Assessment of Potential Groundwater Level Changes from Dewatering at the Proposed Roca Honda Mine

McKinley County, New Mexico

Prepared for:

Roca Honda Resources, LLC
4001 Office Court Drive
Suite 102
Santa Fe, NM 87507

Prepared by:

INTERA Incorporated
6000 Uptown Boulevard NE
Suite 220
Albuquerque, New Mexico 87110

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The following list identifies the pages that were replaced in the March 8, 2012, revision to the *Assessment of Potential Groundwater Level Changes from Dewatering at the Proposed Roca Honda Mine:*

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EXECUTIVE SUMMARY

Roca Honda Resources, LLC (RHR) is planning to develop a new underground mine at a location approximately 23 miles northeast of the City of Grants and 2.5 miles northwest of the community of San Mateo in McKinley County, New Mexico. The Roca Honda permit area encompasses Sections 9, 10, and 16 of Township 13 North, Range 8 West. Mine workings will be developed at depths between 2,100 and 2,800 feet below ground surface within the Westwater Canyon Member of the Morrison Formation (Westwater). The mine will include vertical production shafts, declines, ventilation shafts, and underground workings.

The proposed Roca Honda mine is located within the San Juan Basin. Temporary dewatering will occur in three aquifers: the Gallup Sandstone (Gallup), the Dakota Sandstone (Dakota), and the Westwater, during a 13-year period of mine construction and operation. RHR has filed an Application for Dewatering an Underground Mine with the New Mexico Office of the State Engineer (NM OSE) that proposes maximum dewatering rates for various time periods during construction and operation of the mine. All dewatering will cease with the end of mining.

RHR requested that INTERA Incorporated (INTERA) construct groundwater flow models to evaluate potential changes in groundwater levels from the mine dewatering in order to support the mine dewatering application submitted to the NM OSE and the Mine Permit Application submitted to state and federal agencies. The specific objective is to estimate the groundwater level changes that mine dewatering might have on aquifers, wells, springs, and local and regional water supply systems, including those for the nearby population centers of Grants, Gallup, Milan, Crownpoint, San Mateo, and the Acoma and Laguna Pueblos.

INTERA constructed numerical models of groundwater flow in the San Juan Basin to represent historical groundwater changes within the Gallup, Dakota, and Westwater aquifers, as well as future changes from dewatering at the Roca Honda mine. A United States Geological Survey (USGS) model of steady groundwater flow in the San Juan Basin constructed by Kernodle (1996) was used as a basis for the INTERA models. INTERA significantly improved on the existing USGS model by incorporating new data on aquifer parameters and stratigraphy in the vicinity of the Roca Honda permit area, modifying boundary conditions, increasing the number of calibration data for the steady-state calibration, and carrying out a transient calibration for the period from 1930 to 2012. The calibrated Roca Honda mine models are the best available tools for predicting potential groundwater level changes from proposed dewatering at the Roca Honda mine.

The public water supplies for the Village of Milan and the City of Grants will not be affected by Roca Honda dewatering because they pump groundwater from aquifers that are stratigraphically separated from the Westwater aquifer by thick shale intervals with low hydraulic conductivity.

The model predicted that the maximum extent of the ten-foot groundwater level drawdown contour from the permit area boundary in the Westwater aquifer will be 17 miles. Drawdown at wells in the vicinity of the Roca Honda permit area is predicted to be 10 feet or more at nine wells screened in the Westwater, three of which are used for mining, three for domestic supply, one for livestock, and two for unknown uses. Drawdown is predicted to be 10 feet or more at one domestic well screened in the Dakota, and three wells in the Gallup, of which one is permitted for exploration, one for livestock, and one with an unknown use. Drawdown is predicted to be less than 10 feet at wells in the Mancos Shale and aquifers overlying the Gallup. Drawdown at springs is predicted to be negligible.

The pumping rates and time periods used to represent Roca Honda dewatering in the mine dewatering simulation represent a "worst-case" scenario because actual Roca Honda dewatering rates will not begin at the maximum permitted rates as simulated in the groundwater models, but will instead increase gradually over the 13-year mining period. Thus, model results provide a conservative estimate of changes in groundwater levels from Roca Honda mine dewatering

In summary, INTERA has constructed groundwater flow models that provide a reliable prediction, based on the available data and the model calibration, of the potential changes in groundwater levels from proposed dewatering at the Roca Honda mine. Groundwater level declines in the Westwater aquifer due to RHR dewatering that are greater than 10 feet will not extend farther than 17 miles from the Roca Honda mine. Groundwater declines within the Gallup and Dakota aquifers will not extend beyond the mine permit area. Dewatering the Roca Honda mine will not adversely affect the water resources of the Village of Milan, Acoma Pueblo, Laguna Pueblo, the City of Grants, the community of San Mateo, the Crownpoint area, or the City of Gallup. Mine dewatering will not have any adverse impacts on area springs.

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ABBREVIATIONS AND ACRONYMS

ac-ft	acre-feet
ac-ft/yr	acre-feet per year (10 ac-ft/yr = 6.2 gpm)
ASTM	American Society for Testing Materials
BDR	Baseline Data Report
bgs	below ground surface
Brushy Basin	Brushy Basin Member of the Morrison Formation
Dakota	Dakota Sandstone
DBSAI	Daniel B. Stephens and Associates, Inc.
ft amsl	feet above mean sea level
ft/day	feet per day
ft^2/day	square feet per day
ft^3/day	cubic feet per day
ft^3/s	cubic feet per second
Gallup	Gallup Sandstone
GIS	geographic information system
gpm	gallons per minute
in/yr	inches per year
INTERA	INTERA Incorporated
JSAI	John Shomaker and Associates, Inc.
Mancos	Mancos Shale
NM OSE	New Mexico Office of the State Engineer
NRMSE	normalized root mean square error
PCG	Pre-Conditioned Conjugate Gradient
PWS	public water supplies
Recapture	Recapture Shale Member of the Morrison Formation
RHR	Roca Honda Resources, LLC
US BLM	United States Bureau of Land Management
USGS	United States Geological Survey
Westwater	Westwater Canyon Member of the Morrison Formation

DEFINITIONS

Acre-foot[1]: Volume equal to a depth of one foot over an area of one acre.

Anisotropy: Condition or situation for which physical properties vary with direction.

Aquifer: A geologic unit that conducts water at rates that yield economically significant quantities of water to wells and springs.

Aquifer test[2]: A procedure for measuring the characteristics of an aquifer by pumping a well and monitoring changes in groundwater levels (heads) and the pumping rate. Also called hydraulic testing or pumping test.

Aquitard: A geologic unit or confining bed that retards but does not prevent flow of water to an adjacent aquifer. It does not readily yield water to wells or springs.

Groundwater: Subsurface water found in zone of saturation, wherein all or nearly all pores are water-filled.

Groundwater flow model[2]: A numerical tool for describing and predicting water flow in the sub-surface by solving the equation for flow through porous or fractured media.

Groundwater Vistas[3]: Software for building, testing, and applying groundwater flow and transport models from Environmental Simulations, Inc.

Head: Elevation to which water rises at a point; a measure of the energy in water controlling flow; usually refers to the energy from pressure, elevation, or the sum of the two. Also referred to as "groundwater level."

Hydraulic conductivity: The rate of water flow through a unit cross-section (e.g., 1 foot or 1 meter) under a unit gradient for groundwater head. It is defined by the permeability (the capacity of a material to transmit fluid) and the fluid properties of water.

MODFLOW[2]: The three-dimensional finite-difference code for solving the governing equation for groundwater flow through porous media developed by the United States Geological Survey.

MODFLOW-SURFACT[4]: A version of the MODFLOW modeling code with proprietary improvements to more efficiently solve groundwater flow problems. Developed by HydroGeoLogic, Inc.

Porosity[2]: Volume of empty pore space (voids) within a material divided by the total volume of the material.

DEFINITIONS (CONTINUED)

Specific storage[2]: Volume of water released from a unit volume of confined aquifer solely due to the expansion of water and aquifer compression when the pressure head decreases by a unit amount.

Specific yield[2]: Proportion of porosity from which water freely drains after the water table drops in an unconfined aquifer.

Transmissivity[2]: The product of the thickness of an aquifer and a representative hydraulic conductivity.

[1] Unless otherwise indicated, definitions adapted from Bates and Jackson, 1984, Dictionary of Geological Terms, 3rd ed., Bantam Doubleday Dell Publishing Group, Inc., NYC, NY. 571 p.

[2] Definitions adapted from Domenico and Schwartz, 1998, Physical and Chemical Hydrogeology, 2nd ed., John Wiley and Sons, Inc., NYC, NY. 506 p.

[3] Adapted from Rumbaugh and Rumbaugh (2007).

[4] Adapted from HydroGeoLogic Inc. (1996).

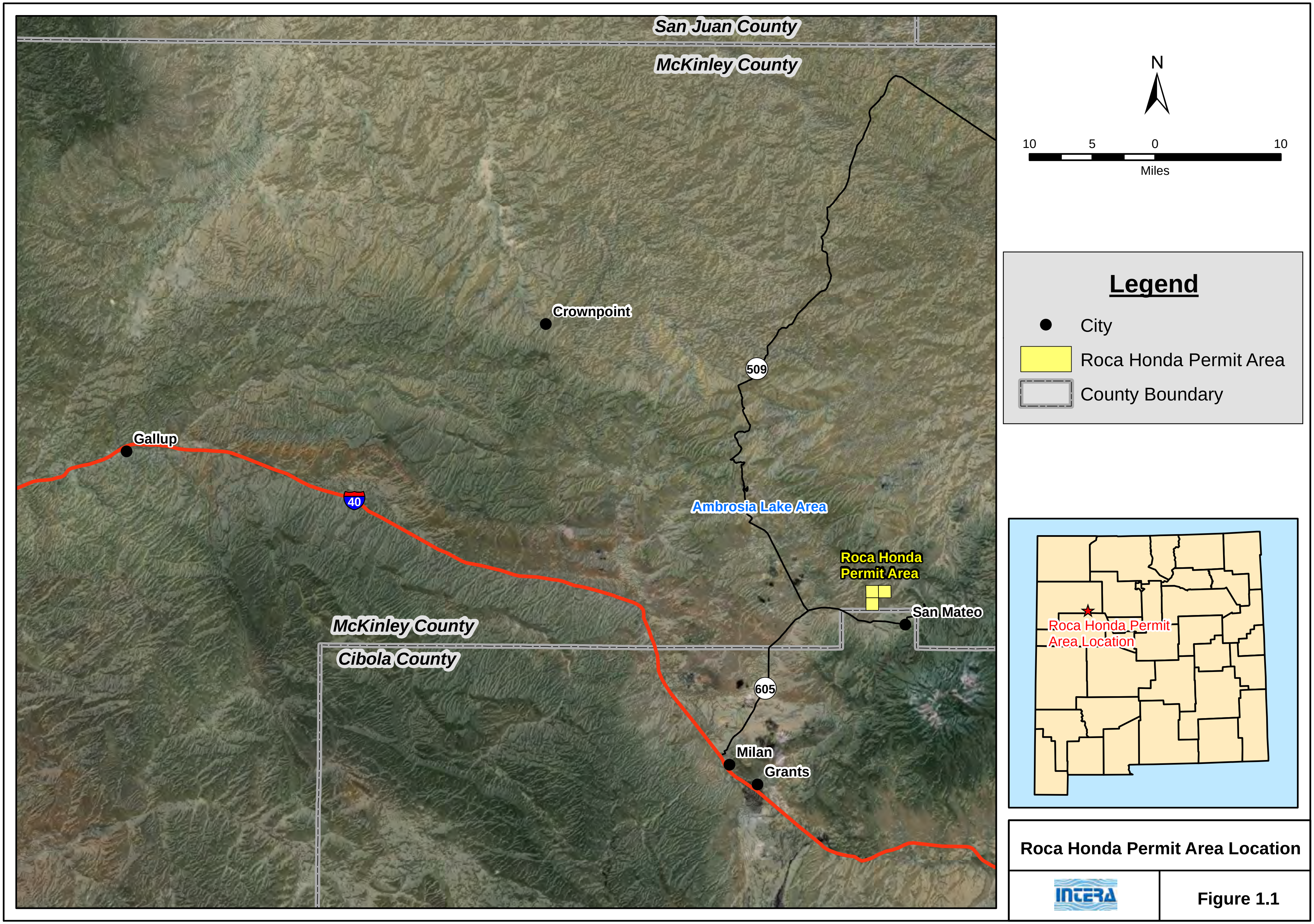
1.0 INTRODUCTION

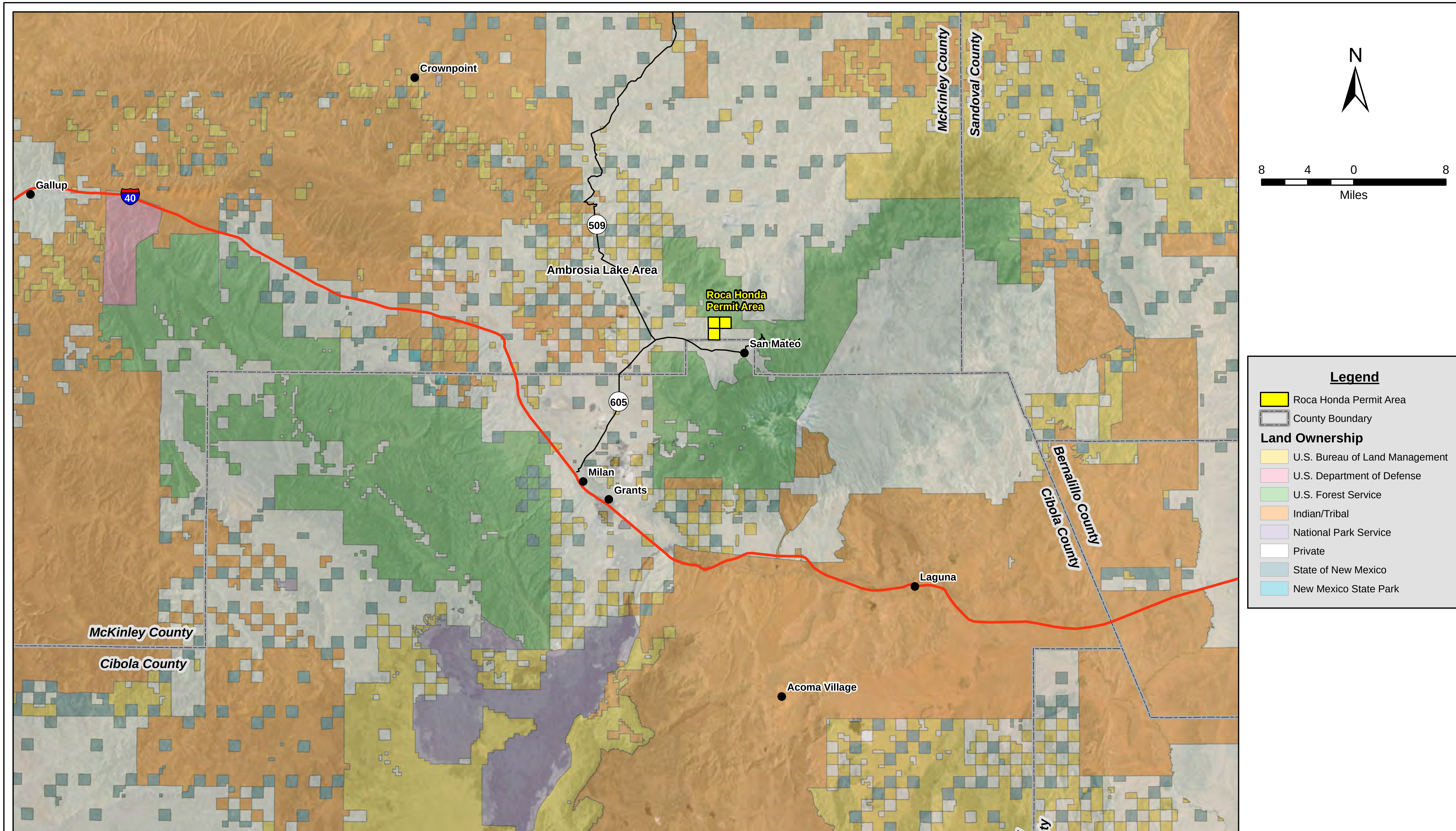
Roca Honda Resources, LLC (RHR) is planning to develop a new underground mine at a location approximately 23 miles northeast of the City of Grants and 2.5 miles northwest of the community of San Mateo in McKinley County, New Mexico (Figure 1.1). The Roca Honda permit area encompasses Sections 9, 10, and 16 of Township 13 North, Range 8 West (yellow squares in Figure 1.1). Mine workings will be developed at depths between 2,100 and 2,800 feet below ground surface (bgs) within the Westwater Canyon Member of the Jurassic Morrison Formation (Westwater). The mine will include vertical production shafts, declines, ventilation shafts, and underground workings.

Construction of the production shaft and surface facilities is projected to take three years; mining will last another ten years. The shaft will pass through three geologic units that contain groundwater in the area of the mine: the Gallup Sandstone (Gallup), the Dakota Sandstone (Dakota), and the Westwater. The mine will be developed in the Westwater. Shaft construction will require temporary depressurization of groundwater in the Gallup, Dakota, and Westwater geologic units in the area of the shaft as it is constructed in each geologic unit. After shaft construction is complete, wells will initially be used to dewater the Westwater, the declines, and drifts constructed to develop the mine. The mine workings will be the primary means of dewatering the mine so that mining can occur safely and efficiently.

The Westwater, Dakota, and Gallup are geologic units within the San Juan Basin, the large depositional basin that encompasses most of northwestern New Mexico and adjacent portions of Colorado, Utah, and Arizona (see Section 2). The proposed mine is situated along the San Juan Basin's southern margin, towards the eastern edge of the Grants uranium district and the Ambrosia Lake sub-district (McLemore and Chenoweth, 1989). Uranium has been mined in the San Juan Basin's late Jurassic sandstones within the Grants uranium district for decades, with most of the mining occurring from the 1950s to the 1980s (McLemore et al., 2005).

The region around the proposed Roca Honda mine is sparsely populated with most people living in the Cities of Grants and Gallup, the Town of Crownpoint, the Village of Milan, the community of San Mateo, and the pueblos of Acoma and Laguna (RHR, 2011a). Landowners include the federal government, the state of New Mexico, pueblos, land grants, and private owners (Figure 1.2). Historical land use was dominated by ranching, forestry, mining, and farming (RHR, 2011a). Ranching, forestry, outdoor recreation, and coal mining are the primary present-day land uses (RHR, 2011a).


San Juan County
McKinley County
Crownpoint
509
Gallup
40
Ambrosia Lake Area
Roca Honda
Permit Area
San Mateo
McKinley County
Cibola County
605
Milan
Grants
N
10 5 0 10
Miles
Legend
City
Roca Honda Permit Area
County Boundary
Roca Honda Permit
Area Location
Roca Honda Permit Area Location
INTERA
Figure 1.1



Regional Land Ownership

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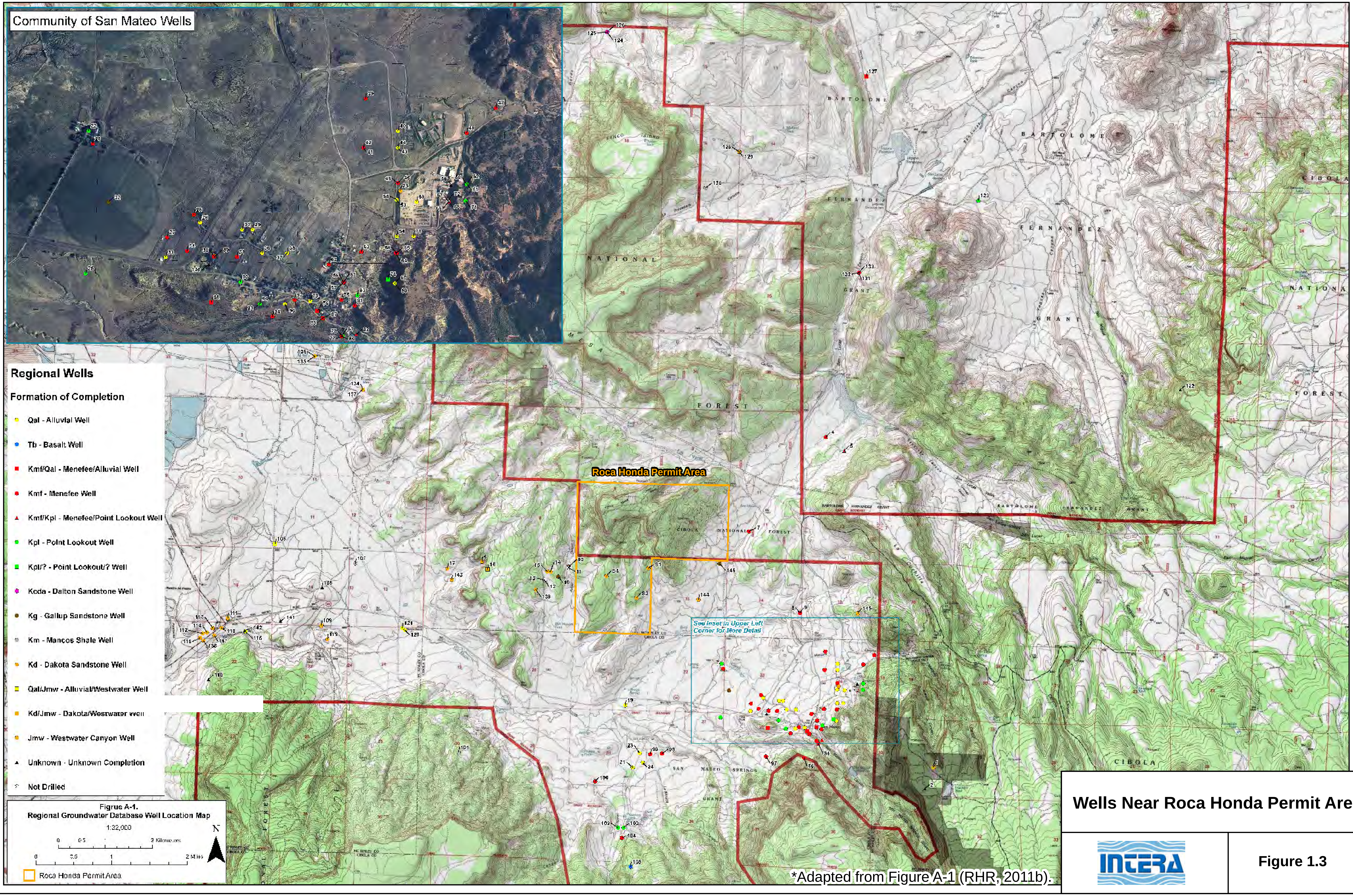
Figure 1.2

Wells are used to extract water from various geologic units for domestic and agricultural purposes in the San Juan Basin. Geologic units that yield economically significant quantities of water to wells or springs are termed "aquifers," whereas units that yield little water to pumping are termed "aquitards" (see Definitions on page ix). The Gallup, Dakota, and Westwater geologic units are aquifers along the southern, eastern, and western margins of the San Juan Basin, including the Roca Honda permit area. Wells located near the RHR permit area are shown in Figure 1.3. This figure is taken from Plate 1 of the RHR Baseline Data Report (RHR, 2011b); information about the numbered wells shown in the figure can be found in Table A-1 of the Baseline Data Report (RHR, 2011b). Mine dewatering in the vicinity of the Roca Honda mine is limited to the Lee Ranch coal mine at present, but historical mining caused significant drops in groundwater levels, which are still recovering.

RHR has filed an Application for Dewatering an Underground Mine with the New Mexico Office of the State Engineer (NM OSE) that proposes maximum dewatering rates for various time periods during construction of the production shaft and during the operating life of the mine (Table 1.1). The rates define the volume of water removed from the Gallup, Dakota, and Westwater aquifers in a given period of time. During the sinking of the production shaft, groundwater will be pumped at a rate of up to 502 gallons per minute (gpm) for a period of up to 12 months (a maximum of 810 acre-feet) from wells finished in the Gallup, the top of which is located 530 feet bgs in the area of the production shaft. After the production shaft is completed through the Gallup, construction of the shaft will continue to the Dakota, where groundwater will be pumped at a rate of up to 144 gpm for a period of up to 12 months (a maximum of 232 acre-feet) from wells finished in the Dakota, the top of which is located at 1,660 feet bgs in the area of the production shaft. Pumping from the Gallup and the Dakota will cease after the shaft has been completed through these formations, except for a continued withdrawal of approximately 30 gpm (50 ac-ft/yr) from the Gallup over the life of the mine.

Table 1.1. Proposed Roca Honda Production Shaft and Mine Dewatering Schedule

Aquifer	Dewatering Depth (feet)	Maximum Pumping Rate (ac-ft/yr)	Maximum Pumping Rate (gpm)	Pumping Period (days)
Gallup	640	810	502	365
Dakota	1,710	232	144	365
Westwater (shaft construction)	2,100	3,228	2,000	720
Westwater (mining)	2,100 – 2,800	7,265	4,500	3,653



Wells Near Roca Honda Permit Area

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Figure 1.3

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After the production shaft is completed in the Dakota, shaft construction will continue into the Westwater. Groundwater will be pumped from the Westwater for a period of up to 12 years during shaft construction, mine development, and over the life of the mine. Groundwater will be pumped from the Westwater at a rate of up to 2,000 gpm during shaft construction over a period of up to two years (a total of 3,228 ac-ft/yr), and no more than 7,265 ac-ft/yr (an average pumping rate of 4,500 gpm) for the ten-year life of the mine. Groundwater will be withdrawn from the Westwater by means of wells and sumps around the production shaft and along the main mine tunnel (called a decline) in advance of its construction, and from within the mine. When mining is complete, pumping from the Westwater and Gallup will end.

1.1 Objectives

RHR requested that INTERA Incorporated (INTERA) construct groundwater flow models to evaluate potential changes in groundwater levels from the mine dewatering in order to support the mine dewatering application submitted to the NM OSE and the Mine Permit Application submitted to state and federal agencies. The specific objective is to estimate the groundwater level changes that mine dewatering might have on aquifers, wells, springs, and local and regional water supply systems, including those for the nearby population centers of Grants, Gallup, Milan, Crownpoint, San Mateo, and the Acoma and Laguna Pueblos (Figure 1.2).

1.2 Approach

INTERA constructed numerical models of groundwater flow in the San Juan Basin to represent historical groundwater changes within the Gallup, Dakota, and Westwater geologic units, as well as future changes from dewatering at Roca Honda mine. A United States Geological Survey (USGS) model of steady groundwater flow in the San Juan Basin constructed by Kernodle (1996) was used as a basis for the INTERA models (see Section 3 below). INTERA's specific modeling tasks are described as follows:

1. Construct and calibrate a numerical model of groundwater flow to estimate predevelopment groundwater levels, i.e., groundwater levels prior to the year 1930, for conditions prior to the onset of large-scale mining in the Grants uranium district.
2. Construct and calibrate a transient historical numerical model of groundwater flow to simulate changes in groundwater levels from 1930 to 2012 caused by pumping at public water supply wells, historical mine dewatering, and partial recovery from the historical mine dewatering.
3. Construct and apply predictive, transient, numerical groundwater flow models that simulate changes in groundwater levels from the beginning of Roca Honda mine construction through the projected end of mining 13 years later.

The models were also used to simulate changes in groundwater levels during the hundred years following cessation of mining activities. The predictive transient models represent scenarios with and without pumping at Roca Honda mine and scenarios with and without pumping by water rights from the Gallup, Dakota, and Westwater aquifers in the vicinity of the Roca Honda permit area. The differences in groundwater levels between scenarios with and without Roca Honda dewatering define the "drawdown" due to Roca Honda mine dewatering.

1.3 Report Structure

The geologic and hydrologic characteristics of the Roca Honda mine area and the San Juan Basin important to the impact assessment are described in Section 2. Construction of the numerical models is detailed in Section 3. Calibration of the predevelopment model and transient historical model is described in Section 4. Section 5 provides the results of the transient predictive models. Section 6 presents INTERA's conclusions, and Section 7 lists the references cited in the report. Appendices A and B depict model boundary conditions and parameter assignments by layer. Appendix C presents calibration plots for the transient calibration. Appendix D lists the wells and the estimated drawdown for the predictive simulations.

2.0 HYDROGEOLOGY

INTERA reviewed available published and unpublished information and data about the geology and hydrology of the San Juan Basin and the Roca Honda mine area to develop an updated conceptual hydrogeologic foundation for this assessment. These studies included Mercer and Cooper (1970), Brod and Stone (1981), Stone et al. (1983), Craigg et al. (1990ab), Dam et al. (1990ab), Kernodle et al. (1989 and 1990), Levings et al. (1990ab), Thorn et al. (1990ab), Levings et al. (1996), and Craigg (2001). Two previously developed groundwater flow models for the basin (Frenzel and Lyford, 1982; Kernodle, 1996) contributed important information to developing the new conceptual foundation and numerical models.

This information and data were used to develop an overall understanding or mental picture of groundwater flow in the San Juan Basin, that is, an understanding of the basin's geologic structure and composition, and how water enters it, moves through it as groundwater and surface water, and leaves it as stream flow, evaporation, or diversions. For this impact assessment, the overall understanding includes the San Juan Basin's geologic structure and stratigraphy, major surface water bodies, aquifer and aquitard characteristics, groundwater flow patterns, recharge, surface water-groundwater interactions, and groundwater pumping stresses. This overall understanding in turn is the basis for designing the numerical groundwater flow models described in later sections of this report.

INTERA further refined its understanding of the hydrogeology around the Roca Honda mine area using data from recent investigations, pump tests, and several sections from the RHR Baseline Data Report (BDR). The RHR BDR, which was submitted to state and federal agencies as part of RHR's Mine Permit Application, describes the geologic, hydrologic, cultural, and biological baseline conditions at the Roca Honda mine area. The specific sections reviewed by INTERA included land use (RHR, 2011a), groundwater (RHR, 2011b), geology (RHR, 2011c), and surface water (RHR, 2011d).

This section of the report provides a general overview of the San Juan Basin as well as key features in the vicinity of the Roca Honda mine. Detailed descriptions of the basin's geology and hydrology can be found in the sources listed above.

2.1 Geologic Setting

Groundwater flow in the Westwater, Dakota, and Gallup aquifers is partly controlled by the geology, extent, and characteristics of the aquifer units, and partly by the overall geologic structure of the San Juan Basin. The overall geologic setting of the San Juan Basin and the RHR permit area are briefly described below.

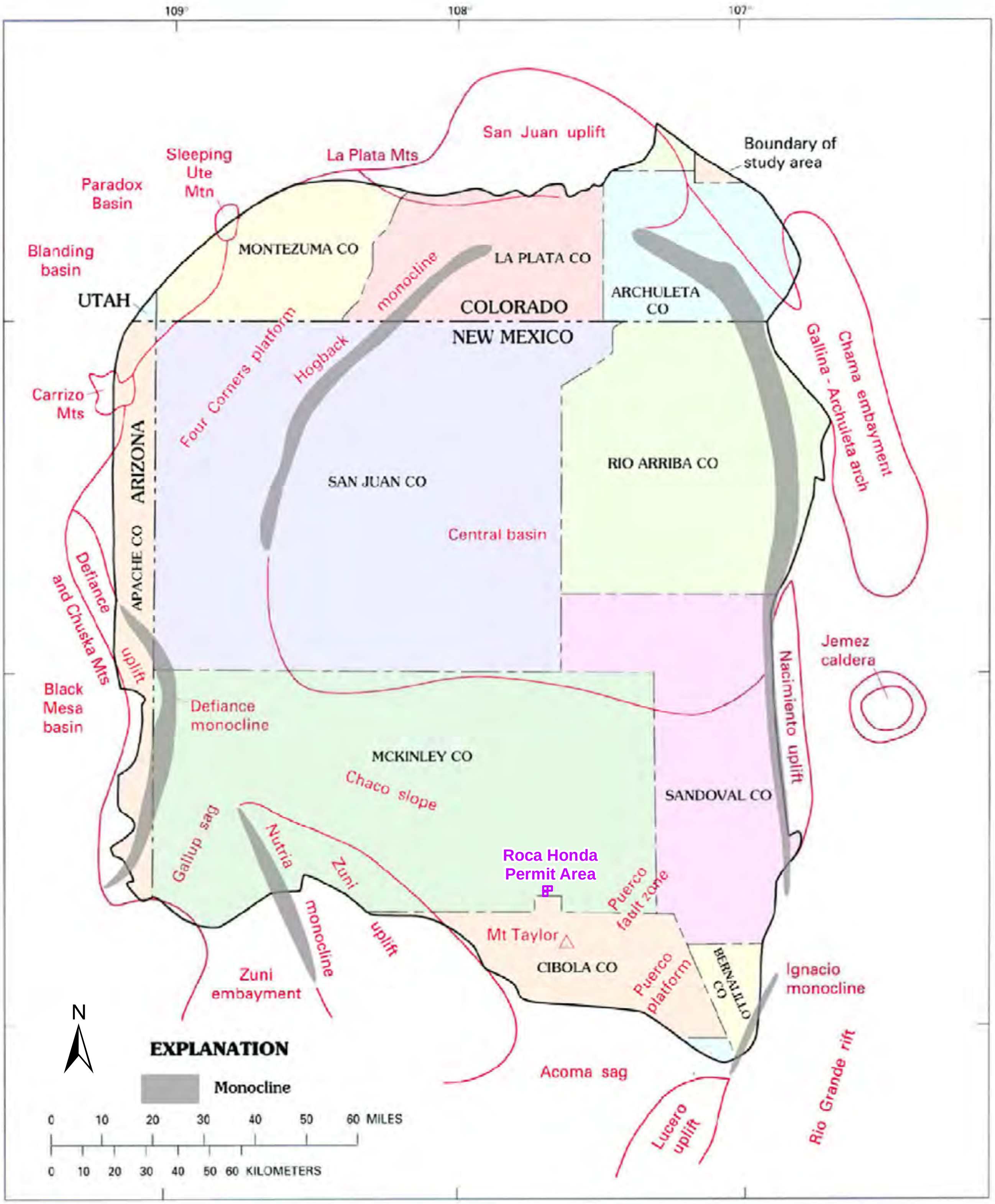
2.1.1 San Juan Basin

The San Juan structural basin covers approximately 21,600 s quare miles, primarily in northwestern New Mexico, with smaller portions in adjacent parts of southwestern Colorado and northeastern Arizona (Figure 2.1). It is about 140 miles wide and 200 miles long. The proposed Roca Honda mine is situated along the basin's southern margin.

The basin is bounded by structural uplifts on all sides (Kelley, 1963), whereas the central part of the basin consists of relatively flat-lying sedimentary rocks. Topographic relief spans more than 7,000 feet between the high-elevation mountains and uplifts and the low-elevation sags and basin center. The structural center of the basin is located beneath the northeastern part of the basin. Up to 14,400 feet of sedimentary rocks ranging in age from Devonian to Tertiary fill the basin (Craigg, 2001). These rocks dip into the basin relatively steeply on the northern, western, and eastern margins of the basin, and less steeply along the southern margin, as illustrated in Figure 2.2, a regional cross section adapted from Stone et al. (1983) and Kernodle (1996). The older rocks crop out along the basin perimeter and are overlain by successively younger rocks toward the center of the basin (Figures 2.2 and 2.3).

As shown in Figure 2.2, the San Juan Basin contains numerous geologic units. Organized by age from oldest to youngest, the major geologic units in the San Juan Basin are:

- Undivided Paleozoic-era rocks and the Permian-age San Andres Limestone and Glorieta Sandstone.
- The upper Triassic Chinle Formation and the upper Jurassic Entrada Sandstone, the Bluff-Cow Springs Sandstone, the Summerville Formation, and the Todilto Limestone.
- The upper Jurassic Morrison Formation, the members of which are, from older to younger: the Recapture Shale Member (Recapture), the Westwater Canyon Member, and the Brushy Basin Member (Brushy Basin).
- The Cretaceous Dakota Sandstone, the late Cretaceous Mancos Shale (Mancos), and the upper Cretaceous Mesaverde Group, which contains the Gallup Sandstone, the Crevasse Canyon Formation, the Point Lookout Sandstone, the Menefee Formation, and the Cliff House Sandstone.
- The upper Cretaceous Lewis Shale, the Pictured Cliffs Sandstone, the Kirtland Formation, and the Fruitland Shale.
- The Tertiary Ojo Alamo Sandstone and the Animas, Nacimiento, and San Jose Formations, shown on Figure 2.2 as undivided Tertiary rocks.



*Adapted from Kelley (1963), Levings et al. (1996), and Craigg (2001).

Structural Features of the San Juan Basin

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Figure 2.1

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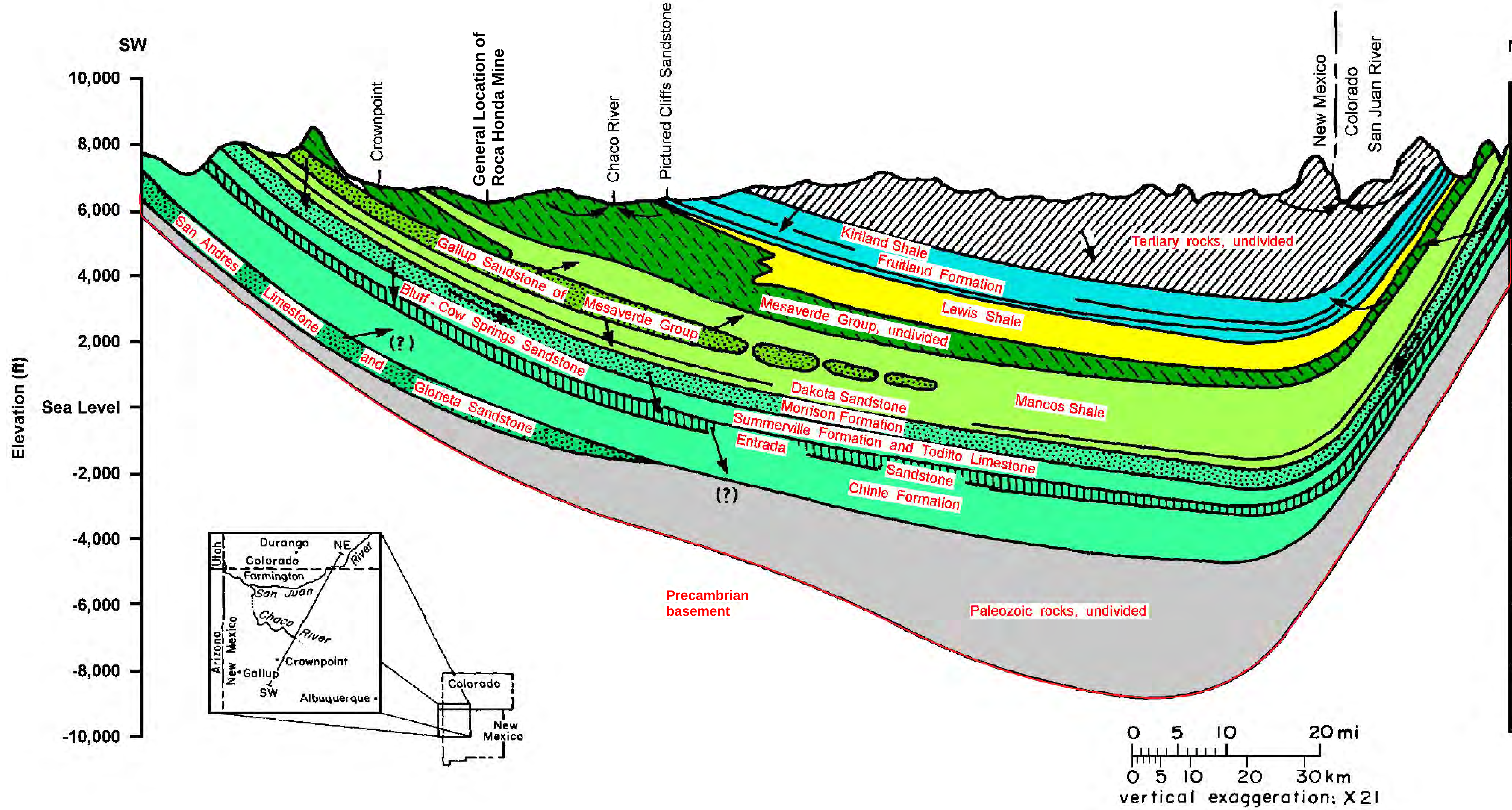

*Adapted from Stone et al. 1983 and Kernodle, 1996.

Generalized Southwest to Northeast Cross Section of the San Juan Basin

Figure 2.2

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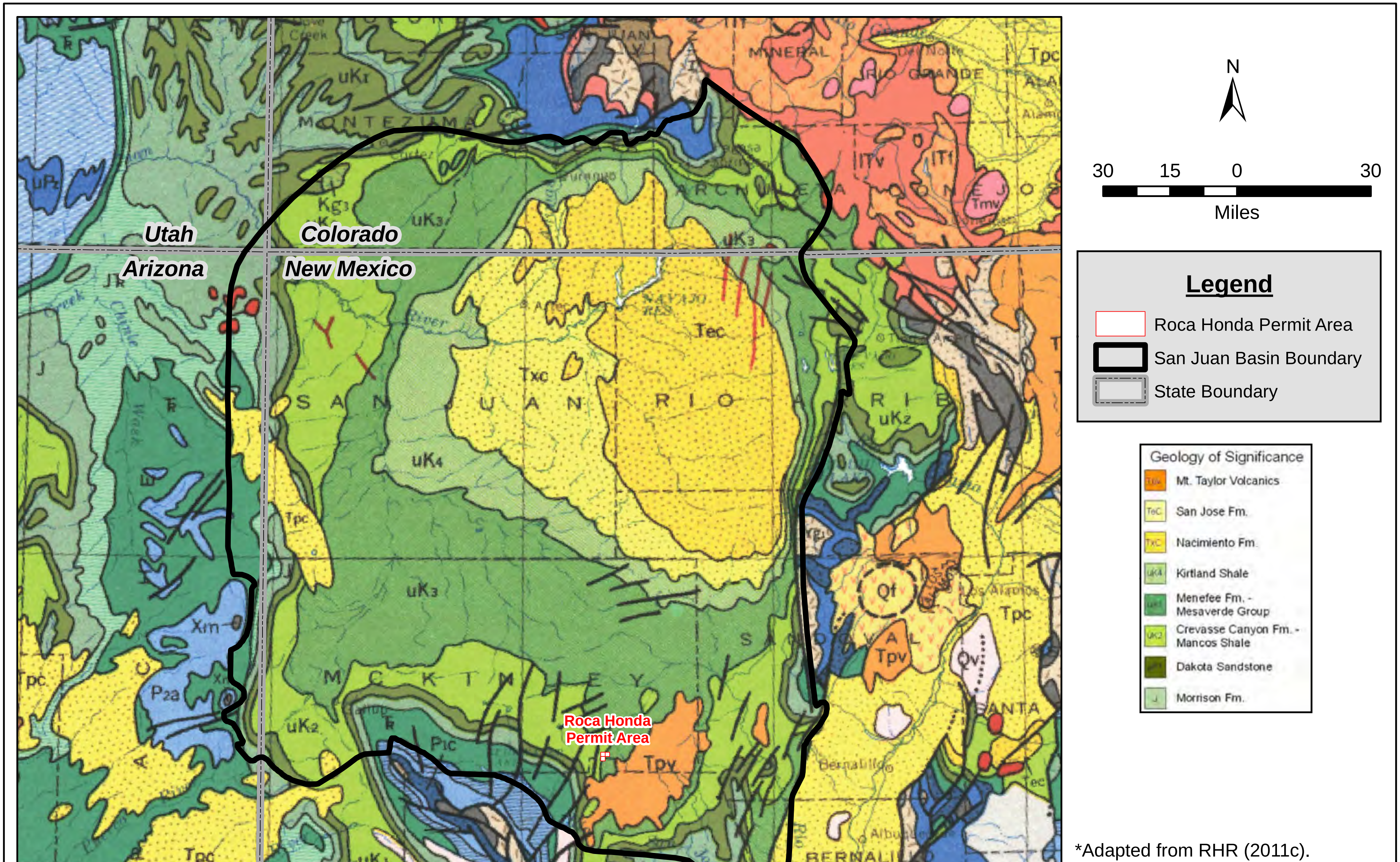

*Adapted from RHR (2011c).

Geologic Map of the San Juan Basin

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Figure 2.3

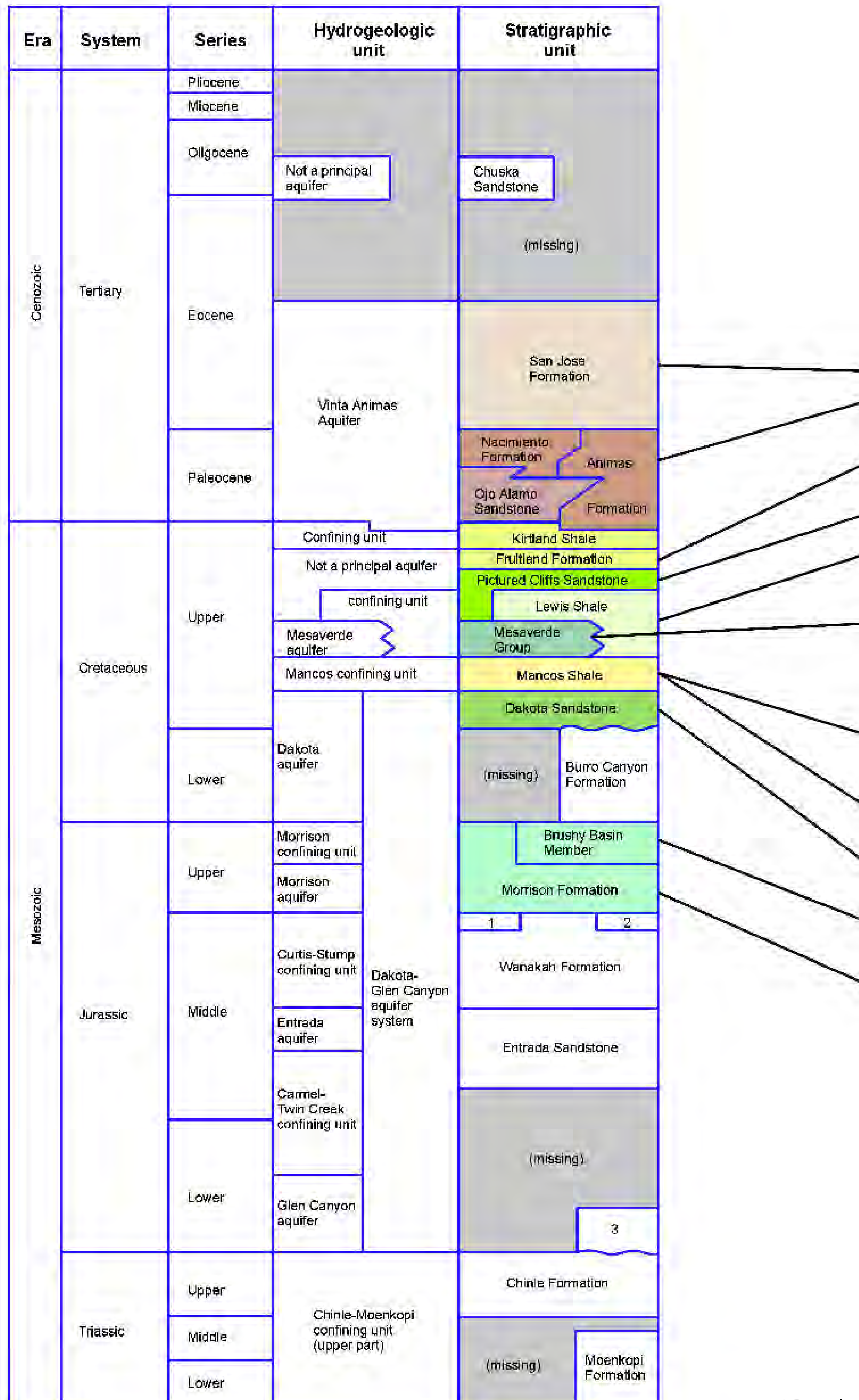
Many of these geologic units, such as the Gallup Sandstone, the Point Lookout Sandstone, and the San Jose Formation, are only found in parts of the San Juan Basin. Other units, including the Mancos Shale and the Morrison Formation, extend across all or nearly all of the San Juan Basin.

The focus of this study is on the sedimentary rocks of upper Jurassic to Cretaceous age in the San Juan Basin, that is, the Morrison Formation, the Dakota Sandstone, the Mancos Shale, and the Mesaverde Group, which are the geologic units that could be affected by the proposed Roca Honda dewatering (Figure 2.4). The vertical and horizontal extents of the geologic units considered in this study were set in accordance with the focus of the study.

The vertical extent of the study area includes the geologic units from the ground surface down to the Westwater Member of the Morrison Formation. The Westwater is considered to form the base of the study area because the geologic unit immediately below the Westwater, the Recapture Shale, is composed of low-permeability shale that greatly restricts the movement of groundwater flow between deeper aquifers and the Westwater. The thick Chinle Formation, which separates the deep aquifers of the San Andres Limestone and Glorieta Sandstone from overlying rocks, has a very low hydraulic conductivity and also restricts groundwater flow in and out of the San Andres Limestone. Even though the geologic units that are younger than the Mesaverde Group are not physically present at the Roca Honda permit area, these younger units are included in this study because of the importance of the groundwater-surface water interactions and the presence of springs and wells within these units. The vertical extent limits the horizontal extent of the study area along the basin's southern margin to the Morrison Formation outcrops where the Westwater likely contains groundwater (Figure 2.3).

The geologic units found in the study area are grouped into hydrostratigraphic units according to the overall behavior of each group, that is, whether the group behaves as an aquifer or an aquitard for the purposes of the study. Figure 2.4 depicts the relationship between the geologic units in the study area and their corresponding hydrostratigraphic unit, which also corresponds to the model layer number (see Section 3.4). Both geologic units and hydrostratigraphic units are discussed in the following subsections; however, only hydrostratigraphic units are discussed in Sections 3 to 6.

The following descriptions of the geologic units are primarily based on the more detailed descriptions in Craigg (2001) for the San Juan Basin. Information about the vicinity of the Roca Honda permit area is taken from RHR (2011c).



Model Layer	Hydrostratigraphic Unit	Thickness (ft)
1	San Jose Formation	200 – 2,700
2	Animas and Nacimiento Fms	500 – 2,700
3	Ojo Alamo Sandstone	20 – 400
	Kirtland and Fruitland Fms	0 – 2,000
	Pictured Cliffs Sandstone	0 – 400
4	Lewis Shale	0 – 2,400
5	Cliff House Sandstone	20 – 500
	Menefee Formation	0 – 2,000
	Point Lookout Sandstone	100 – 350
6	Mancos Shale (NE only)	1,000 – 2,300
	Gallup Sandstone (SW only)	0 – 300
7	Mancos Shale	1,000 – 2,300
8	Dakota Sandstone	200 – 350
9	Brushy Basin Member of Morrison Formation	80 – 250
10	Westwater Canyon Member of Morrison Formation	100 – 300

*Stratigraphic column adapted from Maxim Technologies (2005).

Correlation of Stratigraphic Column to Conceptual Hydrostratigraphy

INTERA

Figure 2.4

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2.1.1.1 Morrison Formation

The Westwater Canyon Member and the Brushy Basin Member are the uppermost two members of the Morrison Formation. The Westwater Canyon Member is present throughout the San Juan Basin at thicknesses that range from about 100 feet on the north, east, and south sides of the basin to about 300 feet in the southwest-central part of the basin; near the Roca Honda permit area, the Westwater thickness is roughly 200 feet. It consists of locally conglomeratic sandstone interbedded with sandstone, shale, and claystone; the proportion of sandstone and the grain size of the sandstones decrease toward the northeast. The Westwater Canyon Member is the uranium-ore-bearing unit in the area around the proposed Roca Honda mine. The Brushy Basin Member consists mainly of calcareous and bentonitic claystone and mudstone and functions as an aquitard throughout the basin. Its thickness ranges from about 80 to 250 feet and is commonly about 185 feet in the San Juan Basin. It is 200 feet thick in the vicinity of the Roca Honda permit area. The Brushy Basin member was removed from the southwestern corner of the basin by erosion that occurred before the deposition of the overlying Dakota Sandstone.

2.1.1.2 Dakota Sandstone

The Dakota Sandstone overlies the Morrison Formation throughout the San Juan Basin. It consists of a basal section of sandstone and conglomeratic sandstone overlain by a middle section of siltstone, shale, and lenticular sandstone beds, and an upper section of fine-grained sandstone interbedded with shale. The Dakota Sandstone ranges from 10 to about 500 feet thick and is commonly 200 to 300 feet thick. Its thickness near the Roca Honda permit area is only 60 feet. The thickness of the Dakota generally increases from the northern and western margins of the basin toward the eastern and southern margins.

2.1.1.3 Mancos Shale

The main body of the Mancos Shale is present above the Dakota Sandstone throughout the basin and intertongues with sandstone units of the Mesaverde Group at some locations. In the northern part of the basin, the main body of the Mancos Shale is up to 2,300 feet in thickness. The aggregate thickness of the Mancos tongues in the southern part of the basin is about 1,000 feet. The main body of the Mancos is 900 feet thick in the area near the Roca Honda permit area.

2.1.1.4 Mesaverde Group

The Mesaverde Group includes the Gallup Sandstone, the Point Lookout Sandstone, the Menefee Formation, and the Crevasse Canyon Formation. The Gallup Sandstone is present only in the southwestern half of the basin, partly because of stratigraphic pinchout and partly because of post-depositional removal by erosion that occurred before the deposition of the upper part of the Mancos Shale (Molenaar, 1973, as cited by Craigg, 2001). It overlies the lower part of the

Mancos Shale and is truncated against the upper part of the Mancos Shale. The Gallup Sandstone is not present northeast of a truncation line that extends from the southeast corner of the basin to slightly northwest of Shiprock. The thickness of the Gallup Sandstone ranges from zero at the truncation line to approximately 300 feet in the southwest part of the basin, near Gallup. Exposures of the Gallup Sandstone crop out along the southern and western parts of the basin perimeter. In the vicinity of the Roca Honda permit area, the Gallup has a thickness of roughly 100 feet.

The Crevasse Canyon Formation is a sequence of shale, sandstone, and coal that overlies the Gallup or the Mancos where the Gallup is absent. It crops out only along the southern part of the basin and pinches out about 30 miles north of its outcrops (Kernodle, 1996). The Crevasse Canyon Formation contains the Gibson Coal Member, the Dalton Sandstone Member, the Borrego Pass Lentil, and the Dilco Coal Member in order from youngest to oldest. Its two sandstone units are separated by the Mulatto tongue of the Mancos Shale. The thicknesses of its members vary with location, but total thickness near the Roca Honda permit area is 870 feet.

The Point Lookout Sandstone typically forms either cliffs and cap buttes or erosion-resistant dip slopes and hogbacks around the margins of the central basin. The thickness of the Point Lookout Sandstone varies irregularly from about 100 feet in the southern part of the basin to about 350 to 400 feet near the Colorado-New Mexico state line. The Point Lookout has an average thickness of 150 feet in the Roca Honda permit area. The Menefee Formation is a repeating sequence of sandstone, shale, claystone, carbonaceous shale, and coal bed. It ranges in thickness from a feather edge at its outcrops in Colorado to about 2,000 feet in the south-central part of the basin. The Menefee is not present within the Roca Honda permit area.

Cliff House Sandstone outcrops form the margins of the central basin, displaying landforms similar to those formed by Point Lookout outcrops. It consists of several sandstone tongues of varying thicknesses and areal extents. The aggregate thickness is reported to range from zero to 300 feet with thicknesses between 20 and 250 feet being common throughout most of its extent (Stone et al., 1983). The Cliff House Sandstone is not present in the Roca Honda permit area.

2.1.1.5 Lewis Shale

The Lewis Shale conformably overlies and intertongues with the Cliff House Sandstone. It is made up primarily of shale and silty shale with thin interbeds of limestone, siltstone, and fine-grained sandstone. The thickness of the Lewis Shale increases from zero, where it pinches out between the Cliff House and the overlying Pictured Cliffs Sandstones in the west-central basin, to about 2,400 feet in the northern part of the basin. It is not present in the Roca Honda permit area.

2.1.1.6 Pictured Cliffs Sandstone

The Pictured Cliffs Sandstone is present in the central basin area, ranging in thickness from zero on the east side of the basin to about 400 feet in the north-central part. It consists of a sequence of sandstone with thin interbeds of shale, particularly in the lower part of the formation. It intertongues with the overlying Fruitland Formation, which contains the principal coal resources of the San Juan Basin and is generally mapped with the overlying and similar Kirtland Shale. The Fruitland Formation and Kirtland Shale both consist of variable thicknesses of interbedded and repetitive sequences of channel sandstone, siltstone, shale, and claystone. Carbonaceous shale and coal are common in the Fruitland. The thickness of the combined formations ranges from zero on the eastern side of the basin to about 2,000 feet in the northwestern part of the basin. It is not present in the Roca Honda permit area.

2.1.1.7 Ojo Alamo Sandstone

The Ojo Alamo Sandstone is the oldest formation of Tertiary age in the San Juan Basin. It crops out inside the central basin and typically forms cliffs and dip slopes, or it caps low mesas and forms rounded hills. The formation pinches out in the northwest between Farmington and the Colorado state line and ranges from 20 to 400 feet thick in the remainder of its extent, with thicknesses between 50 and 150 feet being most common. It is not present in the Roca Honda permit area.

2.1.1.8 Animas and Nacimiento Formations

The Animas and Nacimiento Formations overlie and intertongue with the Ojo Alamo Sandstone in the central basin. The Animas Formation consists of fluvial and volcaniclastic sandstone, conglomerate, and shale. The Nacimiento grades laterally into the upper part of the Animas in the northern part of the basin. It consists of interbedded shale and discontinuous lenses of sandstone, and includes carbonaceous shale and lignite in some areas. The combined thickness of the Animas and Nacimiento Formations ranges from about 500 to 2,700 feet. It is not present in the Roca Honda permit area.

2.1.1.9 San Jose Formation

The San Jose Formation is a sequence of interbedded sandstone, siltstone, and shale that overlies the Animas Formation in Colorado and the Nacimiento Formation in New Mexico. The thickness is variable, but generally increases from about 200 feet on the west to about 2,400 feet on the east and 2,700 feet in the center of the basin. It is not present in the Roca Honda permit area.

2.1.1.10 Other Geologic Units

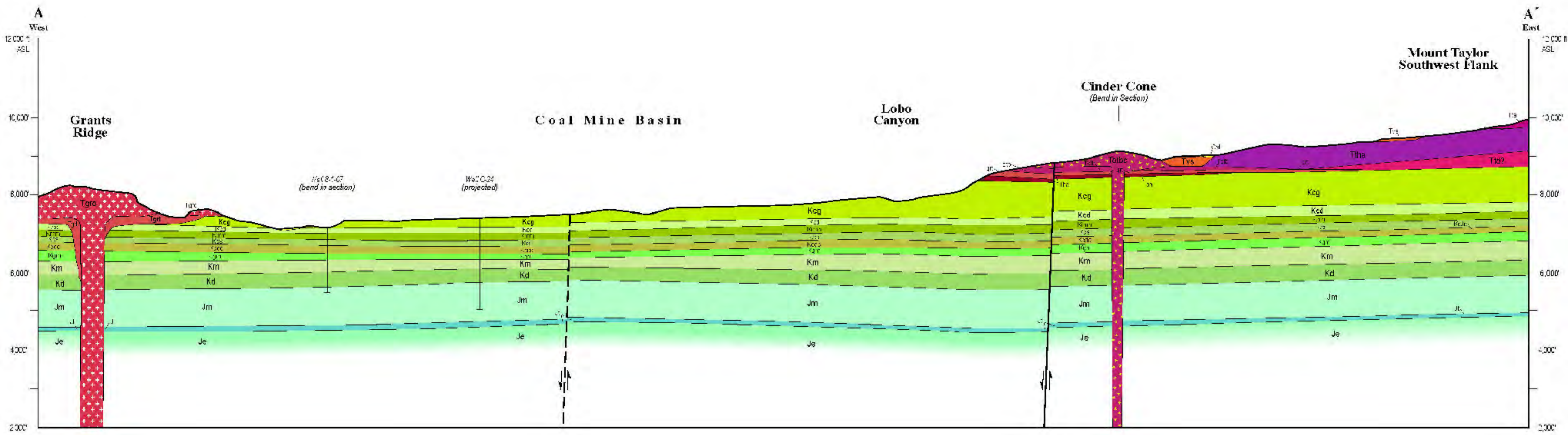
Mt. Taylor's volcanic rocks and associated basalt and andesite flows are important to understanding recharge and groundwater flow near the RHM site. The numerous volcanic necks within Mt. Taylor and Chivato Mesa and in their vicinity crosscut all of the sedimentary units in the area (Figure 2.5ab). The much more laterally extensive basalts and andesite flows created a varying-thickness cover on those same sediments (Figures 2.2 and 2.5ab). By reason of its 11,000-ft elevation, Mt. Taylor collects much more precipitation than the lower lying units.

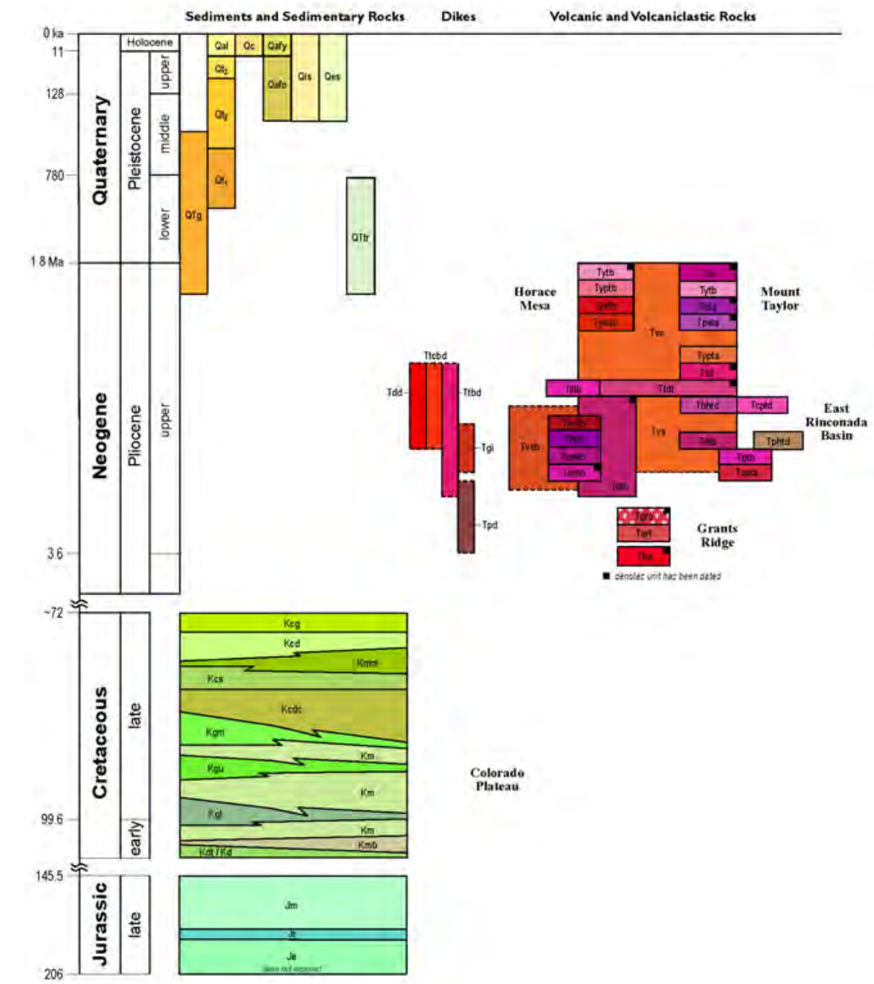
The Chuska Mountains in the western part of the basin along the New Mexico-Arizona border are another important source of recharge to the San Juan Basin (Kernodle, 1996). The mountains comprise the eolian Chuska Sandstone, a series of volcanic necks, and associated basalt or andesite flow caps, and are depicted by the NW-SE trending yellow body labeled Tpc in Figure 2.3. The average thickness of the Chuska Sandstone is reported to be 1,000 feet and appears to be the source for the numerous springs as well as recharge to deeper sedimentary units (Kernodle, 1996).

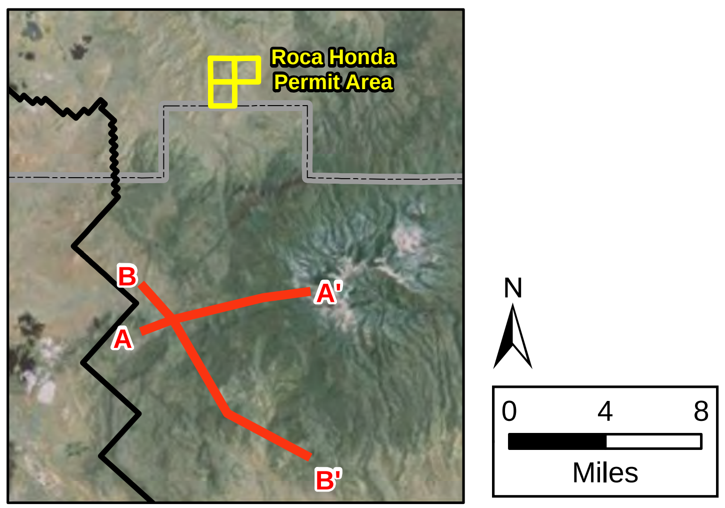
2.1.2 Roca Honda Mine Geologic Setting

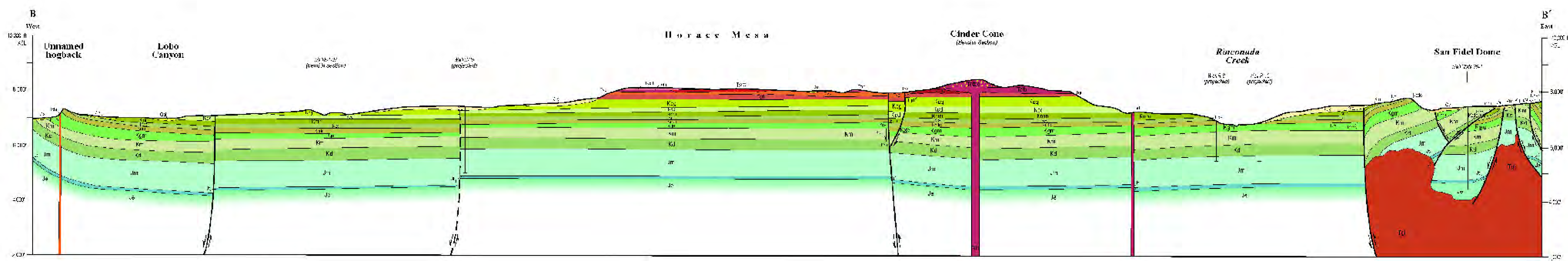
The Roca Honda permit area lies within the San Juan structural basin, and the rocks present within the permit area are the same as those described above for the basin. Approximately 2,100 to 2,800 feet of sedimentary rocks lie between ground surface and the proposed mine workings within the Roca Honda permit area. Shale dominates the strata that lie between the Westwater and the land surface. The Dakota and Gallup sandstone aquifers have average thicknesses of roughly 50 and 100 feet, respectively, and the Point Lookout Sandstone and Dalton Sandstone Member of the Crevasse Canyon Formation account for roughly another 200 feet of sandstone. The younger sandstone intervals are separated from the Gallup by approximately 450 feet of shale and shaley sandstones, and there are approximately 900 feet of Mancos Shale between the Gallup and the Dakota aquifers. Quaternary alluvium and Mesaverde Group units are exposed at the ground surface.

The geologic structure varies around the Roca Honda permit area. To the south and southwest, the Gallup, Dakota, and Morrison units are exposed at the surface where they are not covered by volcanic flows associated with Mt. Taylor. To the east and southeast the sedimentary rocks are covered by the volcanic materials from Mt. Taylor and other volcanic necks. The aquifer units dip steadily downward to the north and less steeply to the west. Greater detail about the site area geology is provided in RHR (2011c).









Surficial Flows and Cores of Mt. Taylor Volcanics

Figure 2.5a

*Adapted from OF-GM 181, May 2008, New Mexico Bureau of Geology and Mineral Resources.

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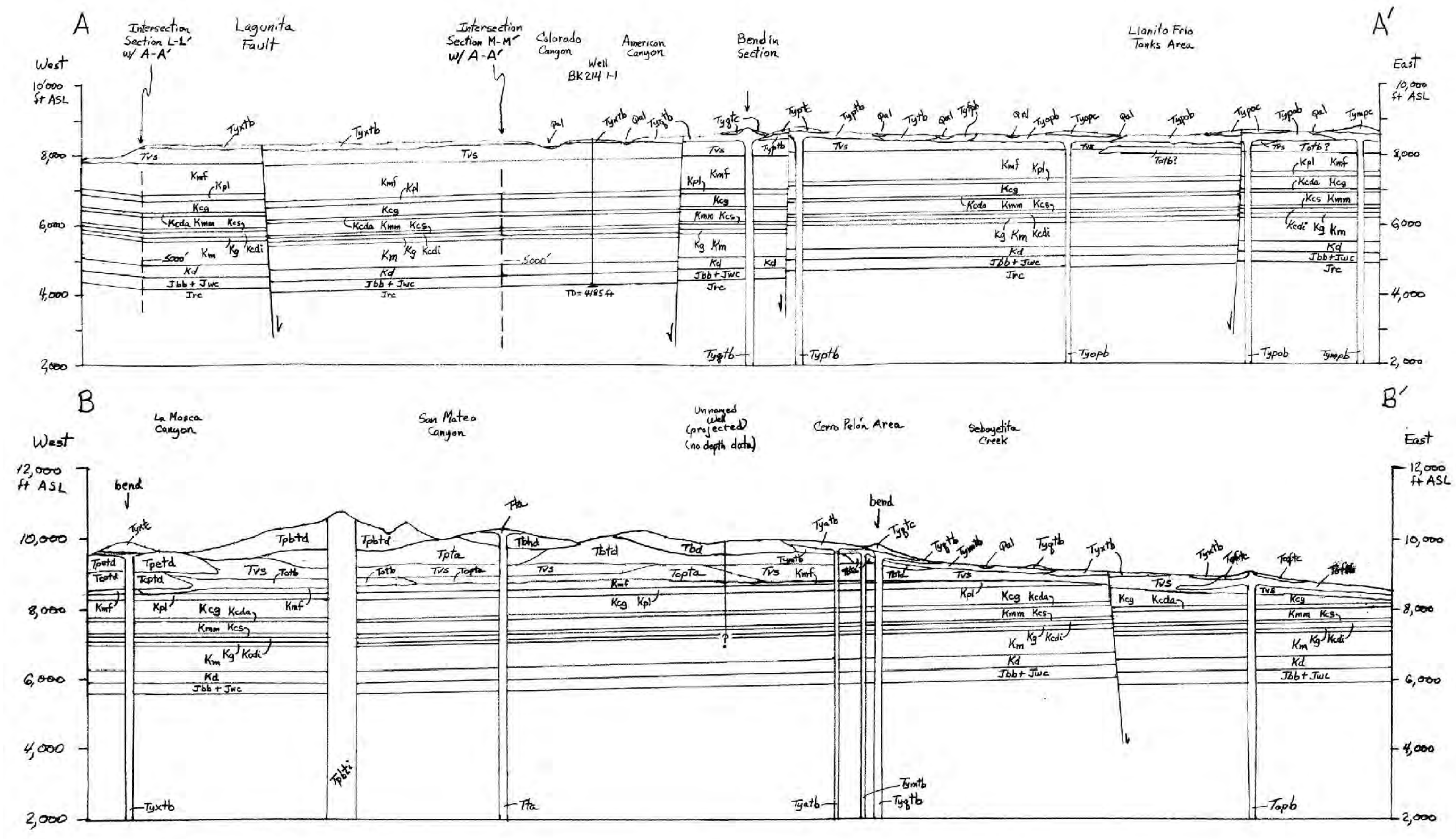

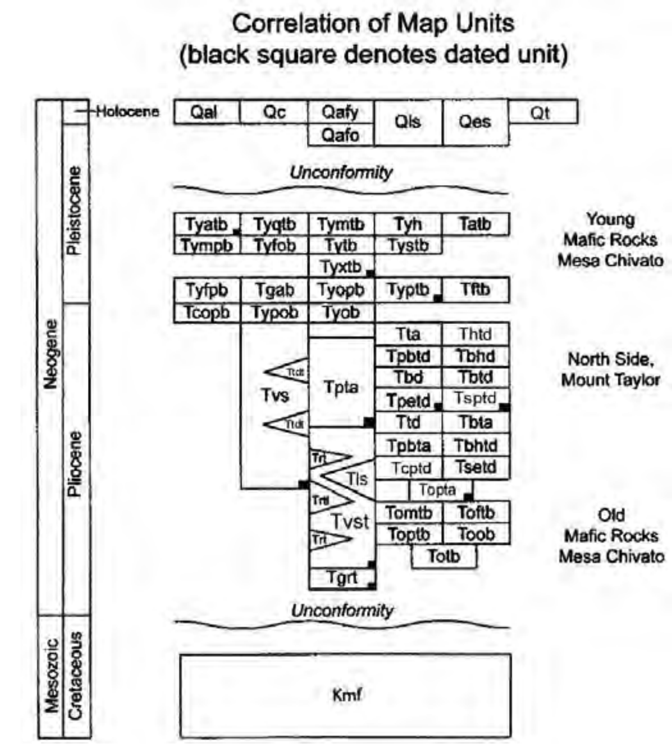

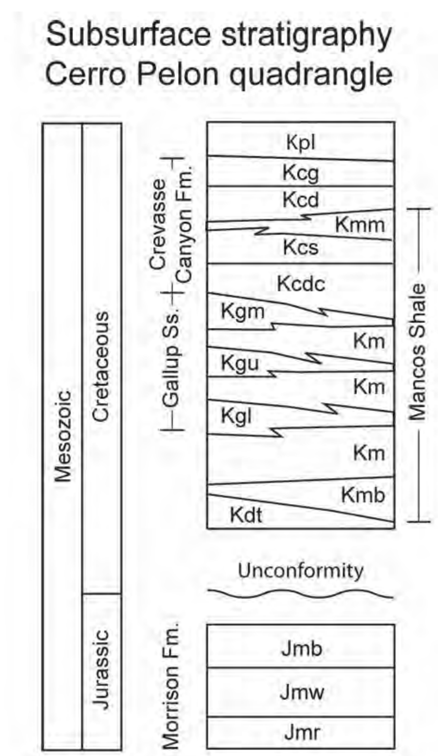

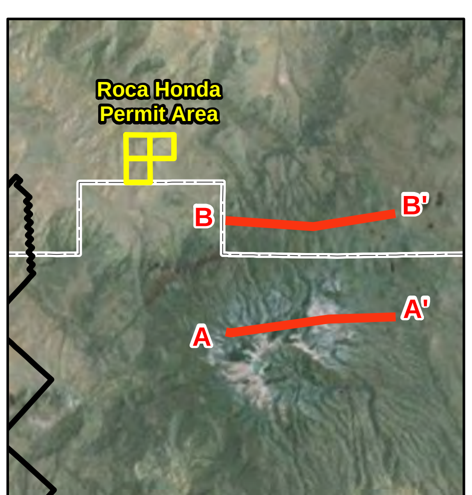

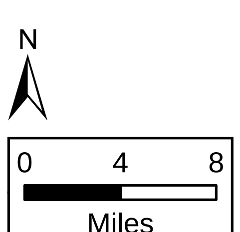

*Adapted from OF-GM 202, June 2010, New Mexico Bureau of Geology and Mineral Resources.

Surficial Flows and Cores of Mt. Taylor Volcanics

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Figure 2.5b

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2.2 Hydrologic Setting

Water enters the groundwater flow system of the San Juan Basin by seepage from flowing rivers or drainages and infiltration within recharge areas, especially along the mountain fronts and basin margins. Groundwater leaves the San Juan Basin aquifer units by flowing into rivers, springs, or drainages, by evaporation and transpiration, and by human extraction. In the area of the Ambrosia Lake sub-district, groundwater levels in the Westwater are presently recovering after having been drawn down by dewatering for historical uranium mining.

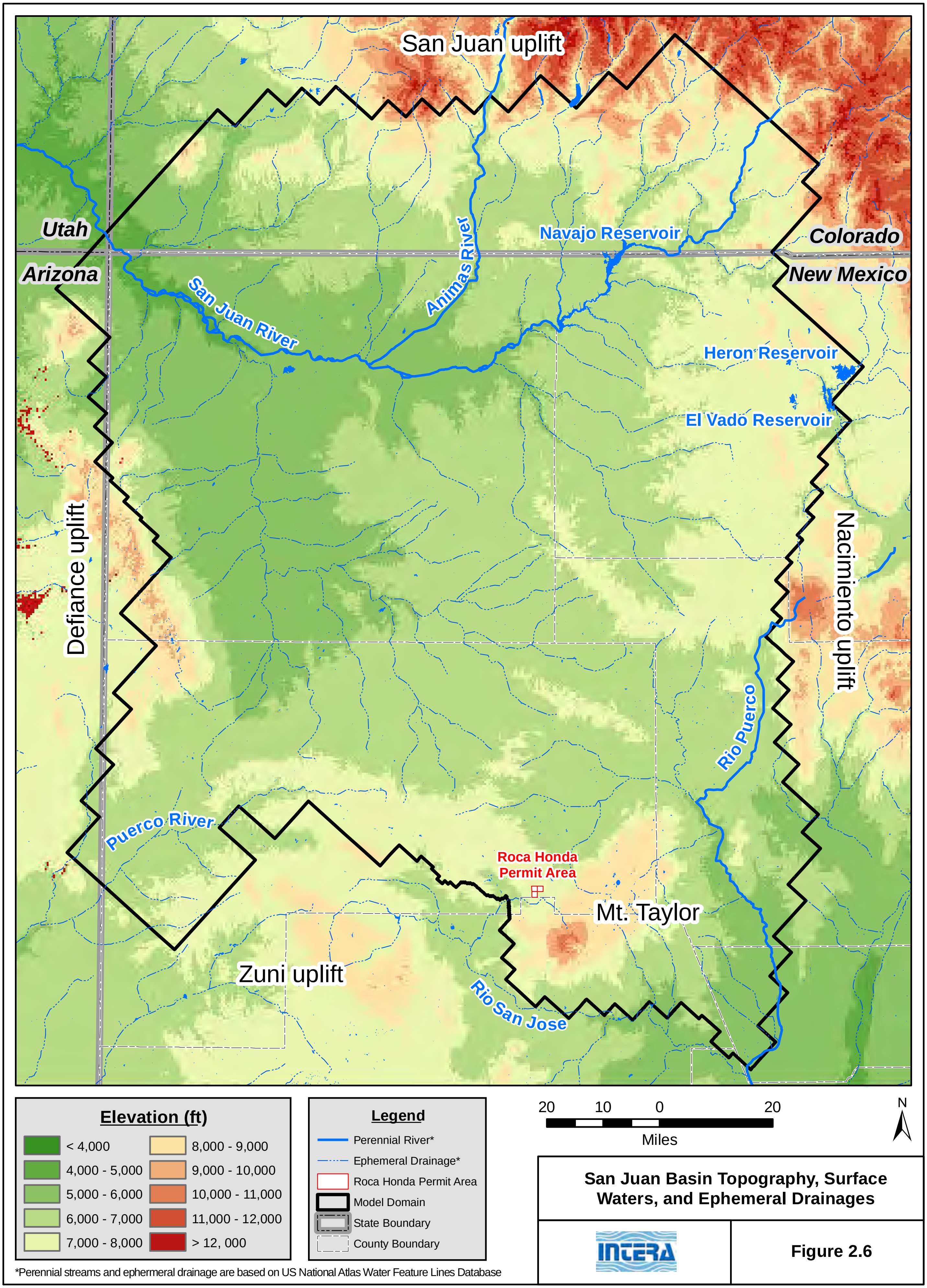
2.2.1 Surface Water

The basin's surface water bodies include a single perennial river system, the San Juan River, and many intermittent and ephemeral rivers and drainages, reservoirs, springs, and irrigation diversions (Stone et al., 1983; Kernodle, 1996). Depending on location and season, surface water bodies can act as recharge areas, where surface water seeps into the subsurface, or as discharge areas, where groundwater seeps out of the subsurface and is carried away by surface flow.

Only the San Juan River and its northern tributaries, e.g., the Animas River, in the northern part of the basin carry water into the San Juan Basin, exchange flows with the near-surface stratigraphic units, and collect groundwater discharging from the Gallup, Dakota, and Westwater aquifers (Stone et al., 1983; Kernodle, 1996). Figure 2.6 depicts the perennial and ephemeral surface water bodies and ground surface elevation across the San Juan Basin, as well as the boundary of the study area, represented in the figure as the model domain (see Section 3.4 for further details). The San Juan River system also supplies many of the irrigation diversions.

The Rio Puerco has perennial, intermittent, and ephemeral reaches in the southeastern part of the basin. This drainage drains the aquifer units it crosses, as do the ephemeral Puerco River in the southwestern corner and the numerous ephemeral drainages throughout the basin (Figure 2.6; Stone et al., 1983; Gold and Rankin, 1994; Kernodle, 1996). All ephemeral drainages, including the Puerco River and the Rio Puerco, can also discharge limited amounts of water to the subsurface during the infrequent occasions that they have flowing water. Perennial flows along short distances have been observed in a number of the ephemeral drainages, presumably where they are supplied by springs or other groundwater discharges (Stone et al., 1983; Kernodle, 1996).

The largest ephemeral river nearest to the Roca Honda permit area is the Rio San Jose (Figure 2.6), which falls outside the San Juan Basin but does have perennial reaches upstream of Grants. There are many small, ephemeral drainages in the vicinity of the mine site, with San Mateo Creek being the nearest (Figure 2.7; RHR, 2011d). Flows in these drainages are, like the Puerco River, restricted to periods following one or more rainstorms, or occur within spring-fed localized perennial reaches (RHR, 2011d).



San Juan Basin Topography, Surface Waters, and Ephemeral Drainages

Figure 2.6

*Perennial streams and ephermeral drainage are based on US National Atlas Water Feature Lines Database

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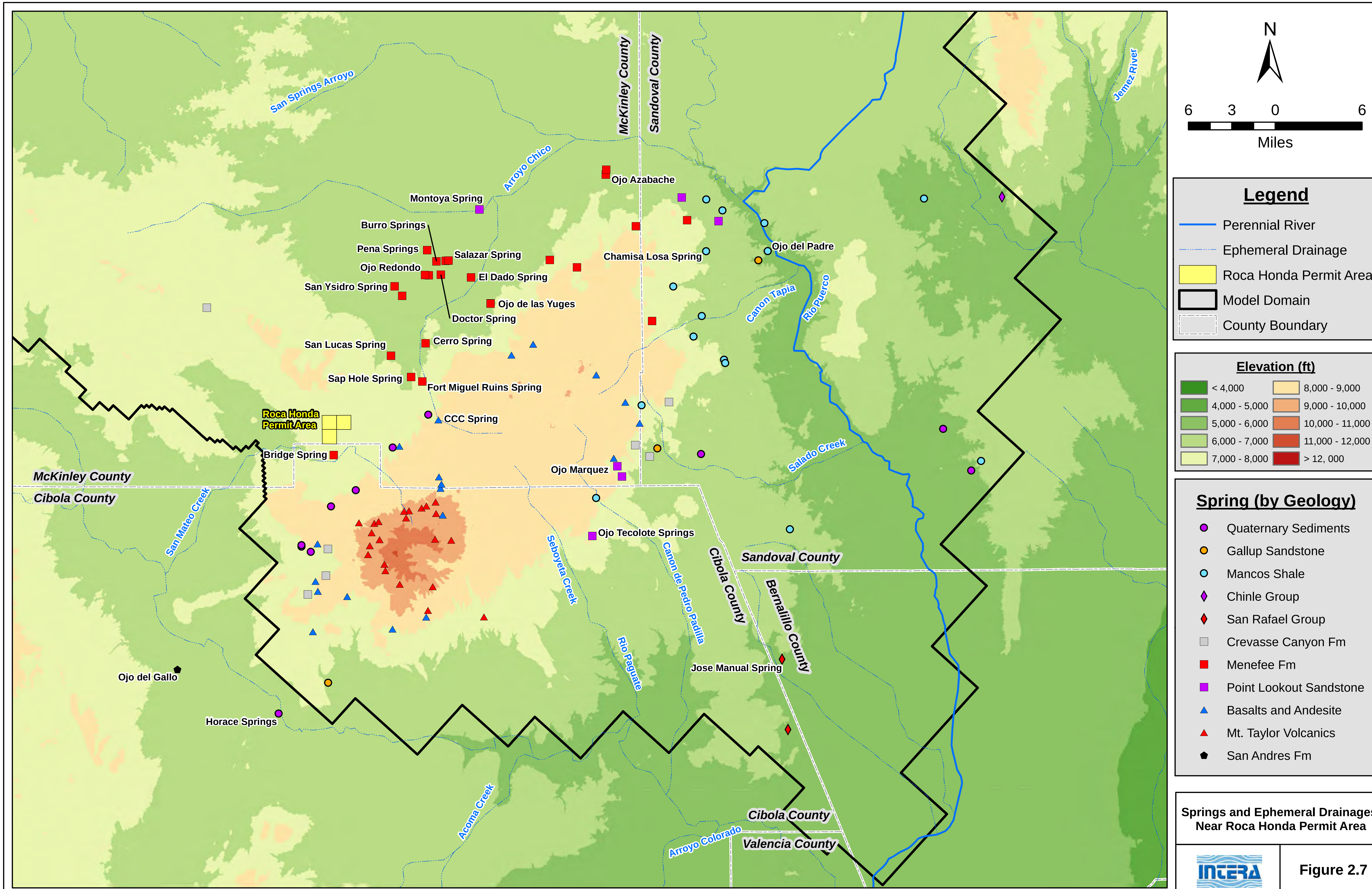


Springs and Ephemeral Drainages Near Roca Honda Permit Area

Figure 2.7

The high elevation and volcanic rocks of Mt. Taylor and Mesa Chivato support the largest proportion of springs in the site vicinity (Figure 2.7). The next largest group of springs is found in the Menefee Formation, Crevasse Canyon Formation, and Point Lookout Sandstone, as is shown in Figure 2.7.

The majority of the springs located in the volcanic rocks, basalt or andesite flows, or Quaternary sediments on the west flank of Mt. Taylor are found at much higher elevations than in the Roca Honda permit area (Figure 2.7; RHR, 2011d). The remaining springs on the west side of Mt. Taylor are found in the Menefee Formation (Figure 2.7), which is not saturated in the permit area (RHR, 2011d).

The Navajo, Heron, and El Vado Reservoirs, and the irrigation diversions associated with the San Juan River, are all located in the northern part of the basin (Figure 2.6). Based on their relatively small areas and great distance from the Roca Honda mine, interactions between groundwater and the reservoirs or irrigation diversions are assumed to be negligible with respect to groundwater levels in the Gallup, Dakota, and Westwater aquifers in the vicinity of the Roca Honda mine.

2.2.2 Groundwater

Water enters the groundwater flow system as recharge in high elevation areas, as mountain-front recharge, and as infiltration from flowing rivers or drainages. Groundwater leaves the San Juan Basin aquifer units by discharging into rivers or drainages, by evaporation and transpiration, and by pumping of groundwater. All but the shallowest aquifers are unconfined along the outcrops and recharge areas, and become confined a short distance towards the basin center. Groundwater flow out of the San Juan Basin through leakage to other basins typically has been assumed to be negligible because of the basin's geometry (Stone et al., 1983; Kernodle, 1996).

Thick, low-permeability shale intervals divide the San Juan Basin's groundwater flow system into two or three relatively isolated flow systems. The Westwater, Dakota, and Gallup aquifers are separated from one another and the aquifers above and below them by units that are dominated by shale. Shale has a low hydraulic conductivity (analogous to permeability) and so offers great resistance to fluid flow. The Recapture Shale, the Brushy Basin, and the Mancos act as aquitards because their hydraulic conductivity is much lower than that of the three aquifers, and so the rate of groundwater flow into or out of the aquifers is much lower than the rate of flow within the aquifers. Similarly, the thick Mancos greatly restricts groundwater movement between the deeper Westwater, Dakota, and Gallup aquifers and those in the younger geologic units, such as the Point Lookout Sandstone or Menefee Formation in the vicinity of the Roca Honda permit area. In the northeastern part of the basin, the Lewis Shale restricts movement of groundwater between the Mesaverde Group and the Ojo Alamo Sandstone (Figure 2.4).

Historical differences in groundwater levels of 100 to 200 feet between the Dakota and Westwater aquifers and between the Gallup and Dakota aquifer prior to the start of historical mining (Stone et al., 1983) are further evidence that the Brushy Basin and Mancos units act as aquitards. The Mancos Shale has enough thickness and sufficiently small hydraulic conductivity values to limit groundwater flow rates between the lower aquifer units (Gallup, Dakota, and Westwater) and the upper water-bearing units (e.g., Point Lookout Sandstone, sandstone lenses in the Menefee Formation) to very small values.

2.2.2.1 Inflows

Recharge from precipitation occurs only after near-surface processes including runoff, evaporation, transpiration, and sublimation have depleted any precipitation, leaving the remaining water to infiltrate. Areal recharge is limited to the northern and southern margins of the basin where elevations are high and precipitation rates are greater than potential evaporation rates. Outside of the high-elevation areas, most of the basin has an arid to semiarid climate, with transpiration by plants and potential evaporation exceeding precipitation and making recharge negligible in low-elevation areas of the basin. Bedrock units receive recharge where they crop out and in higher-elevation areas where they subcrop beneath saturated alluvium (Stone et al., 1983).

Seepage into the subsurface occurs beneath surface water bodies. Infiltration from streamflow losses to the subsurface occurs mainly along the northern margin of the basin where the larger streams draining the San Juan Mountains in Colorado flow across outcrops of the more permeable bedrock units. Infiltration from streamflow losses also occurs along the upper reaches of the Rio Puerco, Rio Salado, and Puerco River. Locally important recharge to the older bedrock aquifers occurs in the Chuska Mountains and along the flanks of Mt. Taylor (Kernodle, 1996). The number of springs around Mt. Taylor is evidence of the higher precipitation rates, resulting in greater infiltration, relative to the lower elevations.

2.2.2.2 Outflows

The San Juan River captures nearly all of the groundwater discharge from the Gallup, Dakota, and Westwater aquifers, with the remainder discharging to the ephemeral Rio Puerco and Puerco Rivers (Stone et al., 1983; Levings et al., 1996; Kernodle, 1996). Groundwater flowing through the stratigraphically higher aquifer units can discharge to ephemeral drainages and rivers (Kernodle, 1996). Evaporation and transpiration remove water from the saturated intervals near ground surface, including ephemeral drainages, intermittent streams, springs, and rivers.

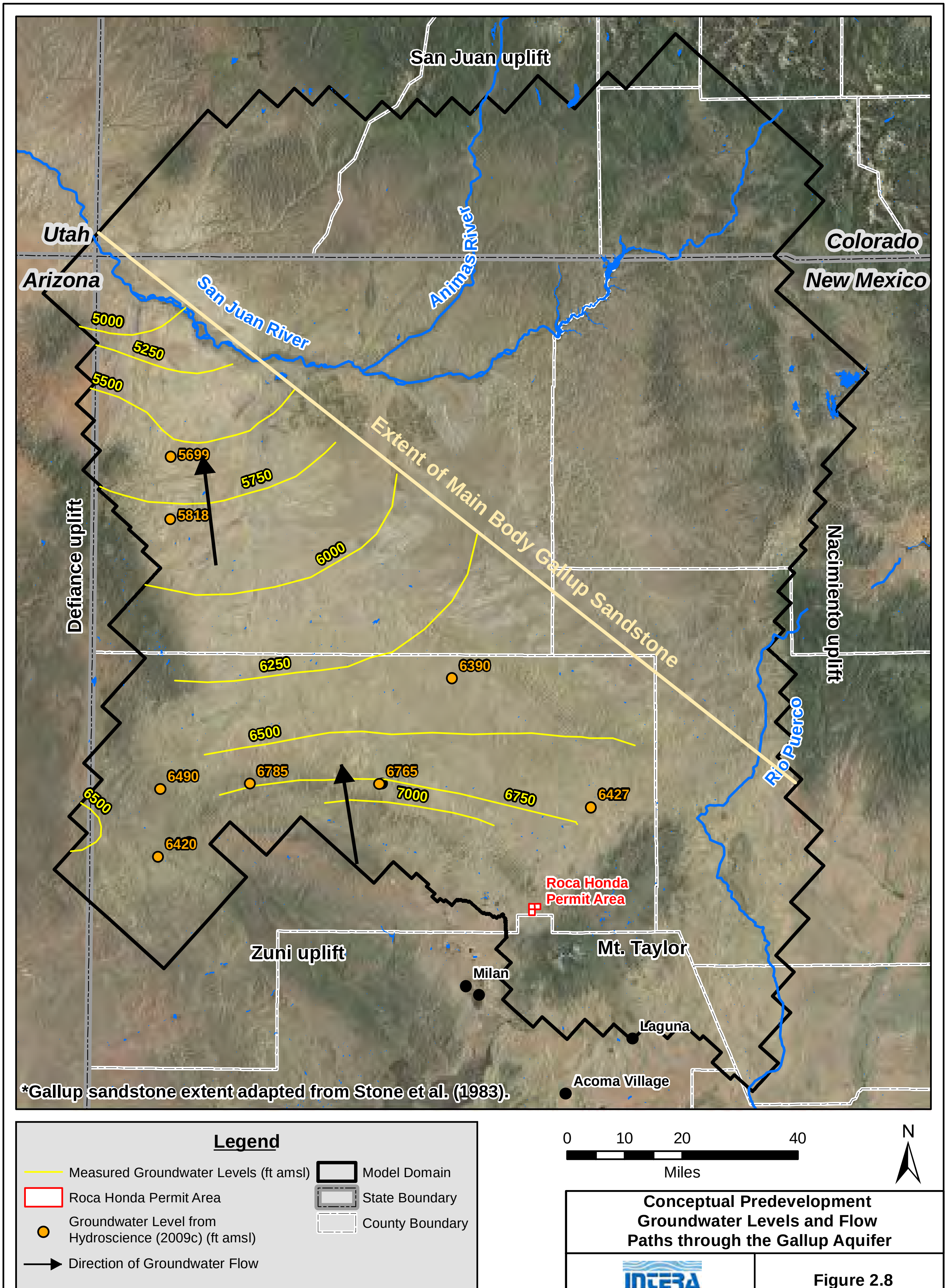
Wells in the San Juan Basin pump groundwater from a number of water-bearing units, including the Gallup, Dakota, and Westwater aquifers. Public water supply wells for Crownpoint and the two well fields for the city of Gallup pump only from these three aquifers, whereas wells for domestic consumption, irrigation, and stock watering pump mainly from shallower aquifers such as the Point Lookout Sandstone, sandstone intervals in the Mancos Shale and Mesaverde Group, and younger (overlying) geologic units. Mine dewatering of the Menefee Formation occurs at the Lee Ranch coal mine, northeast from the Roca Honda mine area.

2.2.2.3 Regional Flow Patterns

At the regional scale, groundwater enters the Gallup, Dakota, and Westwater aquifers as recharge along the southwestern and northeastern basin margins and then moves through the basin center towards the northwest and southeast (Stone et al., 1983; Kernodle, 1996). Prior to large-scale groundwater pumping, during the time period referred to as "predevelopment" time (defined for the purpose of this report as the period prior to 1930), the groundwater levels in the aquifers were high at the primary recharge areas along the southwestern and northeastern margins (Figures 2.8, 2.9, and 2.10). Groundwater flows into the basin center, and depending on its flow path, eventually discharges either to the lower San Juan River in the northwest corner of the San Juan Basin or to the Rio Puerco in the basin's southeast (Figures 2.8, 2.9, and 2.10; Stone et al., 1983). A minor amount of groundwater is discharged into the Puerco River in the southwestern area of the basin. Regional groundwater flow patterns in the shallower aquifers (those above the Mancos Shale) in the interior of the basin follow a similar pattern, but are more strongly controlled by discharge to alluvium in the ephemeral drainages of the Chaco River and its tributaries.

2.2.2.4 Impacts from Historical Uranium Mining

Uranium was mined from the Westwater in the Ambrosia Lake area. Figure 2.11 illustrates known or estimated locations of the mine workings. Dewatering of the mines formed a regional cone of depression within the upper Morrison Formation and lower Cretaceous units during the historical mining period (Bostick, 1985). The Westwater, the Dakota, and local sandstone beds in the lower Mancos Shale were essentially dewatered in the vicinity of the mines after mining started in the late 1950s. Groundwater removed from the mines was discharged to the Arroyo del Puerto drainage system and temporarily saturated portions of the formerly dry alluvium. Water also re-entered the bedrock through downward infiltration into underlying sandstones. Since 1986, when mining and dewatering ceased, groundwater levels in these units have been recovering.



Conceptual Predevelopment Groundwater Levels and Flow Paths through the Gallup Aquifer

Figure 2.8

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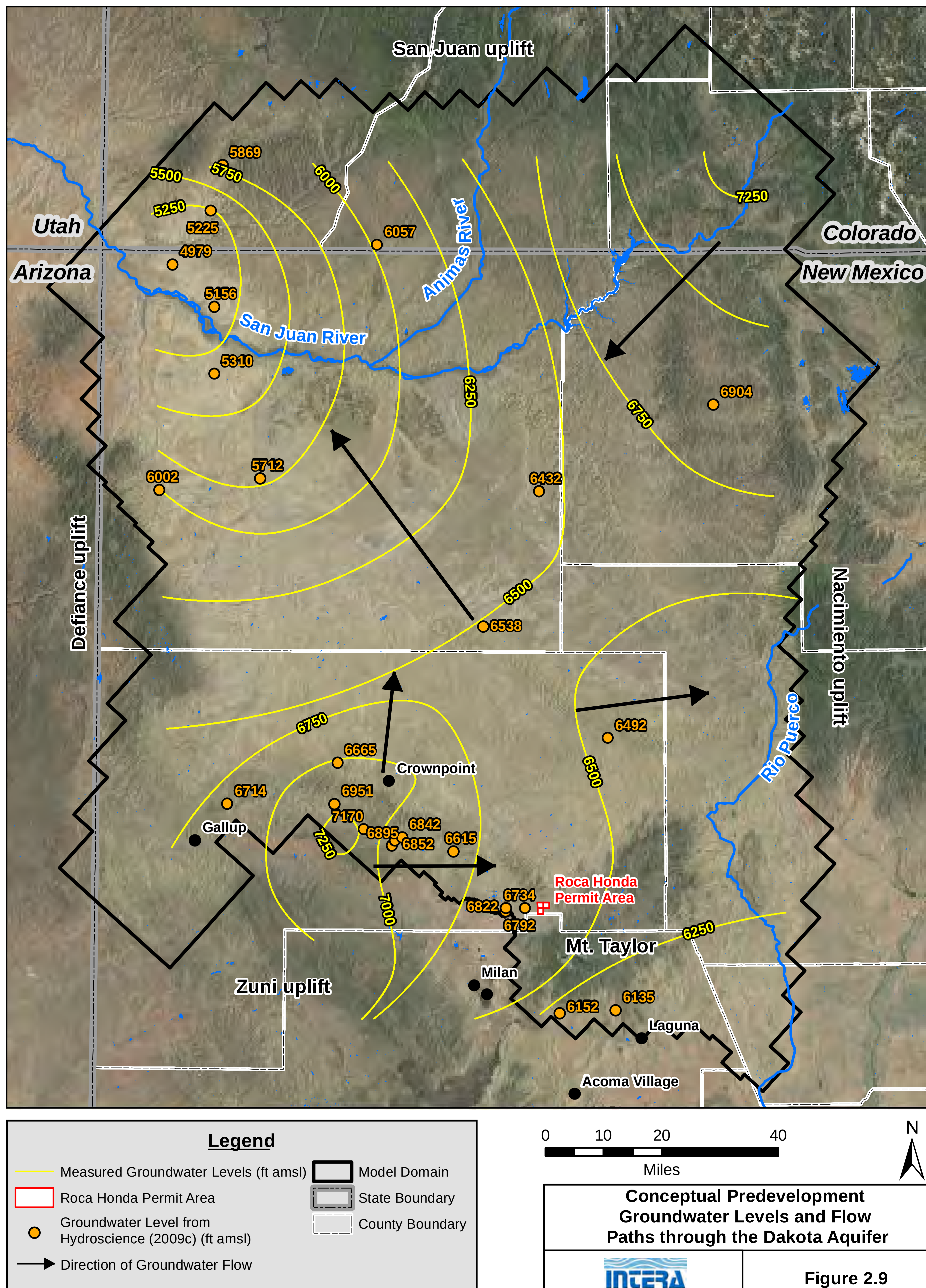

Conceptual Predevelopment Groundwater Levels and Flow Paths through the Dakota Aquifer

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Figure 2.9

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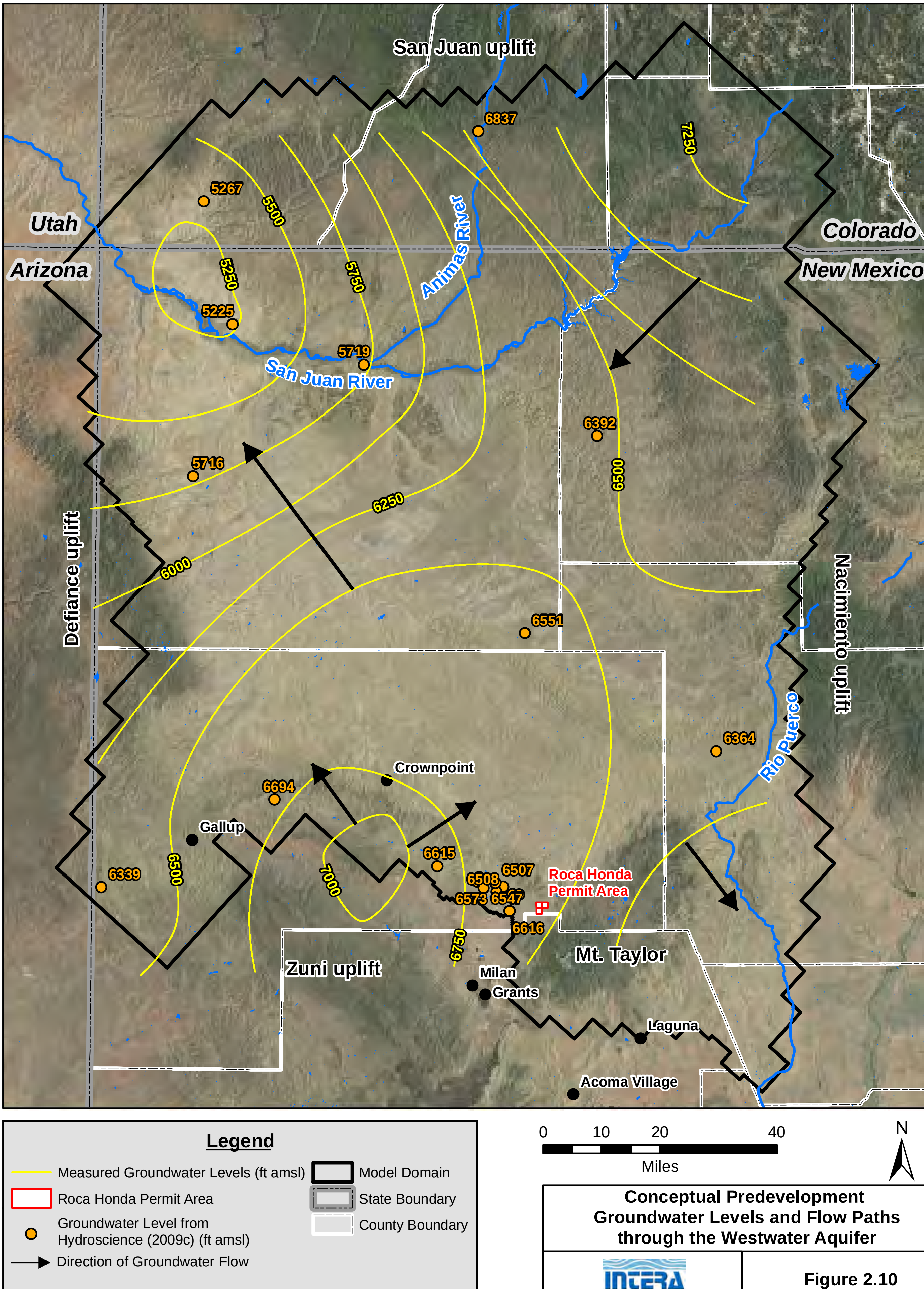

Conceptual Predevelopment Groundwater Levels and Flow Paths through the Westwater Aquifer

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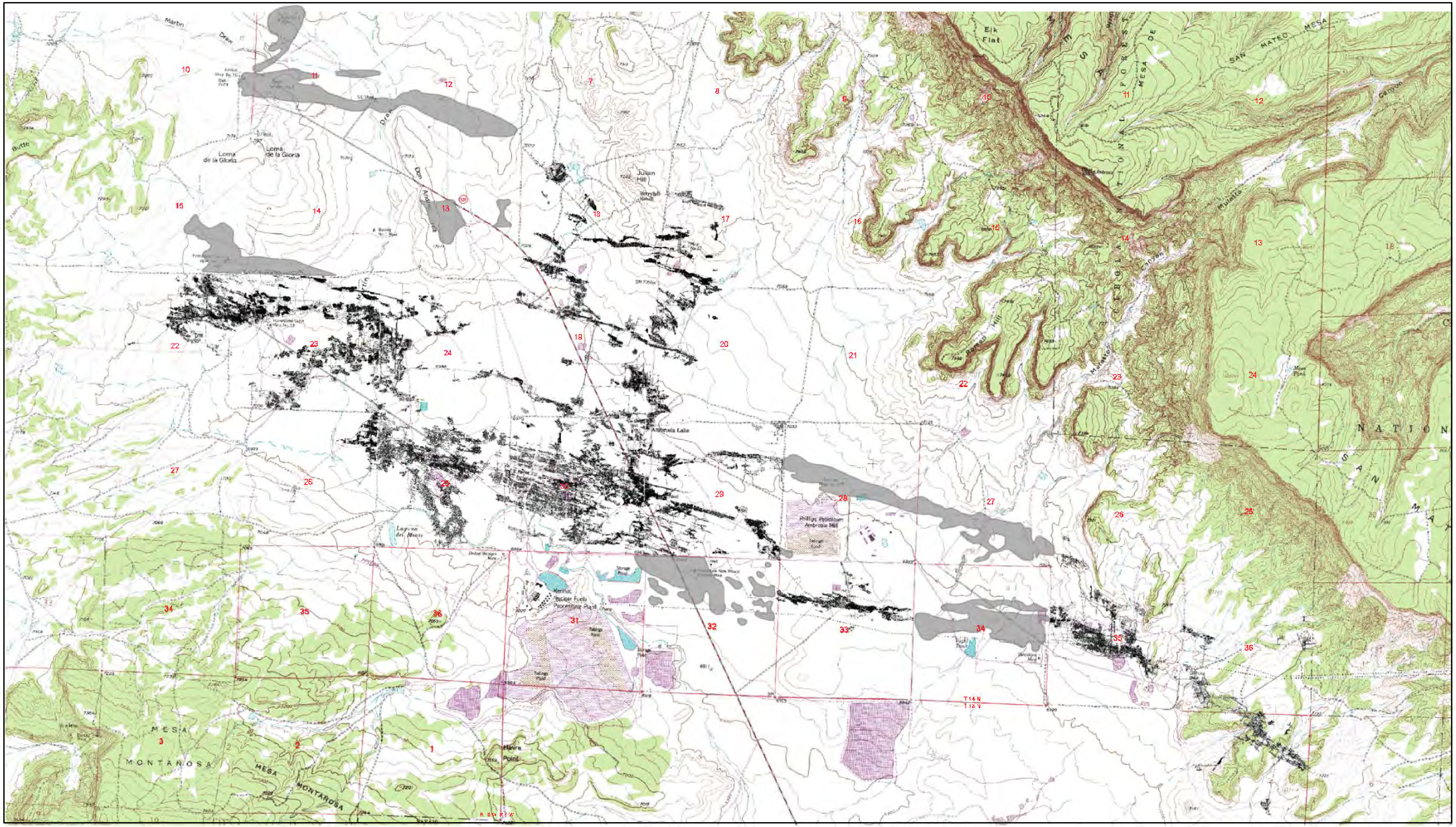
Figure 2.10



N

4,000 2,000 0 4,000

Feet

Legend

Mine workings

Estimated location of mine workings

Underground Mine Workings in the Ambrosia Lake Mining Area, New Mexico

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Figure 2.11

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2.3 Water Balance

Calculation of an annual basin-wide water budget provides information about the overall groundwater flow system and also serves as a benchmark to check numerical simulation results. An annual water budget describes the amount of water added to (inflows) or removed from (outflows) the basin over a 12-month period. Few such calculations for the San Juan Basin are available in the literature, and most were accomplished by carrying out steady-state numerical simulations. Lyford and Stone (1978) estimated that the total inflow (= total outflow) for the Jurassic and Cretaceous sandstones in the San Juan Basin was 60 cubic feet per second (ft^3/s), which equals 5,184,000 cubic feet per day (ft^3/day). Using a simple three-dimensional steady-state flow model, Frenzel and Lyford (1982) estimated that the total inflow (outflow) was 30 ft^3/s (2,592,000 ft^3/day). In comparison, Kernodle's (1996) steady-state groundwater flow model of the entire basin provided a total inflow (outflow) of 195 ft^3/s (16,850,000 ft^3/day), which is equivalent to a basin-wide recharge rate of 0.14 inches per year (in/yr). Roughly 28% of the total inflow in Kernodle's 1996 model was attributable to areal or regional recharge, 2% to localized recharge in the Chuska Mountains, and the remainder attributed to streambed infiltration. The water balance developed using the Roca Honda mine models is discussed in Section 4.1.2 of this report.

3.0 CONSTRUCTION OF THE NUMERICAL MODELS

Potential changes to groundwater levels in the Gallup, Dakota, and Westwater aquifers were estimated by applying calibrated numerical models of groundwater flow. Each numerical model is built from the set of mathematical equations that describe groundwater flow and is based on the hydrogeologic understanding of the San Juan Basin described in Section 2. The mine dewatering schedule shown in Table 1.1 is assumed to describe dewatering at the Roca Honda mine. Section 3 describes the construction of the Roca Honda mine groundwater flow models.

3.1 Modeling Objectives and Approach

The first modeling objective was to construct numerical models that are able to reasonably simulate historical groundwater levels and to compare how well these simulated groundwater levels match historical observations of groundwater levels. The process of comparing simulated groundwater levels (or flow rates if applicable) to historical observations of groundwater levels (or flow rates) and modifying model inputs until the simulated and observed values are sufficiently close is called "model calibration." Model calibration (see Section 4) demonstrates whether the flow models represent the historical changes in groundwater levels within the Gallup, Dakota, and Westwater aquifers accurately enough so that the predictive models can be relied upon to simulate future groundwater levels during dewatering at the Roca Honda mine. The second modeling objective is to construct and apply groundwater flow models to predict the future groundwater levels in the three aquifers with and without proposed mine dewatering at the Roca Honda mine.

To achieve these objectives, INTERA completed the following tasks:

- Construction and calibration of a numerical model of groundwater flow to estimate predevelopment groundwater levels, i.e., groundwater levels prior to the year 1930, for conditions prior to the onset of large-scale mining in the Grants uranium district.
- Construction and calibration of a transient historical numerical model of groundwater flow to simulate changes in groundwater levels from 1930 to 2012 caused by a combination of pumping at public water supply wells, historical mine dewatering, and partial recovery from the historical mine dewatering.
- Construction and application of predictive transient flow models that simulate groundwater levels from the beginning of mine construction to 100 years after the end of the proposed 13-year mining period with and without dewatering at the Roca Honda mine.

The pre-development model represents the time period prior to 1930, the transient model covers the period 1930 through 2012, and the predictive model extends from 2013 through 2125. The USGS steady-state groundwater flow model developed for the same area by Kernodle (1996) was used a basis for constructing INTERA's Roca Honda mine models, but INTERA significantly improved on the USGS model by modifying boundary conditions, incorporating new data on aquifer parameters and stratigraphy in the vicinity of the Roca Honda permit area, increasing the amount of calibration data for the steady-state calibration, and carrying out a transient calibration.

The calibrated Roca Honda mine models provided the basis for predictive simulations that were used to estimate changes in future groundwater levels in the Gallup, Dakota, and Westwater aquifers, including locations near wells and springs, for four pumping scenarios. Dewatering at the Roca Honda mine is conservatively assumed to follow the maximum time periods and maximum pumping rates shown in Table 1.1. The predictive simulations span the period from 2012, when mine construction is assumed to begin, to the year 2125, 100 years after the assumed end of mining. The four pumping scenarios are:

- Scenario 1 – Pumping occurs at the Crownpoint and City of Gallup public water supplies and dewatering occurs at the Lee Ranch coal mine. This scenario estimates the effects on future groundwater levels from current pumping stresses and represents current and future "baseline" conditions.
- Scenario 2 – Pumping occurs at the Crownpoint and City of Gallup public water supplies with dewatering at the Lee Ranch coal mine and dewatering at the Roca Honda mine. This scenario estimates the effects on future groundwater levels from current pumping stresses plus the Roca Honda mine dewatering.
- Scenario 3 – Pumping occurs at the Crownpoint and City of Gallup public water supplies with dewatering at the Lee Ranch coal mine, and pumping of large water rights in the Gallup, Dakota, and Westwater aquifers in the vicinity of the Roca Honda permit area. This scenario estimates the effects on future groundwater levels from large water rights in the Gallup, Dakota, and Westwater on file with the NM OSE (see Section 3.8).
- Scenario 4 – Pumping occurs at the Crownpoint and City of Gallup public water supplies with dewatering at the Lee Ranch coal mine, dewatering at the Roca Honda mine, and pumping of large water rights in the Gallup, Dakota, and Westwater aquifers in the vicinity of the Roca Honda permit area. This scenario estimates the effects on future groundwater levels from dewatering at Roca Honda and pumping of water rights in the Gallup, Dakota, and Westwater on file with the NM OSE (see Section 3.8).

3.2 Other Models of San Juan Basin Groundwater Flow

Numerical models of groundwater flow through the entire San Juan Basin are limited in number. Numerical models were constructed to aid in planning and designing uranium mines in the Ambrosia Lake sub-district (e.g., Williams et al., 1986), but those models did not encompass the entire basin nor were they applied to estimate potential changes in groundwater levels.

Building on the hydrogeologic information provided in Stone et al. (1983), Frenzel and Lyford (1982) constructed a three-dimensional, steady-state flow model to assess potential changes to groundwater resources from new groundwater pumping and development of the basin's energy resources. The specific objective of this groundwater modeling study was to estimate groundwater flow rates between the different aquifer and aquitard units from the Entrada Sandstone up to the Lewis Shale and to estimate a steady-state water balance (see Section 2.3). The area evaluated in this study was similar to the basin area adopted for the Roca Honda mine groundwater flow models; however, recharge and discharge areas were represented by specified head boundary conditions instead of the more commonly used specified flux boundary conditions. The model was built using the Trescott (1975) finite difference code. According to Kernodle (1996), Frenzel constructed an uncalibrated transient flow model to assess potential changes to groundwater systems from mining on federal coal leases (Frenzel, 1983).

Frenzel (1992) also constructed a model of the San Andres-Glorieta aquifer along the southern margin of the San Juan Basin. This model was modified in 2001 by Daniel B. Stephens and Associates, Inc. (DBSAI) to assess the impacts of pumping wells owned by the Atlantic Richfield Company on groundwater levels, stream flows and springs in the San Andres-Glorieta aquifer, and overlying shallow alluvium within part of the southern San Juan Basin (DBSAI, 2001). The original and modified Frenzel models were used for constructing the Roca Honda mine model because they did not include the Westwater aquifer or the units between the Westwater and the San Andres-Glorieta aquifer.

Kernodle (1996) constructed a steady-state groundwater flow model of the entire San Juan Basin using the MODFLOW code (McDonald and Harbaugh, 1988). The objective of his model was to describe and simulate the basin-wide flow system in the San Juan Basin. The model encompassed the same horizontal basin extent as the Roca Honda mine groundwater flow models, but also included the Entrada Sandstone in its vertical extent. The flow model simulated areal recharge as a boundary condition, surface water-groundwater interactions using the river boundary condition, mountain front recharge in the Chuska Mountains as a general head boundary condition, and groundwater discharges to ephemeral drainages as drain boundary conditions. The input files for the Kernodle model are not available. DBSAI reported that John Shomaker and Associates, Inc. (JSAI) partially reconstructed the Kernodle (1996) groundwater flow model (Carpenter and Shomaker, 1998; DBSAI, 2001). This partial reconstruction included the hydrostratigraphic units between the San Rafael Group and the late Cretaceous Mesaverde Group, with the entire Morrison Formation represented in a single model layer. DBSAI revised this model and conducted a transient calibration to 11 wells for the period 1978 to 1990.

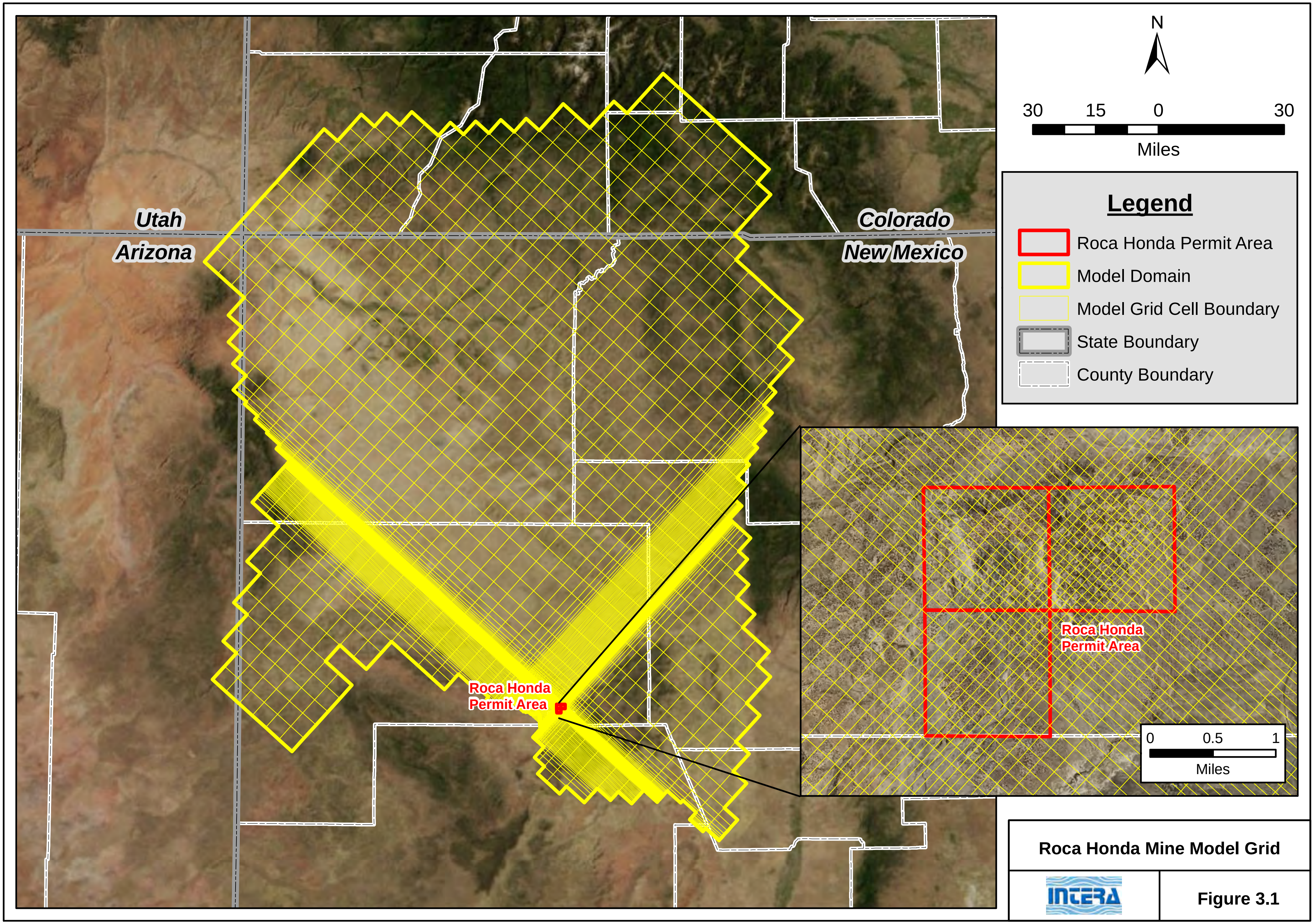
3.3 Computer Code

INTERA selected the MODFLOW-SURFACT (HydroGeoLogic, 1996) version 3 code to conduct the groundwater flow modeling because this model code is superior to MODFLOW in simulating mine dewatering and groundwater level recovery. MODFLOW-SURFACT offers significantly increased capability to quickly simulate rapidly changing groundwater levels and desaturation-saturation, compared to the MODFLOW-2005 code, by simply replacing MODFLOW's BCF package with its BCF5 package. MODFLOW-SURFACT uses nearly all of the many MODFLOW packages, including those to simulate recharge, drains, rivers, and wells, and its solver is much faster than any now available with MODFLOW. Like MODFLOW, MODFLOW-SURFACT is a three-dimensional, finite-difference, block-centered, saturated groundwater flow code, and it has been widely applied and accepted by the United States Bureau of Land Management (US BLM) and other agencies for mine permitting and other uses. All Roca Honda mine numerical models were developed, tested, and applied using the Groundwater Vistas version 5 (Rumbaugh and Rumbaugh, 2007) graphical user interface.

3.4 Model Domain and Discretization

The modeled area, called the "model domain," for the Roca Honda mine groundwater flow models includes roughly the entire San Juan Basin from the center of the basin outwards to the outcrop of the Morrison Formation around the perimeter (Figure 3.1). It is very similar in extent to the domains adopted by both Kernodle (1996) and Frenzel and Lyford (1982). The top of the domain was set to ground surface. The bottom of the domain was set to the contact between the Westwater and its underlying regional aquitard, the Recapture Member of the Morrison Formation.

The model domain was discretized horizontally into 120 rows and 119 columns and vertically into ten layers, yielding 85,222 active cells (Figure 3.1). Grid "north," which is parallel to column orientation, is rotated 43.75 degrees counterclockwise from true north. Grid block dimensions ranged from a maximum of roughly 30,000 feet on each side in locations far from the Roca Honda permit area to 660 feet on a side within the area of interest (Figure 3.1). The model domain and discretization were the same for all Roca Honda mine numerical models.



Roca Honda Mine Model Grid

Figure 3.1

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The model's vertical structure was determined by the impact assessment's focus on the Gallup, Dakota, and Westwater aquifers, and by the San Juan Basin's asymmetric geometry. Table 3.1 and Figure 2.4 show how the geologic units were grouped into hydrostratigraphic units (see Section 2.1) represented as model layers. The three aquifers and adjacent aquitards were represented as single model layers wherever possible. The tops and bottoms of these model layers were constructed to follow the top and bottom elevations of these hydrostratigraphic units (see Section 2.1) across the model domain. Exceptions to this rule were limited to those areas in a particular model layer where a hydrostratigraphic unit thickened or pinched out. For example, in order to represent these changing thicknesses in model layers 2 through 4, individual hydrostratigraphic units were distinguished within a model layer by assigning different hydraulic properties. The top of model layer 1 r epresents ground surface. The top of each layer 1 grid block was assigned an elevation that corresponds to the location of the grid block's centroid as derived from a 30-meter digital elevation model data set.

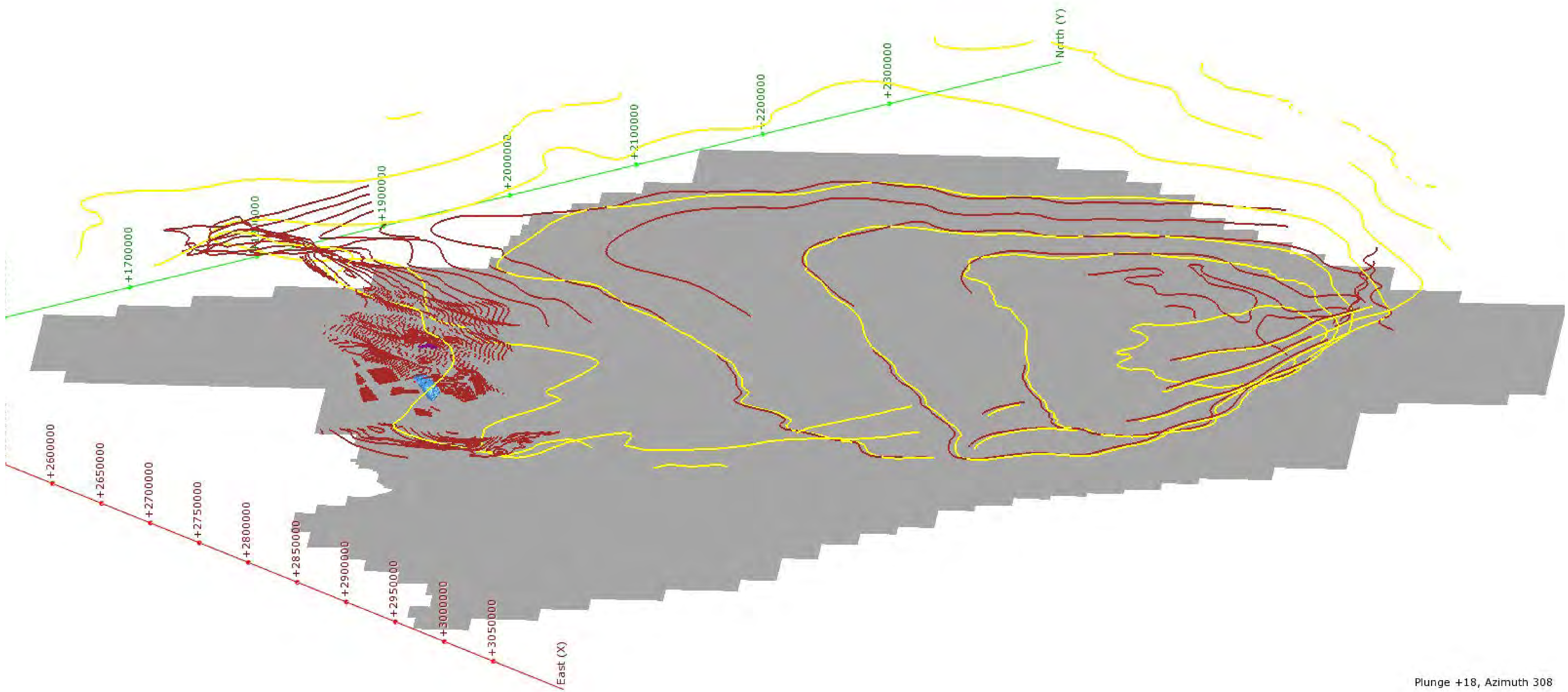
Tops and bottoms of model layers for the Gallup down to the Westwater (layers 6 through 10) were assigned elevations using hydrostratigraphic data obtained from a variety of sources. The bottom of the Dakota Sandstone is used as the reference point for the groundwater model construction. This contact, which represents the top of the Morrison Formation (top of model layer 9), was constructed by combining geologic contour data from Dam et al. (1990a), geologic contour data provided by RHR, an elevation raster of the contact in the mine area provided by RHR, and well logs from published and unpublished reports. Figure 3.2 depicts the Dam et al. (1990a) elevation contours in yellow, updated elevation contours from RHR in red, and RHR's detailed interpretation of the elevation in the Roca Honda permit area as a blue polygon. The top elevations for the Gallup Sandstone, Dakota Sandstone, and other hydrostratigraphic units were constructed in similar fashion. Formation elevation tops were calculated from information about geologic unit thicknesses for geographic areas in which contours had not previously been developed. Even though faults and associated displacements are common throughout the San Juan Basin, the discretization scale in much of the basin averaged out such detailed structural differences. Faults present near the Roca Honda permit area were not specifically represented in the Roca Honda model because there is no information regarding their impact on water flow in the Westwater. Cross sections of the model layering through the Roca Honda mine site are depicted in Figures 3.3 and 3.4.

Table 3.1
Hydraulic Properties of Hydrostratigraphic Units in the San Juan Basin

Model Layer	Hydrostratigraphic Unit	Thickness Range (feet)	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day) Reported (Modeled)[c]	
				Horizontal	Vertical
1	San Jose Formation	200 – 2,700[a]	40 – 117[b]	0.4 – 1.2 (0.2)	-- (0.002)
2	Animas Fm and Nacimiento Fm	230[d] – 2700[e] 500 – 1,300[f]		-- (0.01)	-- (0.0001)
3	Ojo Alamo Sandstone	20 – 400[e]	Deep: 0.05 – 0.39[b] Shallow: 57 – 245[b]	0.14 – 1.2 (0.4 – 0.8)	-- (0.0001)
	Kirtland Shale and Fruitland Fm	0 – 1,500[eg] 0 – 500[eg]	Kirtland: 2.4[b] Fruitland: 0.6 – 130[b]	0.05 – 0.065 (0.4 – 0.8)	-- (0.0001 – 0.003)
	Pictured Cliffs Sandstone	0 – 400[e]	0.001 – 3[b]	0.007 (0.007)	-- (0.00007)
4	Lewis Shale	0 – 2,400		-- ($5x10^{-5}$)	-- ($5x10^{-5}$)
5	Cliff House Sandstone	20 – 500	2.1[b]	-- (0.05 - 0.1)	-- (0.00007)
	Menefee Formation	0 – 2,000[g]	Confining unit: 2.7 – 112[b]	0.001 (0.05 – 0.1)	-- ($5x10^{-6}$ – 0.001)
	Point Lookout Sandstone	40 – 415[a]	0.4 – 236[b]	0.002 – 0.02[ia] (0.13)	-- (.00001 – 0.01)
6	Mancos Shale (NE only)	1,000 – 2,300		-- (0.0001 – 0.0009)	-- ($9x10^{-8}$ – 0.0001)
	Gallup Sandstone (SW only)	0 – 600[c] 0 - 700[a]	15 – 390[b]	0.1 – 1[j] (1)	-- (0.002)
7	Mancos Shale	1,000 – 2,300		-- (0.0001 – 0.0009)	-- ($9x10^{-8}$ – 0.0001)
8	Dakota Sandstone	50 – 350[a]	44 – 134[ah]	0.25 – 1.5[a] (0.25)	-- ($1.4x10^{-5}$ – 0.002)
9	Brushy Basin Member of Morrison Formation	80 – 250		0.0004 - 0.003 (0.0008 – 0.1)	-- ($9x10^{-8}$ - 0.002)
10	Westwater Canyon Member of Morrison Formation	100 – 300	2 – 490[b]	0.02 – 1.6 (0.08 – 0.1)	-- ($8x10^{-6}$ – 0.002)

Data Sources:

[a] Stone et al. (1983).
[b] Table 2 of Levings et al. (1996).
[c] Modeled values taken from Kernodle (1996) unless indicated otherwise.
[d] Barnes et al. (1954)
[e] Fassett and Hinds (1971)
[f] Molenaar (1977a)
[g] Molenaar (1977b)
[h] Brod and Stone (1981)
[i] Craigg et al. (1989)
[j] GMRC (1979)



Red contours: RHR updated contours for bottom of Dakota Sandstone at various intervals

Yellow contours: Contours for top elevation of Morrison Formation from Dam et al. 1990 (USGS HA-720-J)

Blue raster: RHR top of Morrison Formation in mine area

Gray polygon at bottom: Model domain

GIS Data for Bottom of Dakota Sandstone Elevation

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Figure 3.2

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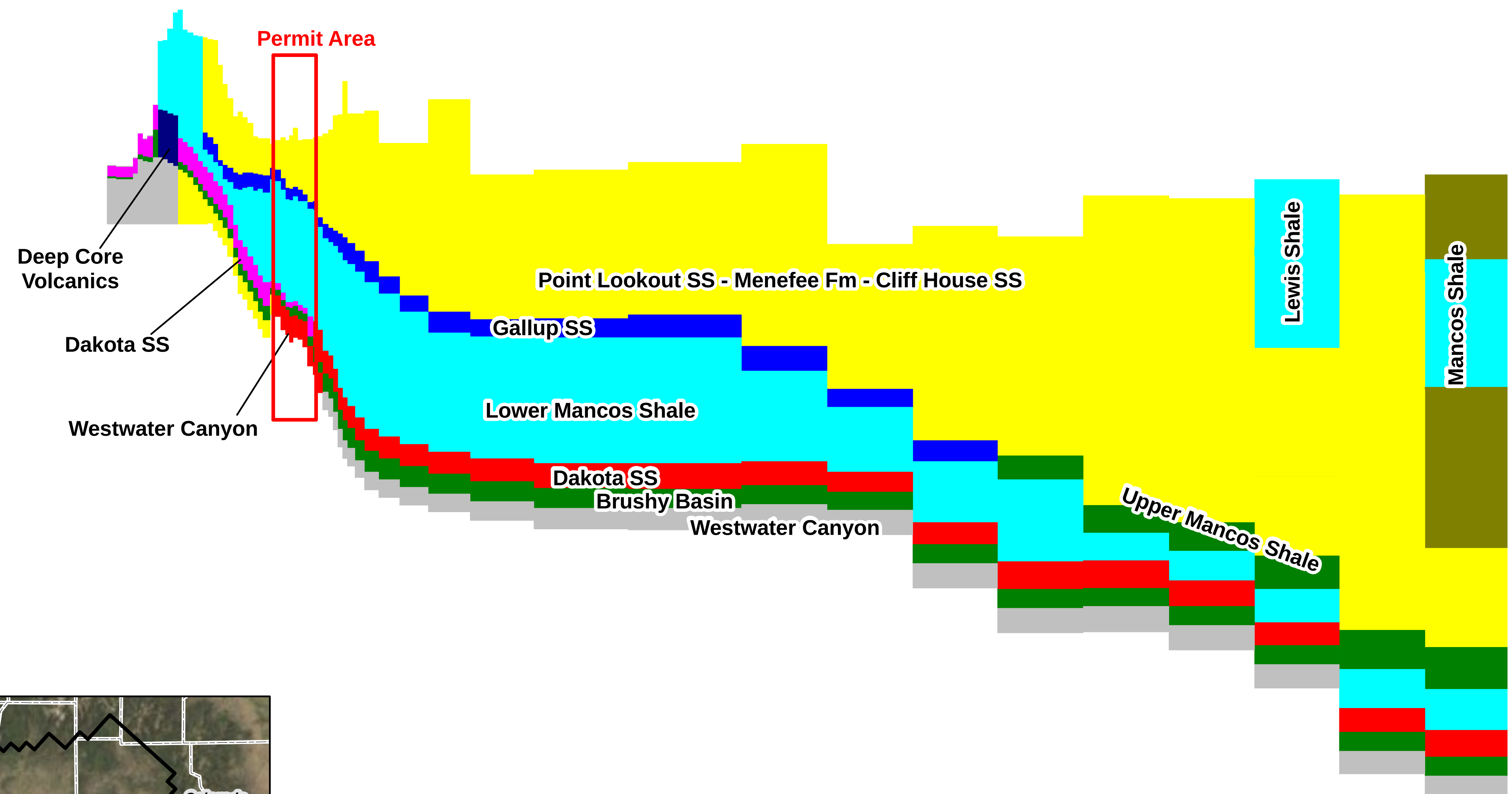
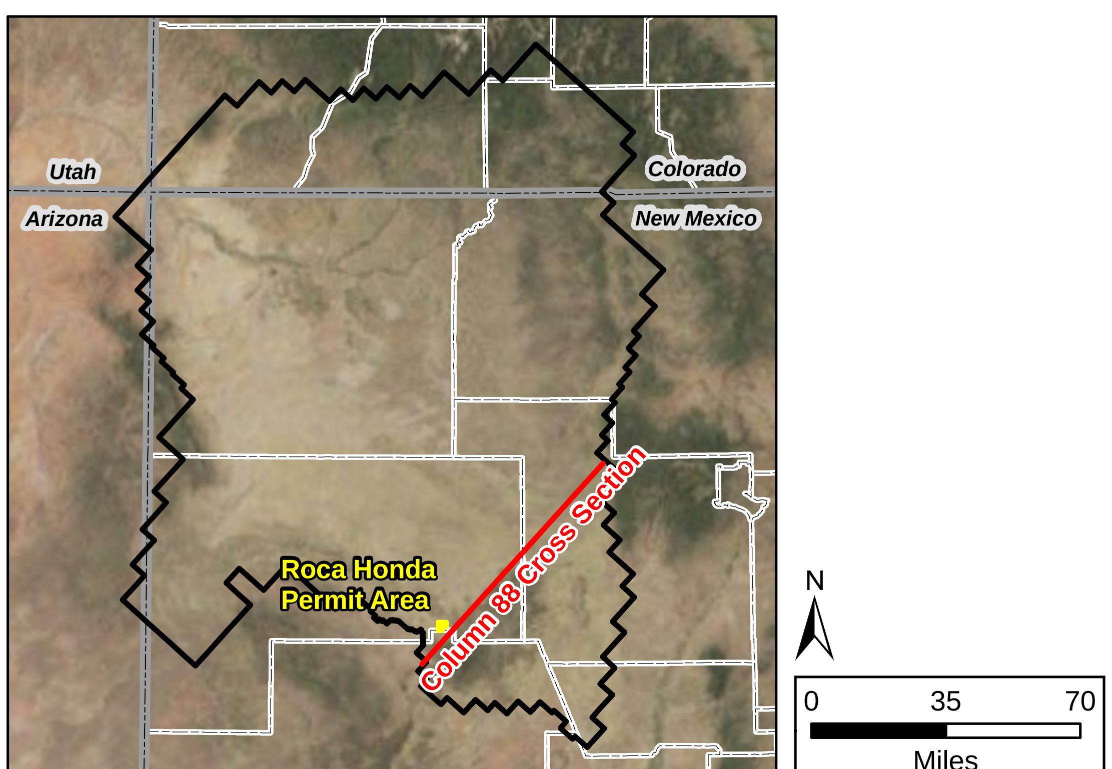
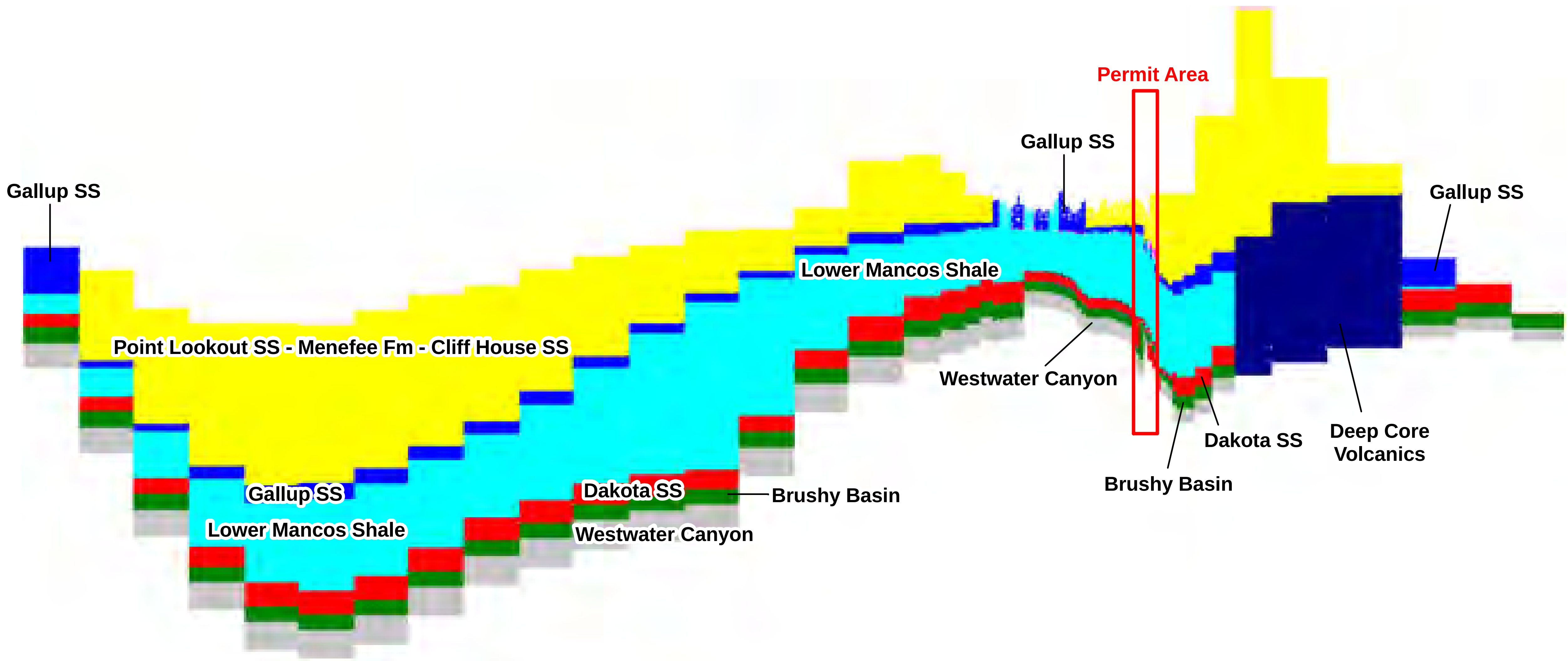


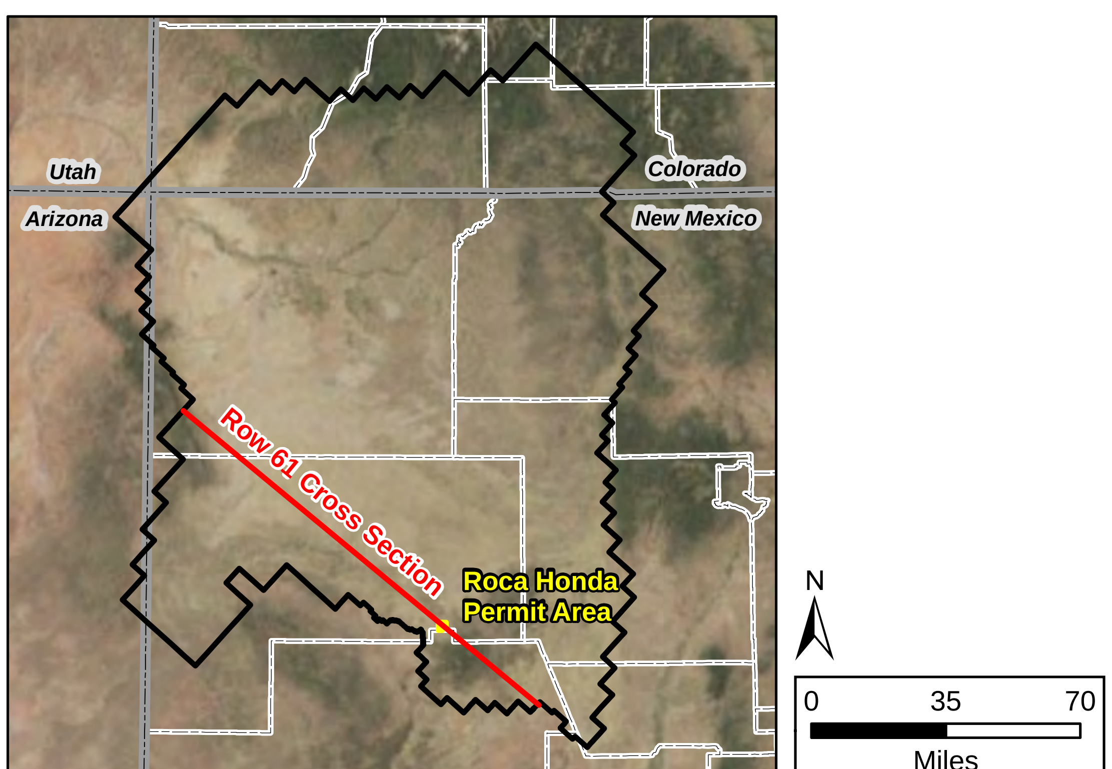


Cross Section along Column 88 in the Roca Honda Mine Model

INTERA

Figure 3.3





Cross Section along
Row 61 in the Roca
Honda Mine Model

Figure 3.4

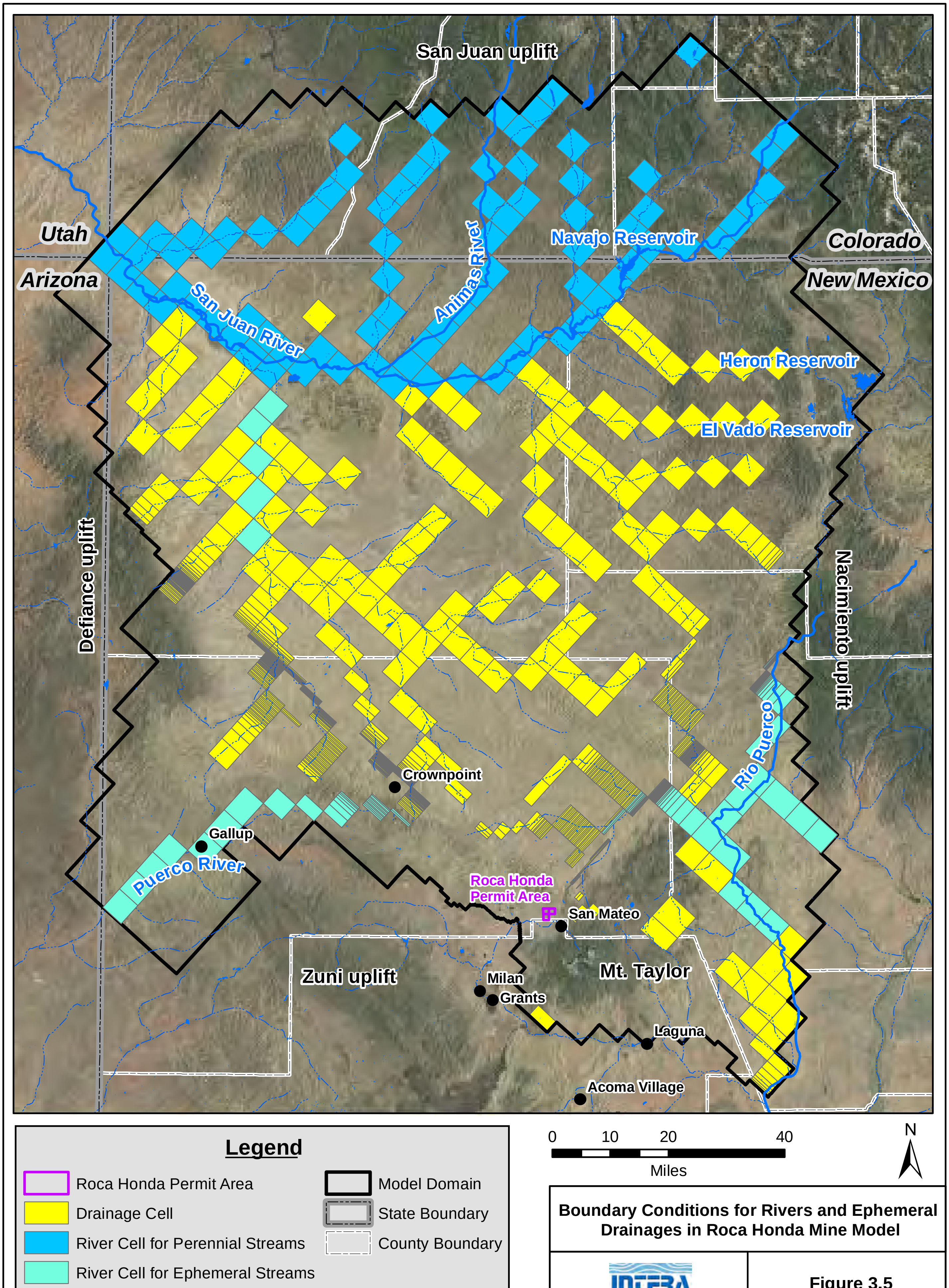
3.5 Boundary Conditions

According to Kernodle (1996, p. 57), "A ground-water-flow boundary is any physical feature or mechanism that alters movement of water in the ground-water-flow system, or is a sink or source of water to the system." A boundary condition can correspond to physical features of the area modeled, such as the limits of aquifers, or to stresses or driving forces for groundwater flow. The Roca Honda mine numerical models used boundary conditions to represent the stresses described in Section 2: areal recharge, mountain-front recharge, groundwater-surface water interactions, groundwater discharge to ephemeral drainages, and pumping for mine dewatering and water supplies. Most boundary conditions remained constant for all Roca Honda mine models. Variable boundary conditions were the time-varying pumping and dewatering stresses, and the variable flows of mine water that were historically discharged into the San Mateo Creek and Arroyo del Puerto ephemeral drainages that were included in the 1930-2012 transient calibration model. Maps of the boundary conditions assigned in each layer are presented in Appendix A.

The perennial sections of the San Juan River system were represented as river boundaries using the MODFLOW River Package (Figure 3.5). River boundaries allow for water to move from the river to the aquifer or vice versa depending on the head in the aquifer relative to the river stage. Geographic information system (GIS) tools were used to determine the river stage in each grid block by calculating the average elevation of water in a river segment in each grid block and adding a factor for river depth. The Rio Puerco and the upper reaches of the Puerco River were also represented using river boundary conditions (Figure 3.5), but the river stages were set at ground surface in order to represent the presence of saturation in the streambeds. Kernodle (1996) employed a similar approach for the perennial rivers and the larger ephemeral drainages.

Groundwater discharge to ephemeral drainages was simulated using MODFLOW's Drain Package (Figure 3.5). These ephemeral drainages control groundwater levels in the interior of the basin (Kernodle, 1996). Drain elevations were set to the ground surface elevation at grid block centers to allow for groundwater flow out of the system if groundwater levels were higher than the drain elevation. In this way, drain cells simulated the removal of groundwater discharged to ephemeral drainages by runoff, evaporation, or transpiration (Stone et al., 1983; Kernodle, 1996).

Areally distributed recharge from precipitation on the land surface was applied to the areas indicated by Kernodle (1996) as likely recharge areas. These included the large Dakota Sandstone and Gallup Sandstone outcrops along the basin margin, the Point Lookout Sandstone outcrops, and the Mt. Taylor volcanics (Figure 3.6). Recharge rates were estimated using the approach described by Kernodle (1996) that showed rates increasing with elevation. Recharge rates spanned a range from 0.004 to 0.35 in/yr. Average annual precipitation ranges from 8 to 40 in/yr across the San Juan Basin (Kernodle, 1996). MODFLOW's Recharge Package was used to represent recharge to the aquifers that was widely distributed, spatially variable, but constant from year to year.



*Perennial streams and ephermeral drainage are based on US National Atlas Water Feature Lines Database

Boundary Conditions for Rivers and Ephemeral Drainages in Roca Honda Mine Model

Figure 3.5

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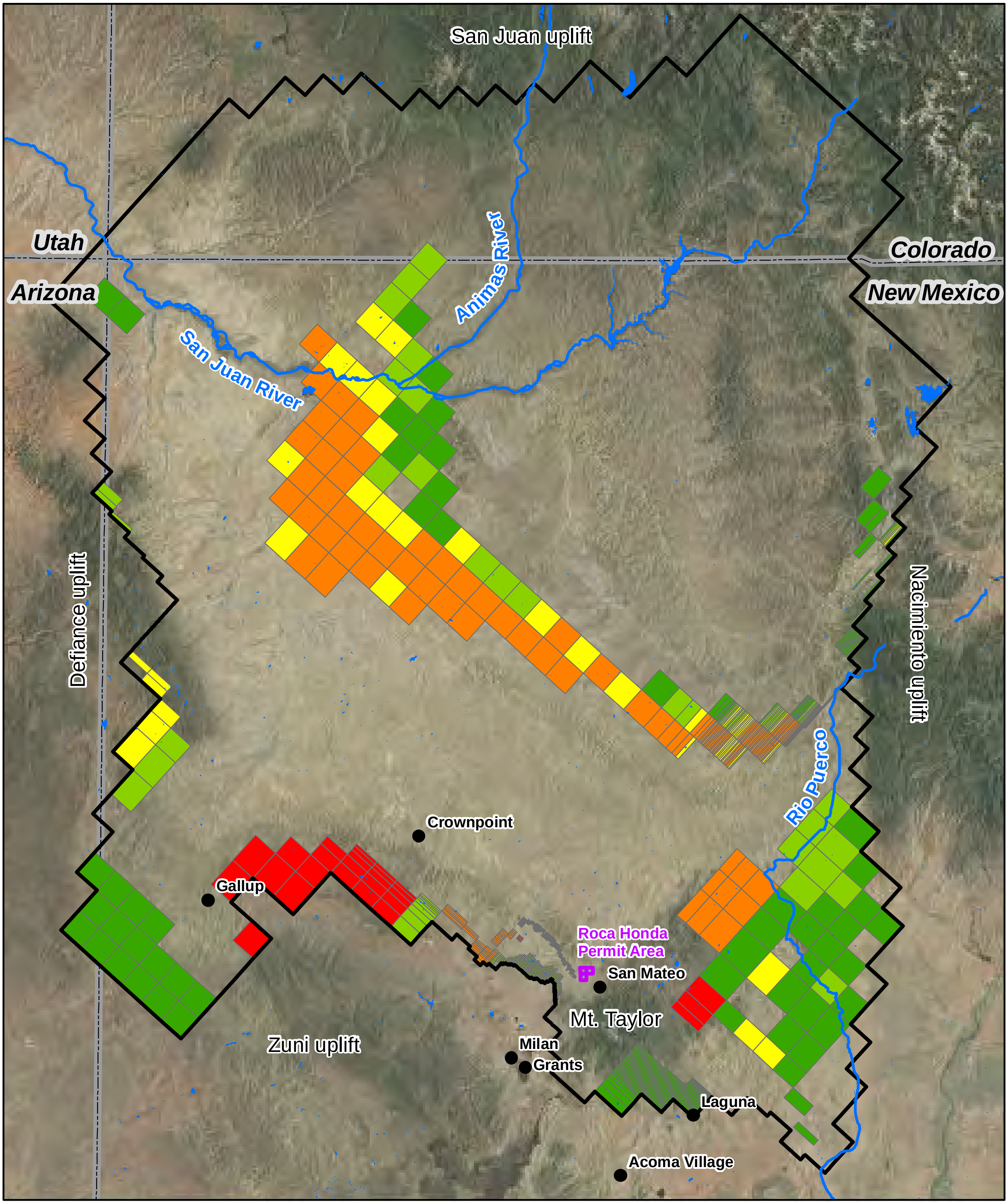


Legend

- Roca Honda Permit Area
- Model Domain
- State Boundary

Recharge (in/year)

- 0.004 - 0.026
- 0.026 - 0.061
- 0.061 - 0.101
- 0.101 - 0.136
- 0.136 - 0.350

Areal Recharge Boundary Condition in Roca Honda Mine Model

INTERA

Figure 3.6

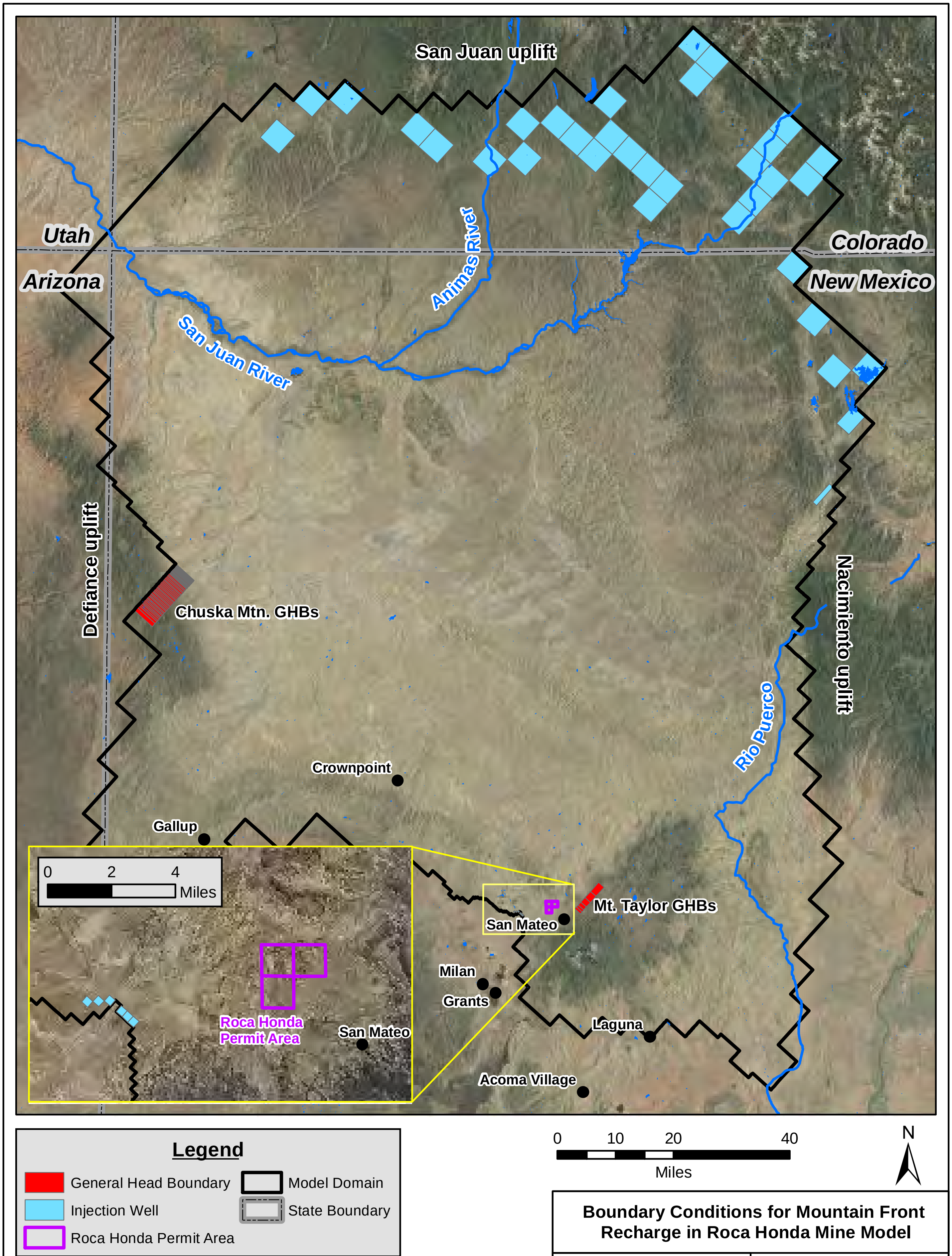
File: S:\Projects\STR-001_Strathmore_Modeling\GIS\Mapdocuments\Addendum_2012\Revised_Original_Report\Figure03_06_ArealRecharge.mxd 3/1/2012

Mountain-front recharge from the mountains along the northern Basin margin was simulated with specified-flux boundaries using the MODFLOW Well Package in layers 5 and 8 (Figure 3.7). Specified fluxes were added at six locations to layer 10 in the area where San Mateo Creek crosses the model domain boundary to simulate the presence of high groundwater levels there (Figure 3.7 inset). Mountain-front recharge from the Chuska Sandstone and Mt. Taylor volcanic was simulated by using the General Head Boundary Package along the subcrop perimeters in layer 6 (Figure 3.7). General Head Boundaries are used to represent recharge or discharge into or out of an aquifer that is dependent on a specified groundwater level. Kernodle (1996) also used the General Head Boundary Package to represent deep recharge along the Chuska Mountains.

Well Package cells were used to simulate pumping for public water supplies (Figure 3.8 and Section 3.7). The two Gallup well fields and the Crownpoint supply well operate in the 1930-2012 transient calibration model and the predictive simulations. Rates were based on documents from the City of Gallup and the NM OSE.

MODFLOW-SURFACT's Fracture Well Package was used to represent mine dewatering at the Ambrosia Lake sub-district mines, the Church Rock Mine, the Gulf Mt. Taylor Mine, and the Johnny M Mine in the 1930-2012 transient calibration model (Figure 3.9). The Fracture Well Package is very similar to MODFLOW's Well Package, but has the additional capability of decreasing the flow rate if the model cell containing the fracture well begins to dry out. Mine dewatering rates and volumes were based on information from historical mine dewatering reported by Stone et al. (1983) as well as more recent compilations by Hydroscience (2009c). Section 3.7 describes the time periods for the historical dewatering.

For the predictive simulations with dewatering at the Roca Honda mine, dewatering was simulated using the specified flux boundary condition with the rates and schedule shown in Table 1.1. These hydraulic sink boundary conditions were placed within and around the Roca Honda production shaft and mine workings to depressurize the Gallup, Dakota, and Westwater aquifers during shaft construction and to dewater the Westwater during mining at the maximum rates stipulated in the dewatering permit application (Table 1.1).



Boundary Conditions for Mountain Front Recharge in Roca Honda Mine Model

INTERA

Figure 3.7

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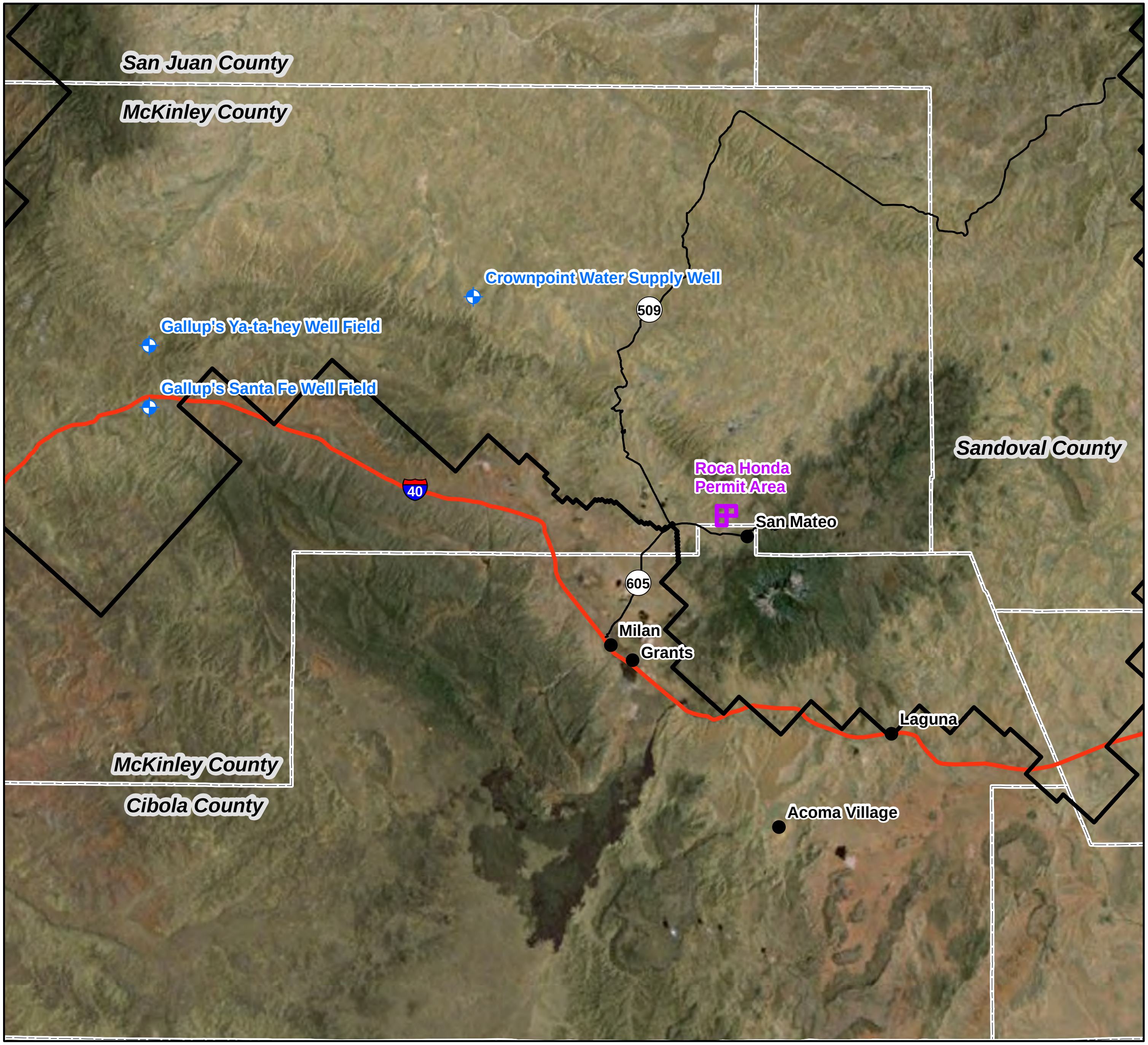

Public Water Supply Wells in Roca Honda Mine Model

INTERA

Figure 3.8

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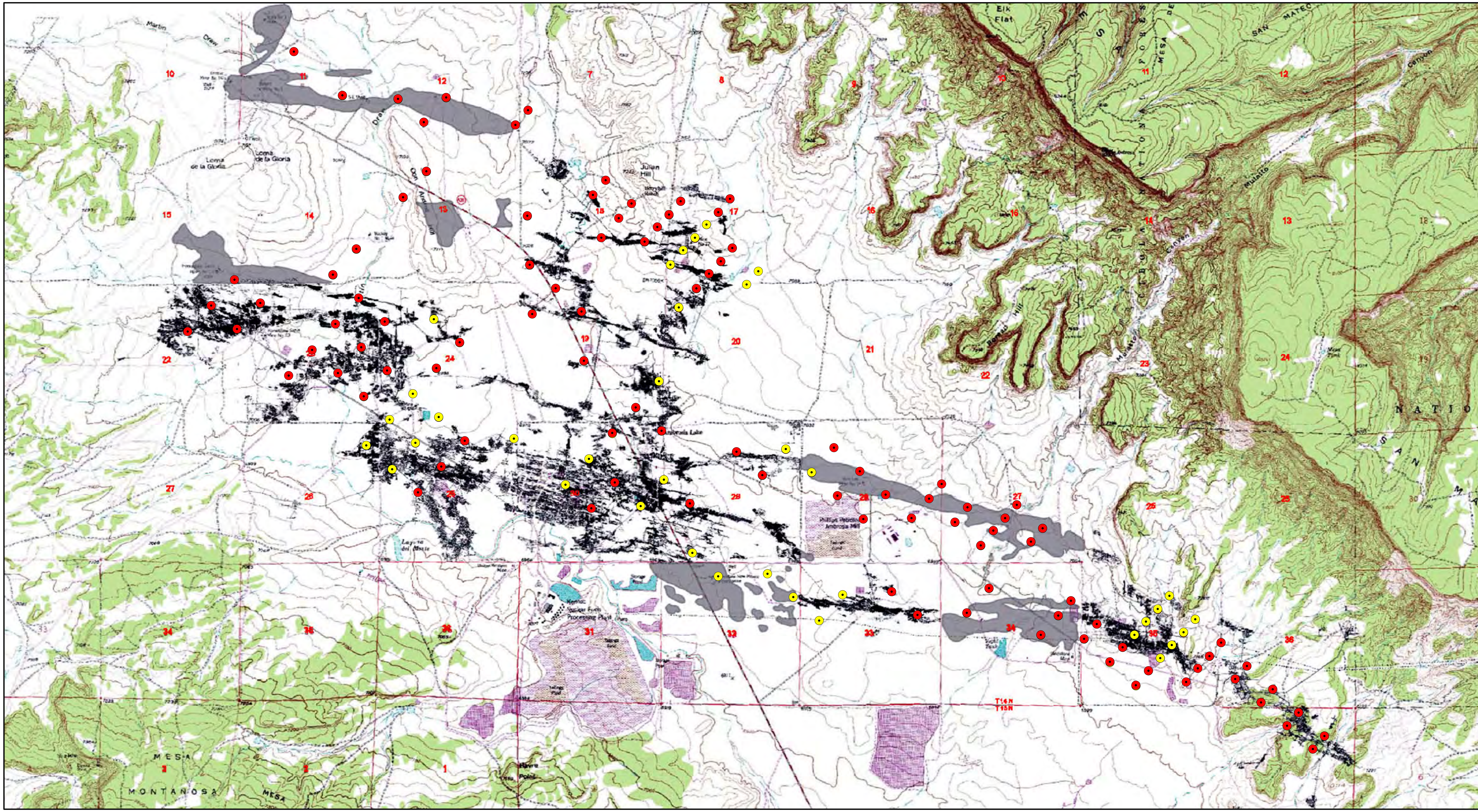

N

3,600 1,800 0 3,600

Feet

Legend

- Dakota Sandstone Well
- Westwater Canyon Member Well

Simulated Well Locations for Historical Mine Dewatering

INTERA

Figure 3.9

3.6 Hydraulic Properties

The hydraulic properties of an aquifer are measures of the aquifer's ability to transmit and store water. Hydraulic properties or parameters include transmissivity, horizontal and vertical hydraulic conductivity, specific storage, specific yield, and porosity. Determining the rates and directions of groundwater flow requires information about the hydraulic characteristics for the San Juan Basin's aquifers and aquitards. In the San Juan Basin, measurements of hydraulic properties are more numerous along the basin margins where the units of interest are closer to the surface. Very few data are available for units near the depositional center of the basin. Reported transmissivity and hydraulic conductivity values typically span a wide range, even for a single aquifer or aquitard (Table 3.1). For example, Stone et al. (1983) reported that the transmissivity of the Morrison ranges from less than 50 to 500 square feet per day (ft^2/day) across the San Juan Basin, with a general trend of values decreasing from locations in the southern margin to the northern margin. Dam et al. (1989) report Morrison transmissivity values ranging between 2 and 480 ft^2/day. Levings et al. (1996) noted that where measurements where available for the Ojo Alamo Sandstone at shallow and deep locations within the basin, the deep hydraulic conductivity values could be smaller by several orders of magnitude (Table 3.1).

Hydraulic conductivity values representative of the hydrostratigraphic units shown in Table 3.1 were assigned to the active cells in the groundwater flow models. The hydraulic conductivity values were selected based on the range and geometric means of values reported for the various hydrostratigraphic units. Selection of hydraulic conductivity values used for the regional aquitards (Lewis Shale and Mancos Shale) was based on the values used in models by Kernodle (1996) and Frenzel and Lyford (1982). The hydraulic conductivity zones are plotted for each model layer in Appendix B.

Site-specific estimates of hydraulic conductivity and storage properties for the Westwater at the Roca Honda mine were obtained from a 2009 aquifer test performed by RHR and applied to the area around the proposed mine workings in layer 10 (Hydroscience, 2009b; Figure B.10 in Appendix B). The site-specific horizontal hydraulic conductivity was set at 0.5 ft/day and the specific storage was set to 1.26×10^{-6} ft^{-1}. Single-well pump test results from a well screened in both the Point Lookout Sandstone and the Gallup Sandstone were used to estimate a site-specific hydraulic conductivity for the Gallup Sandstone of 2 ft/day that was applied to the same grid blocks in the mine area in layer 6 (Hydroscience, 2009b; Figure B-6, Appendix B). Table 9-13 of the RHR BDR (2011c) tabulates the reported ranges of values for hydraulic properties for geologic units in the RHR permit area.

The hydrologic effects of the Jemez Lineament, including the Mt. Taylor intrusive and volcanic rocks, were not explicitly represented in previous San Juan Basin groundwater flow models. Recent mapping by the New Mexico Bureau of Geology and Mineral Resources in the vicinity of Mt. Taylor reveals the presence of numerous volcanic cores that crosscut the sedimentary units represented in the Roca Honda mine groundwater flow models (Figure 2.5). It is likely that the intrusion of lower permeability igneous rocks and the resulting deformation of sedimentary rocks around the intrusions have created a zone of reduced permeability under Mt. Taylor. These low-permeability intrusions beneath Mt. Taylor have been represented by an area of reduced hydraulic conductivity in model layers 6 through 10 (Appendix B). Tests of the sensitivity of changes in groundwater levels to the value of the Mt. Taylor volcanic are described in Section 5.1.3. No changes were made to the hydraulic conductivity values in model layers 1 through 5 for hydrostratigraphic units that underlie Mt. Taylor.

Values for the conductance term for the River Package cells and the Drain Package cells used to represent ephemeral streams were calculated using estimates of hydraulic conductivity for alluvial sediments. A 100 ft/day hydraulic conductivity was assigned to river beds, based on their typically coarse, well-sorted sediments, and a 1 ft/day value was assigned to the ephemeral stream beds, based on their typically medium- to fine-grained, moderately-sorted sediments.

For transient simulations, porosity, specific yield, and specific storage were estimated using data for typical sandstones and shales and data from historical aquifer tests provided to INTERA (Hydroscience, 2009b). Table 3.2 presents a summary of porosity, specific yield, and specific storage for each hydrostratigraphic unit. The specific storage coefficient in the Dakota Sandstone (layer 8) was based on a series of pumping tests conducted in 1977 and provided to INTERA by Hydroscience (Hydroscience, 2009b). For the Westwater Canyon Member (layer 10) values represent an estimate of specific storage based on reported values ranging between $1x10^{-4}$ and $1x10^{-7}$ (Hydroscience, 2009b).

Table 3.2
Transient Model Storage Parameters

Model Layer	Hydrostratigraphic Unit	Porosity	Specific Yield	Specific Storage
1	San Jose Formation	0.3	0.1	$1x10^{-5}$
2	Animas and Nacimiento Fms	0.3	0.1	$1x10^{-5}$
3	Ojo Alamo Sandstone	0.3	0.1	$1x10^{-5}$
	Kirtland and Fruitland Fms			
	Pictured Cliffs Sandstone			
4	Lewis Shale	0.1	0.05	$2x10^{-6}$
5	Cliff House Sandstone	0.3	0.1	$1x10^{-5}$
	Menefee Formation			
	Point Lookout Sandstone			
6	Mancos Shale (NW only)	0.1	0.05	$1x10^{-5}$
	Gallup Sandstone (SW only)	0.3	0.1	$2x10^{-5}$
7	Mancos Shale	0.1	0.05	$1x10^{-6}$
8	Dakota Sandstone	0.3	0.1	$5x10^{-5}$
9	Brushy Basin Member of Morrison Formation	0.1	0.05	$1x10^{-6}$
10	Westwater Canyon Member of Morrison Formation	0.3	0.1	$1.2x10^{-6}$ - $2x10^{-5}$

3.7 Time-Varying Stresses for 1930-2012 Transient Calibration Model

The 1930-2012 transient model was constructed to calibrate the flow system model to the time-varying stresses that operated from early groundwater development in 1930 to the year 2012. This model includes pumping stresses from the City of Gallup and Crownpoint public water supplies, dewatering from the Lee Ranch coal mine, dewatering for uranium mining from the 1950s to the 1980s, followed by the recovery in groundwater levels after uranium mining activities ceased. Initial groundwater levels for the 1930-2012 transient model were the simulated groundwater levels from the calibrated predevelopment model.

The simulation period was divided into 11 stress periods to represent the time-varying stresses (Table 3.3). With MODFLOW and MODFLOW-SURFACT models, stresses are constant within each stress period.

Table 3.3
Stress Periods for 1930-2012 Transient Model

Stress Period	Actual Years	Stress Period Length		Stresses
		Days	Years	
1		Steady-State		None
2	1930 to end of 1956	9,496	26	Gallup and Crownpoint public water supplies (PWS)
3	1957 to end of 1966	3,652	10	Above plus Ambrosia Lake Valley mine shafts and vent holes
4	1967 to end of 1974	2,920	8	Above plus Church Rock mines and Lee Ranch coal mine wells
5	1975 to end of 1982	3,140	8	Same as stress period 4
6	1983 to end of 1985	1,245	3	Same as stress period 4
7	1986 to end of 1992	2,555	7	Gallup and Crownpoint PWS plus Lee Ranch coal mine wells
8	1993 to end of 2009	6,210	17	Same as stress period 7
9	2010	365	1	Same as stress period 7
10	2011	365	1	Same as stress period 7
11	2012	365	1	Same as stress period 7

Public water supplies were included in 1930-2012 transient calibration model and all predictive simulations (see Section 5.0). In 2003, drawdown at the City of Gallup's Yah-ta-hey well field is reported to be 700 feet and "unsustainable in the near term" (City of Gallup, 2010). Table 3.4 shows how the changes in pumping rates for dewatering and water supplies were specified over the 1930-2012 simulation period.

Table 3.4
1930-2012 Transient Model Groundwater Withdrawals

	Groundwater Withdrawal (ft^3/day)						
Stress Period	Ambrosia Lake Mining Area	Church Rock Mining Area	Johnny M Mine	Gulf Mt. Taylor Mine	Coal Mines	Crownpoint Water Supply	City of Gallup Water Supply
1	0	0	0	0	0	0	0
2	0	0	0	0	0	33,000	192,500
3	2,102,004	0	0	0	0	33,000	192,500
4	1,315,312	660,000	0	86,000	23,868	33,000	192,500
5	1,074,161	660,000	240,000	645,319	23,868	33,000	500,500
6	0	0	0	645,319	23,868	33,000	500,500
7	0	0	0	0	23,868	33,000	500,500
8	0	0	0	0	23,868	39,000	500,500
9	0	0	0	0	23,868	39,000	500,500
10	0	0	0	0	23,868	39,000	500,500
11	0	0	0	0	23,868	39,000	500,500

3.8 Pumping Stresses for All Water Rights Predictive Simulations

All water rights for the Gallup, Dakota, and Westwater aquifers in the vicinity of the Roca Honda permit area were compiled for the predictive simulations for Scenarios 3 and 4 (see Section 3.1). Information regarding locations, aquifers pumped, and pumping rates (diversions) was collected from the NM OSE's WATERS database and unpublished reports (Table 3.5). Many of the water rights are assigned to one or more Sections within a Township and Range, so the permitted diversion rates for these water rights were assigned to one or more grid blocks. The sum of pumping rates for all grid blocks assigned to a water right equaled the permitted diversion rate. The simulated wells were assumed to begin pumping at the start of Scenario 3 and Scenario 4 predictive simulations in 2012 and continue to the end of the simulation period, 100 years after the end of Roca Honda mining.

Table 3.5
Groundwater Withdrawals for Scenarios 3 and 4

Water Right	Location	Permitted Diversion (ac-ft/yr)
SJ-109-A et al.	18N 12W Section 1 19N 12W Sections 32 & 36	2,300
SJ-118	21N 9W Section 16	625
SJ-949, SJ-949-S	21N 9W Sections 3 & 4	1,000
SJ-120	16N 10W Section 2	650
G-87, G-88, G-89	16N 20W Sections 5 & 17 17N 20W Section 29	2,425
G-11 (UNC right)	17N 16W Section 35	794
G-11-A (HRI)	16N 16W Sections 8 & 17	650
G-14	15N 9W Sections 3, 4, 9, 10	200
B-993	14N 9W Sections 35, 36, 22, 24 14N 10W Sections 17, 19, 30, 33, 35, 36	4,735
B-994	14N 9W Sections 30, 33, 17, 19, 22, 24 14N 10W Sections 17, 19, 30, 33, 35, 36, 24	5,227
B-375	14N 9W Section 28	93.55
B-376	14N 9W Section 28	371
B-516 (Gulf Mt. Taylor)	13N 8W Section 24	640
B-1442	13N 8W Section 23	305.6
B-1085	13N 8W Section 22	16
B-0428S	13N 8W Section 26	26

3.9 Initial Conditions and Solver Parameters

As with boundary conditions and parameters, each numerical model requires a set of initial conditions, which is the set of groundwater heads for each model grid block that represents the system at the start of the simulation. Initial conditions for steady-state models need only be reasonably representative of the solution, but the system of equations is solved more efficiently the closer the starting heads are to the final solution; consequently, previous solutions were used as the starting heads for the predevelopment model. Results from the predevelopment simulation provided the initial conditions for the 1930-2012 transient calibration simulation. Results from the end of the 1930-2012 transient calibration model provided the initial conditions for the predictive simulations.

The Pre-Conditioned Conjugate Gradient (PCG) 3 s olver, which is part of the MODFLOW-SURFACT software package, was used for all numerical models. Head tolerances for the solver were 0.001 feet for steady-state predevelopment models and 0.05 feet for transient models.

3.10 Modeling Methodology

The modeling methodology presented herein follows the general protocol developed by ASTM International (ASTM) for model application (ASTM 1993a, 1993b, 1994, 1995, 1996a, and 1996b) including:

- ASTM 5447-93 – Application of a Ground-Water Flow Model to a Site-Specific Problem
- ASTM 5979-96 – Conceptualization and Characterization of Ground-Water Systems
- ASTM 5609-94 – Defining Boundary Conditions in Ground-Water Flow Modeling
- ASTM 5981-96 – Calibrating a Ground-Water Flow Model Application
- ASTM 5490-93 – Comparing Ground-Water Flow Simulations to Site-Specific Information
- ASTM 5718-95 – Documenting a Ground-Water Flow Model Application