OPEN-FILE REPORT 08-15

Authors' Notes

Geologic Map of the Bayfield Quadrangle, La Plata County, Colorado

by

David A. Gonzales[1], Katherine E. Potter[1], and Brian E. Turner[1]

[1] Fort Lewis College, Durango, Colorado

Bill Ritter Jr., Governor
State of Colorado

Harris D. Sherman, Executive Director
Department of Natural Resources

Vincent Matthews
State Geologist and Director
Colorado Geological Survey

Colorado Geological Survey
Department of Natural Resources
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Description of Map Units, Structural Geology, Geologic Hazards, Mineral Resources, and Ground-Water Resources

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David A. Gonzales, Katherine E. Potter, and Brian E. Turner

View of the area within the Bayfield quadrangle. Photo was taken from the southeast corner of the quadrangle looking northwest at the La Plata Mountains.

This mapping project was funded jointly by the Colorado Geological Survey and the U.S. Geological Survey through the National Geologic Mapping Program under STATEMAP Agreement No. 07HQAG0083

FOREWORD

The purpose of Colorado Geological Survey Open File Report 08-15, *Geologic Map of the Bayfield Quadrangle, La Plata County, Colorado* is to map and describe the geologic setting, structure, geologic hazards, and mineral resources of this 7.5-minute quadrangle located in the southeastern corner of La Plata County in southwestern Colorado. Dr. David Gonzales and undergraduate students, Katie Potter and Brian Turner, from Fort Lewis College initiated the field work and research on this project between March and August of 2005, completing the northern and eastern part of the quadrangle. Dr. Gonzales completed the mapping in the spring and summer of 2007. Dr. Gonzales was the principal mapper and author for this report, using maps and field notes generated by all three investigators.

During mapping all accessible outcrops and landforms in the map area were inspected and mapped for rock or deposit type, geologic structures, and resource information. Access to some small portions of the area held by private land owners or the Southern Ute Tribe was not permitted. Interpretation of aerial photography and previously published geologic investigations were used to delineate unit contacts in areas not visited by the authors. Black and white and color 1:24,000-scale aerial photograph coverage was used for the entire quadrangle. Map preparation and digitization was completed following field mapping by the authors and Digital Data Services Inc.

This mapping project was funded jointly by the U.S. Geological Survey (USGS) and Fort Lewis College as part of the Education (EDMAP) Mapping Program (agreement number 05HQAG0020), and the U.S. Geological Survey and the Colorado Geological Survey (CGS) as part of the STATEMAP Mapping Program (award number 07HQAG0083). STATEMAP and EDMAP are components of the National Cooperative Geologic Mapping Program, which is authorized by the National Geologic Mapping Act of 1997. This project is a prime example of the cooperative nature of STATEMAP and EDMAP efforts to produce a geologic map. The CGS matching funds were drawn from the Colorado Department of Natural Resources Severance Tax Operational Funds, which are obtained from the Severance Tax paid on the production of natural gas, oil, coal, and metals in Colorado.

Vince Matthews
State Geologist and Director
Colorado Geological Survey

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ACKNOWLEDGMENTS

We acknowledge the support and assistance during this mapping project from Beth Widmann, Dave Noe, and Vince Matthews of the Colorado Geological Survey. We also appreciate the support of the Town of Bayfield. We want to thank all of the landowners who permitted access to their property during this project, and Steve Whiteman of the Southern Ute Tribe for working with us on access issues. Thanks to Mary Gillam for spending time in the field and contributing to ideas on the surficial processes and deposits in the quadrangle. The report and map were improved by the thorough review of Bob Kirkham, and technical reviews of Dave Noe and Vince Matthews. We want to thank Pete Magee for his work to digitize the field map to create the final digital product.

INTRODUCTION

Geologic maps produced by the Colorado Geological Survey through the STATEMAP program provide geologic information for land-use planning, geotechnical engineering, geologic-hazards assessment, analysis and mitigation of environmental problems, and mineral-resource and ground-water exploration and development. These maps portray the geology of 7.5-minute quadrangles and serve as a basis for other research projects.

Figure 1 shows the current status of geologic mapping of 7.5-minute quadrangles in Colorado and La Plata County done by the Colorado Geological Survey (CGS) and the United States Geological Survey (USGS). The Rules Hill, Ludwig Mountain, Durango East, Durango West, Hesperus, Basin Mountain, Hermosa, Electra Lake, and Vallecito quadrangles were mapped and published by the CGS during previous STATEMAP projects (Carroll and others, 1997, 1998, 1999; Kirkham and others, 1999, 2000; Kirkham and Navarre, 2001; Gonzales and others, 2002; 2003; 2004). The Hesperus, Electra Lake, and Vallecito quadrangles were funded in part by the United Stated Geological Survey EDMAP program.

PREVIOUS GEOLOGIC MAPPING STUDIES

The United States Geological and Geographical Survey conducted the first geologic studies in southwestern Colorado during reconnaissance surveys between 1869 and 1875 (Endlich, 1876; Comstock, 1883, 1887; and Van Hise, 1890). The United States Geological Survey initiated the first comprehensive geologic mapping studies in the Needle Mountains in 1895 under the direction of Whitman Cross. By 1910 Cross and his colleagues had compiled 1:62,500 geologic maps for seven 15-minute quadrangles and published the results in a series of folios in the Geologic Atlas of the United States.

Regional investigations of the entire San Juan Mountains by Cross and Larsen (1935) and Larsen and Cross (1956) summarized much of the early work by Cross and his colleagues. The geology within the Bayfield quadrangle was compiled by Cross and Larsen (1935) and Larsen and Cross (1956), but the work was cursory and only showed the distribution of major bedrock and surficial units.

A 1:250,000-scale map was published by Reeside (1924) as part of a regional study of late Cretaceous to Tertiary rocks units in the western San Juan basin. A regional map of surficial deposits was compiled by Atwood and Mather (1932), which included the area within the Bayfield quadrangle.

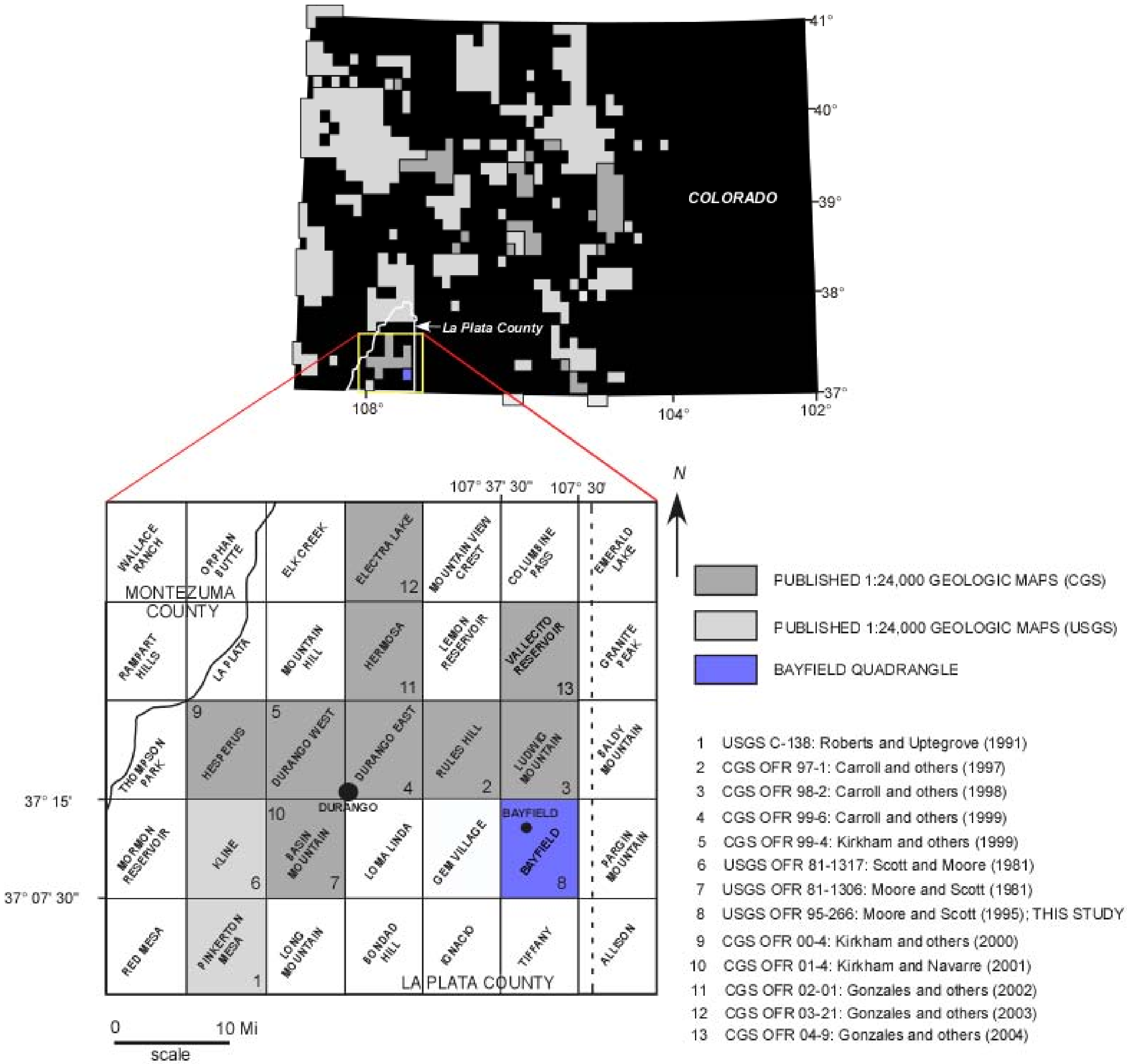

Figure 1: Published 1:24,000-scale geologic maps of 7.5-minute quadrangles in Colorado and La Plata County in southwestern Colorado.

Kelley (1957) gave a synopsis of the geologic events and history in the region and provided a generalized geologic map of the western San Juan Mountains. Barnes (1953) compiled a general geologic map of the Bayfield quadrangle and surrounding area showing the distribution of bedrock and surficial units. In 1964 a geologic mapping project of the Durango 1º x 2º quadrangle was initiated by the United States Geologic Survey (Steven and others, 1974). Fassett and Hinds (1971) published a general geologic map of major rock units in the San Juan basin, and a 1:100,000-scale compilation of the regional geology in the vicinity of Durango was done by Condon (1990). Moore and Scott (1995) produced a 1:24,000-scale geologic map of Quaternary surficial deposits in the Bayfield quadrangle.

An extensive overview of the geology and structure related to natural gas reservoirs that underlie the Bayfield quadrangle is provided by Fassett and others (1997). In addition, descriptions of natural gas systems associated with coalbed methane, and some geologic information, are included in an environmental impact statement published in 2006.

GEOLOGIC SETTING & HISTORY

Figure 2 is a current geologic time scale that has been adopted by the U.S. Geological Survey and Association of American State Geologists. The age constraints and divisions shown on this figure provide a reference for the following discussion.

The Bayfield 7.5-minute quadrangle includes about 60 square miles of chiefly hilly terrain within the eastern part of La Plata County in southwestern Colorado (fig. 1). The west and east boundaries of the quadrangle lie at longitudes of 107° 37' 30" W and 107° 30' 00" W, respectively. The south margin of the map is at latitude 37° 07' 30" N and the north margin is at latitude 37° 15' 00" N. The city of Bayfield is located in the northwestern corner of the quadrangle (fig. 1). The Bayfield quadrangle lies near the transition of the east-central part of the Colorado Plateau physiographic province and western edge of the Southern Rocky Mountains (Hardwick and others, 2008) (fig. 3). The elevation of the terrain in the mapping area varies from 6,500 ft above sea level in the Los Piños River valley to around 8,600 ft in the mountainous terrain on the east margin of the quadrangle. The Los Piños River, which drains much of the southeastern Needle Mountains, flows from north to south across the quadrangle.

Nearly 2,000 ft of stratigraphic-rock record that spans approximately 60 million years of geologic time is exposed in the Bayfield quadrangle. The map area is on the northern edge of the San Juan basin which is defined by south-dipping Phanerozoic strata exposed on 1,800 to 1,400 million-year-old Proterozoic crystalline rocks at the margin of the San Juan uplift (figs. 3 and 4).

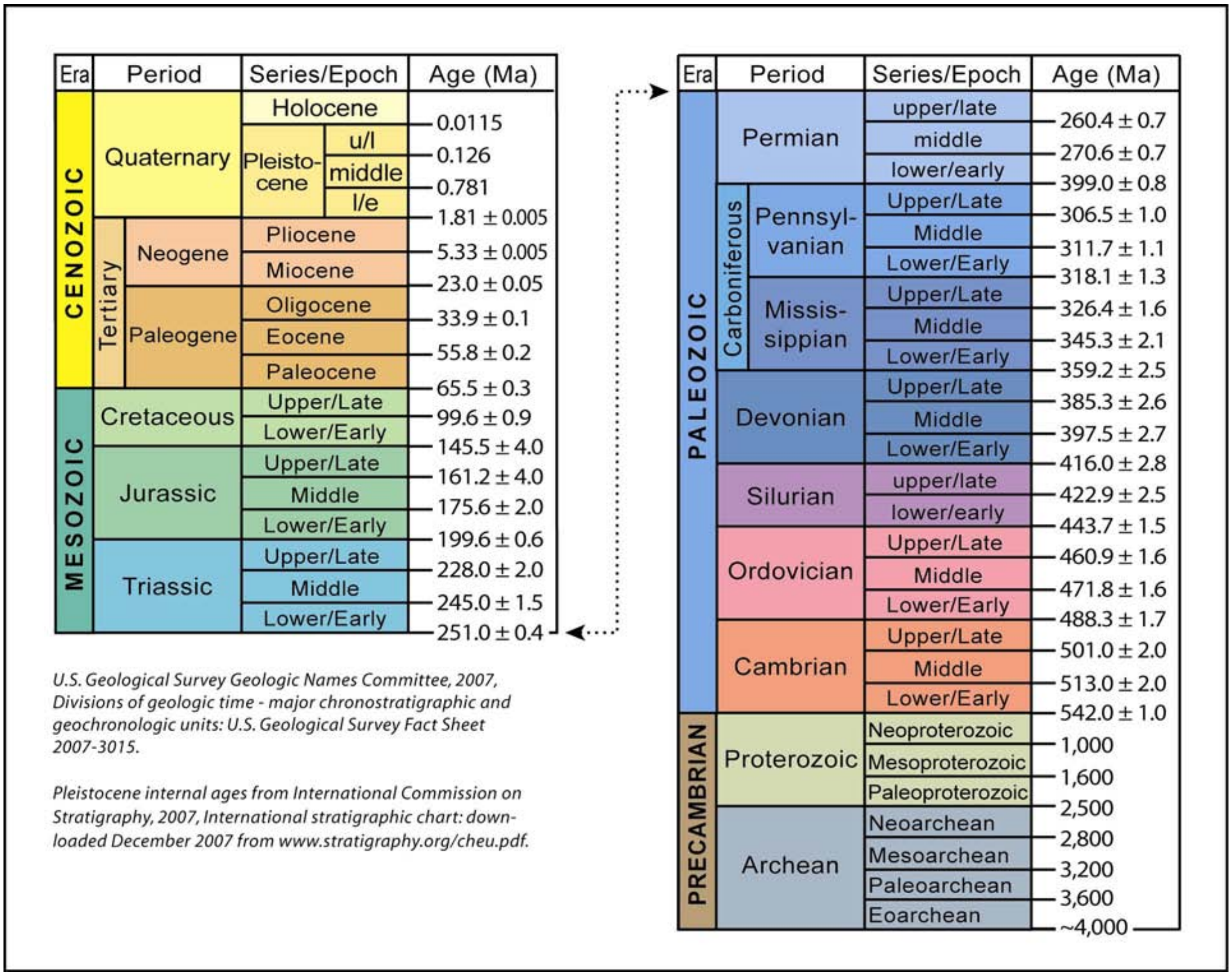

Figure 2: The geologic time scale of the U.S. Geological Survey and the Association of American State Geologists that is adopted by the Colorado Geological Survey. Absolute ages are shown in millions of years.

Cenozoic marine sedimentary rocks (figs. 4 and 5) were deposited over southwestern Colorado from around 145 to 80 million years ago in a vast inland seaway that covered much of the western United States. None of these marine rocks are exposed in the map area, but some sedimentary units of this age are important reservoirs for natural gas (e.g., Fruitland Formation) in the subsurface (refer to cross section for this report and Molenaar and Baird, 1989, 1991).

About 80 million years ago, the area of the San Juan Mountains (figs. 3 and 4) was eroded to sea level and the inland seaway that covered this area began a retreat as the modern Rocky Mountains were formed. The widely accepted model (e.g., Lipman and others., 1971; Dickinson, 1979, 1981) for this mountain-building event is that subduction on the west coast of North America extended far inland and caused broad uplift in the region that forms the Colorado Plateau, and extensive uplift in a roughly north-south pattern that forms the modern Rocky Mountains. In the "flab-slab" subduction model, the rate of subduction increased over time which is thought to have caused the subducted slab to become more buoyant and rise to a lower angle beneath the North America plate. It is thought that this process caused "scraping" of the subducted plate near 1000 kilometers inboard of the western edge of North America (e.g., Dickinson, 1979, 1981), compressing and uplifting the region to create the the Colorado Plateau and Rocky Mountain region. It is likely that the Rocky Mountain belt attained some, but not all, of its present elevation during the Laramide orogeny.

Approximately 70 million years ago, intermediate to felsic magmas were emplaced to form numerous mushroom-shaped bodies (i.e., laccoliths) in the area. Eroded remnants of Laramide laccolithic mountains include Ute Mountain, the La Plata Mountains, and smaller masses exposed on the fringes of the eastern San Juan volcanic field. These intrusive complexes are an older component of a northeast-trending belt of Tertiary magmatism that was the focus of many mineralized deposits. Formation of the La Plata Mountains complex was followed by deposition of alluvial fan deposits that make up the McDermott Formation (fig. 5) which exposed just north of the Bayfield quadrangle.

In southwestern Colorado, the rise of the modern Rocky Mountains was accompanied by subsidence on the southern edge of the mountains creating the San Juan basin (figs. 3 and 4). Streams flowed south and southwest from highlands (Sikkink, 1987) (figs. 3 and 4) and deposited sediment in alluvial plains and lacustrine environments over the San Juan basin from the Paleocene to Eocene. These deposits are exposed in the Animas Formation and San Jose Formation in the Bayfield quadrangle; units with similar ages and depositional records are exposed further south in the San Juan basin (Condon, 1990).

Recent studies by Gonzales and others (2005) and Harraden and others (2007) provide convincing evidence that at least the western San Juan Mountains underwent renewed or continued uplift between the Eocene and Oligocene. The cause of this uplift is not well constrained, but may have involved regional compressive or transpressive tectonic activity. The renewed period of uplift caused reactivation of Proterozoic-cored blocks in the Needle Mountains (fig. 4). Material produced by subsequent erosion of this highland was deposited in an alluvial fan complex in the western San Juan Mountains. These deposits comprise the Eocene to Oligocene Telluride Conglomerate. The absolute of age of the Telluride Conglomerate is poorly constrained but clasts of porphyritic plutonic rocks collected from the base of the unit yield Ar-Ar ages of 50 to 30 Ma (unpublished data determined by the New Mexico Geochronological Research Laboratory in 2005). This broad range of ages is consistent with the idea that the Telluride Conglomerate and San Jose Formation are similar in age. The Telluride Conglomerate, however, also contains fragments of felsic to intermediate volcanic rocks that are similar to those found in the San Juan volcanic field. The presence of volcanic clasts in the basal part of the Telluride Conglomerate near Telluride suggests that development of the alluvial fan complex was contemporaneous and somehow linked with the onset of extensive volcanic eruptions in the western San Juan Mountains in the Oligocene. If this is the case then the Telluride Conglomerate might be Oligocene in age and younger than the San Jose Formation; this was also discussed by Kelley (1957, p. 157). Although the timing of deposition of the Telluride Conglomerate is still not well constrained, the uplift in the western San Juan Mountains from 50 to 30 million years ago contributed to further rise of the San Juan Mountains and additional subsidence in the San Juan basin. Deposition of some of the Tertiary fluvial rocks exposed in the San Juan basin might have resulted from this renewed uplift.

Between 35 and 30 million years ago, the San Juan Mountains (fig. 3) were the site of some of the largest volcanic eruptions on Earth (Steven and Lipman, 1976). It is proposed that around 35 million years ago the subducted slab that caused Laramide tectonic uplift in the region slowed as subduction waned. Foundering and sinking of the subducted plate induced inflow of the mantle leading to widespread melting of the lithosphere and magmatism (e.g., Lipman and others, 1971). This resulted in the expulsion of large volumes of viscous and gas-rich magmas, and subsequent collapse of the land surface, to form a series of caldera volcanoes in the San Juan volcanic field (e.g., Silverton-Lake City calderas). The emplacement of deep-seated magmas during this event caused widespread broad doming of the region covered by the San Juan volcanic field (fig. 4).

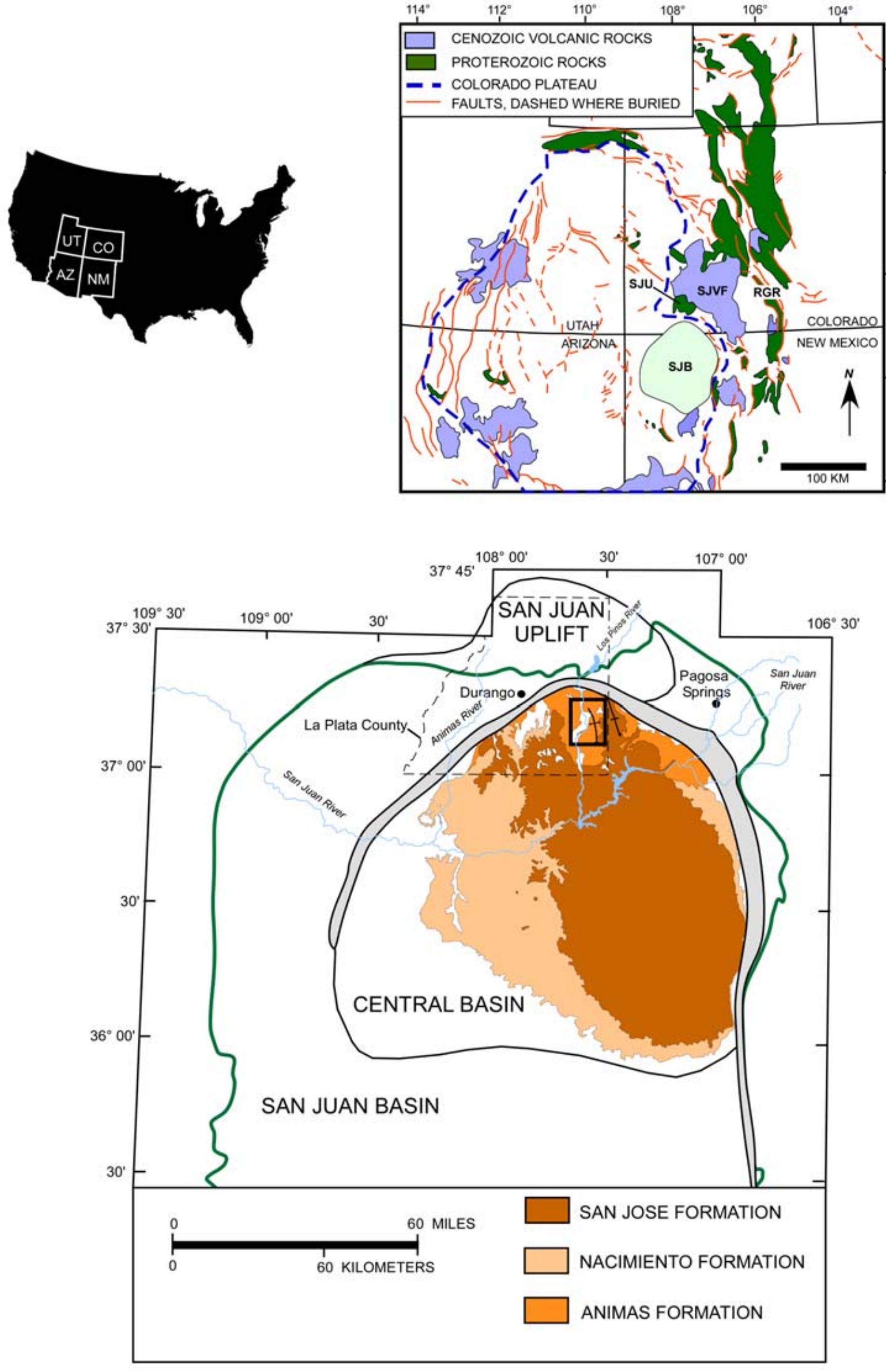

Figure 3: The top right figure is a generalized map of the Four Corners region showing some of the main physiographic and geologic features; San Juan volcanic field (SJVF), (San Juan uplift (SJU), San Juan basin (SJB), Rio Grande Rift (RGR) (modified from Oldow and others, 1989). The lower figure shows the distribution of Tertiary rock units in the San Juan basin within and adjacent to the Bayfield quadrangle (modified from Craigg, 2001). The stippled area defines the Hogback monocline, and the anticline trace shown in the eastern part of the Bayfield quadrangle is from Condon (1990).

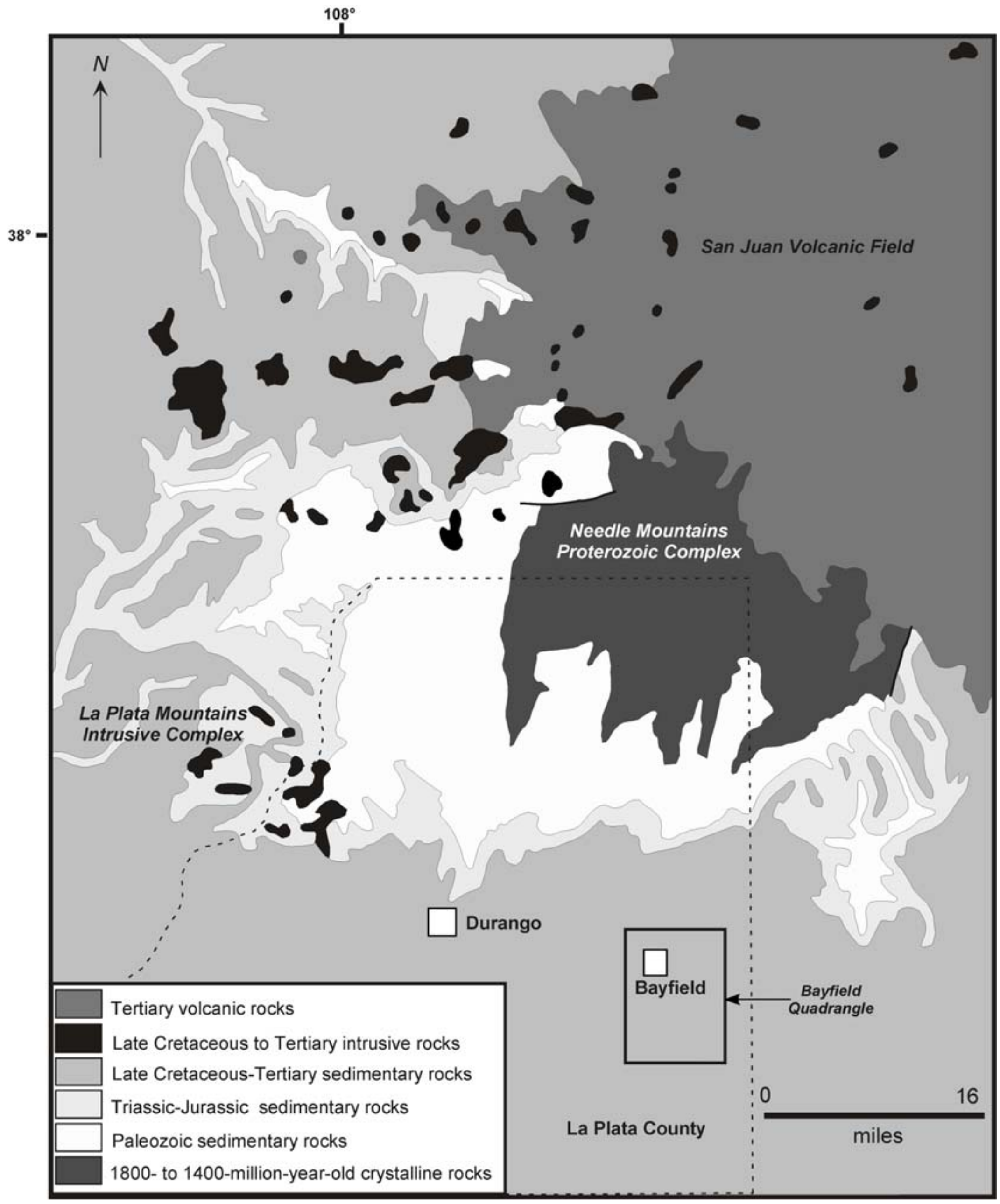

Figure 4: General geologic map showing the principal rock units in southwestern Colorado (modified version of the Colorado Geologic Highway Map, 2003). The area of the Bayfield quadrangle is indicated by the ruled box. The broken line indicates the boundaries of La Plata County.

Oligocene uplift and volcanism was contemporaneous with incipient crustal stretching rifting on the western and eastern margins of the San Juan Mountains (figs. 3 and 4). To the west and southwest of the San Juan uplift this rifting was manifested in a northeast belt of potassium-rich mafic dikes and explosive diatreme volcanoes of the Navajo volcanic field in northeastern New Mexico and southwestern Colorado. East of the San Juan Mountains rifting began in the Rio Grande rift (fig. 3). Rifting along the northern margin of the San Juan basin in the Oligocene or later was accompanied by the emplacement of series of mostly north-trending mafic dikes that cut Eocene sedimentary rocks between Durango and Pagosa Springs (e.g., Wood and others, 1948; Fassett and Hinds, 1971; Condon, 1990). Some of these mafic dikes are exposed in the Bayfield quadrangle.

Active extension in the region is still ongoing as indicated by the hot springs, high heat flow, and young faulting east of the San Juan Mountains as far north as Wyoming. Western Colorado is underlain by some of the lowest velocity upper mantle in the region which comprises the Aspen anomaly (Karlstrom and others, 2005). The Aspen anomaly is characterized by mantle that is similar in shape and character to both the Yellowstone and Jemez hot spot-mantle anomalies. These other areas are associated with caldera eruptions that happened during the past several million years, whereas the Aspen anomaly is not. Mantle gases detected in hot springs throughout the region (Newell and others 2005), however, suggest young and active mantle upwelling beneath the region.

Much of the late Tertiary record in southwestern Colorado was removed by erosion. In the past several million years, the San Juan Mountains have been eroded and sculptured by glaciers and rivers, perhaps at the same time as active uplift in the region (Karlstrom and others, 2005). The Los Piños River and its tributaries, assisted by intense glacial erosion in the Pleistocene and other Quaternary surficial processes, have carved and molded the canyons and ridges in the map area, producing the modern landscape.

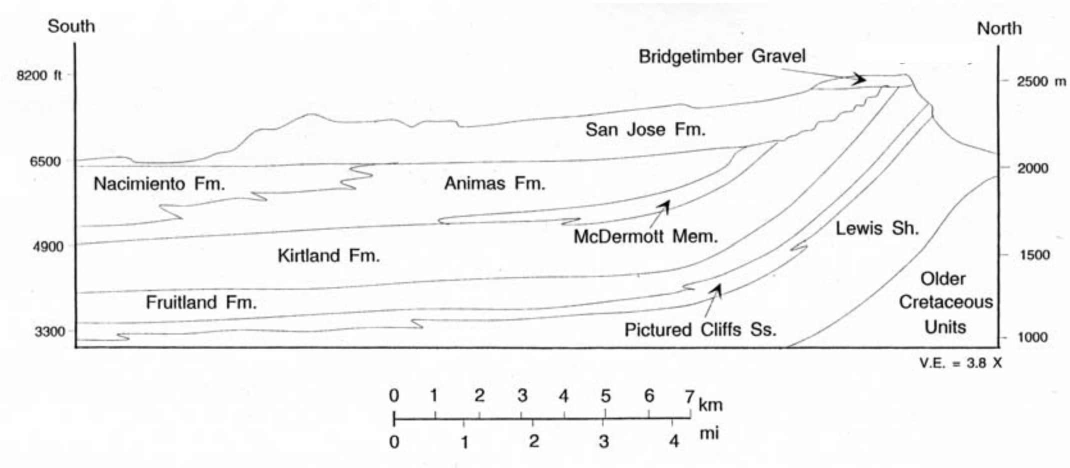

Figure 5. A simplified north-south cross section of the San Juan basin illustrating the stratigraphic relationships of Late Cretaceous to Tertiary units (taken from Condon, 1990). Only the Animas Formation and San Jose Formation are exposed in the Bayfield quadrangle.

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Surficial deposits are widespread in the Bayfield quadrangle. Pleistocene glacial outwash and Quaternary alluvial deposits are the dominant surficial deposits in the area. Most of the surficial deposts are masked by heavy vegetation and not well exposed except along their eroded edges or roadcuts where detailed descriptions of the thickness, texture, stratification, and composition of these units could be determined. Landforms associated with the surficial deposits often provide critical data on which interpretations of their genesis are made. The surficial stratigraphic units are generally classified by genesis or, if genesis is unknown, by the type of material of which they are composed.

Surficial units shown on the map are generally more than about 5 ft thick, but in some instances, particularly for colluvium and fan sediments, the deposits may be less than 5 ft thick. Because of the scale of the map, the minimum width of surficial deposits shown on the map is about 50 ft. Soils and residuum were not mapped in this study. Contacts between many surficial units may be gradational and therefore should be considered as approximate boundaries. The topographic base map was published in 1964, consequently, cultural features that post-date the base map are not depicted.

Clasts (boulder, cobble, pebble, granule) are defined in the following descriptions as rock fragments larger than 2 mm in diameter, and matrix refers to surrounding material 2 mm or less in diameter (sand, silt, and clay). In clast-supported deposits, the majority of the material consists of clasts that are in point-to-point contact. Material smaller than 2 mm is predominant in matrix-supported deposits, and most clasts are separated by matrix material. Grain sizes given for surficial deposits are based upon visual estimates and the modified Wentworth grain-size scale (Ingram, 1989). This classification system describes pebbles, cobbles, and boulders as differing sizes of gravel. The term "gravel" is also commonly used for rounded clasts that show evidence of fluvial transport. To avoid confusion, non-fluvial angular and subangular fragments ranging from 2 to 256 mm are referred to as pebble-sized or cobble-sized clasts.

Divisions of the time used herein correspond to those presented on the time chart shown in fig. 2. Terrace levels mapped in Pleistocene to Quaternary surficial deposits were based on relative heights and surface morphology.

HUMAN-MADE DEPOSITS

af **Human-made deposits (late Holocene)—**Deposits of this unit consist of fill and waste rock placed during construction. These deposits are composed mostly of unsorted silt, sand, and rock fragments but may include concrete and other construction materials. Much of the area in the City of Bayfield contains human-made deposits along roadways, residential and commercial building sites, and sites of oil and gas wells. Although these deposits are numerous in some locations, most are too small to show on the map at a scale of 1:24,000. The only area mapped as human-made deposit is an inactive landfill site in section 24, T34N, R7W where the deposits are distinct enough to show on the map. Maximum thickness of all human-made deposits is about 30 ft. Artificial fill may compact when loaded, if not adequately compacted at the time it is deposited.

ALLUVIAL DEPOSITS—Alluvial deposits are composed of gravel, sand, silt, and clay deposited by flowing water in stream channels and flood plains along the Los Piños River and its tributaries, and by slope runoff or sheet flow. Terrace alluvium along the Los Piños River is chiefly glacial outwash and reworked outwash that was probably deposited during late-glacial and early-interglacial stages. Deposits produced by sheet flow are mapped as sheetwash. Alluvial deposits may include colluvium that is too small to be mapped at a scale of 1:24,000.

Qa **Stream-channel and flood-plain deposits (Holocene)—**This map unit consists of unconsolidated alluvium that was deposited mostly in the stream channels and flood plains of the modern Los Piños River. Sediment in these deposits was transported and placed as sheet- or wedge-shaped deposits of active channel and bar complexes, and overbank areas that are mostly less than 4 ft above channel retreat. In the Los Piños River this unit also includes low-terrace alluvium that was deposited at or near the modern stream levels. In other drainages where Qa is mapped, the deposits are mostly unconsolidated pebbly sand, sand, and silt.

Deposits of this unit in the Los Piños River are mostly composed of poorly sorted, clast- to matrix-supported pebbles to boulders with a sandy to silty matrix. In some locations these gravel deposits are interbedded with or overlain by sheets and lenses of pebbly sand, silty sand, and sandy silt; locally the deposits of silty and sandy sediment are dominant. Some of the alluvium deposited in modern Los Piños River is reworked and remobilized glacial debris from adjacent outwash terraces.

Clasts in gravel deposits of the Los Piños River are mostly subrounded to rounded quartzite and metaconglomerate from Vallecito Conglomerate. Other subordinate clast types include amphibolite from the Irving Formation, granite from the Eolus Granite, vein quartz, and Phanerozoic sedimentary and igneous rocks exposed in the mountains north of the quadrangle. A weak imbrication of these clasts is developed in some of the gravel deposits.

The base of alluvium in the Los Piños River is nowhere exposed. The thickness maximum thickness of these deposits is estimated at about 40 feet. In other drainages where Qa is mapped the deposits are less than 6 feet thick.

$\boxed{Qt_{1\text{-}6}}$ **Terrace alluvium (early Holocene and Pleistocene)—**Heterogeneous deposits of unconsolidated alluvium composed of gravel, sand, silt, and clay that underlie a series of fill and fill-cut terraces. These deposits are mostly comprised of glacial outwash and alluvium that was deposited during late-glacial and early interglacial periods.

Atwood and Mather (1932) mapped most of the gravel deposits of this map unit as outwash deposits of the “Durango stage” or “post-Durango” moraine deposits, although some were included in their older fluvial “Florida gravels”. Richmond (1965) included many of the higher terrace deposits of this map unit as “fg” which correlated with the Florida gravels of Atwood and Mather (1932). Richmond (1965) concluded that the “fg” deposits were middle Pleistocene outwash gravels, and he included many of the lower terrace gravels in his “bg” deposits which were interpreted as late-middle Pleistocene Bull Lake outwash gravels.

The terrace deposits of this map unit slope gently southward and the edges of most of the terraces are approximately parallel to modern channels of the Los Piños River and Beaver Creek. Terrace heights in the Bayfield quadrangle range from 5 to 150 feet above the Los Piños River with the higher terrace gravels located in the southwest corner of the map.

There are no absolute age constraints on the deposits that underlie these terraces. Guido and others (2007) propose that deglaciation in the Animas River valley about 20 miles east was over by about 12 thousand years ago (ka) on the basis of ^{10}Be depth-profile ages. The lowest outwash terraces in the Bayfield quadrangle may have developed from ~12 ka to the early Holocene assuming similar deglaciation histories for the Animas River and Los Piños River.

The relative ages of deposits in this map unit is interpreted on the basis of the heights above the modern channels of Los Piños River and Beaver Creek with the oldest outwash terrace levels at the highest stratigraphic positions and the youngest are preserved near modern river levels.. The lowest terraces are designated as Qt_1 and highest terraces are denoted by Qt_6. These designations only define the relative height of the different terraces and should not be used to make terrace correlations or to assign absolute ages to the deposits. Additional work is needed to fully address the time correlations of these various deposits. In most instances the different terrace margins correspond to Qt_1 to Qt_4 terrace outwash levels mapped by Moore and Scott (1995).

Most of the deposits mapped as terrace alluvium in the Bayfield quadrangle are clast-supported, and poorly sorted boulder to pebble gravels with subrounded to rounded clasts set in a silty to sandy matrix. Clasts were derived from erosion of bedrock units that crop out in the quadrangle and the Los Piños River drainage basins to the north. Quartzite and metaconglomerate from the Proterozoic Vallecito Conglomerate are the dominant clast compositions. Lesser amounts of other Proterozoic clast lithologies include amphibolite, felsic gneiss and schist, and granite. Phanerozoic siltstone and sandstone, pebble conglomerate, limestone, vein quartz, rhyolite, and andesite were also identified in the deposits. Moore and Scott (1995) described rounded sandstone fragments of Mesa Verde Group, Dakota Sandstone, and Animas Formation. Most of the clasts in the gravel deposits are pebble to cobble in size but clasts of metaconglomerate up to 10 feet in maximum dimension were found in some locations.

In some places gravel deposits in the terrace deposits contain thin beds and lenses of silt and sand. The surfaces of the higher terraces can be covered with a thin veneer of sheetwash deposits and alluvium derived by erosion of the Animas Formation.

Qgo **Older gravels (Pleistocene or older)—**This unit is composed chiefly of material deposited on dominantly west-sloping erosional surface that grades to the ancestral valleys of the Los Piños River and its tributaries. Our map unit Qgo includes most of the deposits mapped by Moore and Scott (1995) as pediment gravel (Qpg). Since deposits that they mapped as residual gravels (Qrg) in Sec. 1, T33N, R7W are identical to gravel deposits in Qgo they were also mapped as older gravels. Atwood and Mather (1932) included some of the gravels of unit Qgo in their "Florida gravels." Some of these older gravel deposits (Qgo) may be early Pleistocene in age since they appear to grade to Qt_{5-6} terrace gravels, but the older gravel deposits are clearly incised by terrace levels of glacial outwash on the eastern edge of the Los Piños River valley.

The gravel deposits included in the map unit Qgo are interpreted as sediment transported by thin water-rich debris flows, sheetflow, and streams over a broad and gently sloping erosional plain developed on the western margin of the H-D Mountains. Moore and Scott (1995) mapped a portion of the deposits included in this map unit (Qgo) and interpreted them as pediment gravels that were placed on a bedrock-floored erosion surface. The surface on which these deposits were placed has a generally westward slope of about 120 to 280 ft/mi (Moore and Scott, 1995).

Although the slopes on the upper surfaces of these older gravel deposits are relatively uniform in a given location, our mapping has identified multiple terrace levels within these deposits, mostly along the edges of tributary drainages to the east of the Los Piños River. This evidence indicates that the deposits were placed at different times on cut-in-terraces that developed in the landscape during fluvial erosion of the H-D Mountains. The oldest gravel deposits of this unit are exposed at the highest elevations along ridges and divides between tributaries to the east of the Los Piños River. In a number of locations, multiple terraces developed along the margins of drainages at different stages of stream incision and erosion. These terraces are armored by gravel deposits that represent different generations of alluvial deposition as eroded debris was transported by fans and streams from the HD Mountains west into the ancestral Los Piños River valley. In the northern part of the map area, south of Armstrong Canyon, at least five different terrace levels were identified in these deposits.

The majority of these older fluvial gravel deposits (Qgo) are matrix supported with boulder to granule clasts set in matrix of sand to silt. Clasts are mostly subrounded to rounded granules to boulders of brown sandstone and siltstone from the Animas Formation, along with rare rounded fragments of quartzite and amphibolite. Minor amounts of rounded to subrounded clasts of diorite, granite, petrified wood, pebble conglomerate, siltstone, and sandstone were also contributed to these deposits by erosion of older conglomerates in the Animas Formation and San Jose Formation. In some locations, subrounded fragments of Animas Formation up to 3 by 6 by 10 feet in dimension were found, but most clasts are pebble to cobble sized.

For the most part, these deposits lack any obvious sedimentary structures, but locally they contain faint bedding and cross stratification. In some locations, channels were found at the base of the deposits where erosion had cut into underlying bedrock. Deposits in unit Qgo are up to 30 ft thick.

A diagonal-line pattern is used to denote areas on the map where the older gravel deposits form a thin veneer on Tertiary bedrock units. In these zones the gravel deposits are thin and discontinuous and there are abundant outcrops of bedrock units.

COLLUVIAL DEPOSITS—Unconsolidated silt, sand, gravel, and clay mobilized, transported, and deposited primarily by gravity on slopes adjacent to valleys, and along the flanks of ridges and hills.

Qc **Colluvium (Holocene and late Pleistocene)—**Deposits included in this unit are unconsolidated and unsorted to poorly sorted material composed of varying proportions of angular to subangular, pebble- to boulder-sized rock fragments of sandstone and siltstone from the Animas Formation that are set in a sandy to silty matrix. These deposits can contain a minor amount of well-rounded clasts derived from older fluvial deposits. Colluvial deposits are mostly matrix-supported, have weak or no stratification, and in general become coarser grained upslope.

Colluvial deposits are only well exposed along road cuts, drainage channels, and construction trenches. Thick deposits of colluvium were found on slopes and ridges in the eastern part of the quadrangle. A maximum thickness of around 50 ft is estimated for these deposits, although they are generally much thinner.

Colluvium is derived from weathered bedrock and surficial deposits and is transported a relatively short distance down slope. As used herein, colluvium follows most aspects of the definition of Hilgard (1892), which allows colluvium to include a minor amount of sheetwash. Other processes, particularly debris flows, may be active at different times on the same slope on which colluvium is the predominant material. As a result, many deposits mapped as colluvium will include minor amounts of material of varied genesis that are too small in area or too indistinct on aerial photographs to be mapped separately, including landslide deposits, creep, and debris-flow deposits.

At least several of the larger deposits mapped as colluvium on the south and east side of the quadrangle exhibit, in part, surface morphologic characteristics that are consistent with mass movement. These deposits, however, are heavily vegetated and eroded which masks diagnostic features of landslides.

Qls **Landslide deposits (Holocene and late Pleistocene)—**Heterogeneous unconsolidated deposits composed of unsorted, unstratified rock debris, sand, silt, clay, and older gravel associated with hummocky landforms. Most of the landslides in the map area are interpreted as rotational or translational landslides that developed in steep slopes within the Animas Formation. Maximum thickness of landslide deposits may be up to 100 ft.

ALLUVIAL AND COLLUVIAL DEPOSITS—Unconsolidated silt, sand, gravel, and clay deposited as alluvium and colluvium in fans, stream channels, flood plains, and adjacent hillslopes. Depositional processes in stream channels and on flood plains are primarily alluvial, whereas colluvial, alluvial, and sheetwash processes prevail on fans and on or adjacent to hillslopes.

Qf **Fan deposits (Holocene and latest Pleistocene)—**Crudely stratified sand and silt with minor amounts of pebble- to cobble-sized rock fragments and clasts from older surficial deposits and bedrock units. Transport and deposition of sediment in these fans was by debris flows, hyperconcentrated flows, and fluvial discharge in confined channels during seasonal high-discharge events. Fan deposits mostly post-date glaciation in the map area. Small fan deposits were mapped along the southern valley wall of Armstrong Canyon, at the mouth of Ritter Canyon in the northeast part of the quadrangle, and along the eastern margin of the Los Piños River in the southwestern part of the quadrangle.

All of the fan deposits form fan-shaped landforms at their mouths where stream gradient and velocity decreases and where topography widens from confined channels to open valleys. Gradients on the surface of the fans are generally less than 10 degrees. These deposits tend to be finer grained in the distal end where sheetwash and alluvial processes are more dominant. Maximum thickness of all the fan deposits mapped is estimated at about 25 ft.

Qca **Alluvium and colluvium, undivided (Holocene and late Pleistocene)—**This map unit contains stream-derived sediment and subordinate colluvial deposits that are between 5 and 20 ft thick. Alluvial and colluvial deposits are mapped together in this unit because they are gradational and have boundaries that are difficult to discern. These deposits are very poorly exposed and thickly vegetated, but the upper exposed surface is composed predominately of poorly- to moderately-sorted silt, sand, and pebbly sand. The margins of this map unit are dominated by colluvium (Qc) with poorly sorted, unstratified to poorly stratified, silty sand with angular fragments of surrounding bedrock.

Qcs **Colluvium and sheet wash, undivided (Holocene and late Pleistocene)—**Along with colluvial deposits this map unit includes materials transported by sheetflow on gentle hillslopes. The sheetwash deposits are derived from weathered bedrock and adjacent surficial deposits, and consist mostly of sand and silt with minor amount of pebble- to cobble-sized rock fragments. Sheetwash deposits in this unit are gradational with colluvium (Qc) on steeper slopes. The contacts between the sheetwash and colluvial deposits in this unit are not well defined, and the maximum thickness of these deposits is estimated to be from 10 to 20 ft.

Qsa **Sheetwash and alluvium (Holocene and late Pleistocene)—**This unit includes materials transported chiefly by sheet flow and deposited on gentle slopes along the lower margins of drainages and slopes that are gradational to alluvium in stream valleys. These deposits are mapped as a single unit because they have gradational boundaries, and it is difficult to separate these deposits at a scale of 1:24,000.

Sheetwash deposits are derived from weathered bedrock and surficial deposits, and are composed mostly of sand, silt, and clay-rich silt with minor amount of pebble- to cobble-sized rock fragments. Sheetwash deposits are gradational and interstratified with colluvium (Qc) on their upslope margins, and the contacts between sheetwash and colluvium are not well defined.

Alluvial deposits included in this map unit are present in the channels and narrow floodplains of tributaries to the Los Piños River. These stream deposits are mostly composed of silt- to sand-sized material that is crudely stratified. Some deposits contain minor amounts of subangular to rounded pebble- to cobble-sized clasts eroded from bedrock units and remobilized clasts from Quaternary gravel deposits. The maximum thickness of Qsa is estimated at about 30 ft although it may be thicker in some locations.

CENOZOIC BEDROCK UNITS

TERTIARY INTRUSIVE ROCKS

Tg

Mafic intrusive rocks (Tertiary, Absolute Age Unconstrained)—At several locations in the Bayfield quadrangle, the Animas Formation is cut by gabbroic dikes and sills that are up to 6 ft thick and exposed on strike from several feet to hundreds of feet.

Tertiary gabbroic dike rocks in the Bayfield quadrangle are greenish-black to black, and aphanitic with rare visible phenocrysts or other igneous fabrics and structures. In a few samples a poorly preserved porphyritic texture was noted. A detailed petrographic analysis of thin sections from these rocks established that the majority of the samples contained high concentrations of chlorite-group minerals, epidote, calcite, and opaque oxide minerals (e.g., magnetite). Subordinate constituents include altered euhedral crystals of plagioclase (some preserve relict zoning), clay minerals, and sparse grains of biotite and muscovite. In all of the samples examined in thin section there was about 10% to 25% subangular to angular fragments of quartz ± sandstone ± quartzite. None of the quartz-rich fragments in the rocks appears to be related to crystallization of the mafic magmas.

It is proposed that these gabbroic dikes encountered a water-rich sandstone aquifer at some point along their emplacement paths. This would not only explain the extensive alteration of these dikes, but the presence of quartz-rich fragments. The source of the xenocrystic material was relatively quartz rich (e.g., Pictured Cliffs Sandstone), unlike the Animas Formation which has abundant rock fragments and feldspar grains.

Emplacement of mantle magmas to form the gabbroic dikes in the Bayfield quadrangle was influenced by northwest and west fractures that developed prior to magmatism. Most of the dikes trend between 20° (N20°E) and 320° (N40°W) similar to major fracture systems developed in the Animas Formation.

Intrusive rocks in the Bayfield quadrangle are spatially related to Tertiary mafic intrusive rocks exposed from Durango to Pagosa Springs along the northern edge of the San Juan basin (e.g., Wood and others, 1948; Fassett and Hinds, 1971; Condon, 1990). There are no radiometric age constraints on these dikes, but many were emplaced into Eocene sedimentary rocks in the area. We propose that these dikes are part of a regional emplacement of mantle magmas in the Oligocene to Miocene due to incipient extension along the southern edge of the San Juan Mountains. Sets of north-trending mafic dikes emplaced from 29 to 28 Ma are also exposed in central New Mexico (Chamberlain and others, 2007). Magmatic events in the Oligocene also included the emplacement and development of the diatreme-dike complexes of the Navajo volcanic field, mafic effusions associated with the early phases of the Rio Grande rift systems, and voluminous eruptions of intermediate to felsic magmas associated with the San Juan volcanic field.

The Oligocene volcanic and intrusive events in the Four Corners region appear to have some fundamental connection on a regional scale. Tertiary magmatism on the northern Colorado Plateau and adjacent southern Rock Mountains has been attributed to slab rollback of shallow-subducted ocean lithosphere of the Farallon Plate (e.g., Lipman and others, 1971; Coney and Reynolds, 1977; Elston, 1984). In contrast, these events might have been linked to incipient rifting (indicated by north-northeast dike trends), mantle decompression, and upwelling of magmas that invaded the crust and might have also been the catalyst for contemporaneous eruption of the San Juan volcanic field (fig. 4).

PALEOCENE TO EOCENE SEDIMENTARY ROCKS UNITS

Tsj

San Jose Formation (Eocene)—Eocene sedimentary rocks of the San Jose Formation (fig. 5) are exposed in over a roughly oval area in the northeastern part of the San Juan basin where they are mostly in contact with Paleocene units (Baultz, 1967; Fassett, 1974) (fig. 3). Eocene rocks in the San Juan basin were originally referred to as Wasatch Formation (Granger, 1917; Reeside, 1924; Simpson, 1935 a, b, c) but later this unit was renamed the San Jose Formation by Simpson (1948a, 1948b).

The contacts of the San Jose Formation with the Animas Formation in the northeastern San Juan basin are described as unconformable (Wood and others, 1948) and conformable (Barnes, 1953; Barnes and others, 1954) in the central part of the basin. Along the margins of the basin the San Jose Formation is in unconformable contact with Paleocene to Mesozoic sedimentary units (Baltz, 1953; Barnes and others, 1954).

The San Jose Formation consists of an interbedded sequence of conglomerate, sandstone, siltstone, and shale that was deposited in a fluvial environment. Smith and others (1985) and Smith (1992) concluded that these rocks were deposited in "high-energy, low-sinuosity streams" on sand alluvial plains, muddy floodplains, and flood basins that developed south and southwest of the uplifted range in the San Juan Mountains (Sikkink, 1987).

The thickness of the San Jose Formation varies from 200 feet in the west part of the Central Basin (fig. 3) up to 2,700 feet in its eastern exposures (figs. 2 and 30 in Craigg, 2001). The rocks mapped as San Jose Formation in the Bayfield quadrangle make up about 300 feet of the basal part of the San Jose Formation.

The San Jose Formation is divided into four or five members in the southern San Juan basin that are not defined in northern San Juan basin (Baltz, 1953; 1967; Barnes and others, 1954; Smith and others, 1985; Smith, 1992). The rocks mapped as San Jose Formation in our investigation are similar to a sequence of cross-bedded sandstone and conglomerate that form a persistent basal part of the unit (Simpson, 1950; Baltz, 1967) referred to as the Cuba Mesa Member of the San Jose Formation (Smith and others, 1985; Smith, 1992).

The contact between the San Jose Formation and Paleocene upper Animas Formation has not been well constrained in the vicinity of the Bayfield quadrangle. Poor rock exposure has made it difficult to locate and delineate the contact in the field. Reeside (1924) concluded that the lower 400 feet of the San Jose Formation in Colorado consists of a sequence of interbedded conglomerate, arkosic sandstone, and "variegated" shale and contained upper Paleocene to early Eocene fossils of the "Tiffany" fauna (Granger, 1917; Simpson, 1935 a, b, c; Simpson, 1950). Reeside (1924) mapped the contact between the Animas Formation and overlying San Jose Formation across the south-central part of the Bayfield quadrangle. No evidence was found in our investigation that confirmed the location of the contact mapped by Reeside (1924).

Barnes (1953) mapped the location of a stratigraphic horizon which he identified as "d" and interpreted to coincide approximately with feldspathic conglomerate that Reeside (1924) considered as basal "Wasatch" Formation. Barnes (1953) measured a stratigraphic section showing the approximate location of the "d" horizon in feldspathic conglomerate and sandstone near base of the San Jose Formation; the measured section was located about 2 miles south of the southern edge of the Bayfield quadrangle. Smith (1992) noted that the Tiffanian strata deposited in the upper part of the Animas Formation near the “d” sandstone is laterally equivalent to his Cuba Mesa and Regina Members of the San Jose Formation. Barnes (1953) mapped the “d” horizon on the eastern side of the Bayfield quadrangle at a near constant elevation of about 7,400 feet. Given the fact that all of the strata and contacts in the Bayfield quadrangle have an average dip of approximately 5° south (Barnes, 1953 indicates dips of 7° south in the Animas Formation), it is not possible for the contact between the Animas Formation and San Jose Formation to be horizontal as noted by Barnes (1953). If a reasonable dip of 5° south is applied, then the contact in the eastern part of the Bayfield quadrangle would be located about 900 to 1000 feet higher than 7,400 feet in elevation.

We did not find any evidence to support a contact between the Animas Formation and San Jose Formation near an elevation of 7,400 feet (Barnes, 1953), but at about 8,000 feet elevation the upper member of the Animas Formation is overlain by a sequence of feldspathic conglomerate and conglomeratic sandstone that contain clast types that are distinct from those in the conglomerate of the Animas Formation. The lowest exposures of this distinctive succession of conglomerate sandstone were mapped as San Jose Formation in this investigation.

The contact of the Animas Formation San Jose Formation as we have mapped it in the Bayfield quadrangle is exposed on the extreme eastern and southeast edges of the quadrangle at elevations above ~8,000 feet. In these areas the exposed rocks consist of a sequence of interbedded lenses and beds of pebble to cobble conglomerate, sandstone, and siltstone up to several hundred feet thick. All of these rocks are feldspathic with crystals in some of the coarser beds and lenses being up to an inch in length. The feldspar in these rocks is commonly are partially to completely altered to kaolinite. Basal-scour surfaces in sandstone and conglomerate beds are common in this sequence of rocks, and fragments of fossil wood up to several feet in length occur in some outcrops.

Conglomeratic beds in the San Jose Formation within the Bayfield quadrangle are reddish brown to gray and mostly matrix supported with rounded to angular granule- to cobble-sized rock fragments. The dominant clast types in the conglomerates are quartzite, pebble conglomerate, chert, gray to brown sandstone and mudstone, granite, and monzonite and diorite porphyry similar to intrusive rocks in the La Plata Mountains. Some of the pebble conglomerate clasts contain granules and grains of volcanic fragments similar to rock types in the Animas Formation. The matrix of these conglomeratic beds in the Sand Jose Formation is fine to very coarse grained and mostly composed of quartz, feldspar, and lithic fragments in an iron oxide cement that in some conglomeratic beds is calcareous. Some beds of conglomerate exhibit a poorly developed reverse or normal grading, clast imbrication, and tangential to planar cross stratification.

Sandstone and siltstone beds and lenses examined in the San Jose Formation are reddish brown to tan, very fine- to coarse grained, and dominated by grains of quartz, feldspar, and rock fragments in iron-oxide cement. Most layers of sandstone and siltstone are planar laminated or exhibit planar to tangential cross stratification. Although shale is a dominant constituent of the San Jose Formation in other parts of the San Juan basin it is very subordinate within the sequence of rocks mapped as San Jose Formation in the Bayfield quadrangle.

TKa **Animas Formation (Paleocene and Upper Cretaceous)—**The Animas Formation consists of the late Cretaceous McDermott Member and the unnamed upper member of Paleocene age (Barnes and others, 1954) (fig. 5). The Animas Formation crops out mostly inside the northern edge of the central part of the San Juan basin (figs. 3 and 4). Only the upper member of the Animas Formation is exposed in the Bayfield quadrangle. In some locations in southwestern Colorado the upper member of the Animas Formation is gradational with the Paleocene Naciemento Formation (Baltz and others, 1967; Fassett and Hinds, 1971; Fassett, 1985), which is exposed further west and south of the map area (Craig, 2001, fig. 30). North and west of the Bayfield quadrangle the late Cretaceous Kirtland Shale is overlain by the Animas Formation.

Rocks of the Animas Formation were named the Animas River beds by Emmons and others (1896). The unit name was later changed to Animas Formation (Lee, 1912; Lee and Knowlton, 1917). Reeside (1924) divided the Animas Formation into the lower McDermott Formation and upper Animas Formation. The contact between the McDermott Member and upper member of the Animas Formation have been interpreted as either gradational and conformable (Baltz, 1953; Barnes and others, 1954; Carroll and others, 1997, 1998) or an unconformity representing a time gap of approximately 6 million years (Reeside, 1924; Fassett, 1985, 1988; Kirkham and Navarre, 2001).

The Animas Formation is about 1100 feet thick at the type locality along the Animas River near Durango (Barnes and others, 1954) but is reported to be up to 2,700 feet thick on the eastern side of the Bayfield quadrangle (Reeside, 1924; Fassett and Hinds, 1971). Fossil fauna and flora (Granger, 1917; Simpson, 1935a, b, c; Barnes, 1953) and palynomorphs (Newman, 1987) identified in the upper member of the Animas Formation are mostly interpreted as Paleocene in age. Knowlton (1924) concluded, however, that fossil flora from the upper member were Eocene in age.

The Animas Formation contains interbedded channel, floodplain, and lacustrine deposits formed on alluvial plains that developed on the southern margin of the San Juan uplift at the end of the Cretaceous. The rocks in the upper Animas Formation are probably part of the mid-fan facies that grade into more distal facies to the south (Fassett, 1985; Sikkink, 1987). Paleocurrent measurements (Sikkink, 1987) indicate that material deposited in this alluvial-fan system was transported from the uplifted highlands to the north of the San Juan basin by streams that flowed to the southeast (mean direction of S15E) and southwest (mean direction of S10W). Either before or during the deposition material in the alluvial fan complex there were eruptions of intermediate to felsic volcanic material in the region of the San Juan Mountains (figs. 3 and 4) that are present in the Animas Formation.

The upper member of the Animas Formation exposed in the Bayfield quadrangle consists of interstratified pebble to cobble conglomerate, feldspar-rich sandstone and siltstone, and shale. Most of the rocks in Animas Formation are tan, various shades of brown or olive brown and grayish white. In some locations, especially in the southern part of the map area, there are shale-dominated sequences tens of feet thick with of layers of light yellowish brown, grayish white and maroon shale.

Individual beds in the Animas Formation are mostly planar and continuous over hundreds of feet, but discontinuous lenses of conglomerate and sandstone are exposed in some sections. Sandstone to conglomerate beds in the Animas range from massive with little or no internal structures to planar and tangential cross laminated. In some locations trough cross stratification was observed in coarse grained to pebbly sandstone.

The upper part of the Animas Formation contains abundant plant fossils that are described in detail by Knowlton (1924). In addition, fragments of petrified wood, carbonized-plant impressions, fragments of coal are common in conglomerates, sandstones, and siltstones in the unit. A mammalian fossil bone fragment was collected on the surface of the Animas Formation in the southeastern part of the quadrangle, and this fossil was identified as an incisor tooth of a mid-Paleocene panodont (personal communication with Dr. Tom Williamson, curator of Paleontology at the New Mexico Museum of Natural History and Science, on November 3, 2006). Shale beds in the upper Animas Formation often contain Irregular calcified masses up to 6 to 8 inches in maximum dimension and up to 0.5 inches in diameter that appear to be root casts or branches of vegetation that are replaced by calcite.

Conglomerates in the upper Animas Formation in the Bayfield quadrangle are mostly matrix supported. Granules and pebbles are dominant in the conglomerates, but cobble-sized fragments were found in some beds. Clasts are rounded to subangular and poorly sorted, and most are composed of quartz, quartzite, chalcedony, chert, jasper, reddish brown to brown sandstone and siltstone, grayish white sandstone. Some conglomerate lenses and beds contain abundant angular fragments of perthitic microcline up to an inch in length. Granules to pebbles of porphyritic-aphanitic felsic to intermediate volcanic fragments with phenocrysts of plagioclase, granite, petrified wood, charcoal fragments, and limestone comprise a minor component of the clast assemblage. Some of the porphyritic-aphanitic volcanic fragments have a distinct mineral-flow lamination.

The matrix of conglomerates in the Animas Formation is coarse to very coarse grained and similar coarser-grained sandstones in the unit. The dominant constituents in sandstones and siltstones of the upper Animas Formation are subangular to subrounded mineral grains and granule-sized or smaller rock fragments of quartz, perthitic microcline or orthoclase, plagioclase, microcrystalline quartz (chert, jasper, chalcedony), porphyritic-aphanitic felsic to intermediate igneous fragments with phenocrysts of plagioclase, and quartzite. Most of the feldspar crystals are partially to completely altered to assemblages of one or more of the following minerals: kaolinite, sericite, calcite, and epidote. Other subordinate constituents in sandstones and siltstones in the Animas Formation include biotite, opaque minerals, zircon, sphene, hornblende, and muscovite along with rocks fragments of siltstone, claystone, shale, limestone, petrified wood, charcoal fragments, and limestone. Mineral grains and rock fragments in these rocks, and the matrix of conglomerates, are mostly subangular to subrounded, and set in cement composed of various proportions of hematite, calcite, clay, and quartz.

Shale beds in the Animas Formation vary from light brown, maroon, grayish white, tan, and purplish brown. Shale is a more dominant constituent of sections of the Animas Formation exposed in the southern part of the map area. These exposed sequences contain very thin to thick beds of thinly to thickly laminated shale that erodes into steep to moderate slopes. These deposits are up to several hundred feet thick. In some outcrops, beds of massive fine-grained limestone up to several feet thick were found in shale horizons.

STRUCTURAL GEOLOGY

No major geologic structures are well exposed or defined in the Bayfield quadrangle. A series of north--trending cross sections that extend from near Bayfield to the border of Colorado and New Mexico indicate that the base of the Tertiary section is a gently sloping surface with minor undulations, and structures identified in these sections at depths are subtle (Molenaar and Baird, 1989, 1991).

Dips of bedrock strata in the Bayfield quadrangle are mostly to the south and less than 10°. The dip directions of strata in a given location, however, can be quite variable due to irregular trends of beds and hummocky bedding surfaces in some outcrops. No evidence was found to suggest that folds or faults are responsible for the variation in bedding trends observed. In some areas the extreme variations in strike and dip direction are probably due to local development of channels and other primary sedimentary features, and some post-depositional effects from fracturing.

No mesoscopic or macroscopic faults or folds were identified in the field, but several prominent lineaments do appear on aerial photographs that could be related to faults or fractures at depth. Condon (1990) shows a south-plunging anticline to the east of the Los Piños River. This structure is also shown on the regional map of Steven and others (1974) and is defined by structure contours on the base of the Dakota Sandstone. This structure is not developed in exposed bedrock in the Bayfield quadrangle.

The dominant structures in the quadrangle consist of mesoscopic joint sets that are northwest to north trending (300° to 360°). In some outcrops, northwest-trending joints occur in sets with spacing from an inch to tens of inches. Conjugate joints sets are also developed in some outcrops in the Animas Formation. Joint sets measured in the Bayfield quadrangle have similar trends to sets documented in bedrock units in the Ludwig Mountain quadrangle to the north

(Carroll and others, 1998) and Basin Mountain quadrangle to the west (Kirkham and Navarre, 2001).

ECONOMIC GEOLOGY

Natural Gas: The Bayfield quadrangle is situated on the northern edge of the San Juan Basin which contains the largest proven reserves of natural gas in the United States, and the highest natural gas production in the nation at ~1,397 billion cubic feet (Cappa and others, 2007). The U.S. Geological Survey in 2002 estimated that the San Juan Basin province had a mean of 51 trillion cubic feet of undiscovered natural gas, a mean of 19 million barrels of undiscovered oil, and a mean of 148 million barrels of natural gas liquids (U.S. Geological Survey Fact Sheet, 2002). The San Juan Basin gas production is mostly from beds of coal within the Upper Cretaceous Fruitland Formation or from deeper Cretaceous sedimentary units (Lewis Shale, Mesa Verde Group, Mancos Shale, Dakota Sandstone) (fig. 5). None of these geologic units are exposed within the bounds of the Bayfield quadrangle, but deep wells that intersect these units at depth are developed in the quadrangle.

Development of natural gas in La Plata County was initiated in the 1920s with coalbed-methane production forming an important part of this production by the late 1970s. In 2006 and 2007 La Plata County produced 437,325,305 and 323,874,925 million cubic feet of coal bed and conventional natural gas (Colorado Oil and Gas Conservation Commission Statistics, Production and Sales, http://www.oil-gas.state.co.us/). This production equates to ~35% of the total active wells in Colorado, making La Plata County the number one producer of natural gas in the state. As of October 3, 2007, La Plata County had permitted 2,907 active oil and gas wells, some of which lie within or adjacent to the Bayfield quadrangle (Colorado Oil and Gas Conservation Commission Statistics, Weekly/Monthly Well Activity, http://www.oil-gas.state.co.us/). A current map of well locations and data can be downloaded from the Colorado Oil and Gas Conservation Commission website (http://www.oil-gas.state.co.us/). Of the total active wells in La Plata County, almost 95% are producing natural gas, and coalbed methane wells account for over half of all gas wells.

In 2006 the production value of natural gas and oil produced in La Plata County exceeded $1 billion (Colorado Oil and Gas Conservation Commission, 2007, http://www.oil-gas.state.co.us/). Oil and gas production and equipment generates nearly 66% of La Plata County's total 2006 property tax revenue plus additional income in the form of royalties, impact fees, and earned wages (La Plata County Assessor Information at http://co.laplata.co.us/asr_reports/asrinfo.htm).

Gravel & Aggregate: In 2007, there was active extraction of gravel in the gravel pit located in Section 14U, T34N, R7W. This deposit is developed in the lower glacial-outwash terrace gravels adjacent to the Los Piños River and is under the operation of Four Corners Materials, a division of Oldcastle SW Group, Inc. Gravel deposits that make up units Qa and Qt_{1-6} throughout the Bayfield quadrangle offer potential sources of sand and gravel.

GEOLOGIC HAZARDS

Flooding of the Los Piños River and its tributaries pose a threat to residents and structures in low-lying areas within the current flood plains. Mudflows and debris flows are also common in the channels and fan aprons of tributaries, especially those that flow from the mountains on the east side of the quadrangle.

There is evidence in the Bayfield quadrangle for mass movement both in the distant and more recent past. Slopes in the quadrangle are armored with loose and unconsolidated alluvial and colluvial deposits that could be prone to future development of landslides, slope creep sheetwash, debris flows, and mudflows. These areas are especially vulnerable to mass movement if slopes over steepened by human activity and natural erosional processes.

Fine-grained, low-density surficial deposits may collapse upon wetting or loading resulting in hydrocompaction, settling, and piping. Landslide deposits are potential sites of reactivation and future movement. Landslide deposits are also prone to settlement when loaded and shallow groundwater may occur within them.

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