though we do not have conclusive evidence of recent movement on the Continental Fault, the evidence is certainly permissive for that conclusion. After considering the difficulty in preserving evidence for recent fault movement in this setting, and the various features that suggest but do not demand recent movement, we are convinced that the Continental Fault most likely has undergone movement during the Quaternary Period.

The depth of sediments beneath the Summit Valley provides some control on the amount of offset across the Continental and related faults. It was noted in the earliest geologic studies of the Butte area (Weed, 1912; Atwood, 1916; Meinzer, 1914) that depth to bedrock increases from Rocker eastward toward the center of the Summit Valley, defining a half graben in which bedrock tilts eastward over the west-dipping Continental Fault (cross section B–B', pl. 1). Gravity profiles by Ahrens (1976) and Sill (appendix 2) outline a basin 1,200–1,500 feet (366–457 m) deep at a center roughly beneath the east side of the Bert Mooney airport. The eastern side of the basin is steeper, though the geophysical model slope of 24° derived from the gravity data in appendix 2 is difficult to reconcile with the 64°–85° dip of the Continental Fault observed on the surface. This can be explained at least in part by the necessarily coarse scale of gravity data modeling, as noted in appendix 2.

The geophysical data suggest that the topographic relief between the base of Summit Valley sediment fill and the top of the East Ridge is about 4,134 feet (1,260 m). This is within the range of the most recent estimates of 3,600–4,590 feet (1,100–1,400 m; Houston, 2001) and 3,543 feet (1,080 m; Czehura, 2006) for offset across the Continental Fault.

5.3. Rocker Fault

5.3.1. Previous Studies

What we now call the Rocker Fault was mapped by Pardee (1950) based on the physiography of the valley from Browns Gulch to Divide. Evidence for fault movement of at least 1,200 feet (350 m) was provided by a drill hole at the Buzzard Mine (apparently somewhere north of Rocker) which penetrated that thickness of Tertiary sediments without hitting bedrock, even though bedrock is exposed on the surface nearby to the east.

Haller and others (2000) show the Rocker Fault extending from about 4 miles (6.6 km) north of I-90 to 3 miles (5 km) southwest of Camp Creek, for a length of about 29 miles (47 km). They classify the Rocker Fault as having moved during Quaternary times on the basis of Pardee's 1950 report, but a close reading of the latter reveals that it does not provide evidence for post-Tertiary motion on the fault.

Hanneman and others (1997) and Hanneman (WGI website, retrieved November 19, 2007) used unpublished data to debate the existence of the Rocker Fault along the eastern margin of the Rocker–Ramsay basin. They argue that unconsolidated sediments along the range front marked by the Rocker Fault were deposited in a pre-existing valley, and that their dips are not consistent with what would be expected in the hanging wall of a west-dipping normal fault. They argue, rather, that the significant movement occurred on a north–northwest-trending fault 3 miles (5 km) west of where others map the Rocker Fault. Houston (2001) disputed the above ideas and put the Rocker Fault back where Pardee (1950) mapped it, reporting that it dips 80–90° W. and has 590–984 feet (180–300 m) of sediment fill over the hanging wall, increasing toward the south. His map does not cover the southern extent of the fault.

5.3.2. This Study

Our work shows that the Rocker Fault is segmented as defined by Wong and others (2005). It consists of fault segments that extend south and southwest from just east of the county landfill site to near Divide, where they bend to the southeast along the east side of the Melrose valley (fig. 5.1, pl. 2). Some of the segments contain two or more parallel faults. Though no single segment is more than 3 miles (5 km) long, their cumulative length exceeds 30 miles (50 km). The consistent eastward dip of Tertiary sediments within the valley from Rocker to Melrose shows that the Rocker Fault is indeed a fault and not a depositional contact along the west side of a steeply incised valley (pl. 1).

North of Silver Bow Creek, the contact between Cabbage Patch Formation clays and granite bedrock may be depositional, but outcrop-scale faults immediately to the west reflect a fault zone that probably accommodated significant displacement. The gravity models by Sill in appendix 2 show depth to bedrock of as much as 3,000 feet (914 m) west of the Rocker Fault. This is almost twice as deep as the Summit Valley basin west of the Continental Fault, and much deeper than the drillhole data described by Pardee (1950). Given the relative sizes of the Rocker and Summit Valleys, it seems odd that the former is so much deeper than the latter. Perhaps part of the discrepancy stems from density values used for the gravity models. Those values were based on fine-grained Tertiary sediments from the frontage road on the north side of I-90 and west of Browns Gulch Road. None of the generally less consolidated and coarser-grained sediments from the Summit Valley were tested.

Unlike the Continental Fault, small-scale normal faults related to the Rocker Fault are exposed in natural outcrops. The structures strike north–south and have variable dips. South of Silver Bow Creek, a prominent change in slope at the valley edge marks the trace of the Rocker Fault (fig. 5.5a). Ground-penetrating radar described in appendix 2 located an anomaly where the fault had been mapped by Pardee (1950) and Houston (2001). Using hand tools, the walls of the wash were scraped clean of debris at that site, revealing the sharp normal fault plane and subsidiary fractures marking the edge of granite bedrock precisely where the fault was imaged by ground-penetrating radar (fig. 5.5b). The wedge of grussy detritus beside a sharp fault plane that reaches the surface is good evidence of young movement, but the exposure was not extensive enough to show whether there were multiple motions on the fault. Bedrock exposed in a nearby mine pit shows small faults related to the Rocker Fault that are overprinted by steep northeast-trending shear fractures related to the regional northeast-trending fault set.

The maximum age of faulting is bracketed by the age of faulted sediments near Rocker that contain fossils between 11 and 5 million years old (A. Tabrum, Carnegie Museum, written communication, 2003). The dated sediments are overlain by a thick sequence of older debris flows (QTdf in pl. 1) that are also cut by the fault, constraining the maximum age of faulting at 5 million years. A trench across the southern projection of the Rocker Fault north of Moose Creek showed no evidence of offset after the deposition of 130,000-year-old sediments (Stickney and Bartholomew, 1987). The most obviously active fault segments lie just south of Moose Creek, where a small graben has dropped the valley floor and new alluvial fans have been formed (fig. 5.1, pl. 2). The northeast-trending jogs between segments have displaced sediments dated as Quaternary by Hanneman (1989), as discussed in Geology and Faults above, and therefore moved less than 1.8 million years ago.

The older debris flows (QTdf) found only west of the Rocker Fault represent 10 or more landslide events that carried boulders from a source east of the Rocker Fault to as far west as Buxton. The bouldery deposits extend to some depth and have been noted in water well drill logs. No similar deposits are described in drill logs from the Summit Valley. It seems unlikely that the hills immediately east of the Rocker Fault are high enough or steep enough in our current climate to have produced the debris flows we now see. This suggests the following possibilities, none of which are mutually exclusive:

1. The landslides were triggered by strong earthquakes.

2. The landslides were triggered by very high groundwater levels resulting from high rainfall and/or rapid snowmelt.

3. The landslides originated on steep, high hills east of the Rocker Fault that have since subsided or been removed by erosion. The absence of debris flows east of the Rocker Fault implies that the land beneath the Summit Valley was a topographic high when the debris flows were deposited, and that the Summit Valley did not form—and the Continental Fault did not exist— prior to landslide deposition. This would place an age of less than 5 million years on the last known motion on the Continental Fault.

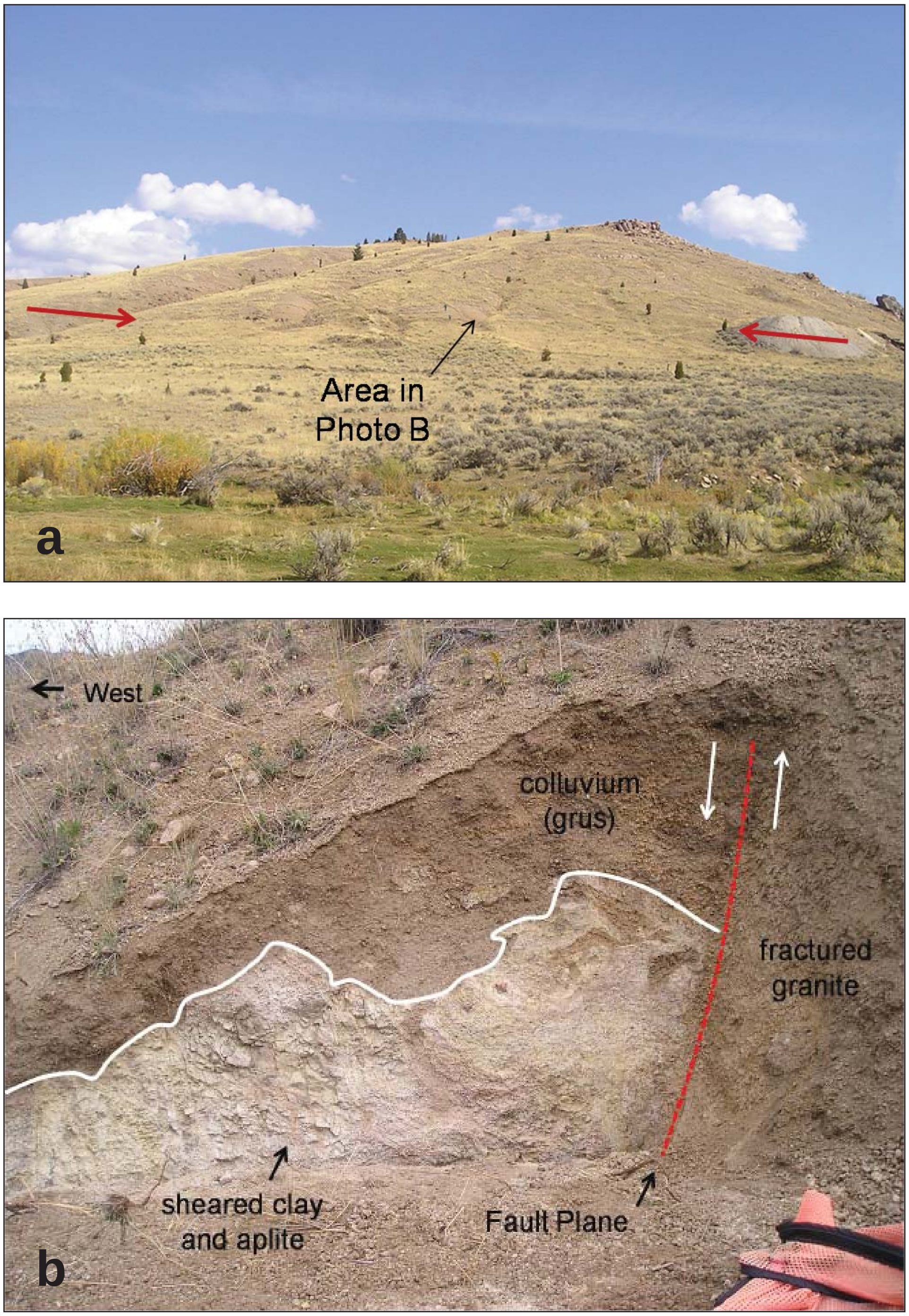

Figure 5.5. Rocker Fault. (a) Looking east at break in slope that marks the Rocker Fault (arrows mark trace of fault along slope). Photo was taken in Canada Gulch, approximately 1 mile south of Rocker. (b) Exposure of Rocker Fault where it was located by ground-penetrating radar. The main fault trace on the right side of the image dips more than 70° west, bringing fractured granite in contact with sheared and altered granite. Colluvium is thicker on west side of fault which has dropped down relative to east side (arrows indicate direction of movement).

5.4. Earthquakes in and around Silver Bow County

Montana ranks fifth in the nation in terms of number of historic earthquakes greater than magnitude 6 (Anderson and Miyata, 2006). Silver Bow County lies along the western edge of the Intermountain Seismic Belt, which extends from western Montana south to southern Nevada (fig. 5.6). Earthquake density within the Intermountain Seismic Belt is anomalous within North America, and 8 of the 16 largest historic earthquakes in the belt occurred in Montana (Stickney, 2007). Further, the largest historic earthquake in the entire belt was the magnitude 7.5 Hebgen Lake earthquake, less than 124 miles (200 km) from Butte.

Figure 5.7 shows the epicenters of more than 1,650 earthquakes that occurred between January 1, 1982 and September 27, 2009 within the rectangular area bounded by lat 46.25° and 45.50° N., and long 112.00° and 113.25° W. Hypocenters range between 3 and 9 miles (5 and 15 km) in depth. None of the earthquakes within Silver Bow County exceeded magnitude 2.8. The most recent FEMA report (Butte-Silver Bow, 2004) and Czehura (1997) both reported a magnitude 3.9 earthquake within Silver Bow County in 1968, but the magnitude and location of the epicenter for that event have since been recalculated. The event appears to have occurred about 10 miles north of Maiden Rock near Mount Fleecer and was not larger than magnitude 2.7. However, due to uncertainty in the data used to locate this event, it is unclear if it was in the county and if it was a natural earthquake (M.C. Stickney, personal communication, 2009).

The largest earthquake to occur near Butte since the Montana Bureau of Mines and Geology began monitoring seismicity in 1982 was a magnitude 2.8

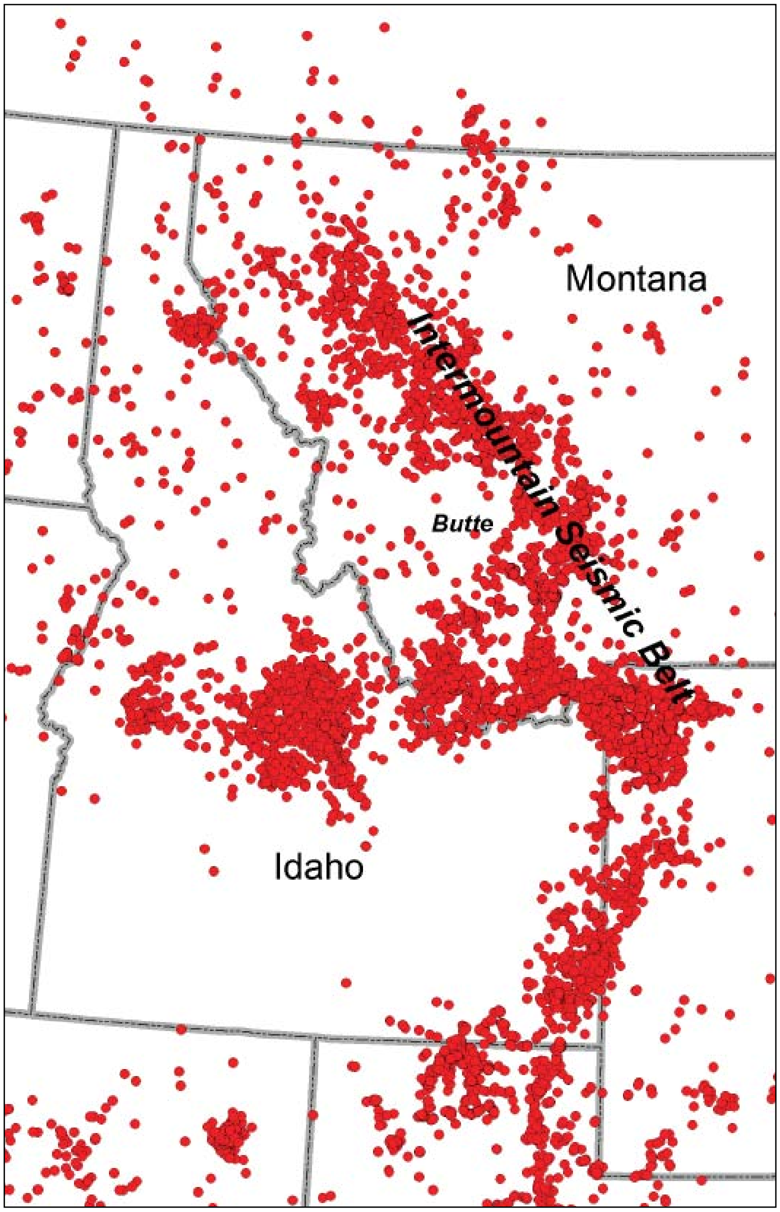

Figure 5.6. Intermountain Seismic Belt. Circles represent Earthquakes recorded between September 1982 and October 2009. Data are from the Montana Regional Seismic Network Earthquake catalog, maintained by the Earthquake Studies office at the MBMG.

earthquake that occurred just 0.74 miles (1.2 km) south of I-90 and 1.5 miles (2.4 km) southwest of the Butte city center on October 9, 2005. The hypocenter of this earthquake was well determined at 6 +/- 0.25 miles (9.7 +/- 0.4 km) below the surface. A focal mechanism based on P-wave first motions indicates strike-slip faulting resulting from east–west tectonic extensional forces. A magnitude 2.7 earthquake that occurred on August 28, 1990, just outside Silver Bow County near Pipestone, was also the result of east–west extension on a fault oriented parallel to the Continental Fault. These earthquakes prove that local tectonic stresses are large enough to trigger seismicity near Butte. The stress orientations inferred from the focal mechanism are consistent with the stress field that causes seismicity in adjacent parts of the Intermountain Seismic Belt (Stickney and Bartholomew, 1987), and are favorably oriented to produce future slip on the Continental and Rocker Faults.

The earthquakes forming the largest cluster in figure 5.6 are aftershocks of a magnitude 4.1 earthquake near Waterloo on October 27, 1998. The Waterloo earthquake was felt in Butte, and as far away as Missoula and the Bitterroot Valley (Stickney, 2002). On July 25, 2005, a magnitude 5.6 earthquake near Dillon (south of the area shown in fig. 5.6) caused significant damage to schools and brick buildings in Dillon. Many Butte residents felt the earthquake, and objects were knocked over in some homes. Over 1,850 aftershocks followed through October 2009, including a magnitude 4.4 aftershock that occurred 35 hours after the main shock. Forty aftershocks had magnitudes ranging from 3.0 to 4.4. This sequence of earthquakes occurred in a region with unremarkable historical seismic activity—a seismically quiet zone like Butte—and away from any mapped Quaternary fault. The Waterloo and Dillon earthquakes are both consistent with regional east–west extension.

5.5. Estimates of Seismic Hazard

The detailed seismic hazard analyses that exist for Butte were completed as part of larger investigations into the stability of Yankee Doodle Tailings Impoundment (IECO, 1981; Poindexter and Holmes, 1983; HLA, 1993; Czehura and Zeihen, 1997). International Engineering Company (IECO, 1981) estimated a Maximum Credible Earthquake of magnitude 6.9 for the Continental Fault. Harding Lawson Associates (HLA, 1993) used the empirical relationships between earthquake magnitude and fault length published by Slemmons (1977) to reach a deterministic estimate of magnitude 6.5 for the Maximum Credible Earthquake on the Continental Fault.

More recent hazard analyses are regional in scope. The United States Geological Survey (Frankel and others, 1996) published maps online (URL: http://earthquake.usgs.gov/hazards/) that present ground shaking in the form of peak horizontal ground acceleration as a fraction of the acceleration of gravity (one ‘g’= 9.8 m/sec^2). The input data are based on national historic seismicity and active faults. Figures 5.8 and 5.9, generated using these data, show peak ground-motion estimates

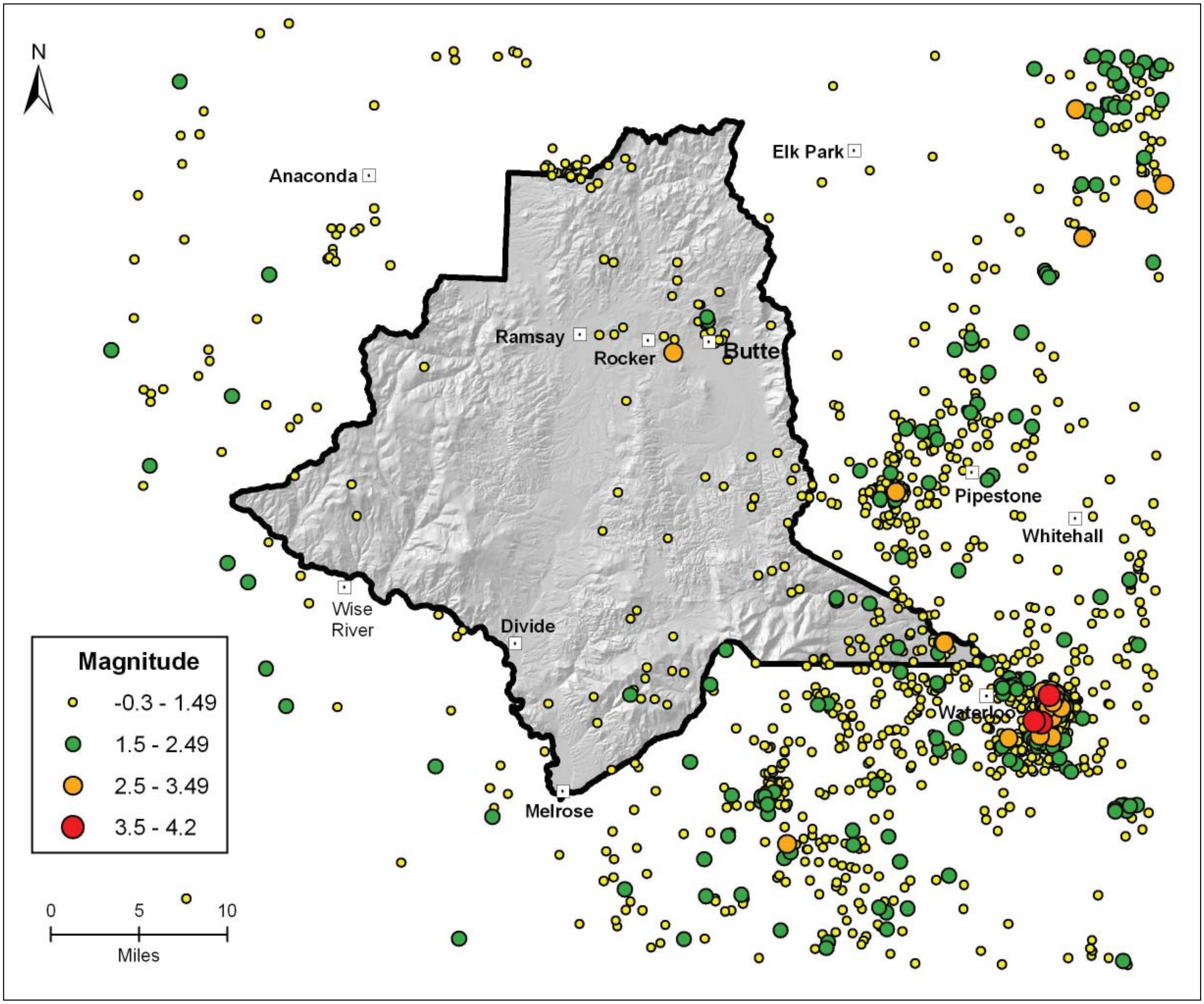

Figure 5.7. Earthquakes recorded in and around Silver Bow County between September 1982 and October 2009. Data are from the Montana Regional Seismic Network Earthquake catalog, maintained by the Earthquake Studies office at the MBMG.

increasing across Silver Bow County from west to east. Figure 5.8 shows that an earthquake peak horizontal acceleration of 20–30% of gravity has a 2% chance of being exceeded in 50 years. Figure 5.9 shows that a peak acceleration of 10–15% of gravity has a 10% chance of being exceeded in 50 years.

Wong and others (2005) used data from 92 faults in and around Montana to develop a set of probabilistic earthquake ground motion maps for the state. This detailed study took into account the geometry, rupture behavior, maximum earthquake magnitude, recurrence interval, and rates of activity for each of the faults along with background seismicity. They produced 18 statewide maps that display peak horizontal ground acceleration and horizontal spectral acceleration hazard (i.e., pertaining to the built environment) at different exceedance probabilities, and ground motions for soft rock and ground surface site conditions, the latter taking into account response effects for areas underlain by unconsolidated sediments. These maps and the accompanying report were published by the Montana Bureau of Mines and Geology and are not reproduced here. Their figure 12c showing total mean hazard for Butte is reproduced in figure 5.10. The graph sums the potential hazard contributions of the Continental Fault, Rocker Fault, and 11 other faults in southwest Montana to produce the total mean hazard values given in table 5.1.

The peak ground acceleration values calculated by

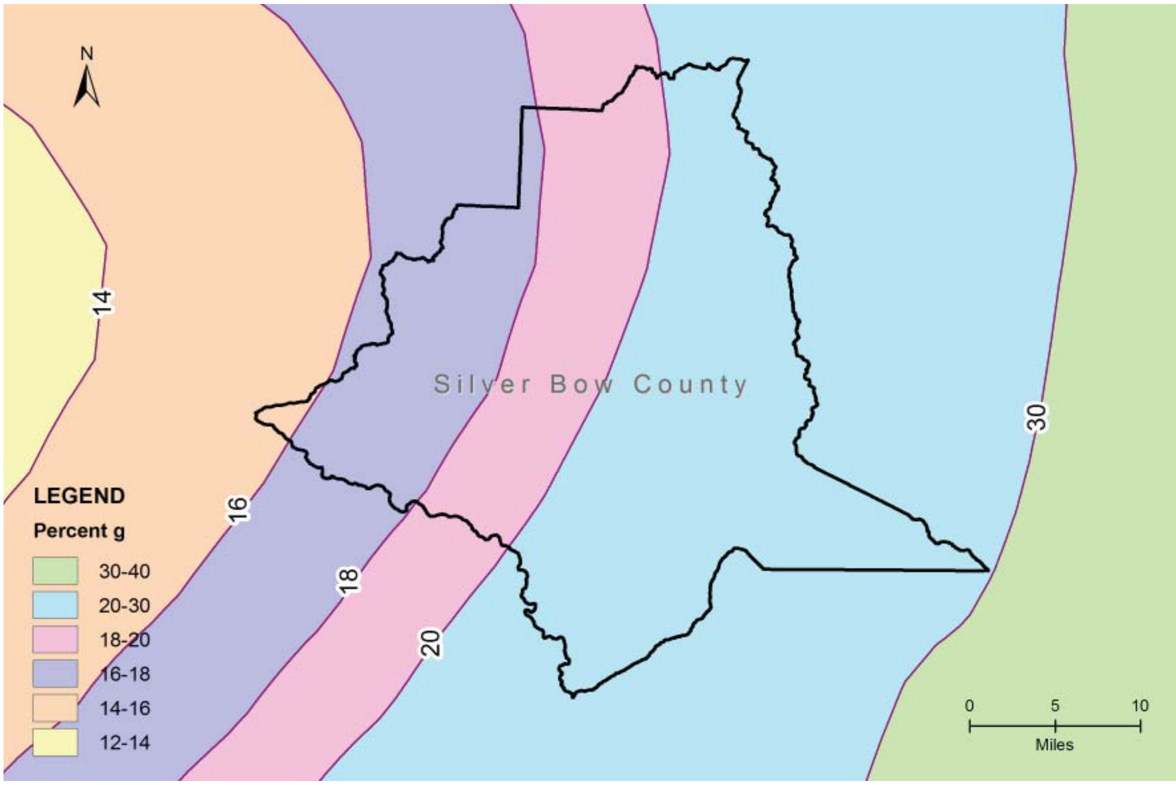

Figure 5.8. Peak horizontal ground acceleration for Silver Bow County with a 2% probability of being exceeded in a 50-year period, as determined by USGS regional overview (http://gldims.cr.usgs.gov/website/nshmp2002/viewer.htm, accessed 10/2009). For the eastern half of Silver Bow, there is a 2% chance earthquake shaking will cause ground acceleration between 0.2 and 0.3 g; predicted accelerations in the western half of the county are less.

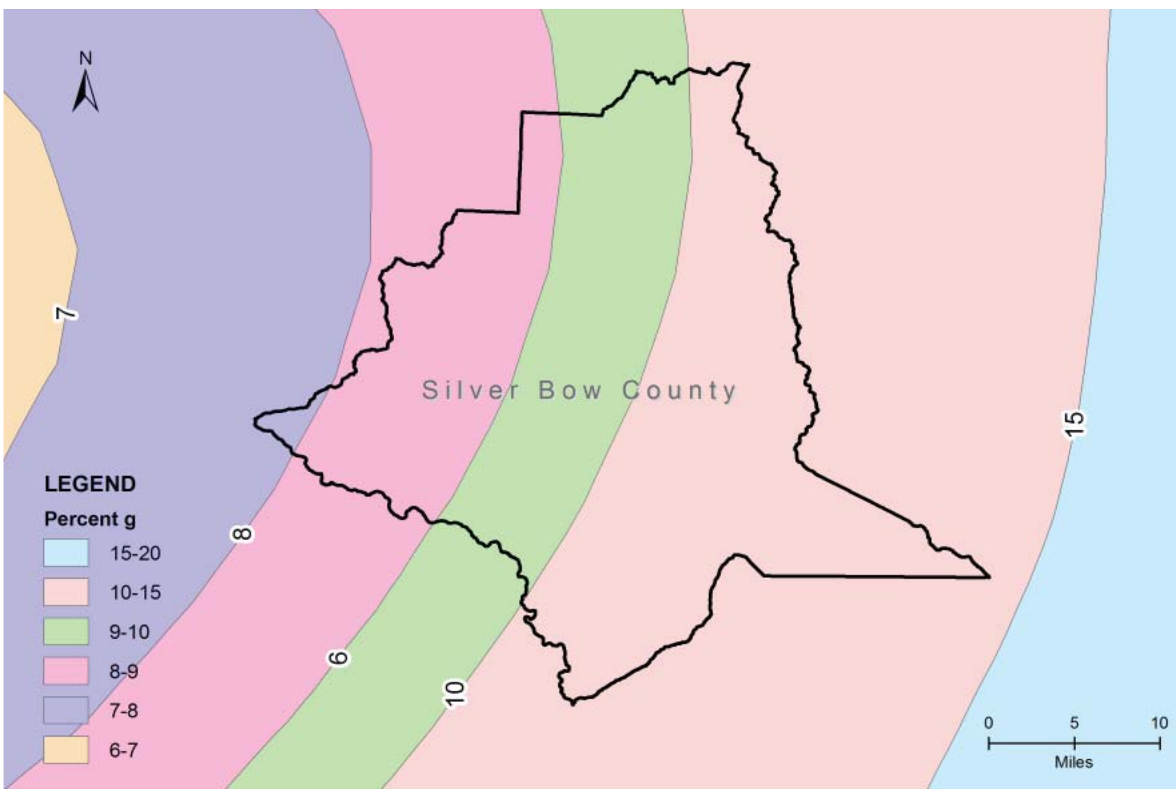

Figure 5.9. Peak horizontal ground acceleration for Silver Bow County with a 10% probability of being exceeded in a 50-year period, as determined by USGS regional overview (http://gldims.cr.usgs.gov/website/nshmp2002/viewer.htm, accessed 10/2009). For the eastern half of Silver Bow, there is a 10% chance earthquake shaking will cause ground acceleration between 0.1 and 0.15 g.

Wong and others (2005; table 5.1) are lower than those produced by the USGS (Frankel and others, 1996). Wong and others explain that part of the difference comes from their use of attenuation relationships specific to extensional tectonic regimes like southwest Montana rather than California-based relationships. The remainder of the difference may be a result of the large-scale spatial smoothing used by Frankel and others (1996) for the conterminous United States, which Wong and others (2005) argue is not appropriate on the scale of the state.

Findings from this study might be used to refine the probability estimates of Wong and others (2005). The fault source parameters they used for the Continental and Rocker Faults are shown in table 5.2 along with data from this study.

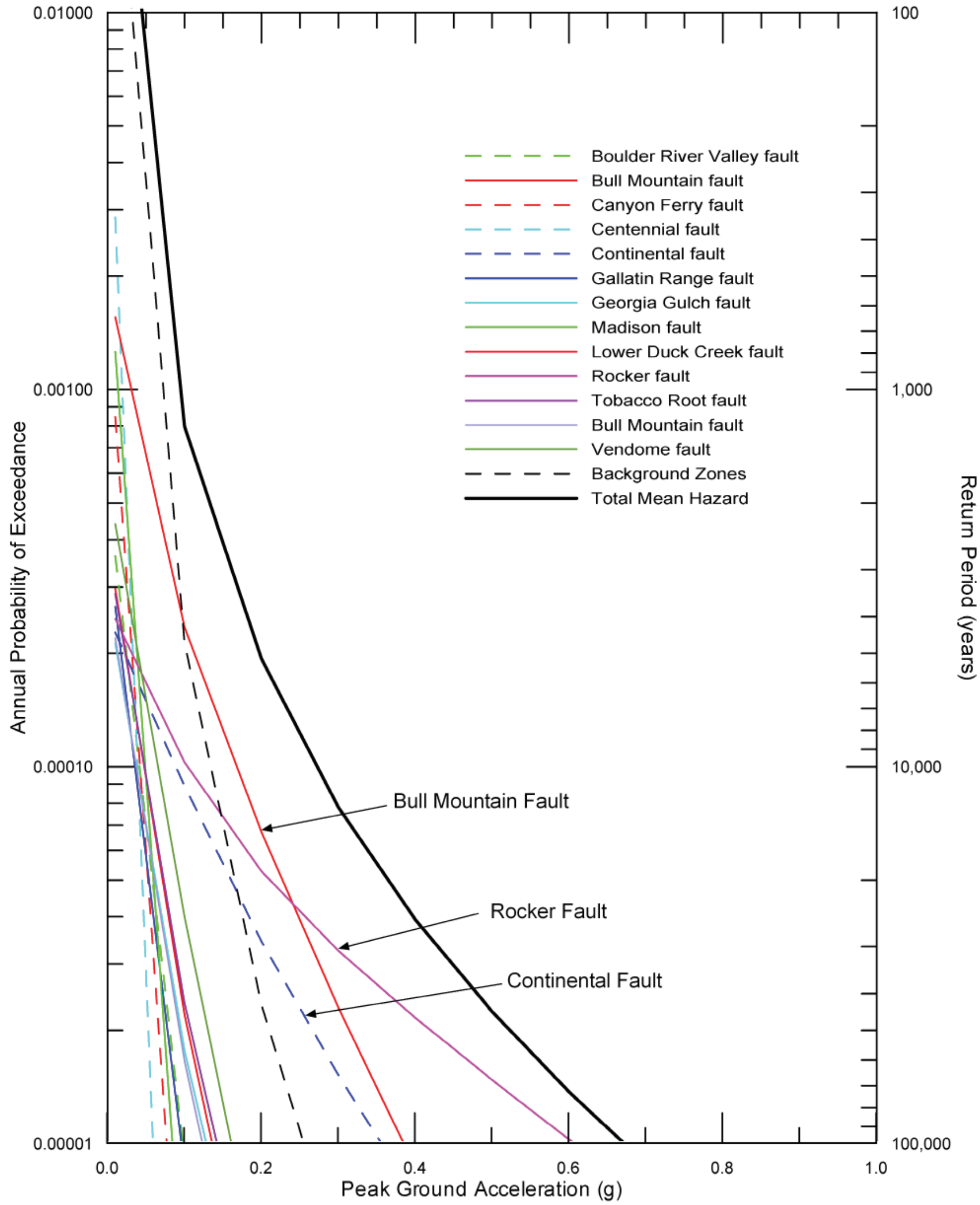

Figure 5.10. Seismic source contributions to mean peak horizontal acceleration hazard for Butte, from Wong and others (2005).

Table 5.1 Peak horizontal ground accelerations (g) for Butte

	Wong and others, 2005						Frankel and others, 1996
Return period:	500 year		2,500 year		5,000 year		2,500 year
	Rock	Surface	Rock	Surface	Rock	Surface	Rock
	0.07	0.07	0.12	0.12	0.17	0.18	0.21

Table 5.2. Comparison of parameters used for the Continental and Rocker Faults by Wong and others (2005) to results from this study

	Wong and others (2005)		This Study	
Parameter	Continental Fault	Rocker Fault	Continental Fault	Rocker Fault
Rupture model[1]	Independent	Independent	Linked	Segmented
Maximum rupture length (km)[2]	18.2	43.5	54	>50
Maximum magnitude[3]	6.2 (0.2) 6.5 (0.6) 6.8 (0.2)	6.7 (0.2) 7.0 (0.6) 7.2 (0.2)	?	?
Dip (°)[4]	30°W (0.2) 55°W (0.6) 70°W (0.2)	30°W (0.2) 55°W (0.6) 70°W (0.2)	65°–90° at the surface	>80°W at the surface
Approximate age of youngest faulting	1.8 million years	1.8 million years	1.8 million years	1.8 million years
Slip rate (mm/yr)[5]	0.005 (0.2) 0.02 (0.6) 0.12 (0.2)	0.005 (0.2) 0.03 (0.6) 0.8 (0.2)	0.08 near the surface[6]	?

[1] An “independent” fault is defined as a single unsegmented plane;“linked” faults may experience rupture together; “segmented “ faults have smaller sections or segments that persistently rupture independently from each other.
[2] Maximum rupture lengths are straight-line lengths.
[3] Values derived using empirical relations from Wells and Coppersmith (1994), based on maximum rupture length. Numbers in parentheses are the weight given to each magnitude.
[4] Dips used by Wong and others (2005) are averaged over the entire depth of the seismogenic crust, and the numbers in parentheses are the weights given to each dip. Dips from this study are observed at the surface.
[5] Slip rates given by Wong and others (2005) are based on a range of assumed offsets, the most heavily weighted being 2 m over 1.8 million years. Weights are shown in parentheses.
[6] If all postulated slip on the fault occurred in the last 5 million years. The slip rate would be 0.28 mm/year near the surface if all slip occurred in the last 1.8 million years.

5.6. Summary of Faults and Earthquakes

There are many faults in Silver Bow County, but many are geologically very old and are not all capable of producing earthquakes. Further, earthquakes in southwest Montana commonly originate on faults that have not been recognized at the surface.

Stratigraphic and crosscutting relationships established in this study show that the most recent fault movement occurred in Silver Bow County within the past 1.8 million years. Faults in the county that are Tertiary or younger have a history of concurrent slip, valley formation, and sediment deposition. In the Basin and Range, the minimum magnitude associated with faults having surface expression is 6.6 (dePolo, 1994), suggesting that total seismicity in the past 15 million years must have been significant. Large debris flows west of the Rocker Fault reflect a history of strong earthquakes, high groundwater levels, steep topography that no longer exists in the source areas to the east of the fault, or any combination of the three.

The faults that created Rampart Mountain, Elk Park, and the East Ridge form a fault zone that is more than 1.9 miles (3 km) wide and as much as 33 miles (54 km) long, striking between 160° and 198° and dipping between 80° east and 65° west. The main fault is the Continental Fault, with over 3,500 feet (1,080 m) of downdip movement. The tightest numeric constraints on the timing over which movement occurred are between 58.8 million years ago and the beginning of written records for the area, which is a huge time span that does not provide any satisfying answer. Probably the strongest evidence suggestive of movement in the past 1.8 million years is the overall character of the range front, including debris flows in Maude S Canyon. Trenching across these flows and radiometric dating could produce better constraints on fault timing.

The Rocker Fault is made of segments with a cumulative length of more than 31 miles (50 km). Its strike varies from north–south near Butte to southwest near Divide and southeast near Melrose, and it dips steeply west. Some segments near Moose Creek moved more recently than others.

Surface exposures suggest the Rocker Fault has had ground-rupturing movement within the past 1.8 million years. Previous studies have produced conflicting interpretations of the Rocker Fault, but during this study a ground-penetrating radar survey across the Rocker Fault confirmed the presence of the fault. Offset of deposits on either side of the fault, the sharp relief across the fault, and trenching near Moose Creek reported by Stickney and Bartholomew (1987) indicate probable Quaternary movement.

Both the Rocker and Continental Faults are overprinted by movement on northeast-trending faults. This does not mean that the Rocker and Continental Faults have not had recent movement. The northeast faults may be acting as transfer faults to accommodate extension on the Rocker and Continental Faults.

Geophysical modeling shows that up to 1,500 feet (457 m) of unconsolidated sediments underlie the Summit Valley and up to 3,000 feet (914 m) of sediment underlies the basin immediately west of the Rocker Fault.

Silver Bow County lies near the western edge of the Montana segment of the Intermountain Seismic Belt, a zone of seismic activity that extends from northwestern Montana to southern Nevada. Crustal stresses here are oriented east–west and both historical and continuing seismicity along the Belt confirm that southwestern Montana should expect occasional damaging earthquakes in the future. Pinning down the significance of this to Silver Bow County is problematic. Both the Continental and Rocker Faults are oriented to accommodate release of regional stress, and the evidence for movement on these faults is permissive, if not compelling, that they have been active during Quaternary time and are potentially hazardous.

Estimates of magnitude 6.9 (IECO, 1981) and magnitude 6.5 (HLA, 1993) for Maximum Credible Earthquake near Butte were derived from seismic stability studies of the Yankee Doodle Tailings Impoundment. More recent probabilistic ground shaking analyses give conflicting results, but those of Wong and others (2005) are more likely to be accurate for Montana. Future analyses might be refined using fault geometry data from this study. At a minimum, statistical data indicate that chances are greater than 1 in 2,500 that an earthquake will produce a ground acceleration of 0.1 or greater in any given year in Silver Bow County. An acceleration of 0.1 g is the threshold at which earthquake shaking begins to cause damage (Wong and others, 2005).

6. LANDSLIDE HAZARDS

Landslides are identified as a natural hazard in the most recent FEMA hazard mitigation plan (Butte–Silver Bow, 2004). At the time the plan was developed, it was recognized that determining landslide vulnerability would be difficult due to the lack of specific data on landslide occurrences in the county. Our county-wide investigation and inventory of landslides completed to address this problem is described below. The landslide inventory map (pl. 3) provides basic data the county can use to improve landslide hazard analyses and mitigation strategies.

6.1. Methods

The landslide inventory and investigation began with the collection and review of existing geologic maps, reports, and other relevant information, and compilation of a preliminary inventory of landslides and related deposits (debris flows, talus/rockfall deposits, and alluvial fans). A GIS database of existing landslide locations was developed and used in the subsequent aerial photograph analysis and field investigation. The preliminary inventory included landslides from existing geologic maps (see index map in appendix 1) and from a regional landslide analysis of southwest Montana (Wilde and others, 2002).

Black and white aerial photos at 1:24,000 and 1:48,000 scale were examined by stereoscope to help verify the presence of previously identified landslides and to identify and delineate potential previously unmapped landslides. Electronic versions of the 2005 National Agriculture Imagery Program natural-color aerial photographs (1 m resolution) and 1:24,000 scale topographic maps imported into a GIS platform augmented the aerial photograph data.

A field investigation was conducted in 2008 to ground-truth landslide locations. The primary goals were to verify the existence and mapped extent of the landslides, determine the type of movement (slide, debris flow, rockfall/talus), and remap the geologic setting if the existing geologic mapping was incorrect. Due to the large number of landslides identified for field inventory and time constraints, the priority was to visit areas most likely to be developed or deposits that appeared questionable based on the aerial photo analysis, especially larger deposits in heavily vegetated areas where landslides are difficult to recognize.

Approximately 300 mass flow deposits (90 slides and 210 debris flow, talus, and alluvial fan deposits) are included in the final landslide inventory (pl. 3). The geology shown on Plate 3 is a simplified version of plate 1 showing rock type rather than geologic age and formation names.

6.2. Landslide Characteristics

Landslide is a general term that refers to rapid movement of a mass of rocks, debris, or earth down a slope under the force of gravity. For the purposes of this report, recent (occurred within the past 1.8 million years) landslide deposits are differentiated into the following geologic map units: Qls (slide), Qdf (debris flow), Qaf (alluvial fan deposit), and Qta (talus/rockfall deposit). Several older slide (QTls) and debris flow (QTdf) deposits are also distinguished.

Slides (Qls, QTls) Approximately 90 slides identified and mapped during this investigation are shown in figure 6.1 and plate 3. Slides occur throughout the county but are most common in mountainous areas or along valley margins where slopes are typically greater than 12%. Size ranges from less than 0.5 acre to approximately 512 acres for a slide located east of Mt. Fleecer in the Fleecer Wildlife Management Area. Slides are characterized by hummocky topography, head scarps, displaced blocks, springs, and tilted trees. Of the slides inspected in the field, most appear to be shallow rotational slides or slumps where failure occurred along a concave-upward rupture surface. The materials incorporated in the slides generally include soil, unconsolidated colluvium, and bedrock.

Slides occur in a wide variety of geologic settings, which in part reflects the diversity and complexity of the geology of Silver Bow County. Table 6.1 summarizes

Table 6.1. Slide occurrence by rock type and geologic unit.

General Rock Type	Number of Slides	Rock Units with Highest Number of Slides (number of slides per unit)
Volcanic rock	15	Tlt- ash flow tuffs (8)
Igneous (granitic) rock	19	Kgt–granite (19)
Sedimentary and meta-sedimentary rock	44	Yg-Greyson Formation (13), Kbl-Blackleaf Formation (6)
Surficial and valley-fill deposits	11	Tcpu, Tcpl-Cabbage Patch Formation (6)

the principal geologic units in which slides occur and the number of slides we found in each unit. The slides occur most commonly in areas underlain by sedimentary and metasedimentary bedrock in the mountains in the southern and western parts of the county. Of these, the majority are in the Proterozoic Greyson Formation (Yg) and the Cretaceous Blackleaf Formation (Kbl), both of which contain a high percentage of mudstone or metamorphosed mudstone.

Granitic rock is widely exposed in the county and underlies an estimated 35% of the surface area. Despite the fact that the steep topography of the East Ridge, Rampart Mountain, and much of the Highland Mountains is underlain by granitic rocks, only 19 slides were mapped in granitic rock, suggesting it has a low susceptibility to failure. Approximately one third of the slides identified in granitic rock are along the trace of the Rocker Fault, south of the town of Rocker (fig. 6.1). In the northern part of the county, most slides occur in volcanic rock simply because that is the predominant rock type. However, volcanic rock that contains a significant ash component (map unit Tlt, pl. 1) is more prone to developing slides.

Relatively few (11) slides were identified in surficial and valley-fill deposits. In this rock group, the Tertiary Cabbage Patch Formation (map unit Tcpu and Tcpl, pl. 1) contains beds of ashy and bentonitic sediments that are prone to swelling when wet and are most susceptible to failure (6 mapped slides). The Cabbage Patch Formation underlies many gently sloping benches along the valley in the Rocker, Divide, and Melrose areas that have seen increased development in recent years, and consideration should be given to potential slide problems prior to future development.

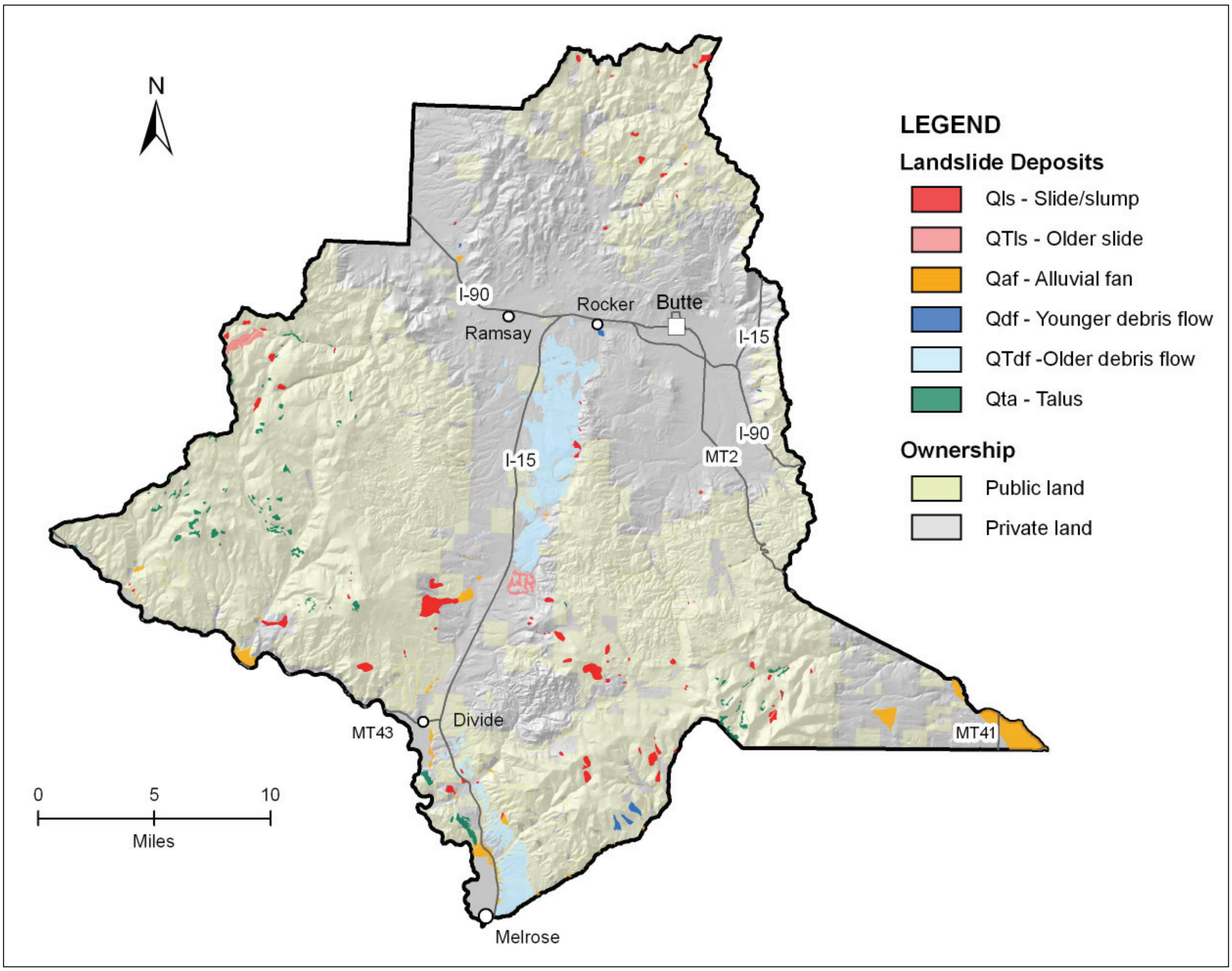

Figure 6.1. Distribution of landslide and related deposits in Silver Bow County. Older debris flow deposits (light blue areas) are included in the map but are not considered a significant landslide hazard due to age, location, and morphology.

Debris Flow Deposits (Qdf, QTdf) A number of deposits in Silver Bow County were interpreted to have been deposited by debris flow (fast moving flows of mud, rock and organic matter; fig. 6.1 and map units Qdf in pl. 1). These deposits are primarily located within steep drainages southeast of Butte near the base of the East Ridge. In general, the debris flow deposits consist of gravel with cobbles and boulders up to 15 feet in diameter. Clast composition reflects bedrock in adjacent slopes.

Numerous older debris flow deposits (map unit QTdf) are located adjacent to the Rocker Fault, from south of Rocker to the Melrose area. The origin and geologic significance of the older debris flow deposits is discussed in Section 5.3. These deposits are important in terms of geologic hazard analysis because they indicate that very large debris flows once moved a considerable distance across the valley, away from their source area. The proximity of these older debris flows to the Rocker Fault further suggests they may have been triggered by movement along the fault. The older debris flow deposits form low benches with gentle slopes (less than 10%) and no longer represent a landslide hazard. Therefore, these deposits are not included in the final landslide inventory (pl. 2).

Debris flows are more closely linked to topography and precipitation than to geology and can occur in most geologic settings where slopes are steep. Debris flows are particularly dangerous to life and property because of their high speeds and the sheer destructive force of their flow. In areas burned by forest or brush fires, debris flows are initiated at a lower threshold of precipitation, making those areas especially vulnerable. Post-fire debris flows in areas burned by wildfires in 2000 caused considerable damage to property and roads in western Montana (Gartner and others, 2005; Parrett and others, 2003).

As a practical matter, mapping debris flow deposits on a county scale turned out to be unrealistic because small debris flow deposits can reasonably be expected to occur in almost any steep drainage, and many are too small to show on a regional-scale map. Therefore, debris flow deposits are certainly more common than suggested by plate 3. The most hazardous areas for debris flows are canyon bottoms, stream channels, areas near the outlets of canyons, and slopes modified for buildings and roads.

Alluvial Fan Deposits (Qaf) Alluvial fan deposits are typically formed over long periods of time by repeated deposition of small to large debris flows at the mouths of canyons or drainages. They are a concern because they are areas of active sediment deposition, are subject to flooding, and are favored sites for development. Many of the alluvial fan deposits in Silver Bow County are small, but there are larger deposits at the mouth of Jerry Creek along the Big Hole River and along the easternmost county border (fig. 6.1 and pl. 3).

Alluvial fans have a characteristic fan-shape with inactive channels across the surface (fig. 6.2). These channels can be future sites of flooding or debris deposition. Alluvial fans occur in many different geologic environments and are underlain by unconsolidated, poorly sorted gravel, sand, and silt with cobbles and boulders. Fortunately, alluvial fans are easily recognizable; the occurrence of debris flows on them is unpredictable, but should not be a surprise when they do happen.

Talus and Rockfall Deposits (Qta) Talus cones (aprons of rock debris at the base of cliffs) and scree-covered slopes (steep slopes covered by rock fragments) are indicators of high rock-fall or rockslide hazard. Talus is ubiquitous in the mountains in Silver Bow County (fig. 6.1) and can be a significant hazard along roads and other transportation corridors.

Any steep, rocky slope with exposed bedrock can be vulnerable to rockfall or rockslides. The East Ridge and Rampart Mountain are close to urban areas, their slopes are very steep (30 to 75%), have exposed bedrock, and are traversed by major transportation corridors. The granitic bedrock along the slopes is riddled with joints (fractures) that parallel the slope (fig. 6.3) and many large boulders appear precariously balanced on the hillside. Much of the land along these slopes is too steep for development but there are areas where development is occurring (primarily north of Maude S Canyon). Under very wet conditions or earthquake shaking, this is an area where rockfall could be a significant hazard. The hazard would be increased in the event of forest fire.

6.3. Areas of Higher Landslide Hazard

The landslide inventory map (pl. 3) gives an overview of the aerial extent of landslides and highlights areas where more detailed studies might be conducted. Our main observation, though, is that the incidence of mass flow in the county is low, with less than 1% of the surface area occupied by landslide and related deposits. Many of the mapped deposits occur on public land at higher elevations in areas unlikely to be developed, and therefore pose smaller risk to the community and associated infrastructure. Others occur in sparsely populated

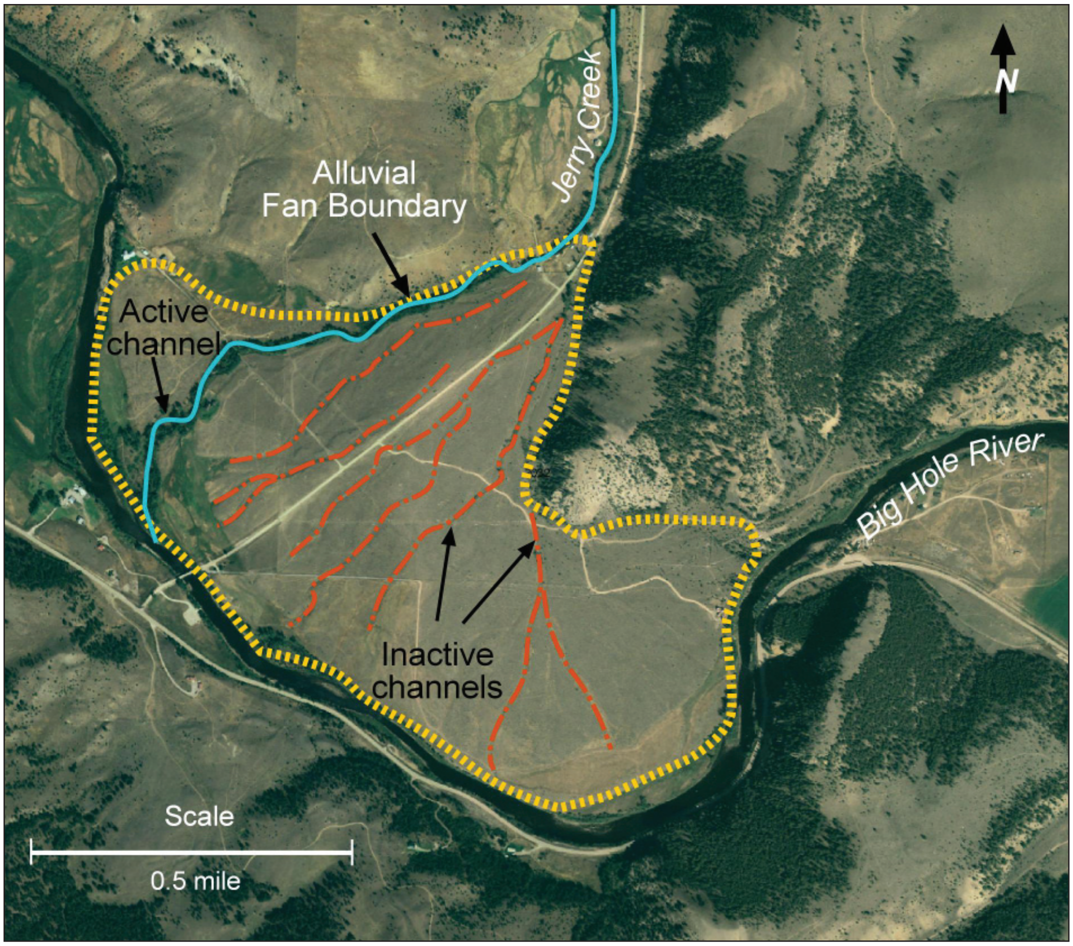

Figure 6.2. Aerial photograph of alluvial fan at the mouth of Jerry Creek. Alluvial fans are often favored sites for development that are prone to flooding and debris flow deposition. (Base photo is 2005 National Agriculture Imagery Program natural-color aerial photograph).

Figure 6.3. Dominant joint sets—vertical and horizontal—in granite on the East Ridge. View looking to the northwest. Photo courtesy of Kirk Waren, MBMG.

areas where impacts would most likely be limited to individual structures or access roads. Landslides occur in most rock types and other factors such as slope, degree of weathering, proximity to faults, elevation, and vegetative cover may be as important in controlling where they form.

Several areas are at a greater risk for future landslide activity (fig. 6.4). Development on known slide deposits should be avoided because they are prone to reactivation or new slides developing at the same location. Slides are most common where the underlying bedrock is sedimentary (in the south part of the county) or volcanic (in the north part of the county). Areas underlain by volcanic rock (Lowland Creek Volcanics) are a greater concern because they are currently being developed, especially the hilly areas west of Rocker along the I-90 corridor (Area 1, fig. 6.4). Although few landslides were mapped in the area, development of these areas, along with expansion of transportation corridors and modification of landscapes by loss of vegetation, changes in natural drainage patterns, and irrigation may lead to an increase in slope failure. More detailed mapping or a more in-depth hazard assessment may be warranted in this area, especially in areas of steeper slopes (fig. 6.5).

In the valley connecting Rocker and Divide, some of the basin-fill deposits contain significant amounts of clay that can be susceptible to failure when wet or disturbed. The Cabbage Patch Member of the Renova Formation (Area 2, fig. 6.4) appears to be most susceptible to failure. Small slides and slumps occur along the steeper slopes of gullies and drainages, and one slide underlies the freeway near Moose Creek. Development may increase landslide activity, although the slides would likely be small.

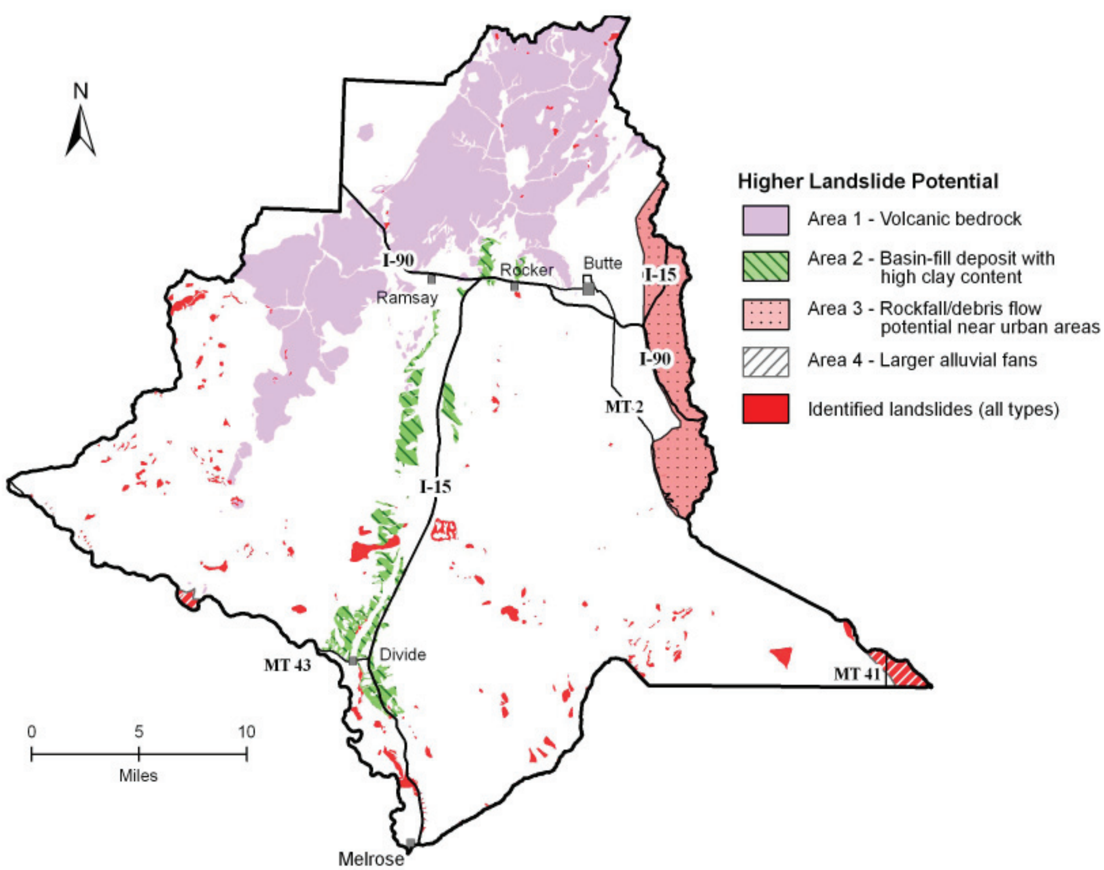

Figure 6.4. Areas of higher landslide hazard.

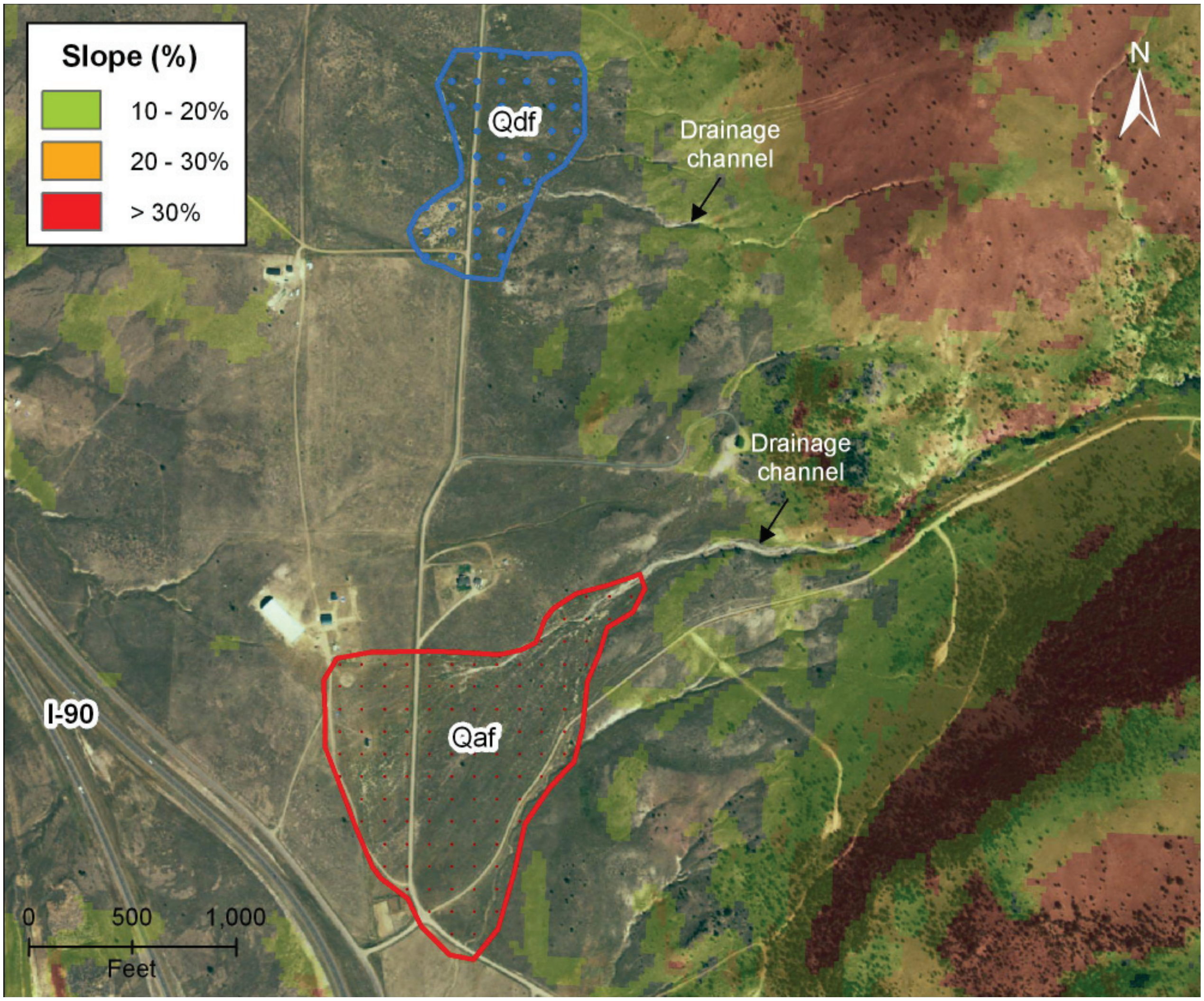

Figure 6.5. Debris flow (Qdf) and alluvial fan (Qaf) deposits in an area undergoing development. Steep slopes and underlying volcanic bedrock are conditions where landslides are more prone to occur. (Base photo is 2005 National Agriculture Imagery Program natural-color aerial photograph).

The steep slopes along the East Ridge and Rampart Mountain may be most vulnerable to debris flows (Area 3, fig. 6.4), especially if the area were to burn. Small talus deposits and jointed outcrops in granitic bedrock along the slopes also indicate rockfall as a potential hazard. The Montana Department of Transportation (Pierson and others, 2005) identified several locations in this area adjacent to Interstate 90 where rockfall hazard is a concern.

Alluvial fans are hazardous development sites. Knowledge of their location and awareness that they are prone to flooding and debris deposition is important for hazard mitigation. The alluvial fans that may be sites of future development are highlighted in fig. 6.4 (Area 4). Debris deposits on alluvial fans would likely be small, but in mountainous areas, high amounts of rainfall in short periods can combine to produce catastrophic debris flows. Even in these events, the directly impacted area is limited to canyon bottoms and a wider area if the debris flow spreads across an alluvial fan.

The inventory prepared for this study is limited in that the county was not uniformly ground-truthed, and mass flow deposits are only located approximately and boundaries may change with additional information. More detailed studies should be done to assess hazards at specific sites.

7. SUMMARY AND RECOMMENDATIONS

7.1. Summary of Conclusions

1) Maps and data included with this report are intended for use at 1:50,000 scale and are designed for general planning.

2) While there are many faults in Silver Bow County, they are not all capable of producing earthquakes. Further, most small- and moderate-magnitude earthquakes in southwest Montana originate on faults that are not recognized at the surface.

3) The age of the most recent ground-rupturing earthquake in Silver Bow County is not well constrained, but geologic evidence shows that it occurred within the past 1.8 million years.

4) Tertiary or younger faults in the county demonstrate a long history of concurrent faulting, valley formation, and sediment deposition. Studies have shown that the minimum magnitude associated with faults having surface expression is 6.5 (dePolo, 1994). This level must have been reached or exceeded many times in the past 15 million years to create the abundance of faults cutting Tertiary beds, bounding range front faults, and the fault-bounded basins that are prominent in the Butte area.

5) The faults that created Rampart Mountain, Elk Park, and the East Ridge form a fault zone that is more than 1.9 miles (3 km wide) and as much as 33.5 miles (54 km) long, striking between 160° and 198° and dipping between 80° east and 65° west.

6) Over 3,500 feet (1,080 m) of downdip movement has occurred on the Continental Fault. The tightest numeric constraints on the timing over which this movement occurred are between 58.8 million years ago and the beginning of written records for the area, but strong evidence exists for movement within the past 1.8 million years.

7) Evidence suggestive of recent fault motion includes debris flows in Maude S Canyon. Trenching across these flows and radiometric dating would likely produce better constraints on fault timing.

8) The Rocker Fault is composed of segments with a cumulative length of more than 30 miles (50 km). Its strike varies from north–south in the north to southwest near Divide and southeast near Melrose, and it dips steeply west. There is evidence that some segments near Moose Creek moved more recently than others.

9) Geophysical modeling shows that up to 1,500 feet (457 m) of unconsolidated sediments underlie the Summit Valley and up to 3,000 feet (914 m) of sediment underlies the basin immediately west of the Rocker Fault.

10) Surface exposures of the Rocker Fault suggest it has had ground-rupturing movement within the past 1.8 million years. Recent movement is suggested by an anomaly detected by a ground-penetrating radar survey across the Rocker Fault trace; the anomaly was subsequently confirmed as a surface-rupturing fault by exposures in a gully wall.

11) Older debris flow deposits west of the Rocker Fault reflect a history of strong earthquakes, high groundwater levels, steep topography that no longer exists to the east of the fault, or a combination of these.

12) Both the Rocker and Continental Faults are overprinted by movement on northeast-trending faults. Motion on the northeast faults appears to have been small, and they may be acting as transfer faults to accommodate motion on the Rocker and Continental Faults.

13) Silver Bow County lies near the western edge of the Montana segment of the Intermountain Seismic Belt, a seismically active zone that extends from northwest Montana to southern Nevada.

14) East–west extensional stresses in the crust are capable of causing seismicity near Butte and are oriented such that they could cause movement on the Continental and Rocker Faults.

15) Previous estimates of Maximum Credible Earthquake in Butte give magnitudes 6.9 (EICO, 1981) and 6.5 (HLA, 1993).

16) There is a 2% chance that during the next 50 years Butte will experience seismic shaking greater than 0.12 g, which is strong enough to damage buildings, especially older unreinforced masonry buildings (Wong and others, 2005).

17) Results from this study may be used to further refine earthquake shaking probability estimates.

18) More than 90 landslides and 210 debris flow, talus, and alluvial fan deposits have been identified in Silver Bow County, but they occupy less than 1% of its surface area. Locations where these have occurred in the past should be regarded as likely sites for future occurrences.

19) Mass movement deposits are clustered preferentially in ashy volcanic rocks in the north part of the county and in sedimentary rocks in the south part of the county and are most abundant in the mountains and along steep valley margins.

20) Damage caused by mass flow can be avoided by performing site-specific studies.

21) Development on known landslide deposits should be avoided because they are prone to reactivation.

22) While some landslides lie along the freeways, most are away from currently developed areas. The largest landslides are on national forest lands.

23) Mass flow in Silver Bow County is primarily a hazard for individual structures built in canyon bottoms, stream channels, outlets of canyons, and on modified slopes.

24) Clay-rich layers in the Tertiary Cabbage Patch Formation present potential difficulties for development along the west side of the Buxton Valley and other small areas in the valley bottom.

25) Debris flows are difficult to predict but are especially dangerous because of the speed with which they occur. There is a high potential for debris flows in mountainous terrain and burned areas, and they can be triggered by intense rainfall and snowmelt, and by ground shaking.

26) Quantitative analysis of the mass flow data provided by this study should be conducted with caution. Mapped boundaries are only relevant for general planning. The maps presented here only show the locations of mapped mass flows and do not reflect a statistically uniform survey of the county.

7.2. Recommendations

1) The data and interpretations presented in this report are accurate at a scale of 1:50,000; they are not site-specific studies, which require more detailed investigations.

2) Trenching and radiometric dating studies along the Continental and Rocker Faults may provide more detailed and precise fault movement histories. We recommend that such studies focus on the East Ridge near Maude S Canyon where crosscutting relationships between debris flows and faults have already been observed, and along the Rocker Fault near Rocker where ground-penetrating radar and surface mapping have established its exact location.

3) Forest fires and other loss of vegetation can drastically raise the level of landslide and debris hazard in the county. If large-scale loss of vegetation occurs, we recommend reanalysis of these hazards.

4) We recommend that hazard analyses take into account possible changes in headwater hydrogeology caused by Butte mine flooding and the large areas of forest killed by pine bark beetles. They should also take into account predictions of increasing rainfall, snowfall, and rapid melting events resulting from global climate change.

5) Sources of data relevant to natural hazards in Silver Bow County include:

a. Detailed soils data for Silver Bow County: U.S. Department of Agriculture, Natural Resources Conservation Service, 2007, Soil Survey Geographic (SSURGO) database for Silverbow County Area and Parts of Beaverhead and Jefferson Counties, Montana. Fort Worth, Texas, U.S. Department of Agriculture, Natural Resources Conservation Service, MT670. URL: http://SoilDataMart.nrcs.usda.gov/, accessed December 14, 2009.

b. Earthquake hazard maps for Montana: Wong, I., Olig, S., Dober, M., Wright, D., Nemser, E., Lageson, D., Silva, W., Stickney, M.S., Lemieux, M., Anderson, L., 2005, Probabilistic earthquake hazard maps for the state of Montana, Montana Bureau of Mines and Geology: Special Publication 117, 72 p.

c. Quaternary fault data for Montana: U.S. Geological Survey and Montana Bureau of Mines and Geology, 2006, Quaternary fault and fold database for the United States, accessed DATE, from USGS web site: http//earthquakes.usgs.gov/regional/qfaults/, accessed December 14, 2009.

d. Groundwater levels and drilling log database: Groundwater Information Center, Montana Bureau of Mines and Geology (GWIC) http://mbmggwic.mtech.edu/, accessed December 14, 2009.

e. Landslide hazard data for Montana: Pierson, L.A., Beckstrand, D.L., and Black, B.A., 2005, Rockfall hazard classification and mitigation system: Landslide Technology, Portland, Oregon. Report prepared for Montana Department of Transportation, September 2005, 280p.

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APPENDIX 1

Description of Map Units and Map References

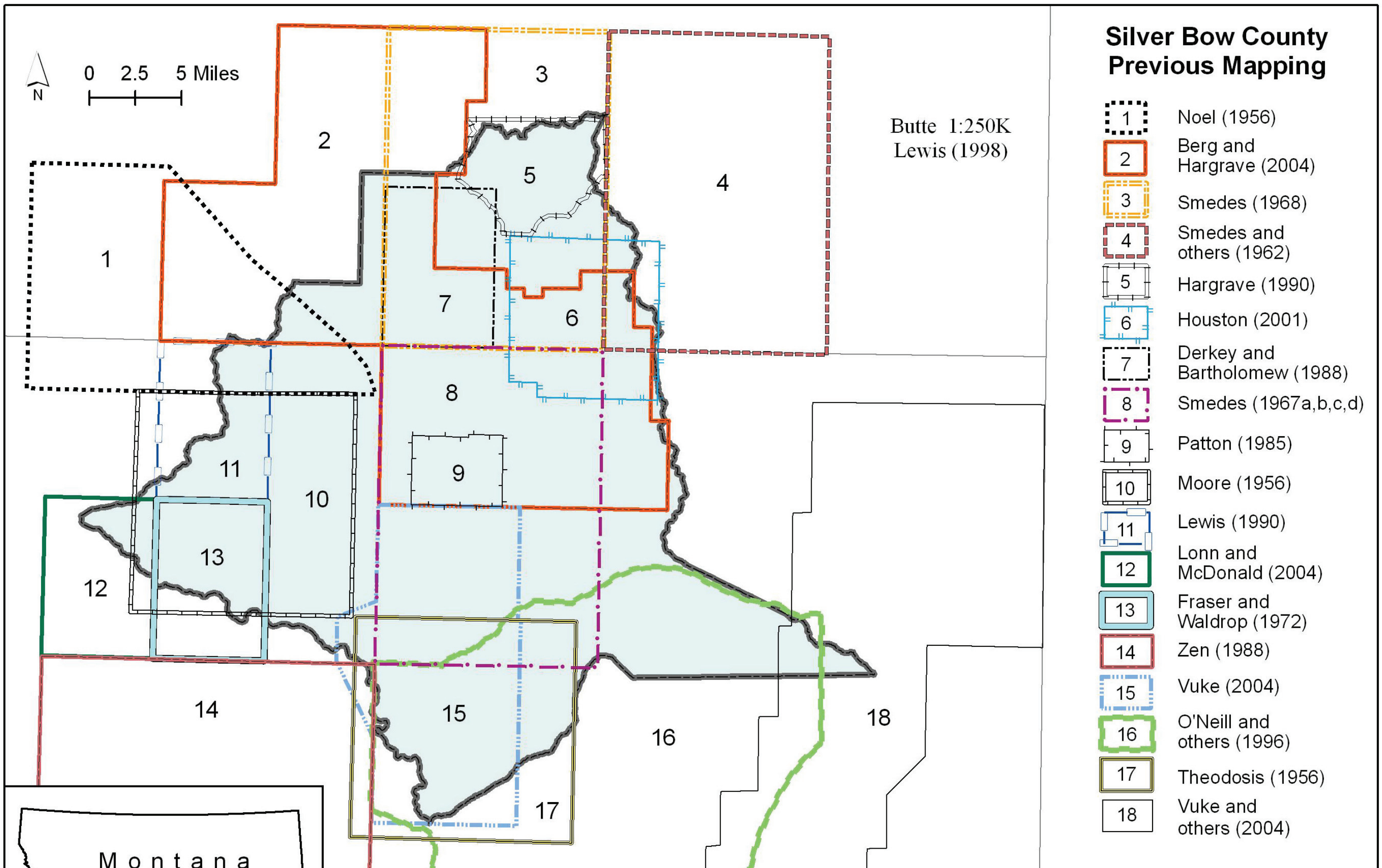

Figure A-1. Location and index map of previous geologic mapping in Silver Bow County

DESCRIPTION OF MAP UNITS

Quaternary Surficial Deposits

Qal Alluvium (Holocene)—unconsolidated clay, silt, sand, pebble, and cobble gravel in modern stream channels. Clasts are typically rounded and locally may be very well sorted.

Qaf Alluvial fan deposit (Holocene)—fan- or delta-shaped landforms at the mouth of canyons, gulches, and steep drainages and valleys. Deposits are unconsolidated, poorly sorted gravel, sand, and silt with cobbles and boulders; coarser sediment near head of fan.

Qc Colluvium (Holocene and Pleistocene)—heterogeneous, unconsolidated, boulder and cobble gravel deposits with a matrix of sand, silt, and clay. Deposits have not been transported far from source rock and clasts are typically angular. Common at base of gentle slopes or hillsides.

Qac Alluvium and colluvium, undivided (Holocene and Pleistocene)—cobbles, pebbles, sand, silt, and clay deposited on valley floors and gentle slopes. Thickness estimated to be as much as 15 feet (4.5 meters).

Qgr Gravel (Holocene and Pleistocene)—surficial deposits of poorly sorted, angular to well-rounded pebbles and cobbles; locally in a matrix of silt, sand or gravel. Typically found on planar to gently dipping slopes along valley margins; clast composition reflects that of the nearby bedrock. Deposits can be very thin to over 10 feet (3 meters) thick.

Qta Talus (Holocene and Pleistocene)—unconsolidated deposits of angular boulders of bedrock at the base of steep rock faces. Thickness estimated as much as 50 feet (15 meters).

Qls Landslide deposit (Holocene and Pleistocene)—mass flow deposit of angular fragments of bedrock mixed with finer grained material derived from adjacent hill slopes; often characterized by hummocky surface.

Qdf Debris flow deposit (Holocene and Pleistocene)—coarse, unconsolidated, locally derived, matrix-supported gravel and sand with angular to subrounded clasts as large as boulder size (some boulders as much as 6.5 feet [2 meters] in diameter).

Qs Surficial deposits, undivided (Holocene and Pleistocene)—unconsolidated surficial deposits not individually mapped; including loess, sheetwash alluvium and colluvium, alluvium in small channels, small debris-flow deposits, pediment gravel, and small landslide deposits. Sediment size ranges from clay and silt to boulders. Sediment generally locally derived, although loess is both locally derived and from distal sources. Ash beds from distal sources to north and west. Thickness generally less than 20 feet (6 meters), but locally 50 feet (15 meters) thick or greater.

Qr Rock glacier and related deposits (Holocene and Pleistocene)—unconsolidated lobate to elongate deposit of coarse gravel and boulders in glacial cirques in the Highland Mountains. Thickness generally less than about 30 feet (10 meters).

Qg Glacial deposits, undivided (Holocene and Pleistocene)—poorly sorted, unconsolidated deposits of silt, sand, gravel, and boulders along valley bottoms and slopes in the Highland Mountains and western Silver Bow County. Maximum thickness probably less than 100 feet (30 meters).

Qat Alluvial terrace deposits along modern stream channels (Holocene and Pleistocene)—alluvium adjacent to and slightly higher than alluvium (Qal) along modern stream channels and flood plains. Deposits generally covered by fine sediment and soil. Thickness not determined.

Qato Older alluvial terrace deposit (Pleistocene?)—rounded to subrounded gravel, pebbles and cobbles with sandy matrix. Clasts are quartzite, hornfels, diorite, rhyolite and brown chert, with rare granite cobbles. Many cobbles have calcium carbonate rinds. These older terrace deposits are mapped near Divide where they occur on flat benches up to 100 feet (30 meters) above the modern valley. Thickness about 200 feet (6 meters).

Qao Older alluvium (Pleistocene?)—light orange to tan, medium- to thick-bedded, coarse clay, silt, sand

and gravel. Light brown, waxy clay layers interbedded with very coarse sediment may be old buried soil horizons (paleosols). Locally contains cobbles and boulders. Deposits are generally adjacent to–but topographically higher than–modern stream channels. Primarily mapped in the Summit Valley. Thickness as much as 650 feet (200 meters) based on well-log data.

QTls Older landslide deposit (Pleistocene and/or Pliocene?)—unconsolidated sand, silt, and clay with subangular to angular clasts up to small boulder size. Estimated to be as much as 100 feet (30 meters) thick.

QTdf Older debris flow deposit (Pleistocene and Pliocene?)—gravel and round to subangular boulders as much as 10 feet (3 meters) in diameter. Locally, finer sediment is lacking and boulders represent lag deposits. The debris flow deposits occur in two separate areas along the east side of the valley between Rocker and Melrose. Between Rocker and the Feely exit, the deposits are dominated by granite and aplite boulders similar to local bedrock; multiple layers representing different debris flow events can be recognized. In the southern part of the county, between Divide and Melrose, deposits consist of dominantly quartzite boulders with subordinate hornfels, fine-grained igneous rock, and limestone, all similar to local bedrock. In both areas, the deposits occur adjacent to and west of the Rocker Fault which may suggest movement on the fault initiated the debris flows. Thickness of deposits estimated to range from 20 to 80 feet (6 to 25 meters).

QTal Older gravel alluvium (Pleistocene and Pliocene?)—gravel, dominantly of well-rounded cobbles and pebbles, with a matrix of sand, silt, and clay; sandy, locally red, clay interbeds. Clasts are dominantly Proterozoic quartzite with subordinate granitic rock. Mapped in area around Moose Creek and interpreted by Vuke (2004) as channel-fill deposits of a south-flowing, ancestral Divide Valley river. Thickness as much as 300 feet (90 meters).

Tertiary Basin-Fill Deposits and Contemporaneous Volcanic Rock

Basin-Fill Deposits

Tcg Conglomerate (Pliocene?)—maroon to light brown, poorly sorted, partially lithified boulder conglomerate interbedded with light gray to tan, tuffaceous siltstone and mudstone. Clasts angular to subangular but with some interbeds of rounded to subrounded boulder conglomerate with a heterogeneous mixture of clast lithologies. Often capped by angular, locally derived boulders and cobbles that appear to grade from the adjacent mountains and may be considerably younger that most of the unit. Mapped along the Big Hole River valley where deposits can be found up to about 200 feet (60 meters) above valley floor. Thickness approximately 500 feet (150 meters).

Tat Alluvial terrace deposit (Pliocene?)—well-rounded to rounded small boulders, cobbles, pebbles, and sand dominantly composed of Proterozoic quartzite and conglomerate. Exposed between Moose Creek and Melrose at higher altitudes than Qat and QTal. Thickness as much as 20 feet (6 meters).

Tme Melrose informal map unit (Miocene and/or Pliocene)(from Vuke, 2004)—unconsolidated cobble-size clasts of platy, angular Newland and LaHood Formation from the Moose Creek area to the Soap Gulch area. In the Soap Gulch area, clasts also include limestone, conglomerate and other lithologies derived from rocks in the immediate area. Locally cemented with calcium carbonate in Soap Gulch and Camp Creek areas, and interbedded with fine-grained sandstone and ashy siltstone with locally derived angular or subangular granules and pebbles. Unit interpreted as a lateral facies equivalent of the Divide and/or Tucker Creek informal map units, and is therefore interpreted as mid- to late-Miocene and/or Pliocene. Age equivalent to Sixmile Creek Formation. Exposed thickness about 300 feet (90 meters).

Ttc Tucker Creek informal map unit (Miocene and Pliocene?)(from Vuke, 2004)—quartz feldspar granule conglomerate and unconsolidated granules derived from weathered granite probably from the immediate area. Basal part to entire thickness cemented with calcium carbonate. Local small pods of breccia or subangular conglomerate with clasts of local rock types, generally granite, and hornfels with subordinate limestone, which decreases towards the north. Local rounded boulders of granite in matrix of granite granules. Equivalent to the "lime-cemented arkose" of Smedes (1967a). Finer grained in northern part of map area with many granule- to pebble-size clasts floating in a matrix of finer grained ashy sediment interbedded with quartz feldspar granule conglomerate (from Vuke, 2004). Age equivalent to Sixmile Creek Formation. Thickness 80 to 110 feet (25 to 33 meters).

Tdiv Divide informal map unit (Miocene and Pliocene?)(from Vuke, 2004)—unconsolidated granules and weakly cemented quartz and feldspar granule conglomerate and pale yellow to pale yellow-red ashy siltstone with dispersed quartz, feldspar and granite granules. Local small pods of breccia or subangular conglomerate with clasts of local rock types, generally granite, and hornfels with subordinate limestone south of Feely, and dominantly granite north of Feely. Local rounded boulders of granite in matrix of granite granules. Siltstone becomes dominant north of Feely. Siltstone with dispersed granules is difficult to distinguish from similar rocks within the Cabbage Patch Member described below. Base of unit placed at the base of stacked paleosol sequences as much as 150 meters thick. Paleosols are poorly vegetated; hard beds that vary in color from white to, more commonly, pale rusty red. May be 10 or more paleosols in a sequence, commonly separated by erosional surfaces. Age equivalent to Sixmile Creek Formation. Estimated thickness as much as 3,250 feet (1,000 meters).

Tpb Parrot Bench informal map unit (Miocene) (from Vuke, 2004)—grayish orange and yellowish brown, fine- to coarse-grained, crossbedded sand or sandstone and subordinate siltstone and mudstone, interbedded with dominantly matrix-supported pebble or cobble conglomerate and breccia with clasts reaching boulder size. Channels and lenses with scour bases contain the coarser clasts. Clast composition includes granite, volcanic, limestone, quartzite, shale, and gneiss derived from nearby mountains. Exposed in the easternmost part of the county. Thickness approximately 3,250 feet (1,000 meters).

Tcpu Cabbage Patch Member of the Renova Formation, upper unit (Oligocene and Miocene) (from Vuke, 2004)—pinkish tan, ashy siltstone with lenses of poorly sorted feldspathic sandstone and very poorly sorted conglomerate with subangular to rounded clasts of hornfels, quartzite, granite, granodiorite, black chert, gray mudstone, rhyolite and limestone. Lenses vary greatly in size, and clast size within lenses reaches 1 meter. The siltstones commonly contain dispersed grains of quartz, feldspar, and granite, and are difficult to distinguish from siltstones of the overlying Divide map unit. The upper part of the member contains white and light gray, diatomite beds. Estimated thickness about 750 feet (230 meters).

Tcpl Cabbage Patch Member of the Renova Formation, lower unit (Oligocene and Miocene) (from Vuke, 2004)—lenses and ribbons of texturally immature granite clast sandstone and conglomerate surrounded by poorly-exposed dark brown to gray, bentonitic clay and silt. The unit represents the lowest exposed part of the Cabbage Patch Member in the county, and is present south of Divide (Thomas, 1995) and in two belts north of Divide–one trending north along the west edge of the valley and one trending northwest to north, east of I-15. The sandstone and conglomerate are trough crossbedded and distinctive in that they contain only granitic clasts, and that two different micas, one dark brown and one light yellow, are found in clasts and matrix. They are the "two-mica sands" of Thomas (1995) and Stroup and others (2009). Estimated thickness from 650 to 2,300 feet (200 to 700 meters).

Tca Climbing Arrow Member of the Renova Formation (informal) (Eocene and Oligocene) (from Vuke, 2004)—dominantly light gray and greenish brown, bentonitic mudstone, red siltstone and shale, and yellowish, chippy weathering, hard, micaceous claystone and siltstone. Other lithologies include poorly sorted and locally well-indurated pebble conglomerate with rounded clasts of light-colored igneous rock, brown chert, and Proterozoic quartzite; breccia of igneous rocks floating in yellowish tan ashy sandstone; dark brown, manganese-cemented, coarse-grained sandstone; and black shale. West of Melrose it includes white to yellowish, fine ash beds that are locally fossiliferous. Exposed thickness about 200 feet (60 meters).

Ts Valley-fill sediment, undivided (Miocene to Eocene?)—very pale orange to grayish orange, soft, unconsolidated to moderately indurated clay, silt, and sand with subordinate gravel. Bedding generally not recognizable except in gullies. Lenses of cobbles contain clasts of volcanic rock, granite, aplite, chert, and chalcedony. Includes some small debris flows containing granite, aplite and volcanic boulders as much as 6.5 feet (2 meters) across. This unit was mapped in north end of county where exposures are poor and correlation with the map units in similar-age deposits to the south was not possible. Thickness not determined.

Tz Zenith Mine informal map unit (Eocene?)—poorly exposed red volcanogenic pebbly clay and silt deposits around Euell Hill northwest of Nissler that are stratigraphically between Lowland Creek Volcanics and the lower unit of the Cabbage Patch Member of the Renova Formation. Mapped as altered andesite by Berger and Berg (2006).

Volcanic Rock

Tlc Lowland Creek Volcanics, undivided (Eocene)—undivided volcanic rock that includes the units described below.

Tlb Volcanic breccia of Lowland Creek Volcanics (Eocene)—hard to moderately hard, volcanic breccia that consists of angular fragments of broken volcanic rock held together in a finer matrix. Includes both brecciated lava flows and ash-flow tuffs with lithic fragments (Smedes and others, 1962; Smedes, 1967b, 1968; Derkey and Bartholomew, 1988; Hargrave 1990; Houston, 2001).

Tlcw Welded tuff of Lowland Creek Volcanics (Eocene)—slightly to densely welded volcanic ash, weathers light gray to reddish brown with conspicuous crystals of quartz and feldspar in a fine-grained matrix. Weathered pumice fragments form cavities on the surface of the rock: where the rock is densely welded the pumice fragments form highly elongate lenses (Smedes and others, 1962; Smedes, 1967b, 1968; Derkey and Bartholomew, 1988; Hargrave 1990; Houston, 2001).

Tll Lava flows of Lowland Creek Volcanics (Eocene)—thick, well-indurated, lava flows that consist of light to dark gray and grayish red volcanic rock, predominantly rhyolite and dacite. The rhyolite is generally lighter color; the dacite is darker color and has conspicuous crystals within a finer grained matrix. Rock often displays flow-banding, jointing, some brecciation, and typically forms resistant ridges with rounded to angular outcrops (Smedes and others, 1962; Smedes, 1967b, 1968; Derkey and Bartholomew, 1988; Hargrave 1990; Houston, 2001).

Tlt Tuff of Lowland Creek Volcanics (Eocene)—yellowish gray to very light-gray, easily eroded, poorly to moderately indurated crystal-rich ash-flow tuff with minor amounts of moderately flattened pumice fragments and subangular to rounded volcanic rock fragments. The ash-flow tuffs often underlie areas of subdued topography and weather to soil with a distinctive light olive gray color (Smedes and others, 1962; Smedes, 1967b, 1968; Derkey and Bartholomew, 1988; Hargrave 1990; Houston, 2001).

Ti Intrusive rocks (Tertiary)—rhyolite. Smaller intrusive bodies (sills, dikes, plugs) of predominantly rhyolitic composition, typically light colored, microcrystalline, but locally with large conspicuous quartz grains. May be related to Lowland Creek Volcanics.

Mesozoic Igneous Rocks

Kem Elkhorn Mountains Volcanics—andesite, welded tuff, tuff breccia. Light gray to dark gray, grayish red, greenish gray, and brown mostly andesitic to latitic welded tuff and tuff breccia (O'Neill and others, 1996).

Ki Intrusive rocks, undivided (Cretaceous)—basalt, andesite, gabbro and granitic intrusive rock. Smaller intrusive bodies interpreted to be contemporaneous with the Elkhorn Mountains Volcanics and Boulder batholith (Vuke, 2004; O'Neill and others 1996; Fraser and Waldrop, 1972; Smedes, 1967a,b,c,d).

Ka Aplite, intrusive (Cretaceous)—white or light gray, hard, typically fine-grained but locally very coarse-grained dikes and sheets associated with the Boulder batholith (Houston, 1999; Derkey and Bartholomew, 1988; Smedes, 1967a,b,c,d). Only larger bodies shown, many are too small to be shown at 1:50,000 map scale.

Kgt Granitic rocks, undivided (Cretaceous)—coarse- and fine-grained, light to dark gray, pinkish and bluish gray intrusive rocks associated with the Boulder and Pioneer batholiths. Often jointed, weathers to grus (disintegrated granite) and sandy soils. Rocks associated with the Boulder batholith were emplaced between 74 and 78 million years ago (Lund and others, 2002; du Bray and others, 2009).

Mesozoic and Paleozoic Sedimentary Rocks

Mesozoic Rocks

Kbl Blackleaf Formation (Lower Cretaceous)—includes the Flood and Vaughn Members.

Vaughn Member—siltstone, mudstone, shale with subordinate sandstone, volcaniclastic sandstone, and conglomerate with chert and quartzite pebbles. Sandstone is light gray to yellow brown, often with volcanic detritus. Finer grained layers are yellow brown and dark gray, partly calcareous, and contain carbonaceous material and wood fragments. Conglomerate occurs as discontinuous lenses up to 20 feet (6 meters) thick.

Flood Member—mudstone, shale and siltstone with subordinate sandstone, limestone and conglomerate. Fine-grained, medium to dark gray mudstone that is locally thinly laminated, calcareous, and rich in calcareous nodules. Sandstone is light gray, very fine- to fine-grained, thin-bedded, laminated, and calcareous. The base of the Flood Member is transitional with the underlying Kootenai Formation and consists of sandstone, siltstone, and mudstone with subordinate limestone, shale, and conglomerate.

Kk Kootenai Formation (Lower Cretaceous)—mudstone, shale, siltstone and minor sandstone with distinctive basal conglomerate and capping gastropod-bearing limestone. The upper part of the formation is composed of gray limestone with subordinate mudstone, siltstone, and sandstone. The middle and lower part of the formation consist of variegated, olive gray to pale red, thinly laminated mudstone and siltstone with minor interbedded limestone. Sandstone beds become more common near base of formation. The sandstones are typically light to dark gray, fine- to coarse-grained, locally calcareous, and contain distinctive black chert grains that give the rock a salt-and-pepper look. The basal conglomerate contains abundant well-rounded pebbles and cobbles of chert. Thickness estimated to range from 980 to 1,940 feet (300 meters to 590 meters) (O'Neill and others, 1996; Fraser and Waldrop, 1972).

Ksm Cretaceous sedimentary rocks, undivided and metamorphosed—near the margins of plutons, the Blackleaf and Kootenai Formation have been metamorphosed to hornfels, quartzite and marble. Mapped as a unit distinct from Kbl or Kk where large areas have been metamorphosed.

TRd Dinwoody Formation (Lower Triassic)—siltstone, sandstone, shale, and limestone. Grayish green, yellowish gray, and grayish brown, calcareous, thinly laminated siltstone, fine-grained sandstone, shale, and gray, pale red and light brownish gray weathering, thin-bedded limestone. Thickness approximately 425 feet (130 meters) (O'Neill and others, 1996).

Mzu Mesozoic rocks, undivided—includes Blackleaf, Kootenai, and Dinwoody Formations, all described above. Rocks are metamorphosed or very poorly exposed making it difficult to differentiate individual formations.

Js Jurassic rocks, undivided—siltstone, sandstone, shale, and limestone. Grayish green, yellowish gray, and grayish brown, calcareous, thinly laminated siltstone, fine-grained sandstone, and mudstone. Includes Morrison Formation. Thickness about 325 feet (100 meters) (Fraser and Waldrop, 1972).

Paleozoic Rocks

Pp Phosphoria Formation (Lower Permian)—cherty sandstone, quartzitic sandstone, phosphatic mudstone, phosphate rock, shale, chert, cherty limestone and dolomite. Upper unit is dominantly yellowish brown to brownish and dark gray chert, cherty sandstone, and quartzitic sandstone. Lower unit includes dark gray carbonaceous, phosphatic mudstone, shale, phosphate rock; light gray to grayish brown, cherty quartzitic sandstone, cherty or sandy dolomite and limestone; yellowish brown and medium bluish gray chert. Thickness approximately 325 feet (100 meters) (O'Neill and others, 1996).

IPq Quadrant Formation (Pennsylvanian)—quartzite and minor sandstone. Light tan to light gray, massive to thick-bedded, vitreous quartzite and minor fine- to medium-grained, quartz sandstone, yellowish orange siltstone, and limestone (Theodosis, 1956; Zen, 1988; Vuke and others, 2004). The formation is very hard and weathers deep ochre to reddish yellow with characteristic concentric bands and rings of red iron-oxide stain on fracture surfaces. It fractures easily into blocky breccia along minor faults and forms talus slopes in places. Estimated thickness 490 to 650 feet (150 to 200 meters).

IPMsr Snowcrest Range Group (Pennsylvanian and Mississippian)—mudstone, limestone, sandstone, siltstone, shale. Divided into the Conover Ranch, Lombard and Kibbey Formations. The following descriptions are from O'Neill and others (1996).

Conover Ranch Formation (Lower Pennsylvanian and Upper Mississippian)—poorly exposed, pale reddish brown to pale reddish purple, calcareous mudstone with subordinate limestone, calcareous sandstone and siltstone, limestone-pebble conglomerate and phosphatic claystone. Reddish siltstone commonly with very light gray spots. Thickness approximately100 feet (30 meters).

Lombard Formation (Upper Mississippian)—light olive gray, thin- to thick-bedded fossiliferous limestone and thin interbeds of silty limestone, siltstone, and shale. Underlain by olive gray and medium red to pale reddish purple, calcareous mudstone. Thickness approximately 260 feet (80 meters).

Kibbey Formation (Upper Mississippian)—pale red to pale yellow, thin- to medium-bedded siltstone, sandstone, and claystone with interbedded limestone and evaporite solution breccia. Thickness approximately 80 feet (25 meters).

ℙMqs Snowcrest Range Group and Quadrant Formation, undivided (Mississippian and Pennsylvanian)—see above for descriptions.

Mm Madison Group, undivided (Mississippian)—limestone. Undivided Mission Canyon and Lodgepole Formations. Near contacts with granitic rock, metamorphosed to coarsely crystalline marble.

Mmc Mission Canyon Limestone (Upper and Lower Mississippian)—limestone. Light gray, massive and thick-bedded, fossiliferous limestone with chert beds, and nodules and zones of solution breccia. The upper part of the formation contains pale red to grayish orange, limestone breccias. Thickness about 1,000 feet (300 meters) (O'Neill and others, 1996).

Ml Lodgepole Limestone (Lower Mississippian)—limestone, shaly limestone. Thin- to thick-bedded, dark gray, finely crystalline limestone, locally containing abundant coral and brown or black chert. The lower part is thin-bedded, laminated, shaly (argillaceous) limestone (O'Neill and others 1996). Locally forms cliffs but more commonly forms steep slopes. Thickness ranges from 325 to 690 feet (100 to 210 meters).

MDt Three Forks Formation (Devonian and Mississippian)—mudstone, shale, limestone, limestone breccia. Poorly exposed, dark gray, pale orange, and greenish gray mudstone and shale, locally densely fossiliferous. Includes subordinate beds of calcareous sandstone, siltstone, argillaceous limestone, limestone breccias, and shale breccia. Thickness estimated from 50 to 130 feet (15 to 40 meters) (O'Neill and others, 1996).

Dj Jefferson Formation (Devonian)—dolomite, dolomitic limestone, limestone. Light to dark gray, thick-bedded, coarse-grained, sucrosic (sugary) textured dolomite and dolomitic limestone; lower part thick-bedded, interbedded with creamy white and locally quartz sand-bearing dolostone and minor grayish black dolomite or limestone. A sulfurous or petroliferous odor is common on fresh surfaces. Near contacts with igneous rock, the dolomite is grayish white, massive marble. Thickness estimated to be about 490 to 650 feet (150 to 200 meters).

MDs Three Forks, Jefferson, and Maywood Formations, undivided (Mississippian and Devonian)—see descriptions above and below.

DꞒmr Maywood and Red Lion Formation, undivided (Devonian and Cambrian)

Maywood Formation (Devonian)—thin-bedded, medium gray or purplish, dolomitic limestone and dolomite interbedded with calcareous shale and siltstone and minor white calcareous quartzite. Thickness about 100 feet (30 meters)

Red Lion Formation (Cambrian)—yellowish brown to light gray, very fine-grained to fine-grained, thin- to thick-bedded dolomite and dolomitic limestone, mottled and ribboned grayish red in lower part. Lower part is olive gray to reddish gray, fissile shale, siltstone and sandstone. Thickness about 100 feet (30 meters).

Ꞓrh Red Lion and Hasmark Formations, undivided (Cambrian)

Red Lion Formation (Cambrian)—see description above.

Hasmark Formation (Cambrian)—massive to medium-bedded, light gray dolomite with subordinate silty, yellow weathering, dolomitic limestone and silty dolomite near base. Faint flat laminations often visible on weathered surfaces. Near contacts with granitic rock, metamorphosed to coarsely crystalline dolomitic marble. Approximately 490 to 980 feet (150 to 300 meters thick) (O'Neill and others, 1996:

Zen, 1988). The Hasmark Formation is equivalent to the Meagher, Park, and Pilgrim Formations shown on some of maps used for this map compilation (Vuke, 2004; O'Neill and others, 1996).

Ꞓsf Silver Hill and Flathead Formations, undivided (Cambrian)

Silver Hill Formation (Cambrian)—shale, argillite, silty limestone. Lower part is thin-bedded, dark brownish gray, olive green to olive gray, micaceous shale and argillite with interbedded reddish quartzite and siltite near base. Near granitic rock, shale is hard dark hornfels. Upper part is interbedded nodular and silty limestone and thin-bedded siltstone and sandstone. Dark gray limestone beds commonly with wavy, yellow brown silty seams that impart a "black and gold" color to rock. Thickness about 230 feet (70 meters). Equivalent to Wolsey Formation shown on some of maps used for this map compilation (Vuke, 2004; O'Neill and others, 1996).

Flathead Formation (Cambrian)—quartzite, subordinate argillite. Pale orange to yellowish brown, thin- to medium-bedded quartzite, feldspathic sandstone, and minor conglomerate. Middle 5-6 meters of formation commonly includes beds of fine-grained sandstone and olive green and pale red mudstone and shale. Thickness about 65 feet (20 meters).

Ꞓs Sedimentary rocks, undivided (includes Red Lion, Hasmark, Silver Hill and Flathead Formations)—see descriptions above.

Ꞓsm Cambrian rock, metamorphosed—pale grayish orange, vitreous quartzite interbedded with thinly laminated, grayish green to dark gray phyllite, argillite, and siltstone (Lonn and McDonald, 2004).

ꞒYq Quartzite, undivided (Cambrian and/or Middle Proterozoic)—purple to light gray, dense, fine- to medium-grained, feldspar-poor, massive quartzite that contains sparse floating pebbles of quartz, interbedded with–and grading downward into–fine- to coarse-grained feldspathic quartzite with abundant mud chips (Lonn and McDonald, 2004). Thickness undetermined.

Precambrian Rocks

Middle Proterozoic Metasedimentary Rocks of Belt Supergroup

Middle Proterozoic Missoula Group—interlayered quartzite and siltstone that thins to the east and west. Divided into four mappable informal formations (O'Neill and others, 1996) with a maximum thickness of about 650 feet (200 meters).

Ym4 formation 4—pebble to cobble conglomerate that is restricted to the area directly east of the Twin Bridges Fault.

Ym3 formation 3—interlayered white to tan, thick-bedded, locally platy and crossbedded quartzite and laminated, very fine-grained, clayey (argillaceous) quartzite that thins and decreases in abundance to the west.

Ym2 formation 2—pinkish white, fine- to medium-grained quartzite interlayered with minor tan hard siltstone. Only present in central Highland Mountains.

Ym1 formation 1—medium gray, laminated, very fine-grained hard quartzite and siltstone with even, parallel laminations. Only present in central Highland Mountains.

Yboq Bonner Formation of the Missoula Group (Middle Proterozoic)—quartzite. Pale purplish to pale reddish, crossbedded, feldspathic, medium- to coarse-grained quartzite and conglomerate. As thick as 1,900 feet (580 meters) (Lonn and McDonald, 2004).

Yhe Helena and Empire Formations, undivided (Middle Proterozoic)—calcareous siltstone, argillite, quartzite, silty limestone. The Empire Formation generally lies beneath the Helena Formation, but the two are locally complexly interlayered and grade laterally into one another (O'Neill and others, 1996).

Helena Formation—tan, pinkish gray to gray green, laminated to thin-bedded, calcareous and commonly pitted siltstone. In the central part of the Highland Mountains, the upper part of the formation consists of calcareous siltstone and argillite with conglomerate lenses. The lower part consists of cycles of very fine-grained, wavy and parallel laminated quartzite overlain by clayey siltstone with very fine-grained quartzite lenses.

Empire Formation—dark gray to black, very fine-grained, clayey siltstone containing elongate pods of tan, silty limestone that is locally interlayered with bedded, purplish gray siltstone. Maximum thickness about 1,150 feet (350 meters).

Ys Spokane Formation (Middle Proterozoic)—

siltstone, argillite, subordinate quartzite. Grayish tan to tan, massive to laminated and commonly crossbedded clayey siltstone and minor dark grayish green silty argillite containing thin (less than 1 inch), discontinuous, very fine-grained sandy lenses. Conspicuous white to pinkish-white, fine- to coarse-grained quartzite beds 3-6 foot (1-2 meters) thick are common in the upper part of the formation and are thickest and most abundant in the central part of the Highland Mountains (O'Neill and others, 1996). Thickness 230 to 460 feet (70 to 140 meters).

Yg **Greyson Formation (Middle Proterozoic)**—argillite and silty argillite. The upper part consists of dark gray to black laminated and platy to massive, argillite and silty argillite. The lower part consists of light to dark gray, parallel laminated, silty argillite and clayey siltstone. Lower clayey and silty beds are locally interlayered with quartzite (Ygq). Interfingers with the underlying Newland Formation. Thickness ranges from about 650 feet (200 meters) in the west to more than 4,265 feet (1,300 meters) in the central part of the Highland Mountains (O'Neill and others, 1996).

Ygq **Quartzite of Greyson Formation (Middle Proterozoic)**—laterally discontinuous, 0.5-1.5 foot (0.2-0.5 meter) thick beds of matrix supported quartzite composed of well-rounded grains and locally dense, tan to white, crossbedded quartzite. Occurs in lower part of Greyson Formation.

Yn **Newland Formation (Middle Proterozoic)**—argillite, silty argillite, siltstone, and sandstone. Dark gray to pinkish gray, argillite and silty argillite with a distinctive blocky bedding character. Massive, thin beds of argillite are separated by ruler-straight, single to multiple laminations of tan siltstone and very fine-grained sandstone. The formation interfingers with the overlying Greyson Formation and the underlying Moose Formation in the eastern part of the county. Reaches a maximum thickness in the Soap Gulch area of 900 feet (275 meters) (O'Neill and others, 1996).

Ync **Calcareous rock of Newland Formation (Middle Proterozoic)**—calcareous, clayey zones commonly associated with thin, discontinuous lenses of fine-crystalline to medium-crystalline, medium gray limestone.

Ymo **Moose Formation (Middle Proterozoic)**—argillite, siltstone, and minor quartzite. Medium gray to tan argillite, siltstone, and minor quartzite. Absent in the southeastern part of the county where the Table Mountain Formation lies directly on the LaHood Formation. Interfingers with the overlying Newland Formation as well as with the underlying LaHood Formation. Thickness from 130 to 260 feet (40 to 80 meters) (O'Neill and others, 1996).

Table Mountain Formation (Middle Proterozoic)—quartzite, siltstone, and argillite. Divided into upper and lower part (O'Neill and others, 1996). Thins and pinches out to west and is locally interlayered with the Newland Formation to the east. Maximum thickness more than 1,650 feet (500 meters).

Ytu **Table Mountain Formation, upper (Middle Proterozoic)**—massive white quartzite beds separated by 3-15 foot (1-5 meter) thick, upward-fining sequences of intraformational conglomerate, quartzite, siltstone, and argillite.

Ytl **Table Mountain Formation, lower (Middle Proterozoic)**—quartzite, siltstone, and argillite approximately 820 feet (250 meters) thick. Basal contact is gradational with the LaHood Formation conglomerate and quartzite.

Ylh **LaHood Formation (Middle Proterozoic)**—argillite, siltstone, quartzite, and subordinate pebble conglomerate and argillaceous grit. Grades laterally into conglomerate unit (Ylhc) (O'Neill and others, 1996). Interfingers with the overlying Moose Creek Formation. In the west, is less than 2,300 feet (700 meters) thick but more than 4,900 (1,500) meters thick in the central Highland Mountains.

Ylhc **Conglomerate of LaHood Formation (Middle Proterozoic)**—cobble to boulder conglomerate that becomes finer grained laterally, grading first into quartz-pebble conglomerate, then into coarse, argillaceous, lithic grit and feldspathic sandstone (O'Neill and others, 1996).

Early Proterozoic and Archean Metamorphic Rocks

Xgn **Gneiss (Early Proterozoic)**—foliated (banded) gneiss present as a large sill-like body in southern Highland Mountains (O'Neill and others, 1996).

XAgb Garnet-biotite gneiss (Early Proterozoic and Archean)—garnet-biotite gneiss. Dark gray to black, medium-grained to very coarse-grained, strongly folded, garnet-rich biotite gneiss and minor biotite gneiss. Locally contains abundant thin, folded quartz-feldspar veins (O'Neill and others, 1996).

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APPENDIX 2

Geophysical Data Explanation

Ground Penetrating Radar (GPR) Profiles to Identify Faults in Silver Bow County, Montana

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Introduction

Since at least the mid-1980s, Ground Penetrating Radar (GPR) has been used to investigate fault zone related geologic hazards. Under ideal circumstances, GPR has been used to identify fault-related deformational features in the subsurface (Bilham and Seeber, 1985; Benson, 1995, Smith and Jol, 1995a; Smith and Jol, 1995b; Cai *et al.,* 1996; Liner and Liner, 1997, Overgaard and Jakobsen, 2001; Cow *et al.*, 2001; Rashed *et al*., 2003). During the May and August of 2008, three Ground Penetrating Radar (GPR) profiles were collected in Silver Bow County Montana to assess the feasibility of using GPR to identify shallow faults that could be associated with recent movement of the faults. Three profiles were collected across suspected fault locations (Figures 1-7). One profile was collected over the Rocker Fault in an area south of the Butte Gun Club in May as a student exercise during the Montana Tech Geology and Geophysics field course (Figures 1-3). In August, two profiles were collected by graduate student David Sunwall and me over suspected splays of the Continental Fault. The first Continental Fault profile was collected in a region south of the Continental Pit—an actively mined open copper/molybdenum mine (Figures 4 and 5). The second Continental Fault profile was collected in the upper drainage area of Blacktail Creek southeast of Butte, Montana (Figures 6 and 7).

GPR Data Collection and Processing

Table 1 shows the field recording parameters for these surveys. 100 MHz transmitting and receiving antennas were used for all three profiles. The profile direction was perpendicular to the suspected fault strike in all cases. Table 2 shows the processing sequence for these data. A depth axis is attached to the right-hand-side of these profiles (Figures 2, 3, 5 and 7). All depth axes were estimated using a velocity of 100 m/μs. Underground radar wave velocity was obtained by fitting subsurface velocity dependent hyperbolic trajectories to point-diffractors that were observed in these data. Only several point diffractors could be observed definitively in these data and these diffractors showed velocities between 90 and 100 m/μs. The Rocker Fault profile was collect across a stream valley and up a steep hill. For this reason, a smoothed topography profile has been added to the GPR profile in Figures 2 and 3 to obtain perspective for interpretation. The two Continental Fault profiles do not have topography added because these profiles cover terrain that is smooth to gently dipping.

GPR Interpretation

The Rocker Fault GPR profile (Figure 2) shows numerous events that are likely caused by reflections from geologic features in the subsurface such as soil layers of contrasting electrical properties. However, the two most likely fault-related radar features are located at the creek

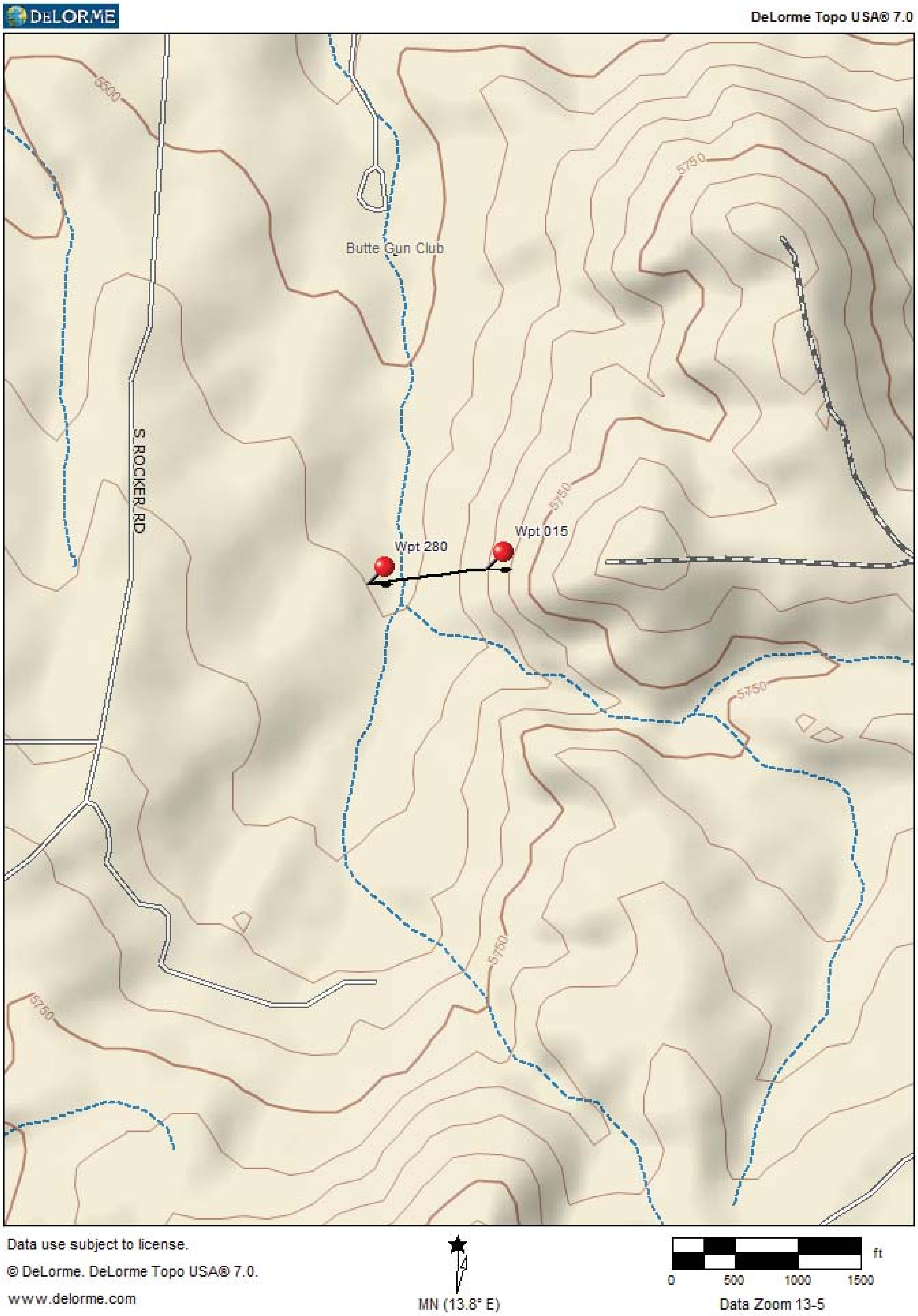

Figure 1. Location map for Rocker Fault GPR profile. Ends of the profile are marked by red waypoint markers.

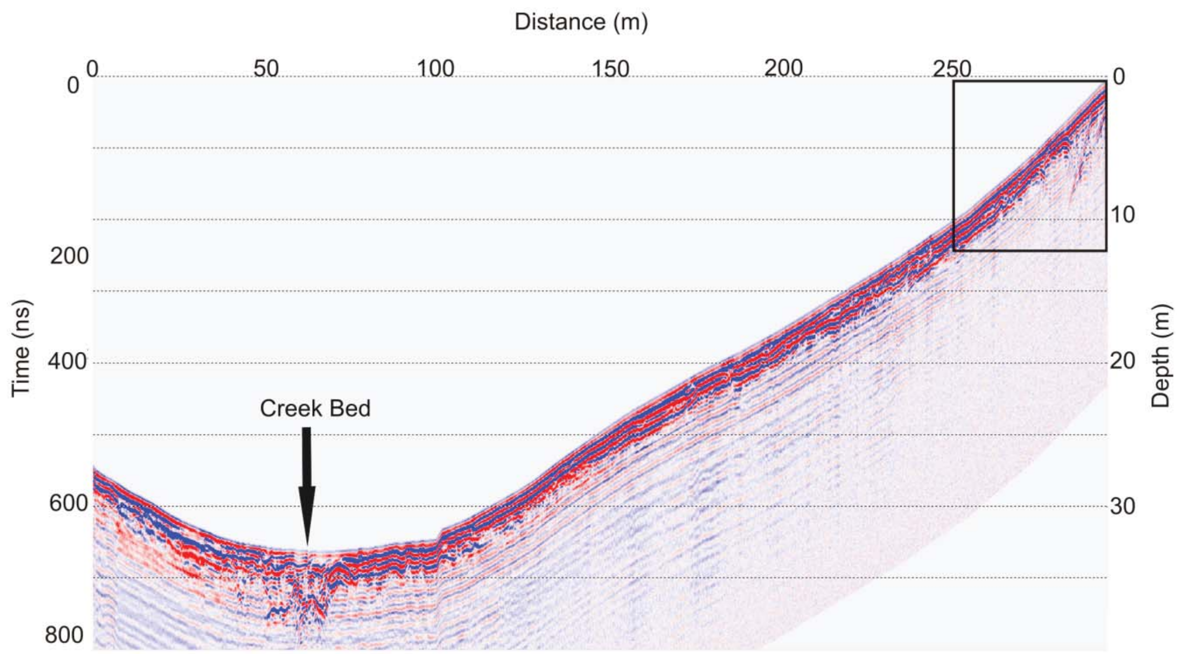

Figure 2. West-east Rocker Fault GPR profile. Smoothed surface topography has been added to the profile. Inset square is the portion of this profile shown in Figure 3.

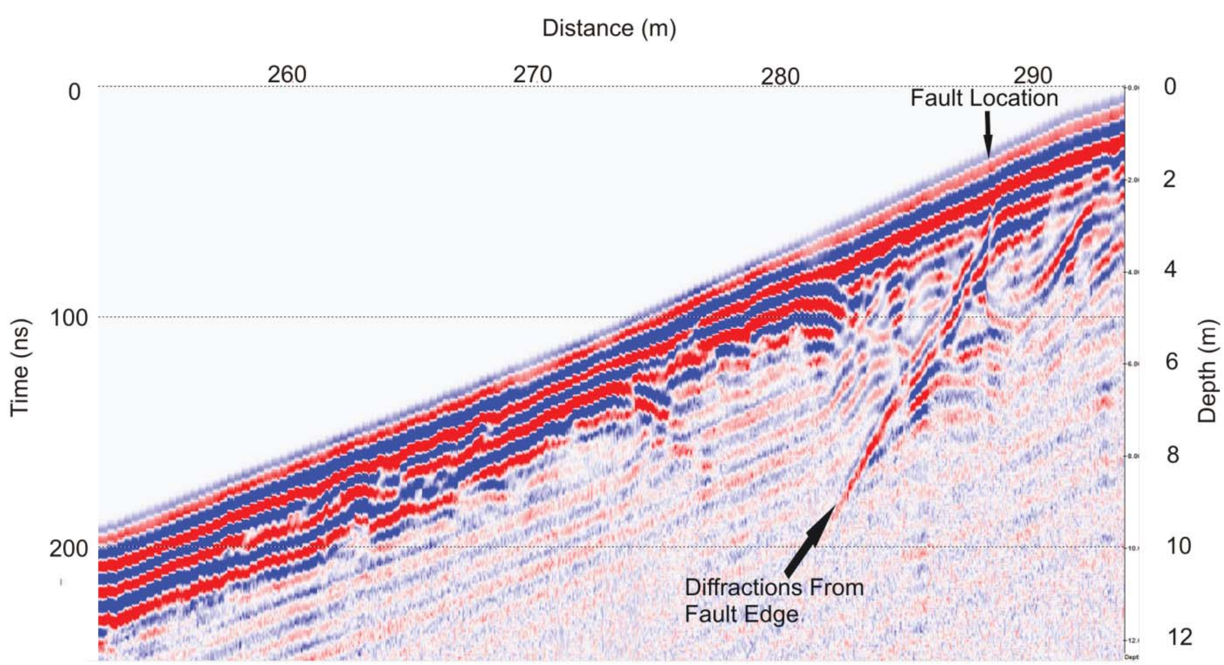

Figure 3. Portion of Rocker Fault profile showing location of suspected fault. Diffractions often associated with discontinuities along the fault are identified. Profile is shown west to east.

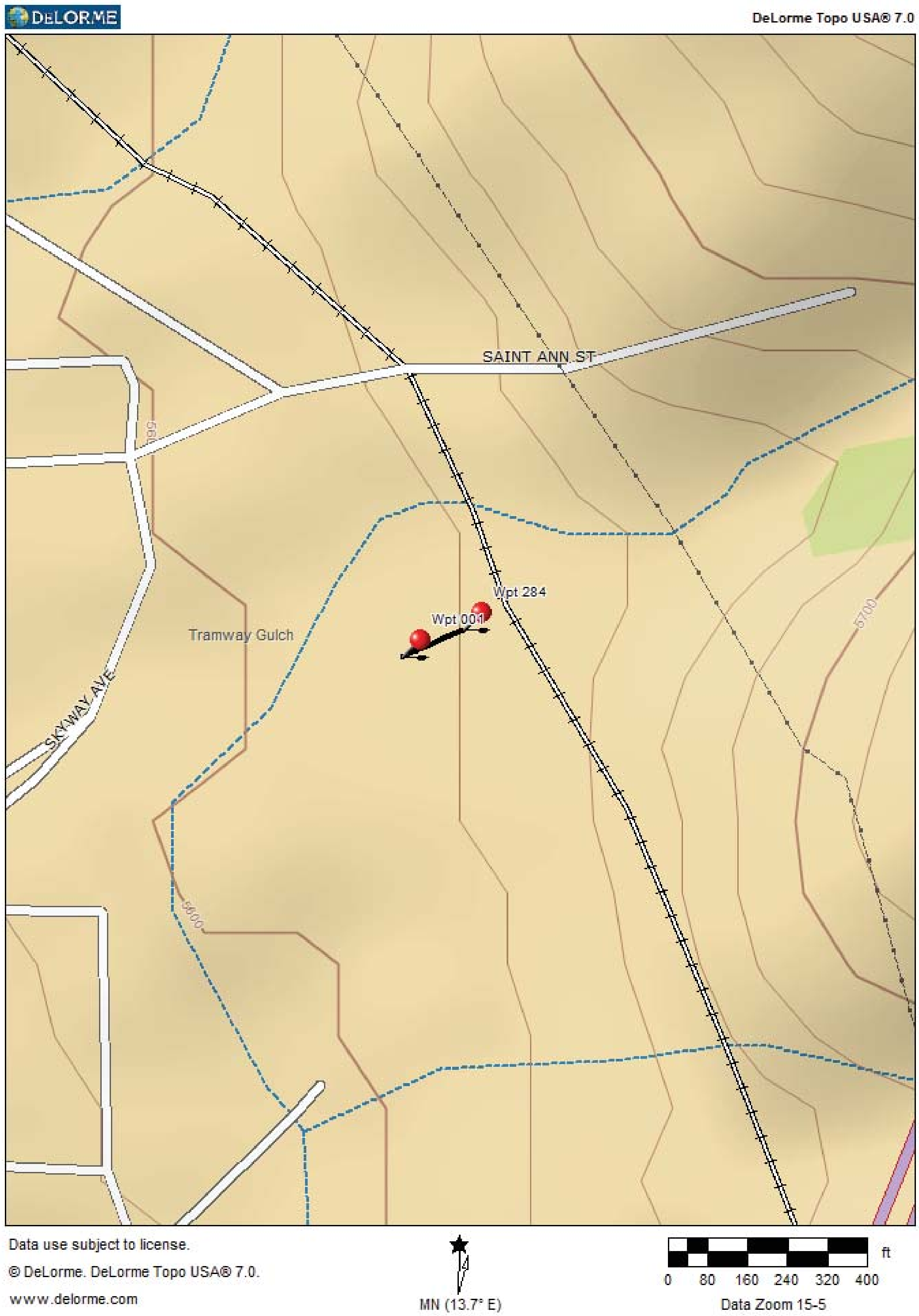

Figure 4. Location map for first Continental Fault GPR profile that was collected south of the Continental Pit. Ends of the profile are marked by red waypoint markers.

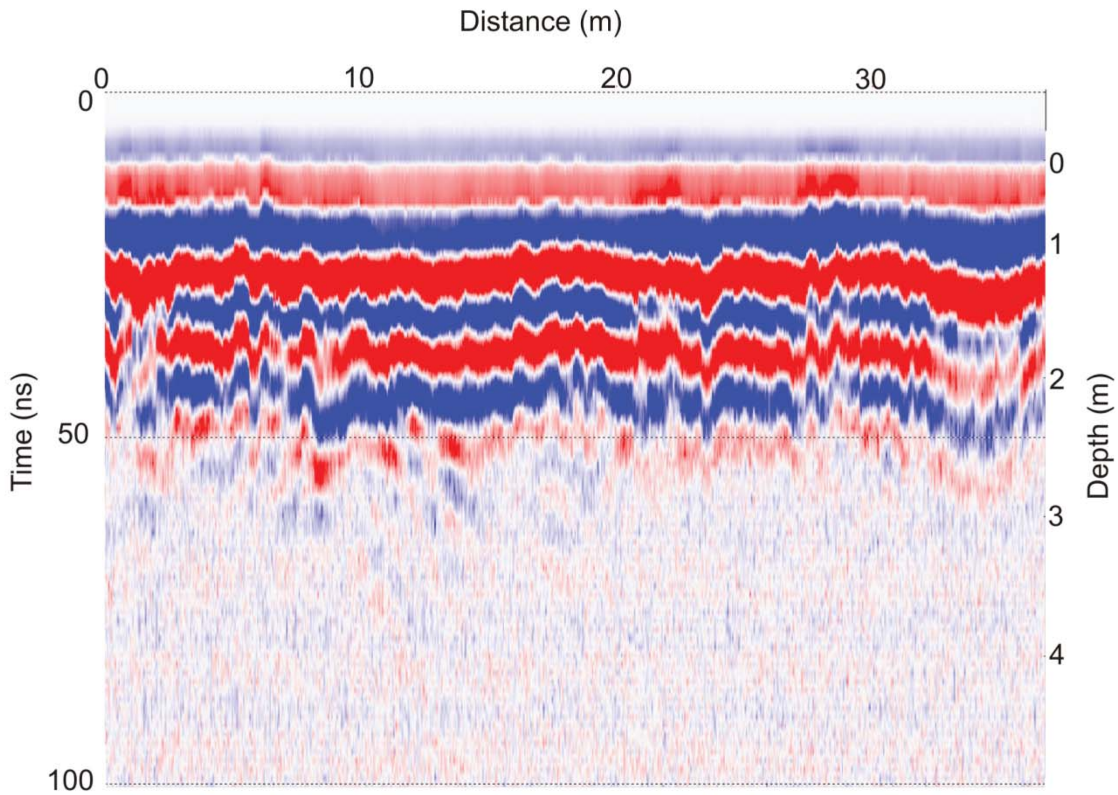

Figure 5. West –east first Continental Fault GPR profile. Profile is shown west to east.

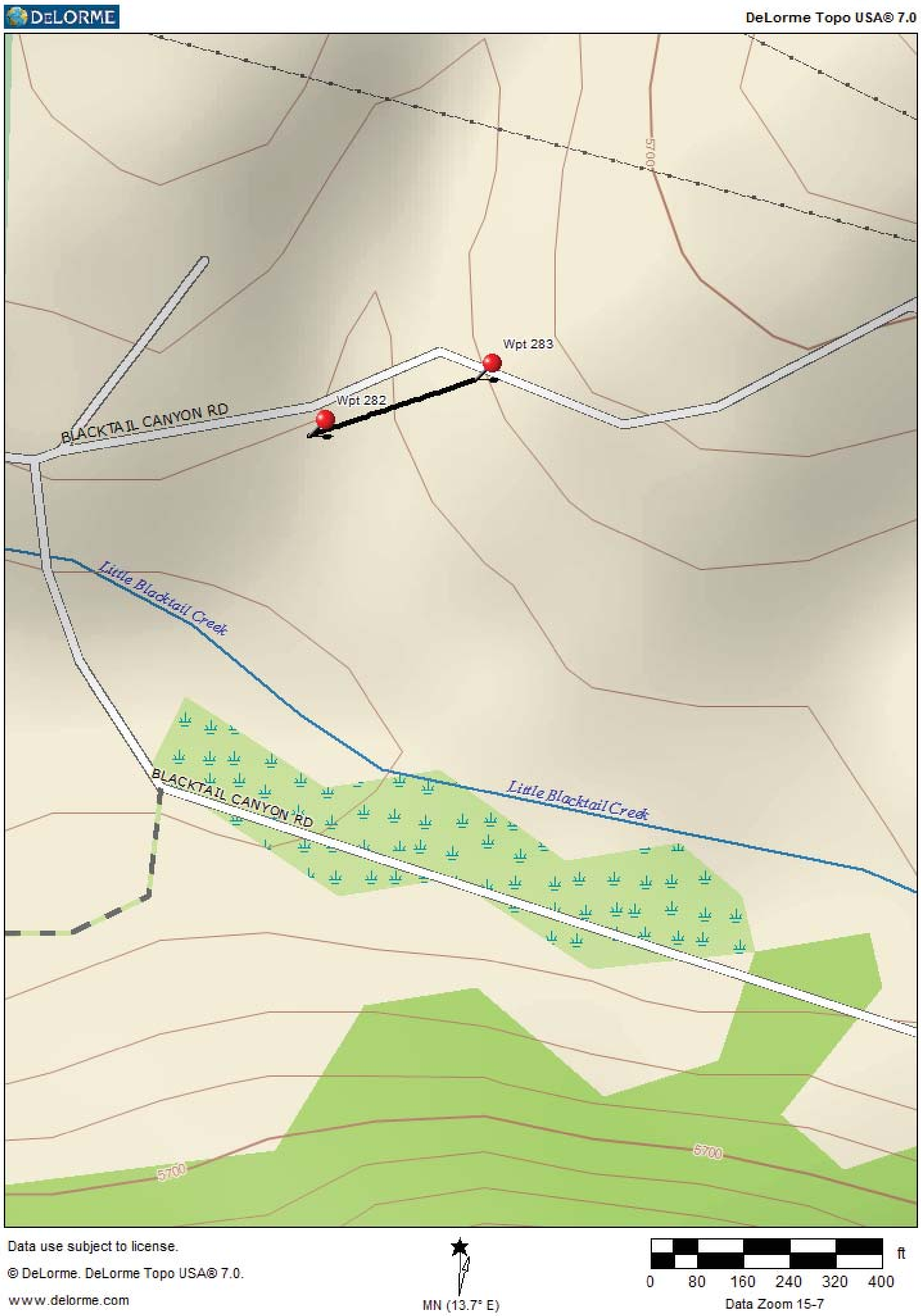

Figure 6. Location map for the second Continental Fault GPR profile that was collected in the Blacktail Creek drainage. Ends of the profile are marked by red waypoint markers.

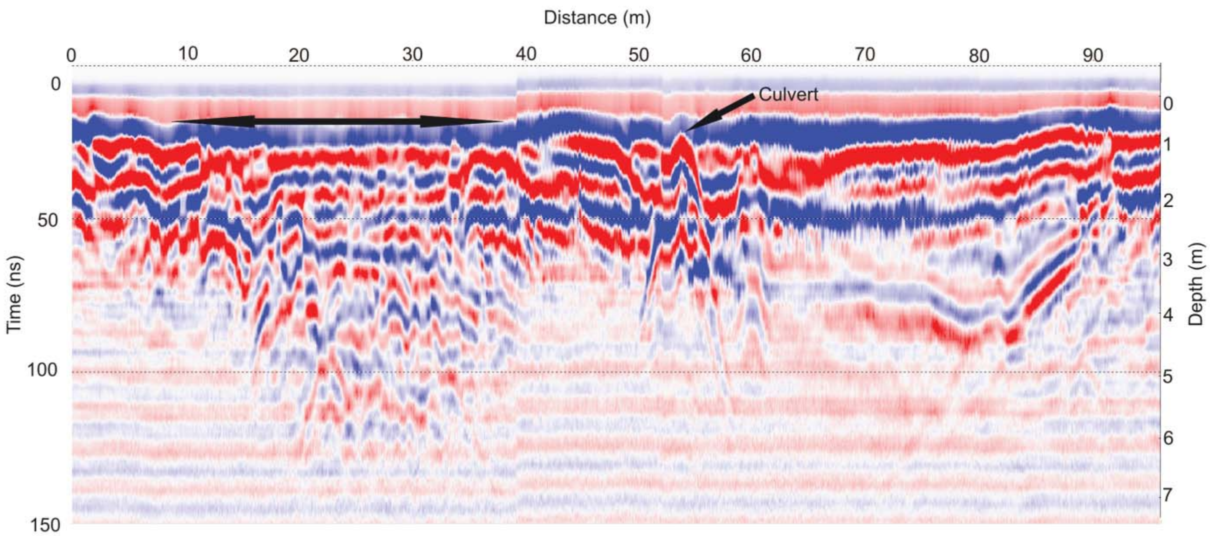

Figure 7. West-east second Continental Fault GPR profile. The image of the culvert that passes under the road is shown. The horizontal arrows show a region of deep radar penetration with significant disruption in reflection continuity below 3 m depth.

Table 1. GPR Survey Field Recording Parameters.

Sampling Frequency	803.57 MHz(Rocker and First Continental); 937.50 MHz (Second Continental)
(Field Summing (Stacks)	4
Distance between Traces	0.05 m
Antenna Separation	1 m
Antenna Orientation	Perpendicular to Profile Direction
Antenna Frequency	100 MHz

Table 2. GPR Data Processing Sequence.

1. DC Removal
2. Set Time Zero
3. Gain: Spherical Divergence and Automatic Gain Control (AGC) with 60 ns window.

and at the east end of the profile that is outlined with a square in Figure 2. At the creek crossing penetration depths of over 10 m are observed in the profiles. This is 7 m more GPR penetration than is observed along much of the rest of the profile. The greater penetration depths are likely result of the removal by water of fine sediments (clays) downstream. Clays increase the conductivity of the soils and this reduces radar wave penetration. Streams often follow faults because faults are typical weak and are easily eroded to become topographic lows that streams can follow. However, trenching would be needed to see if this stream is indeed a fault. At the east end of this profile, a possible fault location has been identified based on the GPR profile (Figure 3). Here diffraction curves are observed that could be cause by discontinuities along a fault boundary. While other explanations could exist for what is observed in Figure3, this represents the most promising evidence for a fault that is seen in any of these profiles.

The first Continental Fault profile (Figure 5) shows relatively horizontal events that are likely caused flat-lying reflectors in the soils/rock layers. The location of this profile was chosen because mapped splays of the Continental Fault are observed in the Continental Pit and project southwards through this location. Moreover a surface rock outcrop that might trace the fault is present at the east end of the profile. A fault with recent movement would likely show offsetting horizons and diffraction curves. Either we did not cross the fault with this profile or the fault has not experienced recent movement that would offset shallow reflectors and deeper GPR penetration would be needed to see the fault.

The second Continental Fault profile crosses a stream drainage that is a suspected location of the main Continental Fault. This profile clearly shows the stream culvert under the road. A zone of relatively deep penetration of 6 m is shown along the western half of the profile. Here, below 3 m depth a disruption in reflection event discontinuity is observed. A zone of deep penetration might be expected along the region of topographic low where the stream is; but, the stream is located just east of the culvert. The zone of deep GPR penetration might identify recent fault movement shown by the zone of disturbance below 3 m; however, trenching would be needed to identify faulting. Complicating this interpretation, we collected this profile alongside a road, and, as a consequence, manmade disturbance along the road bed could be responsible for much of the reflection character that is shown.

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Gravity Surveys of the Butte and Rocker Areas, Silver Bow County, Montana

A Report to the Montana Bureau of Mines and Geology

By

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January 28, 2009

Introduction

During the years from 1987 to 1993, Montana Tech students in the field camp courses, Geophysics 421 and Geology 421, and the gravity and magnetics course, Geophysics 412, collected and reduced gravity data from the Butte and Rocker areas in southwest Montana.

Gravity measurements were made with LaCoste and Romberg D and G gravity meters and elevation control was provided by mapped bench marks, leveling, Electronic Distance Measurement (EDM), and Global Positioning System (GPS) surveys. Gravity values are reported in milliGal (1.0 mGal=10.0^-3 cm/sec^2). The Earth's average gravity value is about a million times larger than this value.

Raw gravity data was corrected for time drift, elevation (free air and Bouguer correction), and topography. The datum for elevation (5423 ft) and gravity (zero relative value) was taken from the base station at bench mark BM 5423 at the intersection of the frontage road and Brown's Gulch road. This bench mark is located north of interstate 15 and east of the Rocker truck stop on the USGS Butte South topographic map.

The purpose of this report is to reexamine this data with an emphasis on the contacts between bedrock and valley fill. Bedrock in this region is mostly Butte Quartz Monzonite (BQM) and associated aplite bodies of Cretaceous age, and valley fill is Tertiary sediments and volcanics. Gravity measurements are useful in this case as there is a density contrast between the bedrock (average density from lab measurements 2.65 g/cm^3) and valley fill sediments (average density around 2.0 to 2.2 g/cm^3). A few measurements on volcanics give values around 2.4 g/cm^3. Gravity values are then expected to be higher over bedrock areas of BQM and lower over the valley fill sediments and volcanics.

Gravity Maps

Figure 1 is the location map for the two gravity study areas in the Summit Valley and the Rocker region. Figure 2 shows the contoured gravity map for the Summit Valley which is the region south of the city of Butte. Gravity values are larger on the left side (west), the right side (east) and the bottom (south). These areas contain bedrock or near surface bedrock. The area near A is Timber Butte which has outcrops of BQM and aplite. To the east near A' is the East Ridge, which is a extensive outcrop of BQM. The south end of the map also contains numerous exposures of BQM. The low area in the center is over the thickest section of the valley fill and has relative anomaly magnitude of more than 5 mGal. The working hypothesis for the valley fill is that it is contained in a graben since this region was under extension during the Tertiary. Large gradients in the gravity values should be located near the steepest contacts between the bedrock and the Tertiary fill. In the simplest case, normal faults, with high dip angles (> 45 degrees) might be expected, but several step faults in the contact zone or reactivation of old low dip angle faults would give lower gradients in the gravity values.

The steepest gradients are on the east side in the central zone, close to the base of the East Ridge where the Continental Fault (Weed, 1912) has been mapped. The other steep gradients are in the southeast portion of the map and the contours might suggest a fault zone with a southwest–northeast trend.

Contours on the west side of the valley are less steep, indicating a gentler slope on the bedrock contact. Overall there is a small decrease in gravity values from east to west which could be caused by an increase in Tertiary volcanics as the bedrock in the region to the west of the map.

The magnitude of the gravity anomaly between the middle of the valley and the base of the East Ridge is around 5 mGal and with a rule-of thumb value of about 200 ft/ mGal the valley fill is at least one thousand feet deep. This assumes a density contrast of 0.5 g/cm^3.

Figure 3 shows the gravity contour map for the Rocker area which is west of Butte and northwest of the map in Figure 2.The top of the map in Figure 2 is at 46 degree north latitude. The station locations are not shown in Figure 3 but they are most dense in the north central part of the map. The approximate locations of profiles D-D' and E-E are labeled. The high gravity values in the eastern third of the map are over exposures of BQM , aplite and in a few places Tertiary volcanics. To the west of this region are some steep gradients and gravity lows over Tertiary sediments. The steep gradients and north-south contours are near the Rocker fault (Pardee, 1950). The gravity low outlines a probable graben between the BQM on the east and the BQM and Tertiary volcanics to the west.

The magnitude of the gravity anomaly varies from 11 mGal, in the south, to 15 mGal, in the north. With the rule-of-thumb used above the depth of fill varies from 2000 ft in the south to 3000 ft in the north. These anomalies and estimated depths are larger than that for the Summit Valley. There could be other explanations for the differences in the anomalies and estimated depths, such as differences in the density of the valley fill material.

Gravity Profiles and Models

The purpose of this gravity modeling is to develop an image of the subsurface interfaces that separate regions of differing density. The modeling program can calculate the gravity effect of any geometrical shape of a given density contrast. The geometry and density can then provide information on the geology. The modeling is not unique and assumptions and geologic constraints are utilized in the modeling process.

Figure 2 shows the location of the Fourmile Road gravity profile from A (west) to A' (east). Figure 4 shows the observed data and modeled data in the top part and the polygonal cross-section of the model in the lower part. The assumption for the calculations is that the profile is perpendicular to the model. In this case the contours should be perpendicular to the profile line and this is approximately true as seen in Figure 2.

The observed data in the figure has had a linear trend removed to account for a regional gravity decrease to the west, due to the presence of lower density volcanics in the west.

The data has also had a level shift of -12.0 mGal so that the relative value is near zero at the ends of the profile where the bedrock outcrops. In this modeling the bedrock (assumed homogeneous) has a density contrast of zero and the Tertiary fill has a negative contrast to account for the negative relative gravity values. The quality of the fit between the observed data and the calculated results from the model is given as the root-mean-square error (RMS). Probable errors in the reduced gravity data are around a few tenths of a milliGal and increase in areas of rough terrain.

The fit of the model to the observed data is obtained by an iterative process of moving the vertices of the polygon along with a least squares fit for the density contrast (Del Rho), between the bedrock and the polygon fill. With a density of 2.65 g/cm^3 for the bedrock and a density contrast of -0.48 g/cm^3, the fill has density of 2.17 g/cm^3.

On the east side, near the Continental Fault, the contact surface (polygon slope) near the surface is about 14 degrees and the deeper slope is 22 degrees. The gravity data in this survey does not have the resolution to determine fine structure in the contact surface and these angles are mostly minimum averages. A similar fit to the observed could be made with steeper slopes in the deeper part of the model. However differences between the average slopes on the east (steeper) and the west (less steep) are evident. There are also some evident mismatches between the observed and the calculated profiles from 8000 feet to 13000 feet. These small scale features cannot be attributed to small scale features on the bedrock topography as short scale bumps at depth give long scale, low amplitude features at the surface. These features must be modeled with density contrasts nearer the surface.

The location of the Sixmile Road gravity transect is shown in Figure 2 (B to B’) and the gravity profile and model are in Figure 5. This data has had a regional removed and a level shift of -12.0 mGal applied. The dip on the right (east) bedrock interface is 22 degrees, similar to that on the Fourmile model. The dip on the west side is 14 degrees. Density contrast and depth of fill is similar to the Fourmile line although the deepest part has shifted to the west.

The profile along state highway 2 or 10 is shown in Figure 2 as the line from C (northwest) to C’ (southeast). The gravity profile and model for this line labeled as HW10 is in Figure 6. This line is perpendicular to most of the contours in the southeast part of Figure 1, and so the modeling assumptions are better. The ends of this line are close to outcrops of bedrock and a regional gravity effect and level shift similar to those used on the previous profiles was applied to this data. In the southeast there is a break in the slope of the bedrock at 15000 feet between a dip of 13 degrees and 6 degrees. In the northwest there is an average slope of about 8 degrees. The deepest fill is 1200 feet, which is similar to the depth in Figure 5 and in fact these lines (Sixmile and HW10) cross in this area.

Moving to the area west of Butte, Figure 3 contains the locations of two modeled profiles. The line from D to D’ is north of Rocker in an area with a grid of fairly closely spaced stations and is labeled as Rocker North in Figure 7. The west end up to 6000 feet is over valley fill. From 5000 to 9000 feet is a region with numerous outcrops of BQM. To the east, beyond 19000 feet, is an area of outcrops of BQM with some Tertiary volcanics to the north. The profile in this figure has been level shifted so the relative value is near zero over the outcrop area in the east. The central region is dominated by a horst-graben structure with a depth of fill of 3000feet. The density contrast in this model is slightly larger than the previous models in the Summit Valley. If a contrast of 0.47 g/cm^3 is used here, the depth could be a few hundred feet deeper. The modeled slopes on the central graben are greater than 70 degrees, indicating larger average dip on the bedrock here (Rocker fault) compared to further east (Continental fault).

The data for the line E to E’ (Figure 3) is shown in Figure 8. The west end of the profile is over valley fill and the east end is over outcrops of BQM. A level shift of 9.0 mGal has been applied to set the relative value to zero over the outcrop area. The dip of the bedrock contact on the east side (13000 to 16000 feet) is 34 degrees and the dip on the west is 15 degrees. The depth of the fill is 2500 feet, which is less than that on the profile to the north. Using a density contrast the same as was used to the north would result in a lesser depth.

Summary

Gravity modeling of the Summit Valley produces subsurface models with a maximum depth of fill of 1200 to1500 feet. In general, the slopes on the bedrock-fill interface are modest (20 to 40 degrees).The deeper and steeper slopes on the east side of the valley are mostly west of the mapped location of the Continental Fault. The contour map and modeling of the south end of the valley suggest a southwest to northeast contact or fault surface.

In the Rocker area the depth of fill ranges from 2500 to 3000 feet and the slopes on the deeper contacts range from 35 to 70 degrees. Here also the deeper and steeper contact slopes are west of the surface expression of the Rocker Fault.

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Report Figures

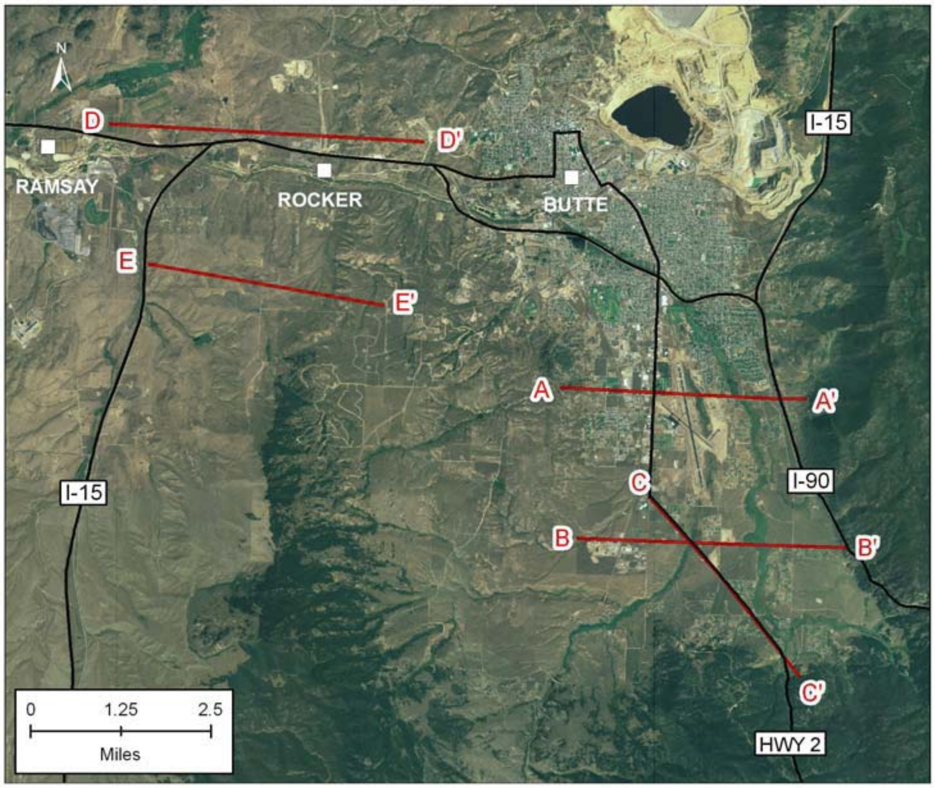

Figure 1. Location map and profiles for the two gravity study areas in the Summit Valley and the Rocker region.

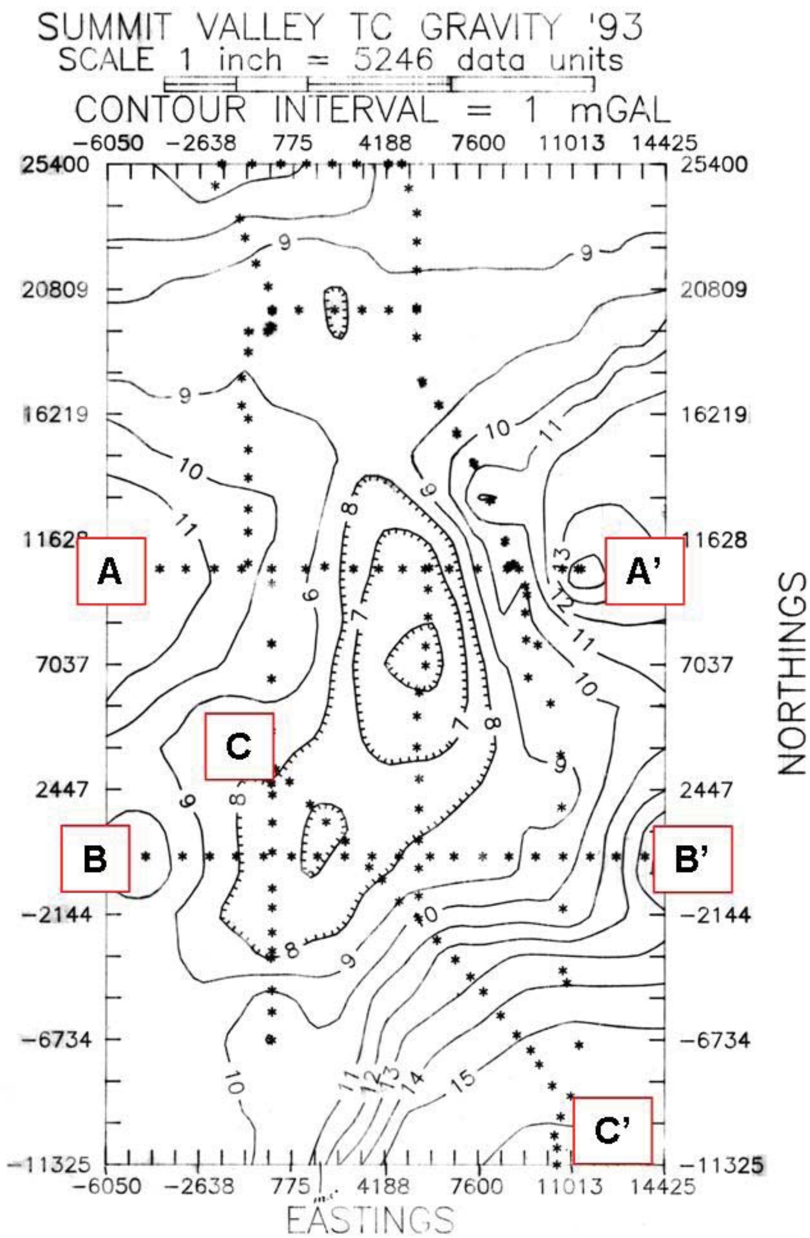

Figure 2. Summit Valley gravity contour map. Distance in feet from BM5592 in the intersection of Harrison Ave and Sixmile Rd on the USGS Butte South topographic map. Stars show location of stations. Profile A-A' is Fourmile Road, B-B' is Sixmile Road, C-C' is Highway 2 (10) profile.

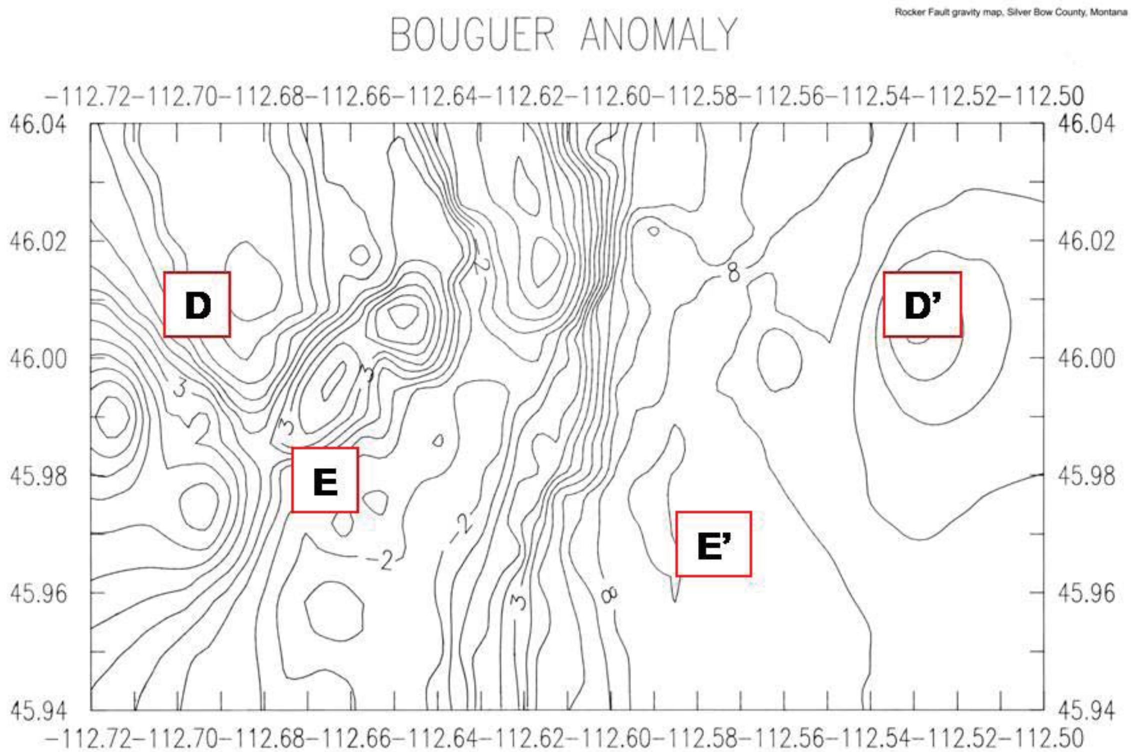

Figure 3. Rocker area gravity contour map. Corresponding USGS topographic maps are Ramsay, Butte North, Butte South, and Buxton.

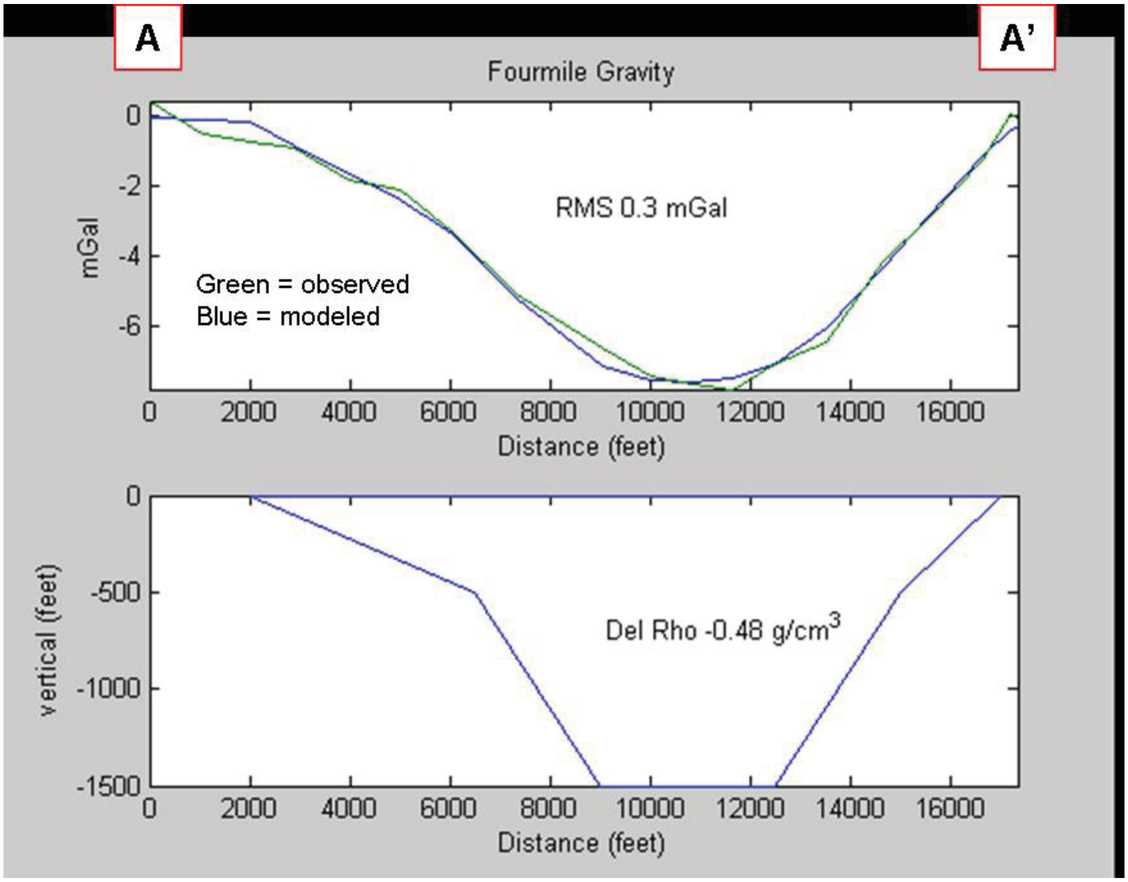

Figure 4. Fourmile gravity profile (A-A'). Top figure is data and model fit, bottom is polygon model.

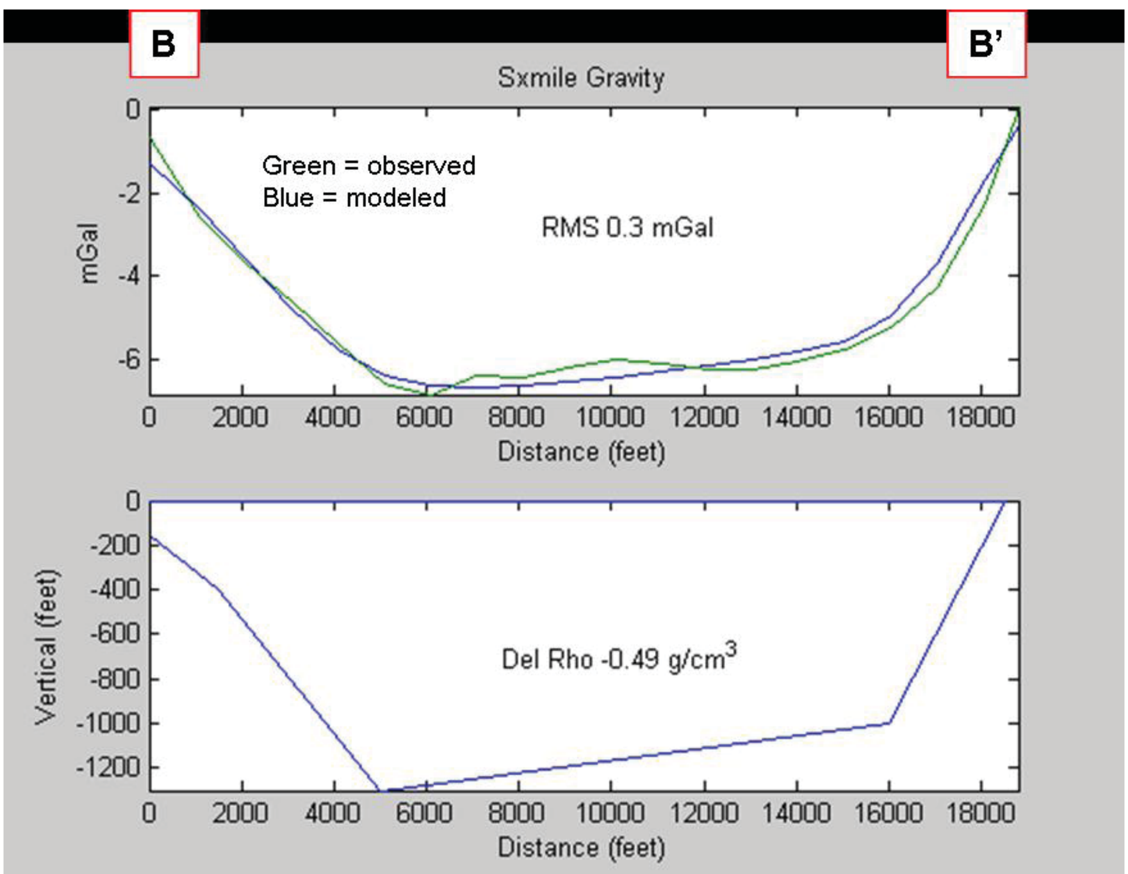

Figure 5. Sixmile observed and modeled gravity profile (B-B') with model cross section.

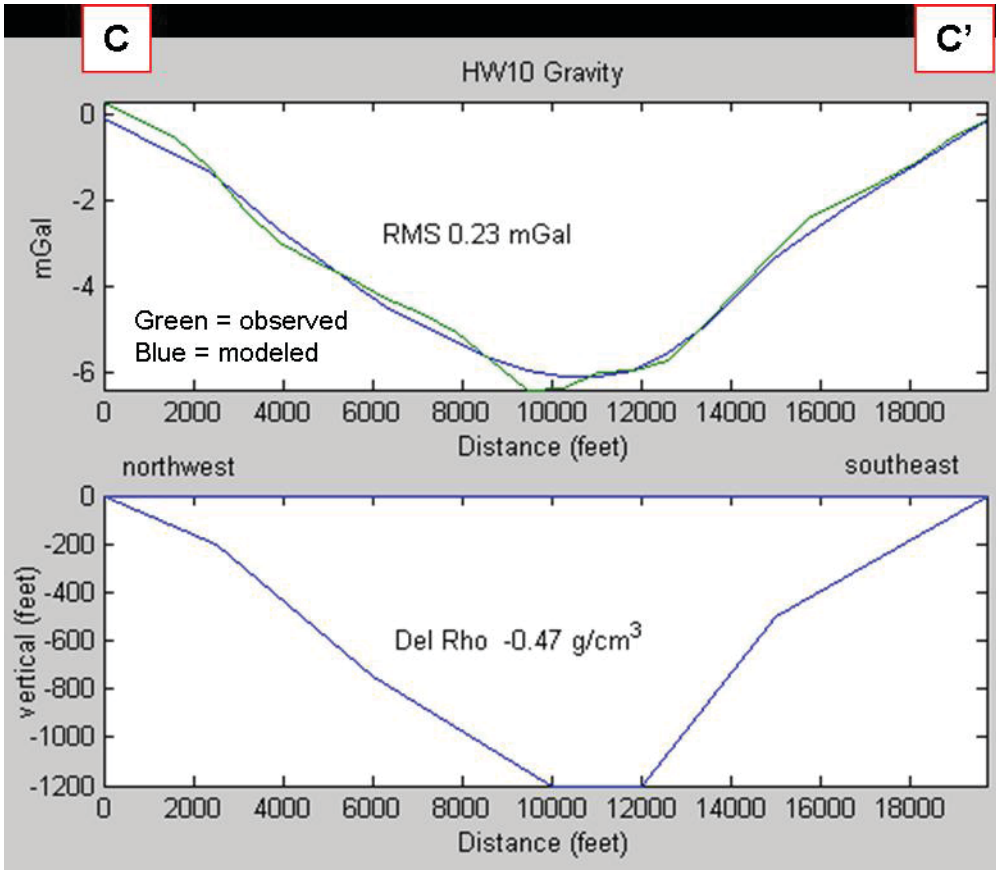

Figure 6. HW10 observed and modeled gravity profile (C-C') with model cross section.

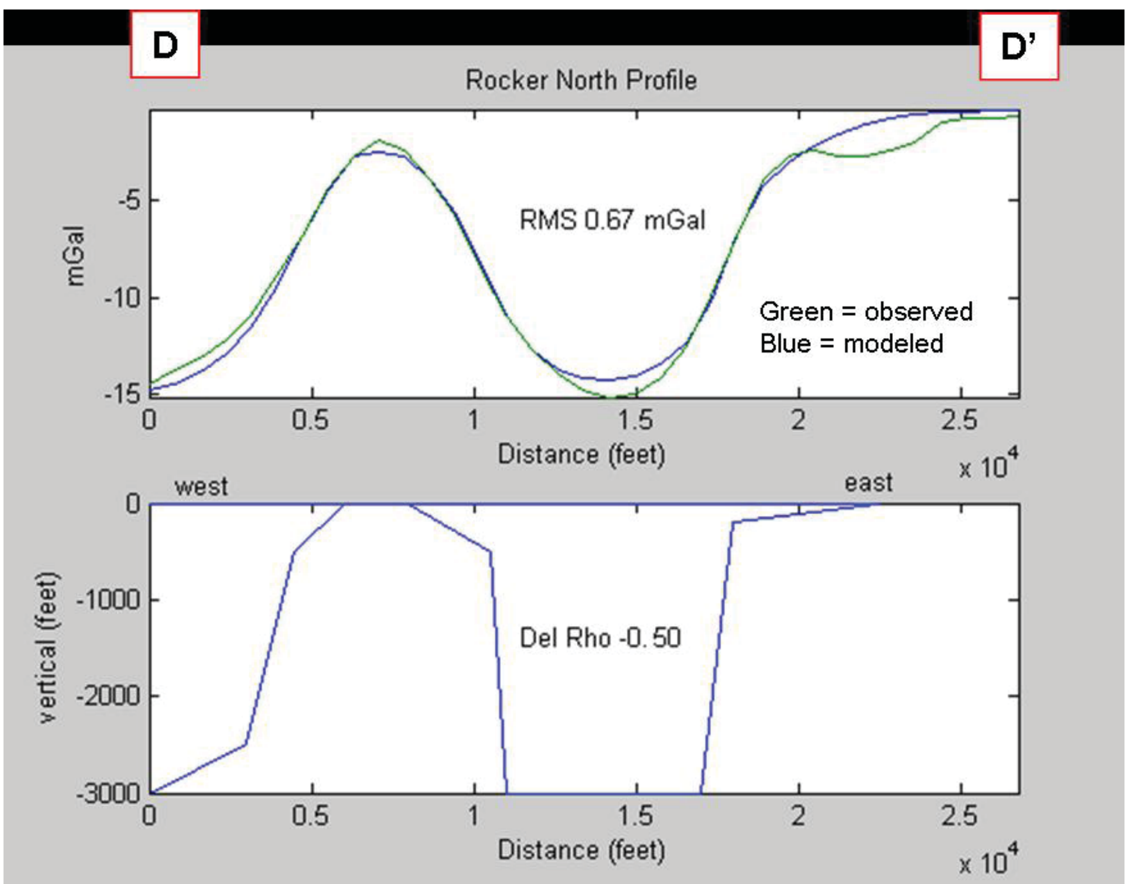

Figure 7. Rocker North profile (D-D') observed and modeled gravity with model cross section.

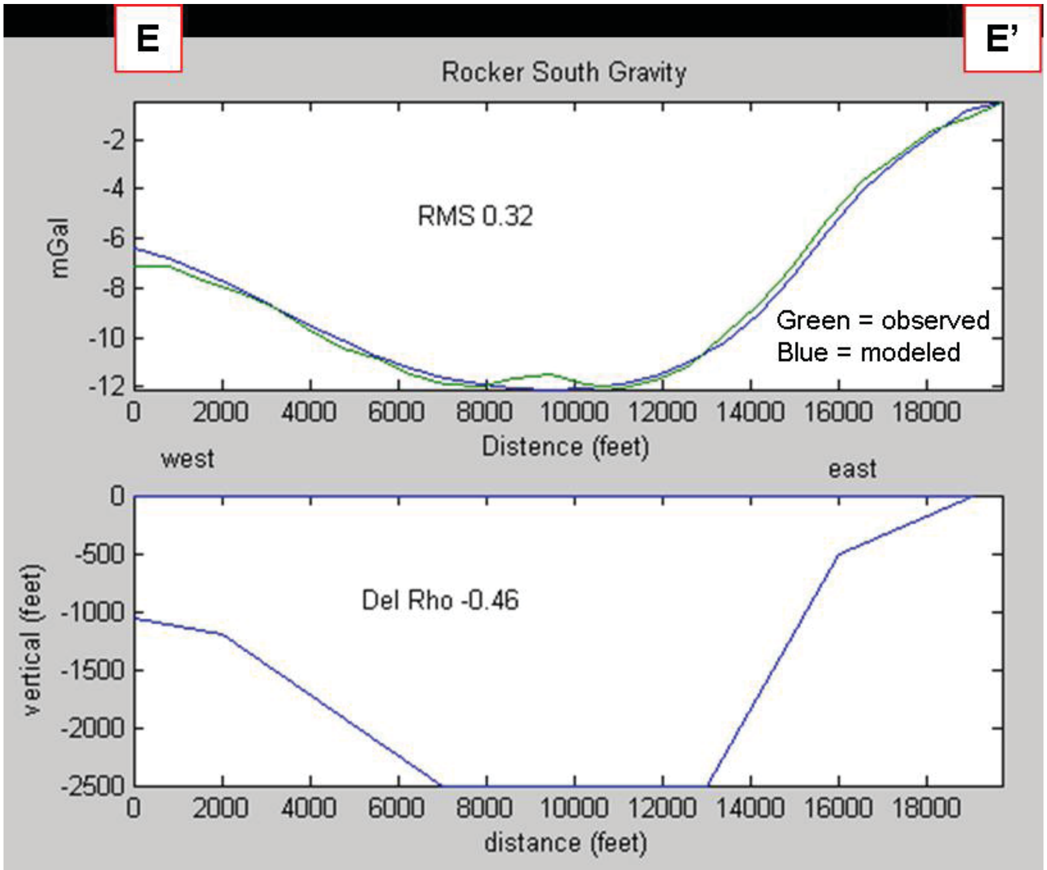

Figure 8. Rocker South) observed and modeled gravity profile (E-E') with model cross section.

APPENDIX 3

Definitions of Fault Activity for the Basin and Range Province

WESTERN STATES SEISMIC POLICY COUNCIL
POLICY RECOMMENDATION 08-2

Definitions of Fault Activity for the Basin and Range Province

Policy Recommendation 08-2

WSSPC recommends that the following definitions of fault activity be used to categorize potentially hazardous faults in the Basin and Range physiographic province:

Holocene fault – a fault whose movement in the past 10,000 years (11,500 cal yr B.P.) has been large enough to break the ground surface.

Late Quaternary fault – a fault whose movement in the past 130,000 years has been large enough to break the ground surface.

Quaternary fault – a fault whose movement in the past 1,800,000 years has been large enough to break the ground surface.

It should be emphasized that some historical magnitude 6.5 or greater earthquakes that produced surface faulting in the Basin and Range Province occurred on faults that have not been active in the Holocene; furthermore, earthquakes in the Province may occur on faults in all three categories. It is the responsibility of the user to decide what level of earthquake hazard (surface fault rupture and ground shaking) is acceptable for a specific structure or application.

Background

Future large, surface-rupturing earthquakes in the Basin and Range Province most likely will occur on faults that display evidence of prior large surface displacements during Quaternary time. The time when the last major earthquake occurred on a fault and the time interval between the most recent earthquake and earlier earthquakes are factors that influence the probability of when a similar-size earthquake might occur within a given time period. For example, a fault that has a major earthquake on average every 1000 years is more hazardous than one that has a major earthquake on average every 100,000 years. It is up to the user to decide what degree of fault activity is considered "hazardous" and what level of hazard is acceptable. Depending on the intended use of the land (critical facilities, fire stations, hospitals, schools, residences, picnic grounds, etc.), different levels of seismic hazard and risk may be acceptable. In addition, understanding the frequency and size of earthquakes on a fault is critical when deciding whether to build across the fault, and when estimating the probabilities of ground shaking at varying distances from the fault. It should be noted, that historical, damaging, moderate to large (< M 6.5) earthquakes have occurred on faults in the Basin and Range Province which do not have any obvious expression at the ground surface.

A **Holocene** criterion (10,000 years {11,500 cal yr B.P.}) to characterize potential fault activity has significant precedence, principally from its past usage and application in California. For purposes of implementing the Alquist-Priolo Earthquake Fault Zoning Act, the California Code of Regulations defines an active fault as *Holocene Active*, that is, there is evidence of surface rupture within approximately the past 11,000 years, although local governments may use a broader definition. The *Holocene Active* definition also has a practical applicability because climate change following the most recent major glaciation has resulted in many recognizable soil horizons and geomorphic surfaces that are used to help date fault activity. Because major historical earthquakes have occurred in the Basin and Range Province on faults that do not show surficial evidence of previous Holocene activity, the Holocene Epoch is too short to span the range of average earthquake recurrence intervals (average earthquake repeat times) on faults in the Province.

A **late Quaternary** criterion (130,000 years) uses the onset of the Sangamon interglacial period as a datum and spans many of the average fault recurrence intervals in the Basin and Range Province. All but one of the major historical earthquakes in the Province occurred on faults that show evidence of late Quaternary activity.

The **Quaternary** Period (1,800,000 years) represents the onset of a major climatic change to the current cycle of glacial/interglacial intervals, during which most of the surficial alluvial deposits and much of the present landscape in the Basin and Range Province formed. All the major historical earthquakes in the Province have occurred on faults that show evidence of Quaternary-age movement at the surface. A Quaternary criterion encompasses an average recurrence interval for essentially all the faults that might produce future earthquakes.

The Basin and Range Province is a large extensional tectonic domain that contains thousands of normal-slip and strike-slip Quaternary faults involved in contemporary deformation. Large earthquakes in the Province, especially those that are associated with surface rupture, commonly involve multiple, distributed faults, and have occurred on faults that have a wide range in the time since their most recent surface-faulting earthquakes. This tectonic behavior in the Province differs from the more focused, higher slip-rate tectonics of the plate boundary system in western California. These different characteristics may warrant different considerations, such as the activity criterion used when establishing fault setbacks and identifying potential earthquake sources.

The identification of faults that pose an earthquake hazard requires application of a fault-activity criterion to exclude ancient faults that are unlikely to rupture during future earthquakes. This criterion allows society to develop guidelines for identifying potential surface-rupture and ground-motion sources. Two fundamental parameters are needed to characterize fault activity for the purposes of hazard assessments: the amount of displacement that occurred during large, surface-faulting earthquakes and the time interval over which the earthquakes occurred, which in some cases can be expressed as an average recurrence interval between earthquakes. These data are used to calculate the fault's geologic slip rate, which is net displacement divided by the time interval over which the strain accumulated that resulted in displacement. Fault slip rates, typically expressed in mm/yr or m/kyr, provide a quantifiable measure of fault activity; the higher the slip rate, the more active the fault.

There are several examples of Basin and Range Province faults that have had major historic movement, but lacked evidence of Holocene or late Quaternary activity. The most dramatic example of the latter is the 1887 Sonoran earthquake in northern Mexico. Different lines of reasoning suggest that prehistoric surface rupture occurred at least 100,000 to 200,000 years ago (Bull and Pearthree, 1988). The 1954 Fairview Peak, Nevada, earthquake (Bell and others, 2004) is another example of a major historic earthquake on a fault that lacked evidence of Holocene displacement (Pearthree, 1990; Caskey and others, 2004). The 1954 Dixie Valley, Nevada, earthquake occurred on a fault zone that has evidence of Holocene activity, but also ruptured major portions of fault traces that lacked Holocene displacement (Bell and Katzer, 1990). Major earthquakes have occurred on faults that had Holocene displacement as well, such as the 1983 Borah Peak, Idaho, earthquake (Hanks and Schwartz, 1987). More than one-half of the major historical earthquakes in the Province produced surface faulting on faults that appear to lack Holocene activity. Thus, the Holocene criterion is a useful but not an complete indicator of where future large earthquakes may occur in the Basin and Range Province.

Prehistoric earthquakes that produced surface ruptures on faults within the Basin and Range Province have a range of recurrence intervals that span from hundreds of years to hundreds of thousands of years. Recurrence intervals of a few thousand to tens of thousands of years are typical. One of the most comprehensive and detailed paleoseismic studies in the Province was undertaken as part of the site characterization of the proposed high-level nuclear waste repository at Yucca Mountain, Nevada. That study revealed that average recurrence intervals for many of the faults at and near Yucca Mountain are between 20,000 and 100,000 years (e.g., Wong and others, 1995). A range of earthquake recurrence intervals can be estimated by considering the typical range of vertical slip rates for faults in the Basin and Range Province (0.01 to 1.0 mm/yr) and typical surface displacements during major earthquakes (1 to 3 m). This yields a range of potential recurrence intervals of 1,000 to 300,000 years.

Elapsed time since the most recent large earthquake and average earthquake recurrence intervals are important parameters needed when determining fault activity levels and earthquake hazard. They should be evaluated along with other considerations related to levels of acceptable hazard and cost/benefit ratios when evaluating earthquake risk for a specific purpose.

Facilitation and Communication

WSSPC recommends that government agencies, regulators, and owners consider these fault-activity definitions when determining which faults are hazardous for specific facilities or purposes. For some facility types, active fault definitions are contained in state and federal regulations. Such regulations commonly use different definitions of fault activity based on the societal importance of the facility being built. Definitions that include less active faults or require more restrictive mitigation measures are typically used for critical facilities where the effect of the facility's failure has grave consequences.

When assessing the impact of future earthquakes, factors to consider are the type of facility and its societal importance; level of acceptable risk; goals, costs, and benefits of risk reduction; and geologic practicality of applying the definition. An example of the latter is found in areas of the Basin and Range Province where widespread latest Pleistocene pluvial lake or glacial deposits facilitate the use of a Holocene criterion, but where the use of a late Quaternary criterion may be impractical because the evidence of activity on some faults of that age is buried by younger deposits. The expense of risk-reduction measures must be balanced against the probability of earthquake occurrence and the resulting risk to society in terms of public safety and potential economic loss. Use of these three broad fault-activity definitions (Holocene, late Quaternary, Quaternary) aid in choosing the appropriate activity class for a proposed facility. It is ultimately up to the regulator and owner to decide how the hazard should be categorized and addressed, although uniform treatment among Basin and Range Province states is desirable.

Assessment

The success of this Policy Recommendation can be assessed based on the use of the definitions by states and local governments in regulations and ordinances. Utah, Colorado, and Clark County, Nevada have adopted these definitions in an earlier version of this WSSPC Policy Recommendation. A periodic re-evaluation of these and other federal, state, and local entities should be made to determine the extent to which these definitions are being incorporated into future seismic-hazard rules, regulations, and guidelines.

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Bell, J.W., Caskey, S.J., Ramelli, A.R., and Guerrier, 2004, Pattern and timing of faulting in the central Nevada seismic belt and paleoseismic evidence for prior belt-like behavior: Bulletin of the Seismological Society of America, v. 94, no. 4, p. 1229-1254.

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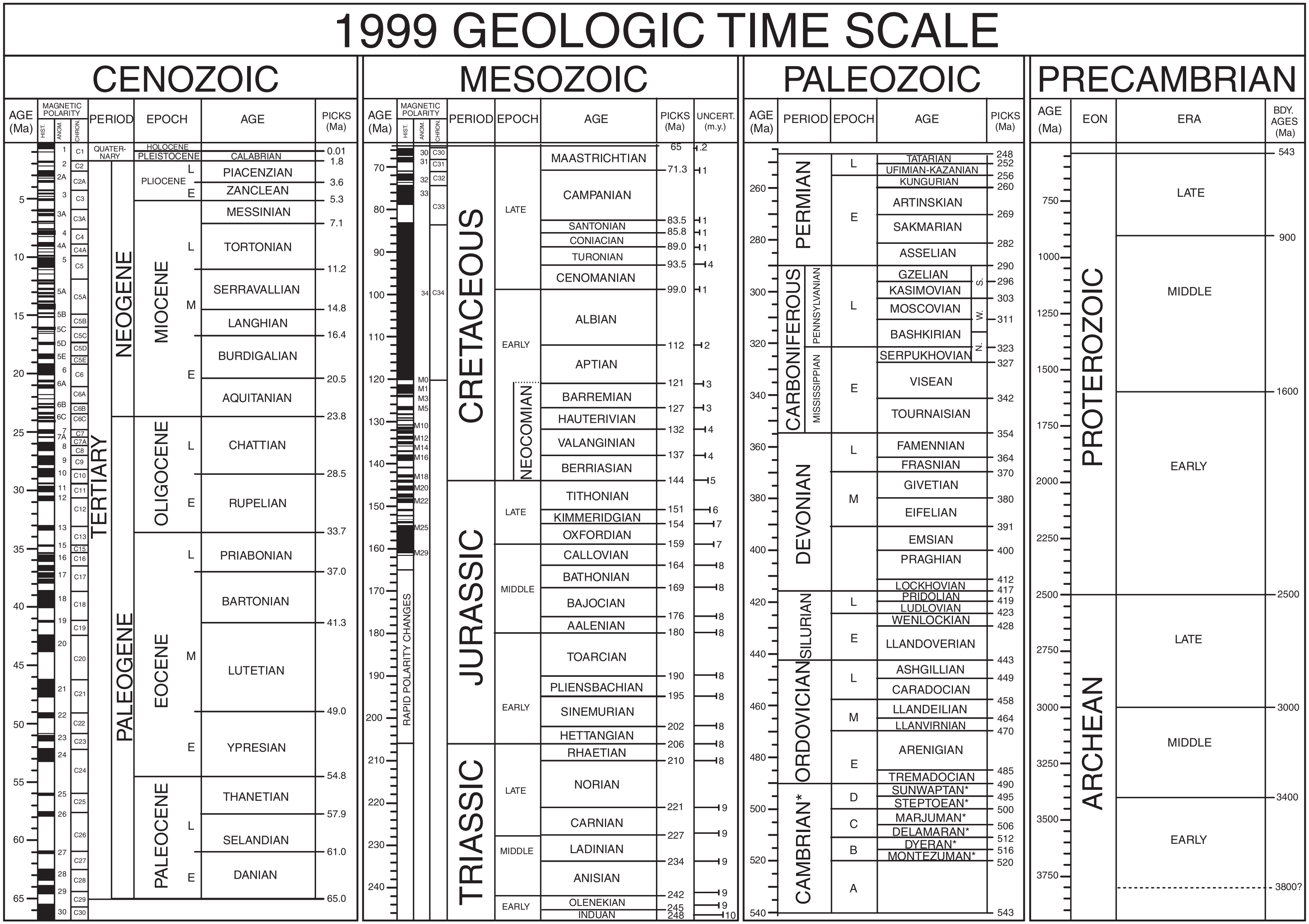
History

WSSPC Policy Recommendation 08-2 was first adopted in 1997 as WSSPC Policy Recommendation 97-1. It was reviewed and re-adopted as WSSPC Policy Recommendation 02-3 by unanimous vote of the WSSPC membership at the Annual Business Meeting September 18, 2002. It was reviewed, revised, and re-adopted as WSSPC Policy Recommendation 05-2 by unanimous vote of the WSSPC membership at the WSSPC Annual Business Meeting September 12, 2005. It was reviewed, revised, and re-adopted as WSSPC Policy Recommendation 08-2 by unanimous vote of the WSSPC membership at the WSSPC Annual Business Meeting April 22, 2008.

APPENDIX 4

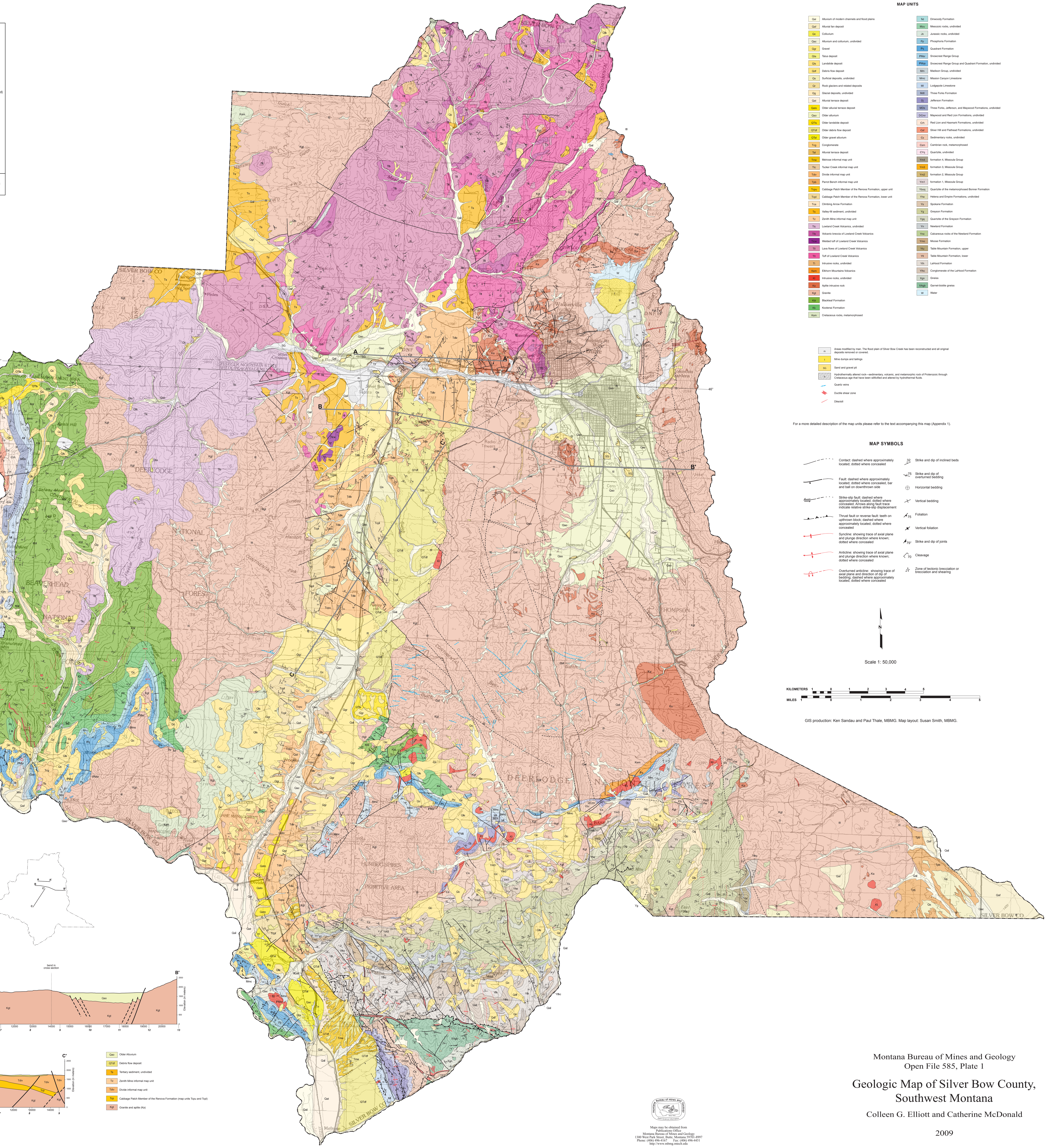
Geologic Time Scale



*International ages have not been established. These are regional (Laurentian) only. Boundary Picks were based on dating techniques and fossil records as of 1999. Paleomagnetic attributions have errors, Please ignore the paleomagnetic scale.

Sources for nomenclature and ages: Primarily from Gradstein, F., and Ogg, J., 1996, *Episodes*, v. 19, nos. 1 & 2; Gradstein, F., et al., 1995, SEPM Special Pub. 54, p. 95–128; Berggren, W. A., et al., 1995, SEPM Special Pub. 54, p. 129–212; Cambrian and basal Ordovician ages adapted from Landing, E., 1998, *Canadian Journal of Earth Sciences*, v. 35, p. 329–338; and Davidek, K., et al., 1998, *Geological Magazine*, v. 135, p. 305–309. Cambrian age names from Palmer, A. R., 1998, *Canadian Journal of Earth Sciences*, v. 35, p. 323–328.

GEOLOGICAL SOCIETY OF AMERICA



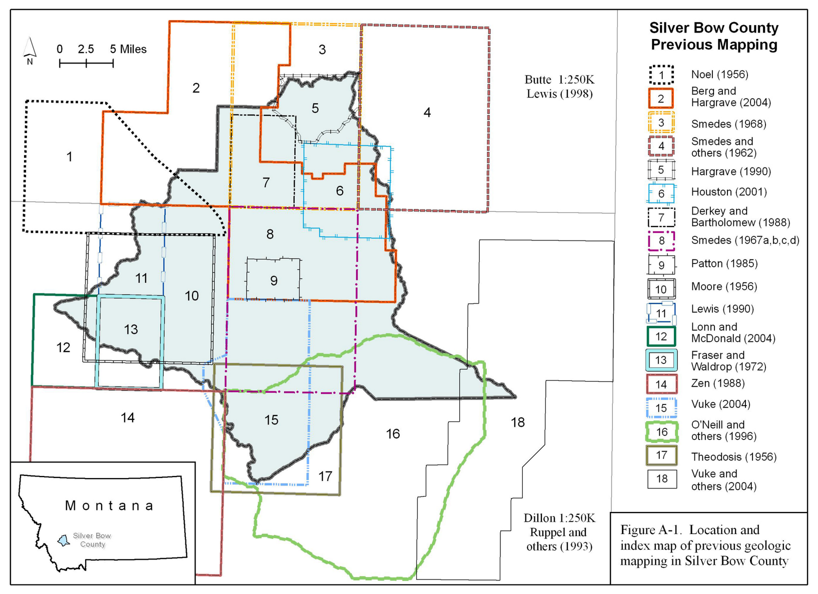
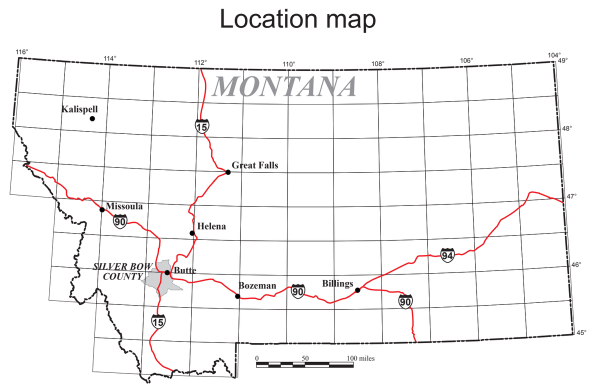
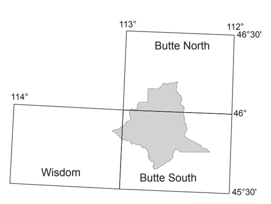


Figure A-1. Location and index map of previous geologic mapping in Silver Bow County

For full citations of previous mapping please refer to the text accompanying this map.

Location map





Base compiled from U.S. Geological Survey maps:

Butte North 30'x60' topographic quadrangle
Map date: 1994
Projection: UTM zone 12; 1927 NAD
UTM grid declination 1°10' West
1980 Magnetic North Declination 16° East

Butte South 30'x60' topographic quadrangle
Map date: 1990
Projection: UTM zone 12; 1927 NAD
UTM grid declination 1°04' West
1980 Magnetic North Declination 18° East

Wisdom 30'x60' topographic quadrangle
Map date: 1994
Projection: UTM zone 12; 1927 NAD
UTM grid declination 1°47' West
1980 Magnetic North Declination 16° East

Contour interval 50 meters
To convert to feet multiply by 3.2808

MAP UNITS

Qal	Alluvium of modern channels and flood plains
Qaf	Alluvial fan deposit
Qc	Colluvium
Qac	Alluvium and colluvium, undivided
Qgr	Gravel
Qta	Talus deposit
Qls	Landslide deposit
Qdf	Debris flow deposit
Qs	Surficial deposits, undivided
Qr	Rock glaciers and related deposits
Qg	Glacial deposits, undivided
Qat	Alluvial terrace deposit
Qato	Older alluvial terrace deposit
Qao	Older alluvium
QTls	Older landslide deposit
QTdf	Older debris flow deposit
QTal	Older gravel alluvium
Tcg	Conglomerate
Tat	Alluvial terrace deposit
Tme	Melrose informal map unit
Ttc	Tucker Creek informal map unit
Tdiv	Divide informal map unit
Tpb	Parrot Bench informal map unit
Tcpu	Cabbage Patch Member of the Renova Formation, upper unit
Tcpl	Cabbage Patch Member of the Renova Formation, lower unit
Tca	Climbing Arrow Formation
Ts	Valley-fill sediment, undivided
Tz	Zenith Mine informal map unit
Tlc	Lowland Creek Volcanics, undivided
Tlb	Volcanic breccia of Lowland Creek Volcanics
Tlcw	Welded tuff of Lowland Creek Volcanics
Tll	Lava flows of Lowland Creek Volcanics
Tlt	Tuff of Lowland Creek Volcanics
Ti	Intrusive rocks, undivided
Kem	Elkhorn Mountains Volcanics
Kl	Intrusive rocks, undivided
Ka	Aplite intrusive rock
Kgt	Granite
Kbl	Blackleaf Formation
Kk	Kootenai Formation
Ksm	Cretaceous rocks, metamorphosed
₸d	Dinwoody Formation
Mzu	Mesozoic rocks, undivided
Js	Jurassic rocks, undivided
Pp	Phosphoria Formation
ℙq	Quadrant Formation
ℙMsr	Snowcrest Range Group
ℙMqs	Snowcrest Range Group and Quadrant Formation, undivided
Mm	Madison Group, undivided
Mmc	Mission Canyon Limestone
Ml	Lodgepole Limestone
Mdt	Three Forks Formation
Dj	Jefferson Formation
MDs	Three Forks, Jefferson, and Maywood Formations, undivided
D€mr	Maywood and Red Lion Formations, undivided
€rh	Red Lion and Hasmark Formations, undivided
€sf	Silver Hill and Flathead Formations, undivided
€s	Sedimentary rocks, undivided
€sm	Cambrian rock, metamorphosed
€Yq	Quartzite, undivided
Ym4	formation 4, Missoula Group
Ym3	formation 3, Missoula Group
Ym2	formation 2, Missoula Group
Ym1	formation 1, Missoula Group
Yboq	Quartzite of the metamorphosed Bonner Formation
Yhe	Helena and Empire Formations, undivided
Ys	Spokane Formation
Yg	Greyson Formation
Ygq	Quartzite of the Greyson Formation
Yn	Newland Formation
Ync	Calcareous rocks of the Newland Formation
Ymo	Moose Formation
Ytu	Table Mountain Formation, upper
Ytl	Table Mountain Formation, lower
Ylh	LaHood Formation
Ylhc	Conglomerate of the LaHood Formation
Xgn	Gneiss
XAgb	Garnet-biotite gneiss
W	Water

m	Areas modified by man. The flood plain of Silver Bow Creek has been reconstructed and all original deposits removed or covered.
t	Mine dumps and tailings
SG	Sand and gravel pit
h	Hydrothermally altered rock—sedimentary, volcanic, and metamorphic rock of Proterozoic through Cretaceous age that have been silicified and altered by hydrothermal fluids.
	Quartz veins
	Ductile shear zone
	Dike/sill

For a more detailed description of the map units please refer to the text accompanying this map (Appendix 1).

MAP SYMBOLS

- Contact: dashed where approximately located; dotted where concealed
- Fault: dashed where approximately located; dotted where concealed, bar and ball on downthrown side
- Strike-slip fault: dashed where approximately located; dotted where concealed. Arrows along fault trace indicate relative strike-slip displacement
- Thrust fault or reverse fault: teeth on upthrown block; dashed where approximately located; dotted where concealed
- Syncline: showing trace of axial plane and plunge direction where known; dotted where concealed
- Anticline: showing trace of axial plane and plunge direction where known; dotted where concealed
- Overturned anticline: showing trace of axial plane and direction of dip of bedding; dashed where approximately located, dotted where concealed
- 32 Strike and dip of inclined beds
- 75 Strike and dip of overturned bedding
- Horizontal bedding
- Vertical bedding
- 75 Foliation
- Vertical foliation
- 79° Strike and dip of joints
- 70 Cleavage
- Zone of tectonic brecciation or brecciation and shearing

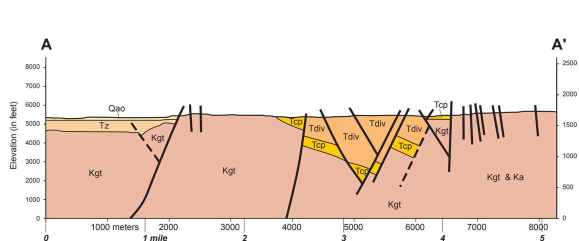
N

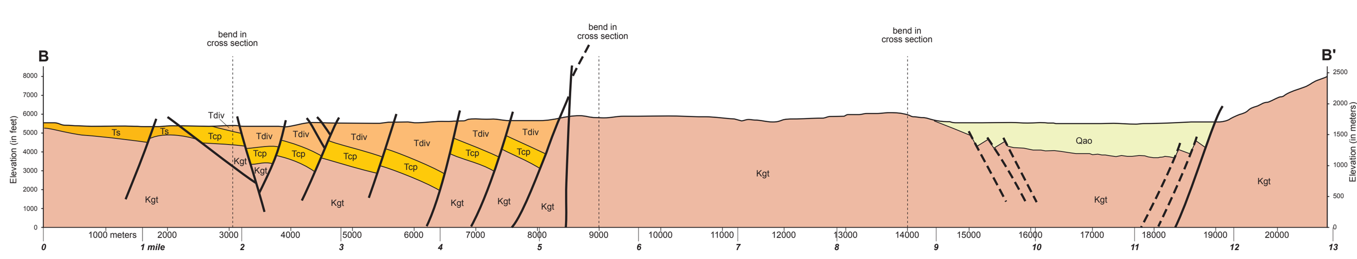
Scale 1: 50,000

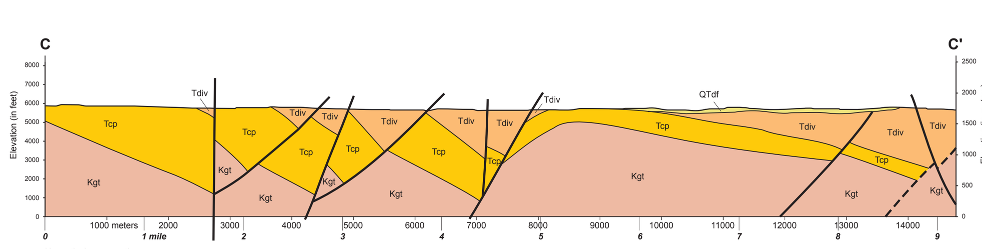
KILOMETERS 1 0 1 2 3 4 5
MILES 1 0 1 2 3 4 5

GIS production: Ken Sandau and Paul Thale, MBMG. Map layout: Susan Smith, MBMG.

Cross Sections







Qao	Older Alluvium
QTdf	Debris flow deposit
Ts	Tertiary sediment, undivided
Tz	Zenith Mine informal map unit
Tdiv	Divide informal map unit
Tcp	Cabbage Patch Member of the Renova Formation (map units Tcpu and Tcpl)
Kgt	Granite and aplite (Ka)

Maps may be obtained from
Publications Office
Montana Bureau of Mines and Geology
1300 West Park Street, Butte, Montana 59701-8997
Phone: (406) 496-4167 Fax: (406) 496-4451
http://www.mbmg.mtech.edu

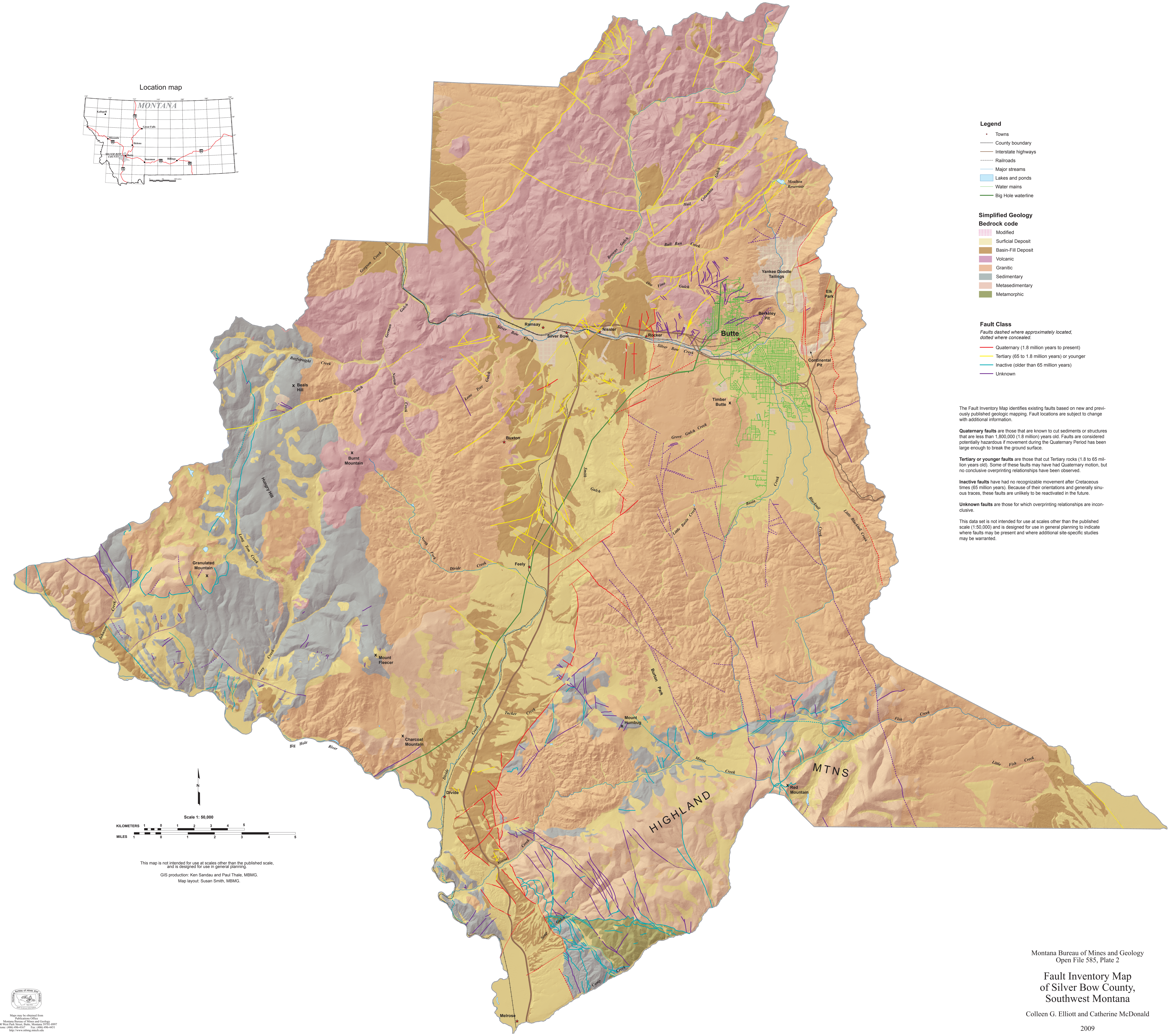
Montana Bureau of Mines and Geology
Open File 585, Plate 1

Geologic Map of Silver Bow County, Southwest Montana

Colleen G. Elliott and Catherine McDonald

2009

Location map



Legend

- Towns
- County boundary
- Interstate highways
- Railroads
- Major streams
- Lakes and ponds
- Water mains
- Big Hole waterline

Simplified Geology

Bedrock code

- Modified
- Surficial Deposit
- Basin-Fill Deposit
- Volcanic
- Granitic
- Sedimentary
- Metasedimentary
- Metamorphic

Fault Class

Faults dashed where approximately located, dotted where concealed.

- Quaternary (1.8 million years to present)
- Tertiary (65 to 1.8 million years) or younger
- Inactive (older than 65 million years)
- Unknown

The Fault Inventory Map identifies existing faults based on new and previously published geologic mapping. Fault locations are subject to change with additional information.

Quaternary faults are those that are known to cut sediments or structures that are less than 1,800,000 (1.8 million) years old. Faults are considered potentially hazardous if movement during the Quaternary Period has been large enough to break the ground surface.

Tertiary or younger faults are those that cut Tertiary rocks (1.8 to 65 million years old). Some of these faults may have had Quaternary motion, but no conclusive overprinting relationships have been observed.

Inactive faults have had no recognizable movement after Cretaceous times (65 million years). Because of their orientations and generally sinuous traces, these faults are unlikely to be reactivated in the future.

Unknown faults are those for which overprinting relationships are inconclusive.

This data set is not intended for use at scales other than the published scale (1:50,000) and is designed for use in general planning to indicate where faults may be present and where additional site-specific studies may be warranted.

This map is not intended for use at scales other than the published scale, and is designed for use in general planning.

GIS production: Ken Sandau and Paul Thale, MBMG.
Map layout: Susan Smith, MBMG.

Maps may be obtained from
Publications Office
Montana Bureau of Mines and Geology
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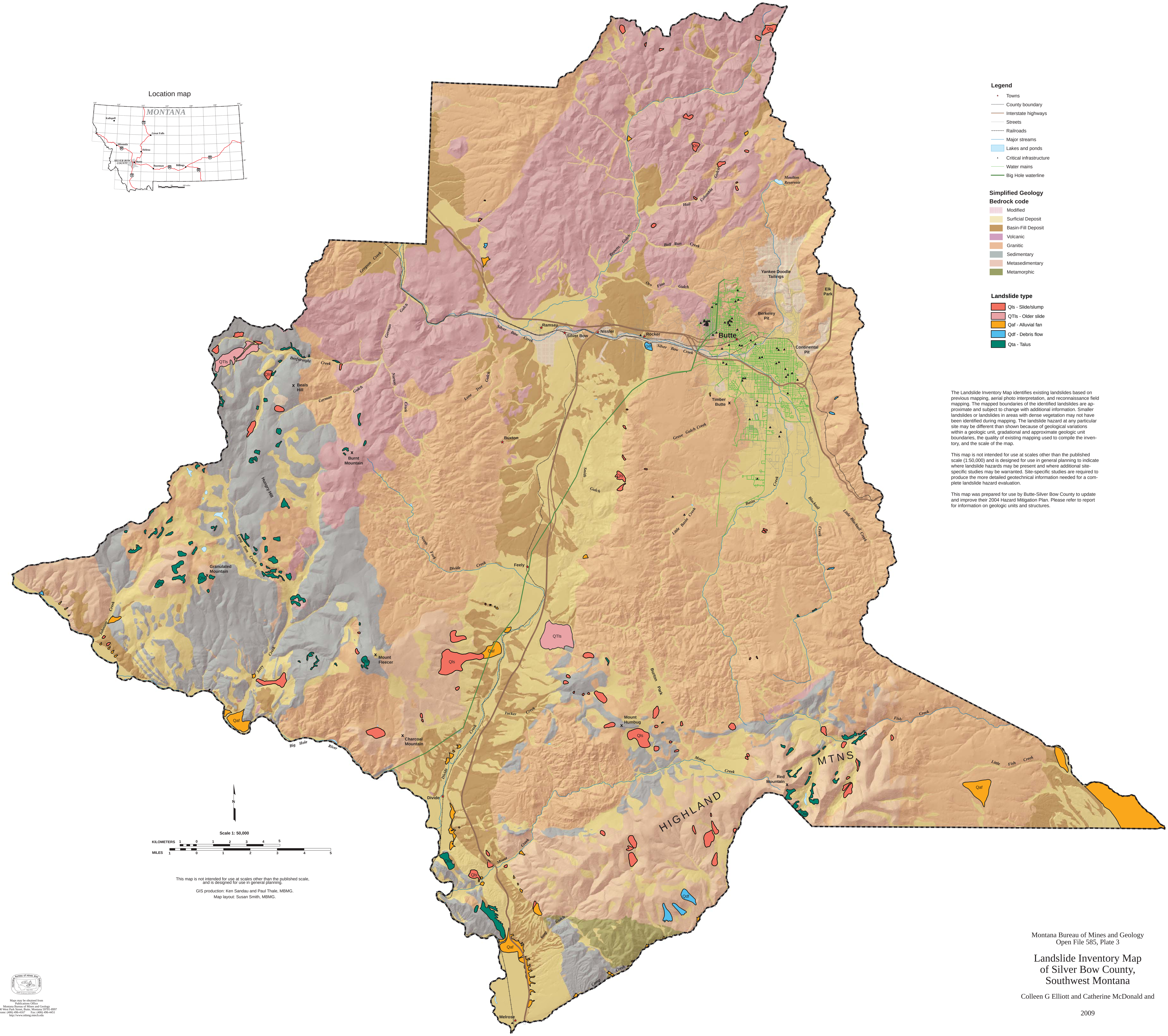
Montana Bureau of Mines and Geology
Open File 585, Plate 2

Fault Inventory Map of Silver Bow County, Southwest Montana

Colleen G. Elliott and Catherine McDonald

2009



Legend

- Towns
- County boundary
- Interstate highways
- Streets
- Railroads
- Major streams
- Lakes and ponds
- Critical infrastructure
- Water mains
- Big Hole waterline

Simplified Geology
Bedrock code

- Modified
- Surficial Deposit
- Basin-Fill Deposit
- Volcanic
- Granitic
- Sedimentary
- Metasedimentary
- Metamorphic

Landslide type

- Qls - Slide/slump
- QTls - Older slide
- Qaf - Alluvial fan
- Qdf - Debris flow
- Qta - Talus

The Landslide Inventory Map identifies existing landslides based on previous mapping, aerial photo interpretation, and reconnaissance field mapping. The mapped boundaries of the identified landslides are approximate and subject to change with additional information. Smaller landslides or landslides in areas with dense vegetation may not have been identified during mapping. The landslide hazard at any particular site may be different than shown because of geological variations within a geologic unit, gradational and approximate geologic unit boundaries, the quality of existing mapping used to compile the inventory, and the scale of the map.

This map is not intended for use at scales other than the published scale (1:50,000) and is designed for use in general planning to indicate where landslide hazards may be present and where additional site-specific studies may be warranted. Site-specific studies are required to produce the more detailed geotechnical information needed for a complete landslide hazard evaluation.

This map was prepared for use by Butte-Silver Bow County to update and improve their 2004 Hazard Mitigation Plan. Please refer to report for information on geologic units and structures.

N

Scale 1: 50,000

KILOMETERS 1 0 1 2 3 4 5

MILES 1 0 1 2 3 4 5

This map is not intended for use at scales other than the published scale, and is designed for use in general planning.

GIS production: Ken Sandau and Paul Thale, MBMG.
Map layout: Susan Smith, MBMG.

Maps may be obtained from
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Montana Bureau of Mines and Geology
Open File 585, Plate 3

Landslide Inventory Map of Silver Bow County, Southwest Montana

Colleen G Elliott and Catherine McDonald and

2009