COLORADO GEOLOGICAL SURVEY
COLORADO SCHOOL OF MINES
GOLDEN, COLORADO

GEOLOGIC MAP OF THE IGNACIO QUADRANGLE, LA PLATA COUNTY, COLORADO
CORRELATION OF MAP UNITS, 3-D OBLIQUE, GEOLOGIC HISTORY, GROUNDWATER, MINERAL RESOURCES, AND CROSS SECTION

OPEN-FILE REPORT 23-02
PLATE 1 OF 2
DOI: https://doi.org/10.58783/cgs.of2302.soni4718

CORRELATION OF MAP UNITS

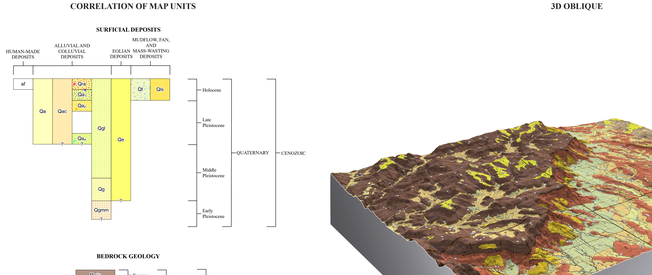


Table 1. Detrital Zircon analysis for bedrock units in the Ignacio quadrangle. Analysis by Darin Schwartz, Boise State University.

Field Number	UTM Easting[a]	UTM Northing[a]	Latitude	Longitude	N[b]	a^{2}	youngest date	youngest population	a^{2}	MSWD[c]	principal	mode2	mode3	mode4
IG22-DZ020	263651	4108913	37.096741	-107.639441	135	1.06	67.2 ± 1.5 Ma	67.2 ± 1.5 Ma	1.06	0.57	1718.9 Ma	1411.9 Ma	145.5 Ma	2152.5 Ma
IG22-DZ059	257328	4107569	37.083297	-107.718282	137	121	68.4 ± 5.5 Ma	75.3 ± 1.4 Ma	5	0.57	160.1 Ma	1693.3 Ma	82.8 Ma	1382 Ma
IG22-DZ10	265989	4109975	37.107082	-107.633946	132	123	68.6 ± 3 Ma	71.6 ± 1.5 Ma	5	0.27	1679.8 Ma	157.2 Ma	1420.7 Ma	74.4 Ma

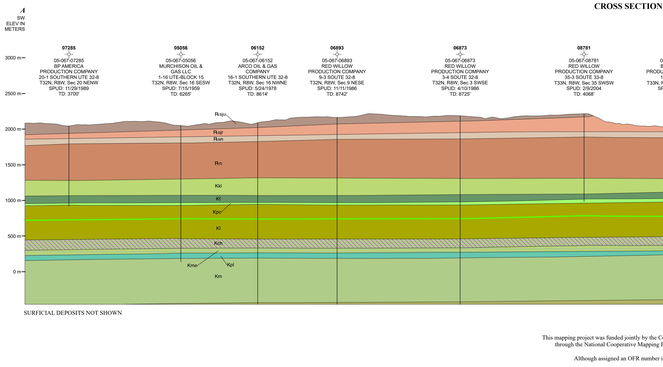
[a] North American Datum (NAD) 1983, zone 13N.
[b] Maximum algorithmical age, reported at 95% confidence.
[c] N = total number of analyses.
[d] a = number of successful analyses.
[e] MSWD = Mean Square of the Weighted Deviates.

Table 3. Optically Stimulated Luminescence (OSL) analysis for Quaternary deposits. Site located one mile to the east outside of the Ignacio quadrangle in the Tiffany quadrangle. Analysis by Steve Forman, Geoluminescence Dating Research Laboratory, Dept. of Geosciences, Baylor University, Waco, TX, USA.

Field Number	Laboratory Number	Map Unit	Material	Grain-size (μm)	UTM Easting[a]	UTM Northing[a]	Latitude	Longitude	Elevation (m)	Depth Below Ground Surface (m)	Aliquots[b]	Equivalent Dose (De) (G_y)[c]	Over dispersion(%)[d]	U (ppm)[e]	Th (ppm)[e]	K2O (%)[e]	Rb (ppm)	H2O (%)	Cosmic dose rate (mGray/ yr)	Dose Rate (mGray/ yr)	SAR OSL-age (yr)[f]
IG21-OSL1/2.3	5527	N/A (Qae, equiv?)	fine to medium sand	150-255	267896	4099202	37.083297	107.718282	1898.2	2.3	35/36	100.24 ± 3.71	22 ± 3	2.86 ± 0.01	8.66 ± 0.01	2.34 ± 0.01	92.1 ± 0.01	15 ± 3	0.234 ± 0.023	2.94 ± 0.09	34,085 ± 1605

[a]North American Datum (NAD) 1983, zone 13N.
[b]Aliquots measured, used to define De population by Central or Minimum age models (Galbraith and Roberts, 2012).
[c]Equivalent dose calculated on a pure quartz fraction with ultra-small aliquots with 20-80 g rains/aliquot and analyzed under blue-light excitation (470 ± 20 nm) by Single-Aliquot Regeneration protocols (SAR; Murray and Wintle, 2003; Wintle and Murray, 2006). Equivalent dose (De) was calculated by the Central Age or Minimum Age model when over-dispersion values are <20% or >20% (at two -sigma) and assuming a normal data distribution (Galbraith and Roberts, 2012; Liang and Forman, 2019).
[d]Overdispersion values reflects precision beyond instrumental errors; values of ≤ 20% (at 1 sigma limit) indicate low dispersion in equivalent dose values and defines a unimodal distribution. Values >20% are associated with mixed equivalent dose signature reflecting multiple grain populations or partial solar resetting.
[e]U, Th, Rb and K content analyzed by inductively coupled plasma - mass spectrometry by ALS Laboratory, Reno, NV.
[f]Includes a cosmic dose rate calculated from parameters in Prescott and Hutton (1994) and includes soft components (Liang and Forman, 2019).
[g]Systematic and random errors calculated in a quadrature at one standard-deviation by the Luminescence Dating and Age Calculator (LDAC) at https://www.baylor.edu/geosciences/index.php?id=962356 (Liang and Forman, 2019) Datum year is AD 2010.

CROSS SECTION A-A'



This mapping project was funded jointly by the Colorado Geological Survey and the U.S. Geological Survey through the National Cooperative Mapping Program under STATEMAP agreement G22AC00302.

Although assigned an OFR number in 2023, this report was published in 2024.

3D OBLIQUE

INTRODUCTION

The Ignacio quadrangle lies in La Plata County, Colorado. The town of Ignacio is in the northeast corner of the quadrangle. Land ownership within the quadrangle is approximately 57.7% Southern Ute Indian Tribe, 41.8% private, and 0.44% state, county, or town (La Plata County Assessor's Office, 2024).

Four main physiographic areas in the quadrangle are: the low-lying Los Pinos River valley near the northeastern corner of the quadrangle; La Boca Canyon near the southeastern corner; the high Mesa Mountains (as locally known), mostly in the southern half, and more subdued mid-elevation drainage swales and low ridges. Several major drainage divides occur in the map area. The highest point on the quadrangle is at 2284.3 m (7495 ft) in the Mesa Mountains on the western boundary of the quadrangle. The highest point of the Mesa Mountains is 55.2 m (181 ft) higher one mile west on the Bondad Hill quadrangle, coinciding with the unconformity between Tertiary and younger bedrock strata in the area. The lowest elevation on the quadrangle is at 1953.1 m (6304 ft) where La Boca Canyon leaves its southeast boundary as it drains toward the Los Pinos River. Most annual streams on the Mesa Mountains are ephemeral, flowing tributaries to the San Juan River, whereas those in the northeastern portion of the quadrangle flow easterly to the Los Pinos River. An unnamed annual stream near the northwestern corner of the quadrangle flows northwesterly toward the Florida River. Precipitation varies across the mapped area with the higher Mesa Mountains receiving more snowfall and having seasonally longer streamflow runtime than the 260 m (853 ft) lower lowlands in the town of Ignacio. The average annual precipitation at the town of Ignacio is 34.3 cm (13.5 inches), with the driest month in June (1 cm or 0.4 inches), and the highest amount in August (5 cm or 1.97 inches) (Colorado Climate Center, 2024). Snow may fall from November through May, with an annual average of 0.86 m (33.8 inches) and the highest amount in February (0.25 meters or 9.8 inches).

GEOLOGIC SETTING

The mapped area lies in the northern part of the San Juan Basin, north of the basin axis, in southern Colorado. This basin contains a variety of sedimentary deposits including marine, near shore, lagoonal, and continental deposits. Most of the geologic history and development of coal-bed methane and other petroleum resources (see the Petroleum Resources section of this report). Sedimentary rock units in the San Juan Basin range in age from Upper Devonian to Lower Eocene (Reynolds and Hagadorn, 2017), and are underlain by older Precambrian basement rocks.

The geologic history discussed here for the Ignacio quadrangle, and the sequence of strata shown on the cross-section, begins with the Permian sedimentary strata of Jurassic and Cretaceous age. Younger rocks in the subsurface units helps to guide structural observations on the ground surface. Continental shale and sandstone of the Jurassic Morrison Formation has been penetrated by multiple deep wells in the quadrangle. Younger Cretaceous strata are economically more significant and are commonly exploited for fossil fuels. The oldest Cretaceous rocks consist of basal deposits of the Dakota Sandstone and the Burro Canyon Formation. Overlying this unit are the Cenomanian-age shoreface and deltaic sandstone of the Dakota Group. The Dakota Group generally accumulated during the Cenomanian and Turonian age Western Interior Seaway (WIS). Continuing transgression and subsequent regression produced marine deposits of the Mancos Shale. Overlying lower strata of Campanian-age Mesaverde Group include the Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone. The youngest of these is the marine Point Lookout Sandstone which forms a resistant hogback on the WIS escarpment. The Mesaverde Formation consists of terrestrial deposits, which are overlain by transgressive marine sandstones of the Cliff House Sandstone as rising sea levels reflooded the western margin of the Cretaceous shoreline of the WIS. The retreat of the seaway deposited marine sediments of the Lewis Shale. The Huerfanito Bentonite bed, within the upper part of the Lewis Shale, is a 75-76 Ma volcanic ash-fall tuff that serves as the commonly used datum in the subsurface well log correlations (Fassett and Boyce, 2005, p. 113). Due to its relative ease of identification and regional extent, this datum greatly aids in subsurface well log correlations and determines the structural and strata relations of subsurface rocks in the San Juan Basin. The final regression of the WIS formed the last marine-derived strata in the San Juan Basin, the Campanian-age Pictured Cliffs Sandstone. Overlying terrestrial deposits of the Campanian-age Fruitland Formation contain numerous coal beds that are exploration targets for coal-bed methane gas. The youngest of accumulating sedimentary rocks, Kirtland Formation generally consists of lower shale units, the Farmington Sandstone Member, and upper shale units.

The tectonic influence of the Laramide orogeny began impacting stratigraphic units in the San Juan Basin as early as 80 Ma (Cather and others, 2019, p. 1657), indicated by local thinning of the Cretaceous Pictured Cliffs Sandstone and deflection of the Lewis Shale. Northeast-directed stresses with changing strikes in the quadrangle but crop out along nearby basin margins. Continuing tectonism also affected younger strata in the San Juan Basin that crop out in this quadrangle. Recent work by Cather and others (2019) provides the most comprehensive understanding to date of the Paleogene lithostratigraphy and depositional history for the northern San Juan Basin. Their work demonstrates a complex interplay between changing subsidence and transport directions over time. Cather and others (2019) attributed this complex fluvial evolution mainly to varying amounts of basin subsidence that were driven chiefly by the weight of accumulating sediments. Corresponding local basin uplift is reflected in Cenozoic hiatuses in sedimentation, which led to erosion and deformation.

Compositional signatures in sediments indicate different source rocks and regions in the neighboring evolving uplifts. In the northwestern part of the San Juan Basin, the Cretaceous age McDermott Formation and Paleocene age Animas Formation reflect a sudden and pronounced influx of coarse debris (Reynolds, 1924). The older McDermott Formation represents debris flows with high portions of boulder and cobble-rich conglomerates with igneous intrusive clasts, in contrast to the finer grained stream and lacustrine deposits containing volcanic fragments of the Animas Formation (Gonzales, 2010). As the basin continued to subside and fill with sediments, the average size of sediment particles decreased. This was likely due to the recycling of earlier sedimentary units concurrently unroofed and transported from neighboring uplifts. A trend of recovering increasingly older recycled detrital zircon in progressively younger Paleogene sandstone deposits appears to support the unroofing and erosion of sedimentary strata in the uplands likely in the San Juan uplift (Phase 2, Table 1).

Surficial map units include unconsolidated river and side-stream alluvium, colluvium, alluvial fan, eolian, and landslide deposits that range in age from Lower Pleistocene(?) to Upper Holocene. Compared to the eroded sedimentary bedrock units and terraces, older deposits are mostly preserved in higher elevations. The oldest deposits are about 275 meters (900 ft) above the Los Pinos River, indicating significant regional erosion during a period whose length is estimated to be approximately 2 million years though the actual duration could be longer or shorter.

PALEOCENE(?) AND LOWER EOCENE(?) STRATA

Paleogene units that crop out in and near the Ignacio quadrangle include the Paleocene-age Animas and Nacimiento Formations as well as the San Jose Formation, which is mostly Lower Eocene, but may include some Paleocene deposits at its base. Only the Nacimiento and San Jose formations are locally exposed in the Ignacio quadrangle.

Stratigraphic relations among these formations are complex and vary locally within the San Juan Basin. In some places their contacts are unconformable, but in others there they are gradational and interfingering. The complexity and the rarity of good exposures in low-relief areas have led some previous mappers either to group formations of the Cuba Mesa Member (Barnes, 1953) or to assign the same rocks to different formations; sometimes with arbitrary changes in nomenclature along river valleys or at state lines (e.g. Fassett and Hinds, 1971; Stone and others, 1976; Green, 1990; and Gregory, 2001). In Colorado southeast of Ignacio, it has identified and mapped formation contacts here and on adjacent quadrangles (see Geological Mapping section), but more detailed work is needed in this area.

Fassett and Hinds (1971, p. 34), suggested that the andesitic Animas Formation grades southward into nonandesitic Nacimiento Formation, the oldest formation exposed in the Ignacio quadrangle, along an interfingering boundary. Recognition of the gradational boundary between the fairly active during or between Nacimiento Formation is problematic, and any resolution would require further regional evidence. However, some previous workers have mapped the Animas Formation on the Ignacio quadrangle. The use of the name Animas Formation is mainly confined to Colorado, although outcrop exposures of the Animas Formation have been correlated along the Animas River southward as far south as Durango, New Mexico (Fassett, 1974). Subsurface correlation of the Animas has been challenging due to difficulty in interpreting the lithostratigraphy in the subsurface. Detailed paleontological investigations of the Animas by Fassett and Hinds, 1971, (p. 33), Advancements in subsurface wireline logging may allow for re-evaluation of this subsurface formation contact. The Nacimiento Formation containing the lower Pearce and overlying Cretaceous formations are found across the San Juan Basin (Baltz, 1967), which could help to resolve formation questions, but these zones have yet to be recognized in Colorado. Also, parts of both formations are similar in outcrop appearance. The stratigraphic nomenclature section was designated (Woodhouse, 2006).

Unfortunately, the senior author was unable to find any recent published data for the Colorado portion of the San Juan Basin that constrains the age range of supposed Paleocene and Eocene deposits. The most recent publications for these deposits in the Colorado portion of the San Juan Basin includes paleomagnetic polarity (Butler and others, 1981, p. 301-310; Sloan, 1987, p. 173, p.177; and Butler and Lindsey, 1985, p. 552), mammalian paleontology (Gingerich, 1983), paleobotany (Rouse, 1924), diagenesis (Simpson, 1950), paleontology (Manfriss, 1984), and fossil bone discovery (Roland Brown, written communication cited by Dane, 1948). Paleontological work, following the classification scheme originally described by Nichols and Ott (1978) and more recently summarized by Nichols (2009), may provide the needed constraints for bracketing Paleocene and Eocene deposits. For example, a rock sample from the Regina Member was correlated to pollen zone P5 of Tiffanian age (Plate 2, Table 2), but a slightly higher assemblage with pollen and palynology are needed. Some Paleocene fossils are known to have correlations based on earlier paleomagnetic measurements in the San Juan Basin. Sloan's revisions to the Butler and others (1981), shifted the Shoen and Paguate Tongues of the Nacimiento NALMA from the top of chron 27 to the middle part of chron 25, or 62.3-56.2 Ma, and essentially Upper Paleocene. The last major paleontological and mammalian studies of the Eocene in the northern part of the San Juan Basin was by Gazin (1987, fig. 2, p. 167) proposed that two separate continental divides were present in the region affecting drainage directions over time. During the Paleocene, the Hogback monocline was not present and sediments from the Cuba Mesa Basin drove to the approximately mid-Utah, that served as the continental divide. Later, during the deposition of the San Jose (during the Tiffanian time), the Hogback monocline was present, mid-Colorado/mid-New Mexico, continental divide.

The San Jose is the youngest formation in the San Juan Basin (Simpson, 1948; Simpson, 1950, p. 86), reaching 680 m (2,230 ft) in thickness (Brimhall, 1973, p. 198). The name San Jose Formation was first used by Simpson (1948, p. 257-258) for a sequence of rocks that crop out in the northern San Juan Basin. Barnes (1953) made excellent observations and correlations of Tertiary marker beds in the Colorado portion of the San Juan Basin, but were unnamed in the adjacent Bondad Hill and Loma Linda quadrangles where named facies of the San Jose Formation in New Mexico, the more recent member names of Smith (1992) have been used. Fassett and Hinds (1971) named the Nacimiento Formation. Presently, the subsurface and outcrop work of Smith (1992) seems to best represent the San Jose Formation's lithologic units in both the northern Colorado and adjacent New Mexico portions of the San Juan Basin. Smith (1992) divided the San Jose Formation into the Cuba Mesa Member, Regina Member, and informal lower and upper parts of the Ditch Canyon Member. Smith (1992) suggested that a tongue of the shale-dominated Regina Member projects into the middle of the Ditch Canyon Member in Colorado.

The Cuba Mesa Member is the basal unit of the San Jose Formation. It has not been identified in the Ignacio quadrangle. It is the description of these beds as hard sandstone and fine conglomerate (Barnes, 1953, p. 1955, in Simmons, 1960, p. 67) suggests that they may be in the Cuba Mesa Member and not the Ditch Canyon Member (lower part). However, suggestions of these sandstone beds to the Ditch Canyon Member (lower part) cannot be ruled out. Beds that could be part of three units (Cuba Mesa Member of the San Jose Formation, Nacimiento Formation, and Ditch Canyon Member (lower part), and Nacimiento Formation) are the Oxford tract has one of the highest selenium concentrations of 4,800 ug/L (Butler and others, 1993, p. 541, 90 times the allowable MCL for human consumption. Overlaying the maps of Broadhead and Ortiz (1979, Plate 1), with selenium maximum contaminant level exceedance maps of Sebol and others (2021, Fig. D-9), and this geologic map suggests that the area of selenium concentrations exceedance coincides with the locations of the Nacimiento-San Jose contact and Ignacio-Bondad anticline. Further investigation is needed to confirm this potential geological control on selenium content in ground water now in wells in the Mesa Mountains were tested.

GEOLOGIC MAPPING

This mapping project was aided by a review of previous geologic maps that covered the Ignacio quadrangle at varying scales. Those included published maps by Reeside (1924, 1:250,000 scale), Atwood and Mather (1932, 1:250,000 scale), Barnes (1953, 1:63,360 scale), Fassett and Hinds (1971, Plate 1; 1:380,160 scale), Stone and others (1974, 1:250,000 scale), Gordon (1990, 1982, 1:100,000 scale) and Craigg (2001, 1:500,000 scale). A preliminary 1:250,000 scale landslide map by Colton and others (1975) also aided our mapping. Sand and gravel deposits were mapped by Panos (1989, 1:24,000 scale). Geologic maps of adjacent or nearby quadrangles, previously published or in preparation by the Colorado Geological Survey at 1:24,000 scale include the following quadrangles: Bondad Hill quadrangle (Lewis and Barnett, 2005), Bayfield (Gonzales and others, 2008), Loma Linda (Lindsey and Gillam, in prep.), Bondad Hill (McCalpin and Gillam, in prep.), and Gem Village (Rogers, in prep.). Several geologic maps have been published for adjacent areas of the San Juan Basin in New Mexico, such as that by Manley and others (1987, 1:250,000 scale).

NOTES AND METHODS

The geologic descriptions and mapped contacts in this report are based on field observations in accessible areas. However mechanical leveling of irrigated agricultural fields obscured some geologic features. For land without access, contacts are based on observations from other accessible areas, publicly available aerial imagery, lidar digital elevation data, and hillshade models. Particle-size classes for sandy to clayey sediments are based on the Udden-Wentworth scale (Carpenter and Kreze, 2023, p. 161), except for USDA soil textural terms that are used for the near-surface parts of certain Quaternary units (Pannell and others, 1988; Carpenter and Kreze, 2023, p. 461). Descriptive phrases for textural matrices are based on the Folk classification (Folk, 1974). Color names and Munsell codes were obtained for dry sediments with the aid of Munsell and Globe soil color books (Munsell Color, 1975; Visual Color Systems, 2012) or from soil-series data (Pannell and others, 1988). Descriptions of soil calcium carbonate ($CaCO_3$) stage morphology are after Machette (1985). Divisions of geologic time follow Cohen and others (2023), and U. S. Geological Survey (2018). The methodologies utilized in the Optically Stimulated Luminescence (OSL) analysis (Table 3) of Steve Forman reference a variety of publications (Forman, 1984; Murray and Wintle, 2003; Wintle and Murray, 2006; Galbraith and Roberts, 2012; Liang and Forman, 2019).

GEOLOGIC STRUCTURE

Most strata in the Ignacio quadrangle dip about 2° to the south, like other strata in the central part of the San Juan Basin. However, moderate dips are recorded along the Hogback monocline which forms the northern basin margin. The Ignacio-Blanco anticline is the most significant anticlinal structure in the quadrangle feature in the quadrangle and is unique in the central part of the basin (Fassett and Boyce, 2005, p. 113). Location of the Ignacio-Bondad anticline for this map was based on its subsurface expression at the base of the Dakota Formation (Anderson, 1995; Steven and others, 1974) where it has more than 30.5 m (100 ft) of closure in the Dakota Group (Bowman, 1978, p. 132-133). Surface dips and closure are less in outcrops of the San Jose Formation. Such upward-decreasing dips (Reeside, 1924) from older to younger strata occur in the Mesa Mountains and Bondad Hill quadrangles, however, the exact amount of dip and Nacimiento formations. Earlier mappers and the present authors have had difficulty in accurately measuring surface dips that are caused by the unconformity between the base of the San Jose Formation and the youngest Nacimiento Formation, probably because of the lenticular nature of fluvial sandstones in the San Jose Formation (Barnes, 1953).

GEOLOGIC HAZARDS

The major hazard in the Ignacio quadrangle is the risk of landslides along the northern flank of the Mesa Mountains, as indicated by the presence of recent and historic landslide deposits. Landslide monocline which forms the northern basin margin. The stability of soil and rock subjected to rockfall and debris-flooding. The siting of soil and rock subjected to rockfall and debris-flooding. The siting of roads, pipelines, and other human-made features along these steep, unstable shale slopes should be avoided or carefully engineered. Steep slopes in the Mesa Mountains are also subject to soil creep, debris drainage channels, cause channel avulsion, and bury and damage or destroy roads, structures, driveways, exposed pipelines, and culverts.

Low-lying areas along the Los Pinos River may be subject to flooding (FEMA, 2024a,b; Colorado Water Conservation Board, 2024). In addition, occasional heavy rains have caused flash flooding along ephemeral streams in the area, especially during the Wand River basin, Wyoming: Palynology, v. 2, p. 93-112. https://www.jstor.org/stable/40072719.

Many of the bedrock and surficial units are easily erodible and have moderate to high shrink-swell potential (Pannell and others, 1988; Noe and others, 2014). Also, poorly consolidated low-density surficial units may form unstable slopes, especially in the subsurface. Locally prone to settling, forming piping voids, and collapsing when wetted (White and Greenman, 2008). In general, surficial deposits are not well exposed without trenching or digging. Detailed investigation for any construction project is typically needed on a site-by-site basis.

GROUNDWATER RESOURCES

There are 409 records of constructed water wells in the Ignacio quadrangle as of January 2024 (Colorado Division of Water Resources, 2024), although records may not exist for all wells constructed. Also, the majority of recorded wells (269) are for industrial use, of which 35 in the Mesa Mountains have depths from 700 to 1,675 m (2,600 to 5,500 ft). Twenty-six wells are for stock use in remote areas with no commercial, domestic, household, or stock watering. These wells are all in lower-elevation areas of the quadrangle. Of these wells, two was noted that parts of the well-casing had been stabilized by a range from 9 to 95 m (30 to 310 ft). Numerous springs indicate that there is a perched water table near the base of unit Qa, that is likely recharged by seasonal runoff and irrigation water applied to the terrace top. This water table would likely drop and spring discharges cooled decline if irrigation decreases in the future.

In this quadrangle, some ground-water locations have selenium concentrations that exceed the allowable maximum contaminant level (MCL) established by the Environmental Protection Agency (EPA) which is 0.05 mg/L (Butler and others, 1993, p. 1). Ground and surface waters have elevated concentrations of contaminants, especially in the northern portion of the Ignacio quadrangle. In U.S. Geological Survey studies (Butler and others, 1993), Rock Creek surface-water samples have concentrations for selenium (45 ug/L, p. 13), cadmium (0.3 ug/L, p. 54), and manganese (1,400 ug/L, p. 63) that are greater than the MCL. Surface water from the Oxford tract of the Gem Village quadrangle, adjoining the north-edge of the Ignacio quadrangle, has selenium concentrations as high as 9 ug/L(Butler and others, 1993, p. 54). Groundwater from the Oxford tract has one of the highest selenium concentrations of 4,800 ug/L (Butler and others, 1993, p. 541, 90 times the allowable MCL for human consumption. Overlaying the maps of Broadhead and Ortiz (1979, Plate 1), with selenium maximum contaminant level exceedance maps of Sebol and others (2021, Fig. D-9), and this geologic map suggests that the area of selenium concentrations exceedance coincides with the locations of the Nacimiento-San Jose contact and Ignacio-Bondad anticline. Further investigation is needed to confirm this potential geological control on selenium content in ground water now in wells in the Mesa Mountains were tested.

MINERAL RESOURCES

Oil and gas and gravel are present mainly along the Los Pinos River and beneath its alluvial terraces. Gravel is also quarried on small areas on top of the Mesa Mountains in the southern part of the quadrangle (T. 32 N., R. 8 W.) has been used as an aggregate source for construction of roadways and gas pipelines in the Mesa Mountains. Elsewhere on the Ignacio quadrangle, sand and gravel deposits may be extracted commercially as aggregate, either because the deposits are thin, or because they underlie developed areas in and near the town of Ignacio. However, there is some potential for limited use by local landowners as borrow material or fill.

PETROLEUM RESOURCES

As of January 2024, there are 642 oil and gas wells in the Ignacio quadrangle: 512 producing gas, 52 plugged and abandoned, 46 shut-in, 15 drilled and abandoned, 5 temporarily abandoned, 5 permitted, and 2 injection wells (Colorado Energy and Carbon Management Office, 2024). Most are in the Ignacio-Blanco field, one of the largest gas fields in the United States (Coalson, 2014). Hart (1988), Fassett and Boyce (2005), and Fassett (2010) provide more information for the Colorado portion of the Ignacio-Blanco field. Historically, gas production was from the Morrison and Burro Canyon Formations and Dakota Group along the Ignacio-Bondad anticline. Early drilling followed surface mapping of the Ignacio-Bondad anticline. Development of gas from the Mesaverde Group in the 1950's, early 1960's, and late 1970's to early 1980's was primarily from the Point Lookout Sandstone. Currently the vast majority of gas in the area is being produced from the Fruitland-Pictured Cliffs gas "pool," as shown by well counts and cumulative production. This includes gas from the Basal Fruitland Cliffs Sandstone, the overlying coals of the Fruitland Formation, and sandstones above the coals. Coalbed methane (CBM) is produced by pumping large volumes of water to reduce the hydrostatic pressure and freeing gas contained in coal seams that have been adsorbed onto the coal-clast surfaces to flow toward the well bore. Coalbed methane production began in the 1980's and dominated activity for the following decade. Recently horizontal drilling into the coal beds and testing of Lewis and Mancos shales have occurred in the area.

There are two deep test wells in the Ignacio quadrangle. The deepest oil and gas well in the 1-mile area Basin is in this quadrangle, the 1976 Amoco Hale #11 (API: 05-067-06114). This well was drilled to a total depth of 4,420 m (14,503 ft) in SE ¼ SW ¼ sec. 15, T. 33 N., R. 8 W., penetrating 65.5 m (215 ft) into the Precambrian basement rocks. Only one other well also penetrated Precambrian basement in the Colorado portion of the San Juan Basin. Another significant deep well is the 1955 Stanolind Oil & Gas Ute Indian TR* 6 well (API: 05-067-05416), which reached the Carboniferous Molas Formation at a depth of 4,001 m (13,127 ft) in SE ¼ SE ¼ sec. 17, T. 33 N., R. 7 W. This is the second deepest test well of only 1980's was primarily from the Point Lookout Sandstone. Currently the vast majority of gas in the area is being produced from the Fruitland-Pictured Cliffs gas "pool," as shown by well counts and cumulative production. This includes gas from the Basal Fruitland Cliffs Sandstone, the overlying coals of the Fruitland Formation, and sandstones above the coals. Coalbed methane (CBM) is produced by pumping large volumes of water to reduce the hydrostatic pressure and freeing gas contained in coal seams that have been adsorbed onto the coal-clast surfaces to flow toward the well bore. Coalbed methane production began in the 1980's and dominated activity for the following decade. Recently horizontal drilling into the coal beds and testing of Lewis and Mancos shales have occurred in the area.

There are two deep test wells in the Ignacio quadrangle. The deepest oil and gas well in the 1-mile area Basin is in this quadrangle, the 1976 Amoco Hale #11 (API: 05-067-06114). This well was drilled to a total depth of 4,420 m (14,503 ft) in SE ¼ SW ¼ sec. 15, T. 33 N., R. 8 W., penetrating 65.5 m (215 ft) into the Precambrian basement rocks. Only one other well also penetrated Precambrian basement in the Colorado portion of the San Juan Basin. Another significant deep well is the 1955 Stanolind Oil & Gas Ute Indian TR* 6 well (API: 05-067-05416), which reached the Carboniferous Molas Formation at a depth of 4,001 m (13,127 ft) in SE ¼ SE ¼ sec. 17, T. 33 N., R. 7 W. This is the second deepest test well of only four in the Colorado portion of the San Juan Basin and the 11th deepest well in the entire San Juan Basin. These two wells, and three others that penetrate the Entrada Sandstone in the Ignacio quad, provide the best subsurface control in the quadrangle for strata older and deeper than those of the Dakota Group. These formations penetrated and logged below the Dakota in these wells include the Morrison, Entrada, Wingate, Chinle, Cutler, Hermosa, Molas Formations, and Precambrian rock. The units below the Morrison Formation are not shown in the map cross section.

GEOLOGICAL MAPPING

This mapping project was aided by a review of previous geologic maps that covered the Ignacio quadrangle at varying scales. Those included published maps by Reeside (1924, 1:250,000 scale), Atwood and Mather (1932, 1:250,000 scale), Barnes (1953, 1:63,360 scale), Fassett and Hinds (1971, Plate 1; 1:380,160 scale), Stone and others (1974, 1:250,000 scale), Gordon (1990, 1982, 1:100,000 scale) and Craigg (2001, 1:500,000 scale). A preliminary 1:250,000 scale landslide map by Colton and others (1975) also aided our mapping. Sand and gravel deposits were mapped by Panos (1989, 1:24,000 scale). Geologic maps of adjacent or nearby quadrangles, previously published or in preparation by the Colorado Geological Survey at 1:24,000 scale include the following quadrangles: Bondad Hill quadrangle (Lewis and Barnett, 2005), Bayfield (Gonzales and others, 2008), Loma Linda (Lindsey and Gillam, in prep.), Bondad Hill (McCalpin and Gillam, in prep.), and Gem Village (Rogers, in prep.). Several geologic maps have been published for adjacent areas of the San Juan Basin in New Mexico, such as that by Manley and others (1987, 1:250,000 scale).

NOTES AND METHODS

The geologic descriptions and mapped contacts in this report are based on field observations in accessible areas. However mechanical leveling of irrigated agricultural fields obscured some geologic features. For land without access, contacts are based on observations from other accessible areas, publicly available aerial imagery, lidar digital elevation data, and hillshade models. Particle-size classes for sandy to clayey sediments are based on the Udden-Wentworth scale (Carpenter and Kreze, 2023, p. 161), except for USDA soil textural terms that are used for the near-surface parts of certain Quaternary units (Pannell and others, 1988; Carpenter and Kreze, 2023, p. 461). Descriptive phrases for textural matrices are based on the Folk classification (Folk, 1974). Color names and Munsell codes were obtained for dry sediments with the aid of Munsell and Globe soil color books (Munsell Color, 1975; Visual Color Systems, 2012) or from soil-series data (Pannell and others, 1988). Descriptions of soil calcium carbonate ($CaCO_3$) stage morphology are after Machette (1985). Divisions of geologic time follow Cohen and others (2023), and U. S. Geological Survey (2018). The methodologies utilized in the Optically Stimulated Luminescence (OSL) analysis (Table 3) of Steve Forman reference a variety of publications (Forman, 1984; Murray and Wintle, 2003; Wintle and Murray, 2006; Galbraith and Roberts, 2012; Liang and Forman, 2019).

REFERENCES

Anderson, R.C., 1995, The oil and gas opportunities on Indian lands: Exploration policies and procedures (1995 edition): Golden, Colo., U.S. Department of the Interior, Bureau of Indian Affairs, Division of Energy and Mineral Resources, General Publication G-95-3, 149 p.

Atwood, W.W., and Mather, K.F., 1932, Physiography and Quaternary geology of the San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 166, 171 p., https://doi.org/10.3133/pp166.

Aubrey, W.M., Molenaar, C.M., and Baird, J.K., 1991, Geologic framework and stratigraphy of Cretaceous and Tert