



Environment

Submitted to:
Bureau of Land Management
Carlsbad Field Office

Submitted by:
AECOM
Fort Collins, Colorado
July 2012

Environmental Geology Assessment Report for Issues Related to the Proposed Ochoa Mine, Lea County, New Mexico



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A handwritten signature in black ink that reads 'William R. Berg'. The signature is written in a cursive style and is positioned above a horizontal line.

Prepared By: William R. Berg

A handwritten signature in blue ink that reads 'Ellen Dietrich'. The signature is written in a cursive style and is positioned above a horizontal line.

Reviewed By: Ellen Dietrich

List of Acronyms

°C	degrees Celsius
°F	degrees Fahrenheit
BLM	Bureau of Land Management
ICP	Intercontinental Potash Corporation
NMBGMR	New Mexico Bureau of Geology and Mineral Resources
OCD	Oil Conservation Division
P&A	plugged and abandoned
SOP	sulfate of potash
SWD	Salt water disposal
U.S.	United States
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WIPP	Waste Isolation Pilot Plant

Contents

1.0 Introduction	1-1
1.1 Purpose of Report.....	1-1
1.2 Scope of Investigation.....	1-1
2.0 Environmental Setting.....	2-1
2.1 Project Location and Climate.....	2-1
2.2 Physiography and Topography	2-1
3.0 Regional Geology	3-1
3.1 Delaware Basin	3-1
3.2 Stratigraphy	3-1
3.3 Karst and Caves.....	3-7
4.0 Study Area Geology	4-1
4.1 Stratigraphy	4-1
4.1.1 Permian Rocks.....	4-1
4.1.2 Triassic, Tertiary, and Quaternary Deposits	4-5
4.2 Structure	4-6
5.0 Mineral Resources.....	5-1
5.1 Potash Mining.....	5-1
5.1.1 Historical and Current Mining	5-1
5.1.2 Proposed Polyhalite Mining, Ochoa Project.....	5-1
5.2 Oil and Gas Production.....	5-2
5.3 Potash Mining and Oil and Gas.....	5-2
5.4 Other Minerals.....	5-3
6.0 Environmental Geologic Conditions in the Study Area	6-1
6.1 Karst	6-1
6.2 Anthropogenic Subsidence.....	6-3
6.2.1 General Principles of Mining Subsidence	6-3
6.2.2 Expected Subsidence Due to Potash Mining.....	6-6
6.2.3 Effects of Subsidence	6-7
6.2.4 Subsidence Due to Brine Mining and Oil and Gas Activities.....	6-8
6.2.5 Oil and Gas and Proposed Polyhalite Mining	6-12

7.0 Summary and Recommendations 7-1

 7.1 Subsidence and Polyhalite Mining 7-1

 7.2 Oil and Gas Production and Proposed Polyhalite Mining..... 7-1

 7.3 Potential Karst Features 7-2

8.0 References 8-1

List of Tables

Table 3-1	Delaware Basin Generalized Stratigraphic Column	3-1
Table 3-2	Upper Guadalupian-Ochoan Formations in Project Area	3-5
Table 6-1	List of Potential At-risk Wells Within and Adjacent to Proposed 50-Year Mine Area.....	6-16

List of Figures

Figure 2-1	Project Location Map	2-2
Figure 2-2	Physiographic Map of Region	2-3
Figure 2-3	Topographic Features in the Study Area	2-4
Figure 3-1	Map of Major Structural Elements	3-3
Figure 3-2	Structure Contour Map and General East-West Cross Section of the Delaware Basin ..	3-4
Figure 3-3	Stratigraphic Relationships between Upper-Guadalupian-Ochoan Series	3-6
Figure 4-1	Geologic Map of the Study Area	4-2
Figure 4-2	Stratigraphy of the Rustler Formation	4-4
Figure 5-1	Oil and Gas Wells in the Vicinity of the Proposed 50-year Mine Area and Surface Facilities	5-4
Figure 5-2	Secretary's Potash Area and Proposed Ochoa Mine	5-5
Figure 6-1	Plan View of Room-and-Pillar Mining	6-4
Figure 6-2	Subsidence Effects Zones	6-5
Figure 6-3	Location of Jal and Wink Sinks	6-10
Figure 6-4	Development of Wink Sink	6-11
Figure 6-5	Typical Oil and Gas Well Casing and Cementing in Study Area	6-14
Figure 6-6	At-Risk Wells Within and Adjacent to the Proposed 50-Year Mine Area	6-15

1.0 Introduction

1.1 Purpose of Report

This report provides a review of environmental geology factors that may affect the Bureau of Land Management (BLM) decision regarding the proposed Ochoa polyhalite mine by Intercontinental Potash Corporation (ICP) in Lea County, New Mexico. The geological assessment will address factors that should be considered in assessing the potential impacts on the existing surface and subsurface infrastructure including oil and gas wells, pipelines, power lines, roads, and other surface features that may result from implementation of ICP's proposed mine.

In addition to potential subsidence from mining, there are other concerns and hazards related to the presence of abandoned and active oil and gas wells that penetrate the polyhalite mining zone. The report provides a description of the regional and study area geology, mineral resources, and conditions relating to potential geologic and environmental hazards.

1.2 Scope of Investigation

The environmental geology assessment is intended to provide information on the potential effects of subsidence and guidance for analyzing alternatives to the proposed Ochoa Mine project. The Delaware Basin in which the project is located has extensive deposits of evaporite minerals (salts of various compositions) that are readily dissolved by unsaturated water solutions. When the evaporite deposits are dissolved, voids are created that can migrate to the surface, resulting in topographic and subsurface features (e.g., sinkholes, broad depressions, fissures, and caves), referred to as evaporite-karst (Johnson 2005). Dissolution of evaporite minerals can be caused by natural conditions or by human activities (e.g., mining, oilfield operations, improperly constructed water storage reservoirs or disposal wells). Subsidence resulting from dissolution of evaporite rocks can have negative impacts on structures, aquifers, surface water flow, wells, and livestock.

Subsidence also results from the mining of evaporite minerals which creates voids that cause collapse of strata above the mining level. The migration of the collapse to the surface also results in subsidence effects as described above that are due to dissolution of evaporite rocks.

Oil and gas exploration and production has taken place in the Delaware Basin since the 1920s. The potash bearing zones were discovered as a result of oil and gas exploratory drilling (Davis 2009). Potash mining and production began in the 1930s. As a precaution for the potash mines in this region, the mining companies historically left protection pillars around the oil and gas boreholes (Intrepid Potash/Shaw 2008). Well casing corrosion is a common problem in the Delaware Basin, caused by contact with the brine fluids being withdrawn or injected depending on the purpose of the well (Powers 2003). There are documented cases where escape of unsaturated brines and dissolution of salt formations caused catastrophic collapse to the surface, not only in the Delaware Basin, but in other basins having substantial thicknesses of salt layers and numerous wells penetrating the salt for the purpose of fluid withdrawal. There are concerns that 60 years of oil and gas exploration and production through the layers proposed for polyhalite mining have created conditions that have not yet manifested themselves on the surface that could create hazards, not only due to subsidence, but to the efficiency and safety of the proposed polyhalite mining operations.

This investigation and report will summarize the issues and concerns identified above based on existing data provided by ICP, its consultant, INTERA, Inc., and published reports or other information available in the public domain.

2.0 Environmental Setting

2.1 Project Location and Climate

The proposed Ochoa Mine Project is located about 45 miles southeast of Carlsbad, New Mexico (**Figure 2-1**). The study area for this report consists of the 50-year mine area, and surface processing, loading, and storage facilities located in Lea County, New Mexico encompassing approximately 28,000 acres with project elements located north and south of New Mexico State Route 128.

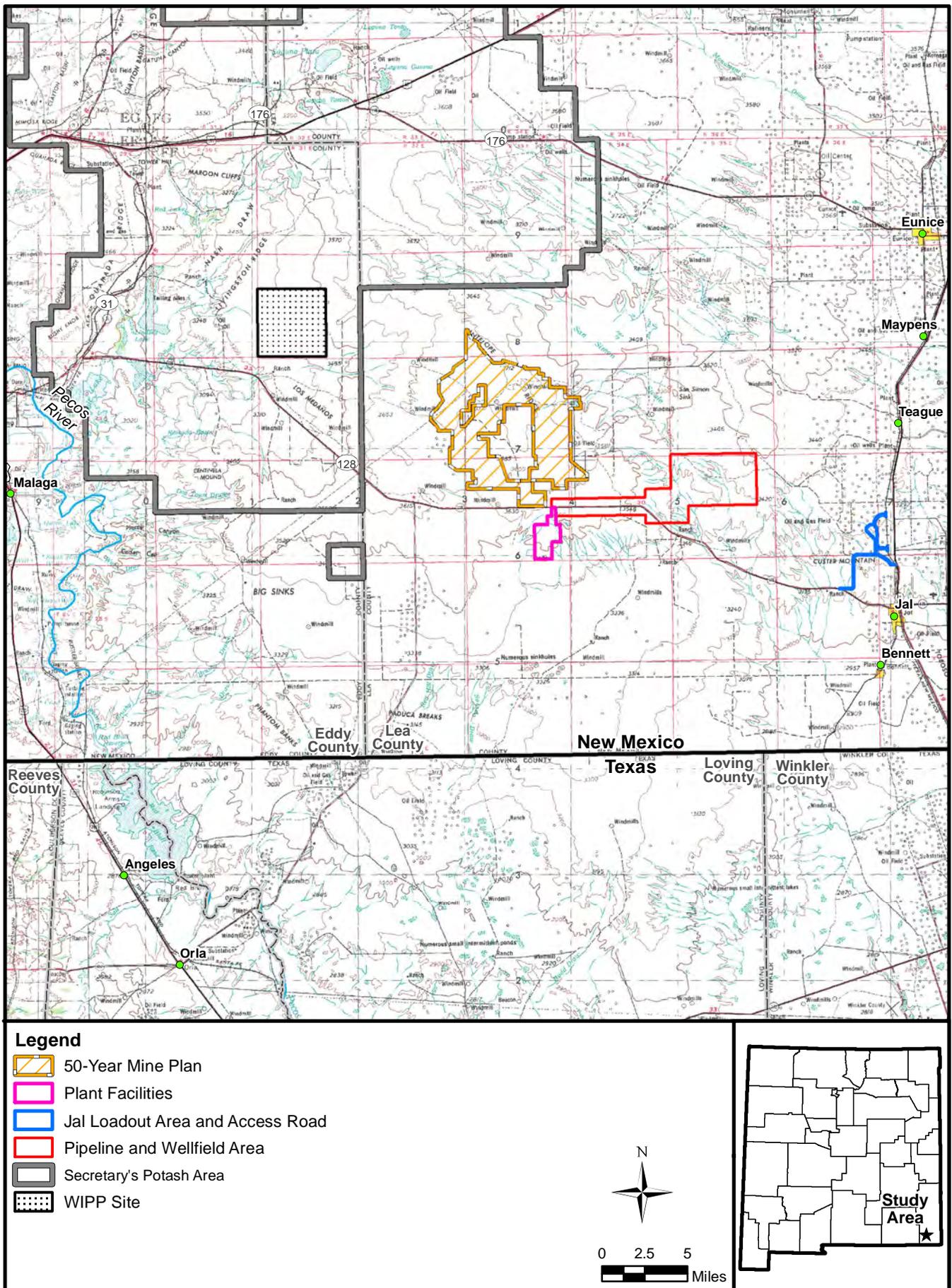
The area is semi-arid with an average precipitation of about 13 to 14 inches per year (Western Regional Climate Center 2012). Most of the precipitation falls as rain from summer thunderstorms. The area experiences hot, sunny summers and mild winters with an average maximum temperature of 95.3 degrees Fahrenheit (°F) in July and an average minimum temperature of 29°F in January.

The primary industries in the study area consist of livestock grazing, potash mining, and oil and natural gas production. Of note is the Waste Isolation Pilot Project (WIPP), located about 8 miles northwest of the study area. The WIPP is actively storing low-level radioactive waste in a salt formation more than 2,000 feet below the ground surface (Rempe et al. 1999).

2.2 Physiography and Topography

The proposed project is located in the Pecos Valley Section of the Great Plains Physiographic Province (Fenneman 1928). The Pecos Valley Section is located between the High Plains on the east, the Raton Section to the north, the Edwards Plateau on the south, and the Mexican Sacramento Section of the Basin and Range Province on the west (**Figure 2-2**) (Trimble 1990). The Pecos Valley was formed by the Pecos River as it eroded into the mantle of Tertiary sedimentary rocks (capped by the Ogallala Formation) that used to gird the front range of the Rocky Mountains from Texas to Montana. The High Plains to the east of the Pecos Valley is a remnant of the Tertiary rocks that have been stripped away from the mountain front by the Missouri, Platte, Arkansas, and Pecos rivers. The Pecos Valley is characterized by rolling hills and mesas. Another prominent feature of the lower half of the valley is the presence of karst topography typified by sinkholes, caves, and enclosed depressions (Hill 1996). The karst topography resulted from the dissolution of evaporite deposits in the subsurface that are highly soluble in water.

The study area lies within the Mescalero Plain, a west sloping pediment between the High Plains and the Pecos River (Reeves 1972). Elevations in the study area range from less than 3,500 to about 3,700 feet above sea level. The topography in the project vicinity is dominated by features thought to be related to subsidence that resulted from natural dissolution of evaporite minerals in the subsurface. There are depressions with no surface drainage, escarpments along the boundaries of subsided areas, and many other smaller features such as sinkholes and sinking drainages (Vine 1963). Prominent topographic features in the project vicinity include the Antelope Ridge and the San Simon Swale (**Figure 2-3**). Antelope Ridge crosses the proposed mine permit area from northwest to southeast and elevations along the ridge range from about 3,650 to 3,700 feet above sea level. The San Simon Swale is a broad draw that also trends northwest to southeast to the northeast of the proposed mine permit area. Six miles east of the study area is the San Simon Sink, a closed topographic depression. Another similar feature is a closed topographic feature located in the southern portion of the permit area and is the location of Bell Lake. The San Simon Sink and the Bell Lake Sink are thought to have formed from the dissolution of evaporite rocks in the subsurface leading to subsidence of the surface. The origin and implications of these features as they relate to the proposed project will be discussed in detail in Section 6.1.



Legend

-  50-Year Mine Plan
-  Plant Facilities
-  Jal Loadout Area and Access Road
-  Pipeline and Wellfield Area
-  Secretary's Potash Area
-  WIPP Site



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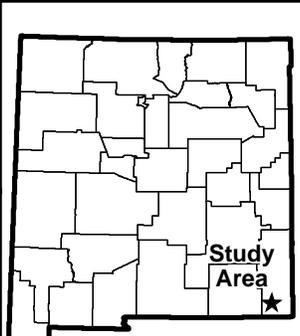
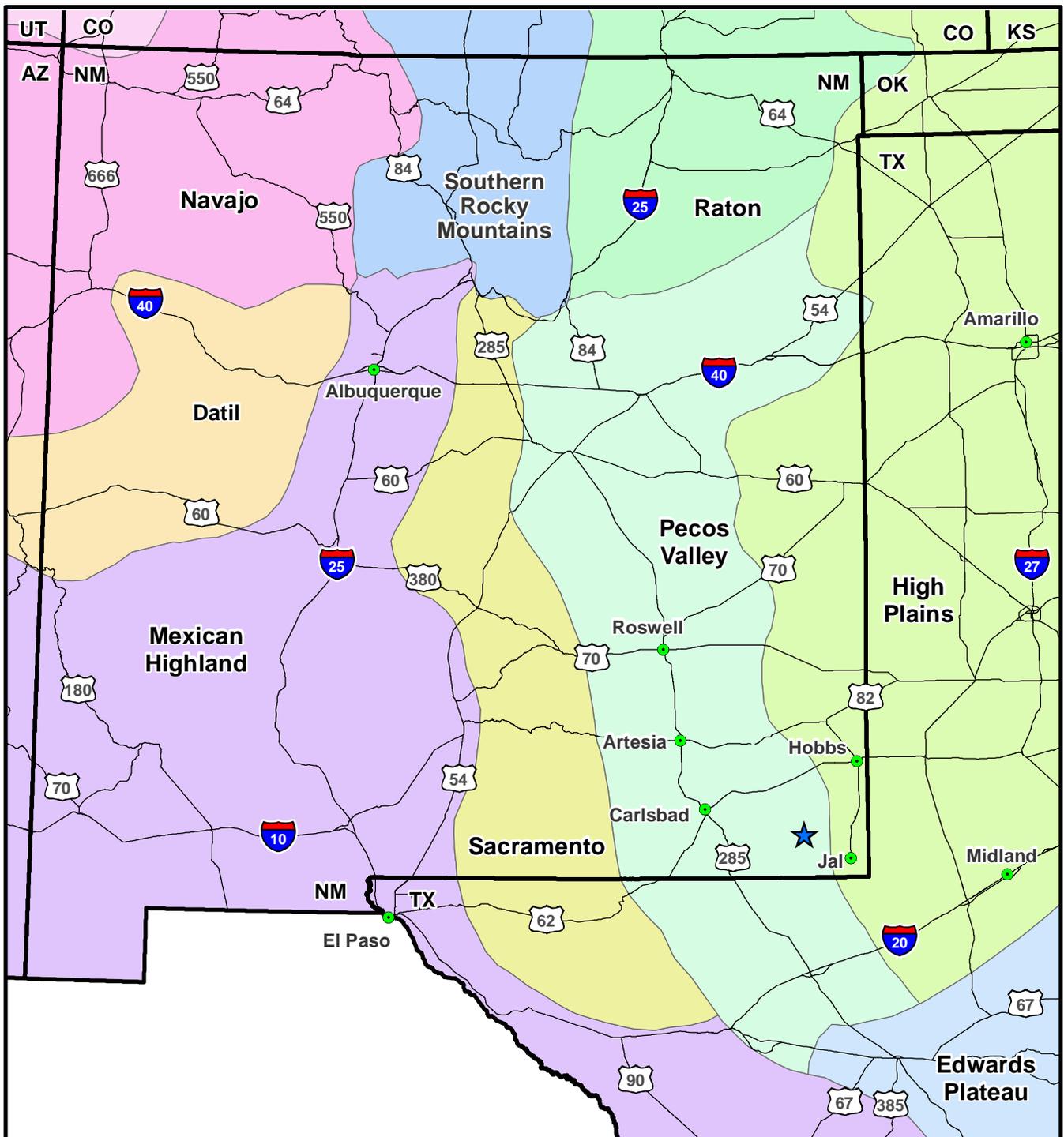
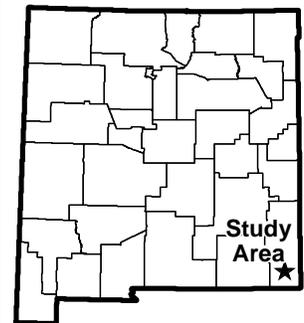


Figure 2-1. Project Location Map



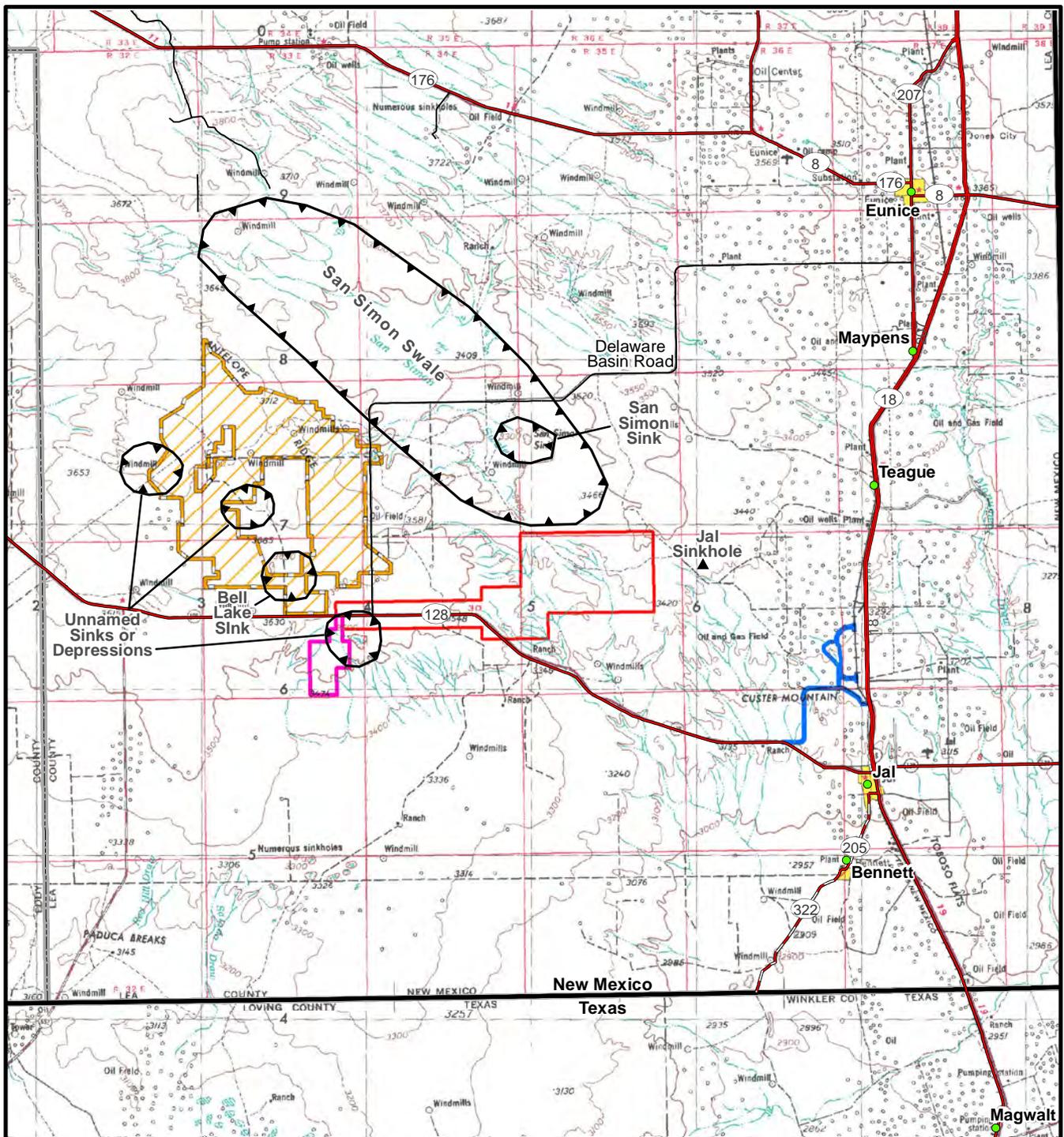
Legend

- ★ Study Area
- Town



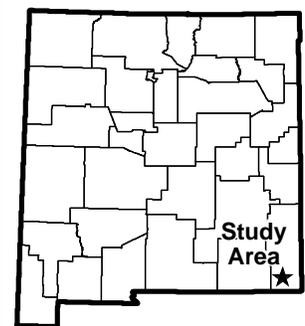
Source: Fenneman (1928).

Figure 2-2. Physiographic Map of the Region



Legend

-  50-Year Mine Plan
-  Jal Loadout Area and Access Road
-  Plant Facilities
-  Pipeline and Wellfield Area
-  Karst Feature



Source: Nicholson and Clebsch (1961); Powers (2003).

Figure 2-3. Topographic Features in the Study Area

3.0 Regional Geology

3.1 Delaware Basin

The proposed project is located in the Delaware Basin, a subbasin of the greater Permian Basin of west Texas and New Mexico (**Figure 3-1**). The basin is bounded on four sides by basement uplifts that include the Marathon fold belt to the south, the Diablo Platform on the west, the Northwest Shelf to the north, and the Central Platform to the east (Montgomery et al. 1999). The sedimentary rocks in the basin dip gently to the south and east and the deepest part of the basin is on the southeast side in Pecos County, Texas (**Figure 3-2**). There are complex bounding fault zones on the east, south, and west sides of the basin. Along the structural boundary of the Northwest Shelf to the north, there are no faults as rocks dip gently to the south from the shelf into the basin (Hill 1996). Internally in the basin, the structure becomes more complex at depth with relatively little faulting and folding of the thick Permian section, but large complex structures are present in the deeper parts of the basin.

3.2 Stratigraphy

The sedimentary stratigraphy is shown in **Table 3-1**. The basin may contain up to 30,000 feet of sedimentary rock with deposits ranging in age from Cambrian to Quaternary (Hill 1996; Roche 1997). The Precambrian basement consists mainly of granitic and metamorphic sedimentary rocks, but volcanic rocks also may be present. The Paleozoic section from Cambrian to Pennsylvanian consists of clastic and carbonate rocks deposited in a variety of environments including continental, shallow marine, shelf, and basin. The pre-Permian rocks are largely known from the drilling of the deeper oil and gas wells and limited surface outcrops.

Table 3-1 Delaware Basin Generalized Stratigraphic Column

Era	System/ Period	Series/ Epoch	Time (MY)	Series/Group/Formation
Cenozoic	Quaternary	Holocene	0.01	Sand and Gravel/Cave Deposits
		Pleistocene	2	Gatuña Formation/Mescalero Caliche
	Tertiary	Pliocene	6	Ogallala Formation
		Miocene	25	Absent
		Oligocene	35	Volcanic intrusive and extrusives
		Eocene	52	Absent
		Paleocene	65	
Mesozoic	Cretaceous	Upper	—	Gulfian Series
		Lower	136	Comanchean Series
	Jurassic	Upper	—	Absent
		Lower	190	
	Triassic	Upper	—	Chinle Group
		Middle	—	Santa Rosa
		Lower	235	

Table 3-1 Delaware Basin Generalized Stratigraphic Column

Era	System/ Period	Series/ Epoch	Time (MY)	Series/Group/Formation
Paleozoic	Permian	Upper	—	Ochoan Series
			250	
		Middle	—	Guadalupian Series
			260	
		Lower	—	Leonardian Series
			270	
	Pennsylvanian	Upper	—	Cisco/Gaptank
			—	
		Middle	—	Strawn
			300	
		Lower	—	Atoka
			320	
	Mississippian	Upper	—	Barnett Shale
		Middle	—	Mississippian Limestone
			330	
		Lower	—	
			345	
		Devonian	Upper	—
	Middle		370	Absent
			380	
	Lower		390	Thirtyone Formation
	Silurian	Upper	400	Absent
			410	
		Lower	—	Wristen Formation
			420	Fusselman Dolomite
	Ordovician	Upper	455	Montoya Group
			—	
		Middle	475	Simpson Group
—				
Lower	495	Ellenburger Group		
Cambrian	Upper	—	Bliss Sandstone	
	Lower	500	Absent	
Proterozoic	Precambrian		>570	Precambrian

Source: Modified from Hill (1996).

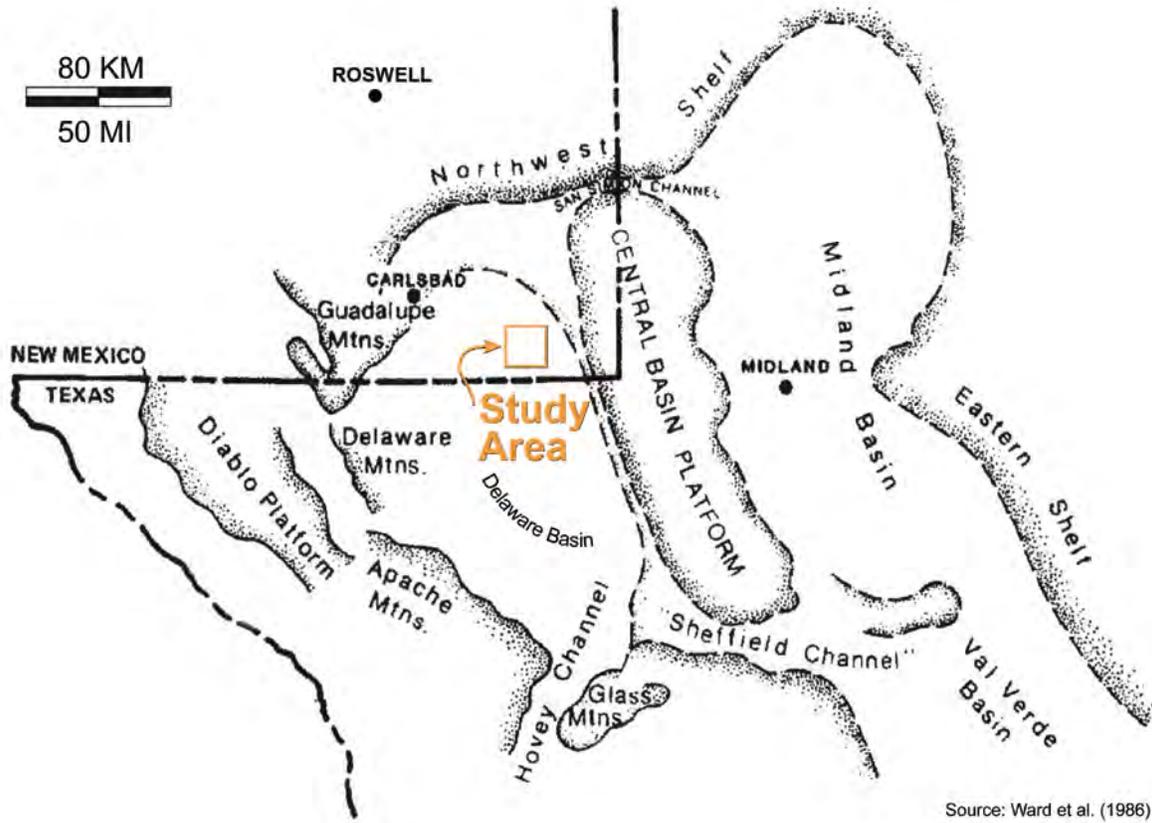


Figure 3-1 Map of Major Structural Elements

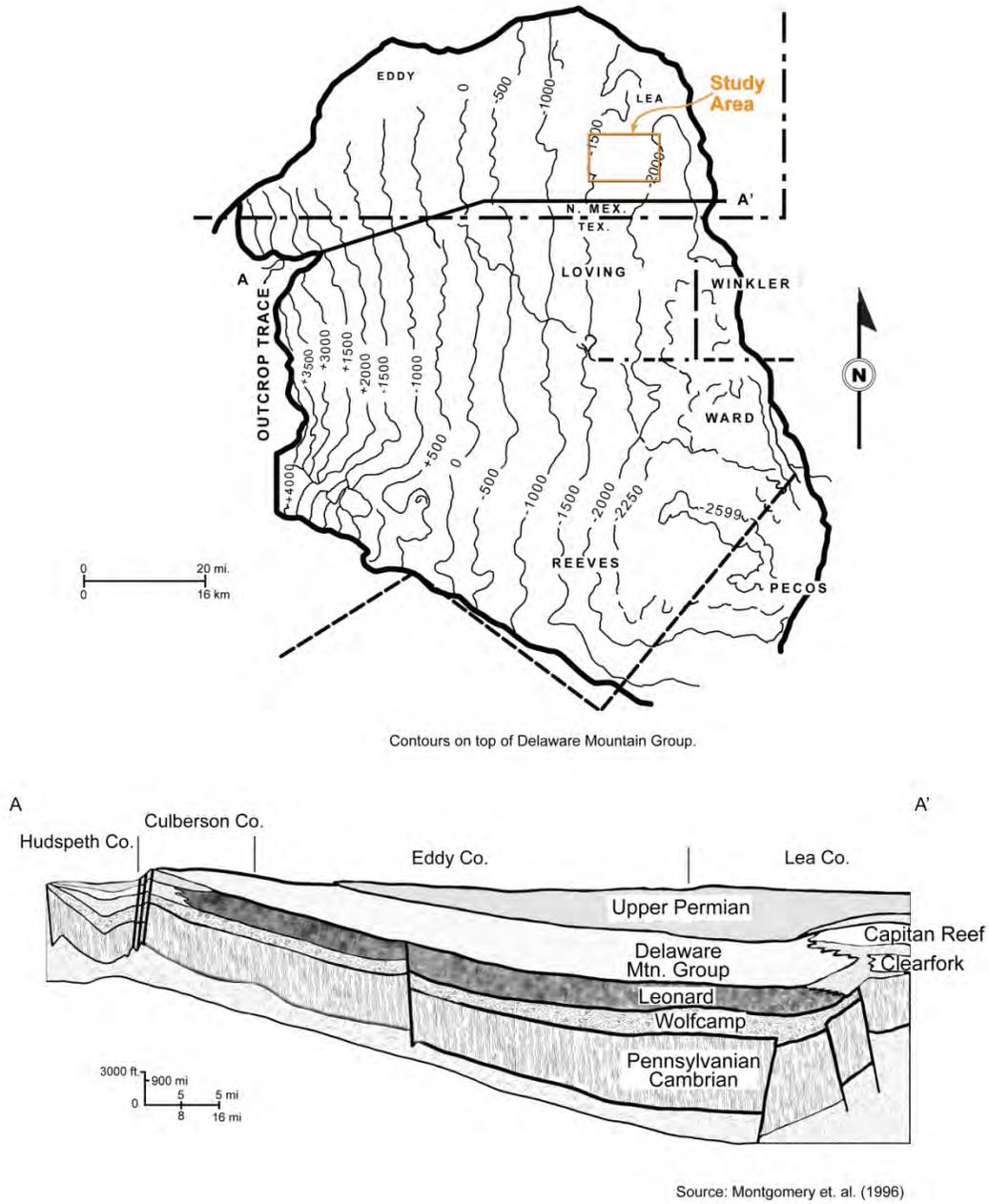


Figure 3-2 Structure Contour Map of Delaware Mountain Group and General East-West Cross Section of the Delaware Basin

The Permian section is approximately 10,000 feet thick (Adams et al. 1939) and consists of clastics, carbonates, and evaporite rocks. Rocks in the upper Permian are the most important for purposes of this project, but the following summarizes the Permian stratigraphy of the Delaware Basin. The Permian has been divided into series based on fossils (Adams et al. 1939). The Permian Series, from oldest to youngest, are the Wolfcampian, Leonardian, Guadalupian, and Ochoan (**Table 3-1**). The Wolfcampian and Leonardian rocks are characterized by limestone and shales predominantly in the basinal areas and reefs or carbonate shoals along the basin rim. The Guadalupian represents a time of deposition dominated by a reef system that rimmed the basin on the west, north, and east sides. The reef system provided a distinct break between deep basin and back-reef shallow lagoon shelf deposits (**Figure 3-3**). The major reef former is the Capitan Limestone, which hosts the caves at Carlsbad Caverns National Park. After the Guadalupian are rocks that represent a drastic change of depositional environments from marine basin to a restricted marine and continental setting. The Ochoan Series succeeds the Guadalupian Series and is characterized by rocks called evaporites.

The Ochoan Series consists of the Castile, Salado, Rustler and Dewey Lake formations (Hill 1996) (**Table 3-2**). The Ochoan Series was named by Adams et al. (1939), but is local in nature. The type locality is a subsurface section in Lea County, New Mexico, and is better defined in the subsurface than in outcrop (U.S. Geological Survey [USGS] 2007). This report will use this colloquial term as it is ingrained in the literature to avoid confusion, although it is not a formal designation recognized by the USGS. The Ochoan Series consists of anhydrite, gypsum, halite, soluble potash minerals, dolomite, and minor amounts of siltstone, mudstone, and shale. See Chapter 4.0 for a detailed description of the Ochoan Series Formations in the study area.

Table 3-2 Upper Guadalupian-Ochoan Formations in Project Area

System	Series	Project Area		Northeast		Approximate Thickness in Project Area (feet)
		Delaware Basin		Central Platform		
		Basin	Basin Margin - Reef	Shelf - Back Reef		
Permian	Ochoan	Dewey Lake Formation				Up to 500
		Rustler Formation				500
		Salado Formation				1,800-2,000
		Castile Formation		No equivalent		1,400-1,500
	Guadalupian	Bell Canyon Formation	Capitan Limestone	Tansill Formation		1,000 (Bell Canyon Formation)
				Yates Formation		
				Seven Rivers		

Sources: Hayes 1964; Hill 1996; Lambert 1983; New Mexico Oil Conservation Division (OCD) 2012; U.S. Department of Energy (USDOE) 2004.

The Mesozoic is represented by late Triassic- and Cretaceous-aged rocks. The Triassic rocks consist of the Chinle and Santa Rosa formations that occur largely as remnants of more extensive deposits that have been eroded. These formations consist of conglomerates, cross-bedded sandstones, and claystones and siltstones that were deposited in a continental fluvial environment (Hill 1996). The Cretaceous rocks in the Delaware Basin area are largely found in outcrops exposed in mountain ranges adjacent to the basin. There are lower Cretaceous conglomerates, but most of the Cretaceous rocks were formed in the upper Cretaceous, and are composed of limestones that were deposited during marine transgressions into the area. Cretaceous rocks also have been found in collapse features in the Pecos Valley (Lambert 1983).

Sedimentary Cenozoic deposits consist of the Ogallala and Gatuña formations and the Mescalero Caliche. The Ogallala is Miocene-Pliocene in age and is composed of poorly cemented sand and conglomerate with minor beds of shale, clay, and limestone (Dane and Bachman 1958). The Ogallala is the “cap rock” of the High Plains and is a major aquifer. The Ogallala outcrops east of the study area and forms the Mescalero Ridge, the physiographic boundary between the Pecos Valley and High Plains sections. The Gatuña Formation consists of isolated sand and gravel lenses with layers of volcanic ash thought to have been ejected from the Yellowstone eruption 600,000 years before present (Lambert 1983). The Gatuña Formation was deposited in erosional depressions or in collapse features and is useful for dating those features. The Mescalero Caliche formed on a former surface that was present from the Pecos River to the High Plains during the Pleistocene from 410,000 to 510,000 years ago (Hill 1996).

3.3 Karst and Caves

The Delaware Basin is well known for karst topography and caves. The carbonates and evaporites that compose a large proportion of the geologic section are susceptible to solution; the rocks have been subjected to solution processes in the geologic past as well as in the present. Karst is defined as “a landscape that is principally formed by the dissolving of bedrock” (Kastning et al. 2001). The following features are common in karst terrains: sinkholes, caves, closed basins or depressions, and sinking streams, all of which are present in the Delaware Basin. The Delaware Basin contains rocks that are susceptible to dissolution, including carbonate rocks, gypsum, and salt deposits. Karst that occurred in geologic history is referred to as “paleokarst.” There are numerous examples of paleokarst in the Delaware Basin (Hill 1996). Paleokarst can be an important mechanism for trapping oil and gas and the development of other mineral deposits.

The most well-known example of karst in the Delaware Basin are the Carlsbad Caverns, located in Carlsbad Caverns National Park, approximately 20 miles southwest of Carlsbad, New Mexico. One theory proposed for the formation of the caverns is that acidic fluids, probably sulfuric acid, dissolved the rock in stages that led to the present-day cavern configuration (Hill 1996). The basin contains other examples of karst and paleokarst, indicating that dissolution has been a process in the geologic history of the basin as well as a currently active process. The discussion of karst in this report will be limited to the study area, although examples of karst in other locales may be cited for illustrative purposes.

4.0 Study Area Geology

4.1 Stratigraphy

The important units in the study area consist of Permian rocks of the Guadalupian and Ochoan Series, which are described below. The units are categorized by their locations relative to the Capitan reef, which marks the transition from shelf (back reef) to reef (basin margin) to basin. The stratigraphic relationships are shown in **Figure 3-3** and a correlation diagram is shown in **Table 3-2**. From west to east, the study area spans depositional settings that range from basin to basin margin-reef area, defined by the Capitan Limestone. In addition to the upper Permian rocks, there are surficial exposures of Triassic, Tertiary, and Quaternary deposits in the study area that are described below. A geologic map of the general project vicinity is provided in **Figure 4-1**.

4.1.1 Permian Rocks

4.1.1.1 Guadalupian Series

Rock units in the Guadalupian Series of interest in the study area consist of the Capitan Limestone, Bell Canyon Formation, and the upper Artesia Group. These units are time-equivalent: the Capitan Limestone is the basin margin reef-derived unit, the Bell Canyon Formation was deposited in the basin, and the upper Artesia Group consists of back reef and shelf deposits.

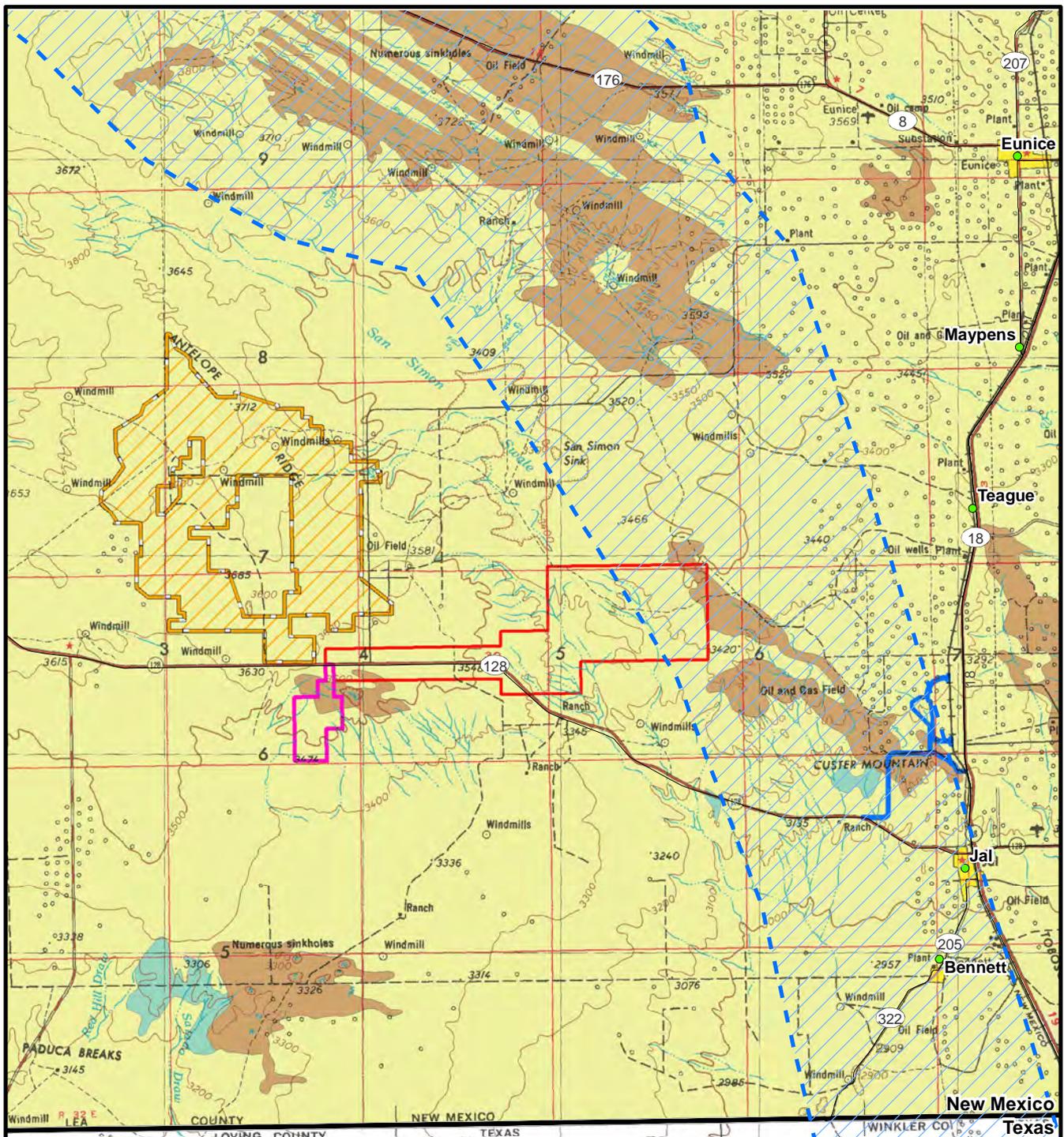
Capitan Limestone

At the beginning of Permian time, the configuration of the Delaware Basin as we know it began to take shape (Hayes 1964). In late Guadalupian time, conditions were favorable for reef growth at the basin margin so the Capitan Limestone reef deposits built upward and toward the basin.

The Capitan Limestone is composed of massive reef material and associated reef talus zones (Hayes 1964). The reef material is thought to have been derived from organisms such as algae and sponges, but diagenetic changes and recrystallization have obscured much of the fossils. Because the massive reef building facies built upward and toward the basin, it developed on top of its own talus deposits. The talus resulted from erosion of the reef material at the water surface to wave base. Porosity in the Capitan massive reef facies is generally low because of cements, but there are occasional vugs and cavernous porosity (Hill 1996). The Capitan Limestone is not present within the 50-year mine plan area, but is located 10 miles to the east. The Capitan Reef is important as a potential water source for the proposed project.

Bell Canyon Formation

The Bell Canyon Formation is the uppermost formation of the Delaware Mountain Group, a designation for the basinal formations of the Guadalupian Series. It is equivalent to the Capitan Limestone and is generally composed of turbidite sandstones that were deposited in a deep water setting (Berg 1979). Carbonate rocks also are present in the Bell Canyon Formation in areas close to the reef and Bell Canyon sediments interfinger with the talus slope of the Capitan reef. The Delaware Basin was a "sediment starved" basin, but during times of sea level drop, clastic sediments were moved to the shelf margin and eventually deposited in the basin by turbidity flows. The turbidite flows deposited sand in elongate sinuous channels with sediment transport generally from north to south and southwest across the shelf and into the basin (Payne 1976).



Legend

- 50-Year Mine Plan
- Plant Facilities
- Jal Loadout Area and Access Road
- Pipeline and Wellfield Area
- Quaternary - Wind Blown Sand
- Tertiary - Ogallala Formation
- Triassic - Triassic Rocks Undivided
- Capitan Reef Complex

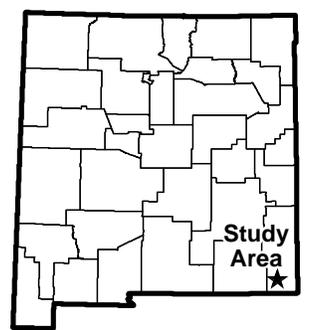
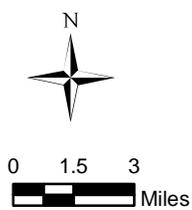


Figure 4-1. Geologic Map of the Study Area

Artesia Group

The formations in the upper part of the Artesia Group are composed of rocks that are the shelf time-equivalent units to the Capitan Limestone. The formations are the Tansill, Yates, and Seven Rivers. The Seven Rivers Formation, time-equivalent to the lower Capitan Limestone, is largely composed of dolomite in areas close to the reef, but transitions into gypsum or anhydrite facies toward the shelf. The Yates is equivalent to the middle Capitan Limestone, consisting of up to two-thirds sandstone with intervening beds of dolomite (Lambert 1983). The Yates grades to evaporites in the direction of the shelf. The Tansill Formation is equivalent to the upper Capitan Limestone and is composed of dolomite in the basin margin-reef areas, transitioning into evaporites towards the shelf. The Artesia Group also is not present in the 50-year Mine Plan area, but bears mentioning for the overall description of Guadalupian rocks in the general vicinity.

4.1.1.2 Ochoan Series

Castile Formation

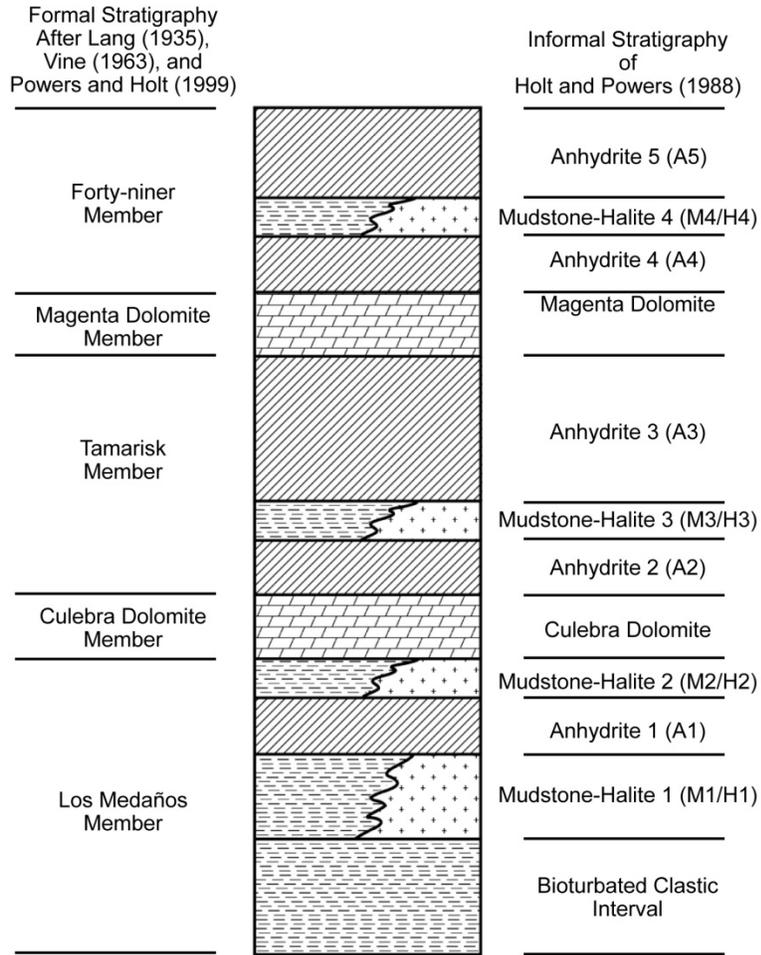
The Castile Formation marks the end of open marine conditions in the Delaware Basin and the onset of conditions favorable to evaporite deposition. The Castile is mainly composed of anhydrite, but contains two thick halite beds that range from 250 to 330 feet thick (Oil Conservation Division [OCD] 2012). Although the Castile can be up to 1,600 feet thick, it is about 1,400 to 1,500 feet thick in the study area. Theories abound related to the mechanism for the deposition of Ochoan evaporites and whether they are from deep or shallow water deposits (Hill 1996). However, it is certain that a combination of contributing factors were involved including tectonic uplift, paleogeography, and hot, dry climate.

Salado Formation

The Salado Formation is the primary salt formation in the area and the formation from which potash is mined in the region. The Salado can be 2,000 feet thick, but thickness ranges from 1,800 to 2,000 feet thick in the study area. It contains four distinct members and is mainly composed of halite, but also contains anhydrite, siltstone, polyhalite, and soluble potash minerals. At the base of the Salado Formation is an unnamed lower member composed mainly of massive halite, but also contains an anhydrite bed that is used to mark the base of the Salado in areas over the Capitan Reef (Hill 1996). This lower member is used as the repository host at the WIPP facility about 8 miles northwest of the study area. Overlying the lower member of the Salado is the McNutt Potash Member, which contains the potash ore zones that have been mined since the 1930s northwest of the study area. The Vaca Triste Sandstone overlies the McNutt Potash Member and while 10 feet thick, is a highly recognizable and widespread marker bed (Hill 1996).

Rustler Formation

The Rustler Formation continues the succession of Ochoan units and is composed of anhydrite, dolomite, siltstone, sandstone, gypsum, halite, and polyhalite and varies from 450 to 550 feet thick in the study area. The top of the Rustler in the 50-year mine plan area is about 1,200 to 1,300 feet below the surface. Members of the Rustler Formation from bottom to top are the Los Medaños, Culebra Dolomite, Tamarisk, Magenta Dolomite, and the Forty-niner, shown in **Figure 4-2**, which represents the general stratigraphic sequence of the Rustler Formation in the region. The Los Medaños member is composed of siltstone, gypsum, and fine-grained sandstone. The Culebra Dolomite is a thin-bedded crystalline dolomite that also has vugular porosity (Hill 1996). It is very resistive to weathering and forms prominent outcrops where exposed. The Culebra Dolomite is exposed west of the study area at the southern end of Nash Draw. Above the Culebra, the Tamarisk member is largely composed of massive anhydrite that weathers to gypsum in outcrops. It also contains minor amounts of halite and siltstone. The evaporite



Source: Lorenz (2006)

Figure 4-2 Stratigraphy of the Rustler Formation

zone in the Tamarisk Member, the M3/H3 zone contains the polyhalite deposit that is proposed to be mined. The polyhalite zone stratigraphy and origin will be discussed in Chapter 5.0. The next member is the Magenta Dolomite, which is 20 to 30 feet thick and identified by pink to red to purple colors when it weathers (Hill 1996). The uppermost member, the Forty-niner, is composed of gypsum, anhydrite, siltstone, shale, and clay.

Dewey Lake Formation

The Forty-niner member of the Rustler Formation represents the end of the marine incursions into the basin; the change to continental deposition is represented by the Dewey Lake Formation (Hill 1996) (the Dewey Lake Formation is also informally referred to as the Dewey Lake Red Beds). The Dewey Lake Formation is composed of reddish-orange siltstone with minor sandstone and clay and is not exposed on the surface in the study area or general vicinity. The Dewey Lake Formation appears to have been deposited in a "low-energy" fluvial environment and represent the end of Permian (Hill 1996).

4.1.2 Triassic, Tertiary, and Quaternary Deposits

Triassic-aged rocks, the Santa Rosa Formation and possibly the Chinle Formation (or Group) are present in the study area. Undivided Triassic rocks mapped by Dane and Bachman (1958) in the study area are composed of maroon, red, and gray sandstone interbedded with red, sandy shale and purplish limestone. The Chinle Formation consists of red and green mudstone interbedded with lenses of sandstone and conglomerate (Mercer and Orr 1977). Isolated outcrops of Triassic rocks have been mapped in the vicinity of the study area, but not within the 50-year mine plan area (**Figure 4-1**). The Triassic rocks have been ascribed to various formations, but the cover of surficial deposits, the limited exposures of Triassic rocks, preclude positive definition of the Triassic rock units. The Triassic beds may attain a thickness of 800 feet east of the San Simon Swale, but in the study area the Santa Rosa was assigned a thickness of 200 feet (USDOE 2004).

The Tertiary Ogallala Formation may be absent or very thin in the 50-year mine area. The plant facilities may lie partially on the Ogallala Formation. Nicholson and Clebsch (1961) identified Ogallala Formation in the upper 125 feet the Continental Oil Company Bell Lake #2 well in Section 30, Township 25 South, and Range 34 East, less than half a mile east of the mine area. The Ogallala Formation is composed of sandstone, silt, and cemented gravel capped by discontinuous caliche layers (New Mexico Bureau of Geology and Mineral Resources [NMBGMR] 2003). The Ogallala Formation was deposited during the Oligocene when uplift and erosion of the Rocky Mountains caused sediment to be deposited over a large area east of the mountains. In addition to fluvial deposits, the Ogallala contains considerable wind-blown deposits.

Although Tertiary (Oligocene) igneous dikes and sills are present in the northwest Delaware Basin, such igneous rocks have not been identified in the 50-year mine plan area (Calzia and Hiss 1978). Dikes have been reported in other potash mines and occur as parallel and nearly vertical, with widths up to 12 feet. The dikes appear to die out in the Ochoan rocks and do not appear on the surface. The igneous rocks also have been documented from boreholes.

The oldest Quaternary deposit is the Gatuña Formation, which is present in limited outcrops in the Nash Draw area (Vine 1963). The extent and occurrence of the Gatuña Formation in the study area has not been determined. The Gatuña Formation consists of clasts of Triassic and Ogallala rocks and volcanic ash beds (Lambert 1983). It is thought to have been deposited in depressions formed by collapse due to dissolution of evaporites in the subsurface.

The Mescalero Caliche is an informal unit defined on the basis of persistent caliche beds that are widespread on the Mescalero Plain. It is described as consisting of two zones, an upper caliche caprock and a lower zone composed of nodular limestone (USDOE 2004).

Recent geologic materials in the study area consist of layers of alluvium and eolian (windblown) sand (NMBGMR 2003). Where deep channels have been cut into the bedrock or in depressions created by subsidence, recent materials may attain a thickness of 500 feet.

4.2 Structure

The localized structure of the area is dominated by salt dissolution and flowage and is not related to tectonic stress. The regional dip is 90 to 100 feet per mile (1 degree) or less to the southeast (Montgomery et al. 1999). What structures may be present may be the result of salt dissolution or flowage. Since there has been little tectonic movement since Permian time, there are no major tectonic structures (Nicholson and Clebsch 1961). There are no major faults or structures in the 50-year mine area. The structures present may be the result of the plastic nature of salt, because it responds to stress by flowing and this flowage results in deformation of adjacent strata.

5.0 Mineral Resources

5.1 Potash Mining

5.1.1 Historical and Current Mining

Potash was discovered in Eddy County in 1925 in a well that was being drilled for oil and gas by the Snowden McSweeney Company (Davis 2009). By the mid-1930s, there were 11 companies exploring for potash in southeastern New Mexico (Barker et al. 2008). The potash in southeastern New Mexico has been a major potash resource (Cheeseman 1978). The remaining potash reserves are estimated to be 500 million tons (USGS 2012). Potash production continues in the Delaware Basin with active mining by Intrepid Mining and Mosaic Co., about 20 miles west and northwest of the study area. Although much of the high-grade zones have been mined out, exploration for commercially viable deposits continues (Muller and Galyen 2009). Intrepid Potash, Inc., has recently been approved to conduct solution mining of potash minerals in order to extract some of the remaining ore from suspended mines in the main potash mining area.

The potash zones in the Salado Formation present a complicated mineralogy of potash minerals. There are twelve ore zones present, eleven of which are located in the McNutt Potash zone with varying mineralogy and commercial viability (Cheeseman 1978). The ore zones were numbered from the deepest to the shallowest by the USGS, with the First Ore Zone being the deepest and the Twelfth Ore Zone being the shallowest. Mining has occurred in commercial quantities from First, Third, Fourth, Fifth, Seventh, and Tenth Ore Zones. The First Ore Zone was the richest in terms of potassium content and has been extensively mined. The major commercial minerals in the ore are sylvite and langbeinite. Non-ore (gangue) minerals include leonite, kainite, carnalite, polyhalite, kieserite, halite, and anhydrite. Potash has a variety of uses with the most common being for agricultural fertilizer.

5.1.2 Proposed Polyhalite Mining, Ochoa Project

The proposed Ochoa Mine is a departure from the traditional potash mining in the area in that ICP proposes to mine the mineral polyhalite from the Rustler Formation. The polyhalite is present in the M3/H3 of the Tamarisk Member of the Rustler Formation (**Figure 4-2**). Polyhalite has long been considered a potential potassium source, but regional and international interest has been directed primarily to mining high-grade sylvite deposits (Muller and Gaylen 2009). Polyhalite offers end-use advantages over sylvite because it does not contain chlorides and can be used on chloride-sensitive crops. Polyhalite is described as “a hydrated potassium-calcium-magnesium-sulfate salt” (Muller and Gaylen 2009). It is distinguished from other potassium minerals in that it has less solubility in water. It is thought to have formed as a replacement mineral from the dissolution of anhydrite by brine solutions.

The polyhalite bed that is the target of the proposed mine occurs about 1,500 to 1,600 feet below the ground surface and about 220 feet below the top of the Rustler Formation (ICP 2011). The zone varies from 4 to 6 feet thick, and averages 5 feet thick. It was identified on geophysical logs from oil and gas wells and was further defined by extensive cores and logs taken by ICP.

The polyhalite would be recovered using room-and-pillar mining methods with an expected recovery of 90 percent, except in areas of requiring additional support and in the vicinity of active or abandoned oil and gas wells (ICP 2011). The ore would be cut by continuous mining machines, then transported from the working face by shuttle cars. The extraction height is expected to be 6 feet, including the ore as well as an unstable anhydrite bed that occurs directly above the polyhalite zone.

In general, ICP would process the raw polyhalite mineral to make a sulfate of potash (SOP) product (Felton et al. 2010). The proprietary process involves calcination (heating at 450 degrees Celsius [°C])

that drives water from the polyhalite to increase solubility. The calcined polyhalite would then be dissolved in water and solid SOP would be recovered after processing the solution in crystallizers.

5.2 Oil and Gas Production

Oil in southeastern New Mexico was discovered in 1909, 8 miles south of Artesia, but the well was never completed as a producer due to mechanical problems (Montgomery 1965). Oil and gas production began in the New Mexico portion of the Delaware Basin in 1924 with the discovery of the Dayton-Artesia Field (Independent Petroleum Association of New Mexico Undated). Until the year 2000, 4.5 billion barrels of oil had been produced mainly from fields on the Northwest Shelf and Central Platform areas in the Delaware Basin (Broadhead et al. 2004). More than 3.5 billion barrels of the total production was extracted from Permian-age rocks. The USGS estimates that the greater Permian Basin area, including parts of southeastern New Mexico and west Texas, contains substantial undiscovered oil and gas resources on the order of 1.3 billion barrels of oil and 41 trillion cubic feet of gas (Schenk et al. 2008).

Early exploration and development was conducted along the edge of the deep basin, in areas along the Capitan Reef and along the shelf areas to the north and northeast of the 50-year mine area (see Chapter 3.0). Oil and gas production began in the 50-year mine area in the early 1950s with the blowout of the Continental Oil Bell Lake Unit #1 (Section 31, Township 23 South, Range 34 East) (Kinney 1954). On March 13, 1954 the well blew out at a depth of 12,616 feet and burned for 15 days until the fire was extinguished. However, the well continued to flow and was not brought under control for another 51 days when the flow was staunched. The discovery ushered in deep basin drilling which continues to the present. The Bell Lake Unit #1-A was drilled and completed in a Devonian limestone from an interval from 14,942 to 15,025 feet deep (Hills 1968).

Oil and gas exploration targets range from relatively shallow oil and gas at 5,000 feet deep in the Delaware Canyon Formation to deep gas targets in middle Paleozoic formations in excess of 16,000 feet deep (Crowl et al. 2011). Oil and gas wells and unit boundaries within the 50-year mine plan area are shown on **Figure 5-1**.

5.3 Potash Mining and Oil and Gas

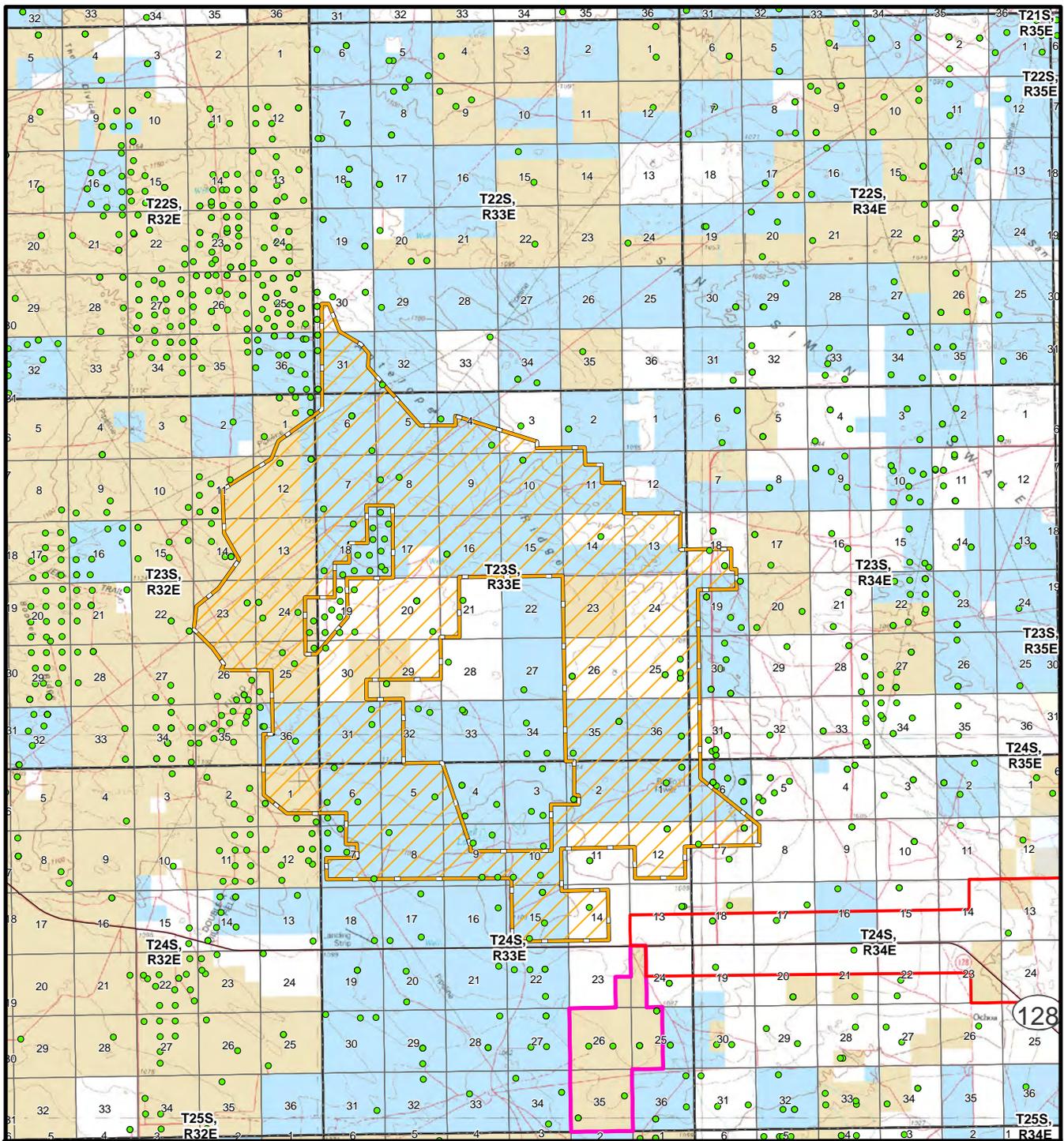
Although potash was originally discovered by wells that were drilled for oil and gas, conflicts between the oil and gas industry and potash mining emerged early on. In 1939, the federal government, through an order by the Secretary of the Interior, withdrew 2,560 acres from oil and gas leasing in deference to potash mining (1939 Order). The 1939 withdrawal remained in effect until 1951, at which time the Secretary of the Interior issued a new Order withdrawing the 1939 Order allowing for concurrent operations in the prospecting and development and production of oil and gas and potash deposits owned by the U.S. A succession of orders followed (1951, 1965, 1975, and 1986), expanding the Secretary's Potash Area each time. In 1986, the Secretary of the Interior issued the latest Secretary's Potash Area order (*Federal Register* 1986) which expanded the area to 497,002 acres. The proposed mine area is not within the Secretary's Potash Area (**Figure 5-2**).

Since 1955, the New Mexico OCD issued a series of orders to specifically address how oil and gas operations are to be conducted in the potash enclave. The original OCD order was R-111 and the current order is R-111-P, issued in 1988. As noted in the most recent order, many revisions were necessary as a result of disputes between the potash and oil and gas industries and management uncertainties caused by boundary changes.

5.4 Other Minerals

Other minerals produced in Lea County include sand and gravel, caliche, salt, and sulfur as a byproduct of natural gas production (USGS 2012). Salt is extracted by two methods:

- Solution mining where a well is drilled into the salt formation and unsaturated water is pumped into the well to dissolve the salt. The saturated solution is extracted and used as make-up water for saturated drilling fluids for oil and gas well drilling. There are no brine extraction wells in the study area.
- Mining salt that precipitated in playas. Mining in this manner is typically accomplished with the use of scrapers.



Legend

- | | |
|---|---|
|  50-Year Mine Plan |  Surface Ownership |
|  Plant Facilities |  BLM |
|  Pipeline and Wellfield Area |  Private |
|  Oil and Gas Wells |  State |



Figure 5-1. Oil and Gas Wells in the Vicinity of the 50-year Mine Plan and Surface Facilities

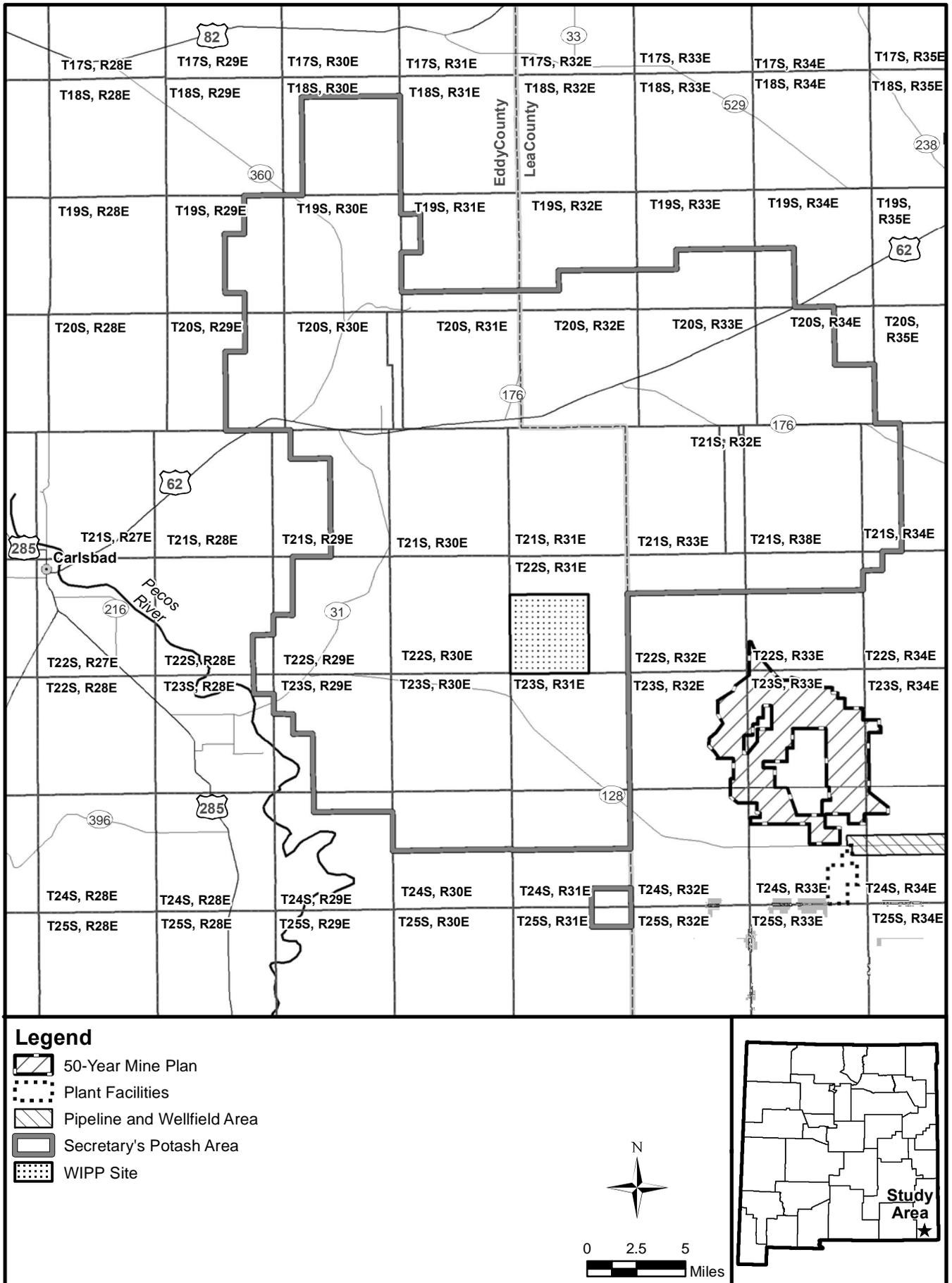


Figure 5-2. Secretary's Potash Area and Proposed Ochoa Mine

6.0 Environmental Geologic Conditions in the Study Area

6.1 Karst

As described in Section 3.3, karst is widespread in the Delaware Basin. Of particular concern is the presence of evaporite karst. Because evaporite minerals are much more soluble than calcium carbonate, dissolution of evaporites can occur rapidly compared to the dissolution of limestone. Most of the karst in the Delaware Basin is evaporite karst. On the north side of the basin within the study area, karst is manifested in a number of features, some that can be identified on the surface and others hidden in the subsurface (Hill 1996). Some of the major features include cavernous or vuggy porosity, sinkholes, breccia pipes, blanket breccia zones, caves, karst valleys, and dissolution breccias. Breccia is a deposit consisting of fragmented rock materials which results from the collapse of underground voids as the result of the dissolution of evaporite layers. Other karst features can result from the property of anhydrite that causes it to expand in size when it becomes hydrated and turns to gypsum. The expansion can result in buckling and deformation of adjacent rock layers and cracking in the gypsum bed (Bachman 1983). The cracking and deformation of adjacent beds can allow fluids to infiltrate into lower layers.

The Capitan Reef contains cavernous areas in the subsurface and anomalously high porosity, indicating the presence of large vugs, "honeycomb" structure, and evidence of solution (Hill 1996). The Capitan Limestone does not outcrop in the study area and is not present in the subsurface in the 50-year mine area. However, the formation of cavernous porosity may be relevant to the formation of some of the karst features in the vicinity.

In the study area, subsidence features believed to be related to evaporite karst consist of broad elongate depressions or smaller nearly circular sinks. These features consist of the San Simon Swale, the San Simon Sink, and the Bell Lake Sink (**Figure 2-3**). In addition to these features, there are other topographic depressions and sinks in the area also shown on **Figure 2-3**. The San Simon Swale is a northwest-southeast depression that covers about 100 square miles in Township 22 South, Ranges 33 and 34 East and Township 23 South, Range 34 East plus small parts of adjacent townships (Nicholson and Clebsch 1961). The swale is northeast of the Ochoa study area and is covered with stabilized dunes.

At the southeast end of the swale is the San Simon Sink, located in Section 18, Township 23 South, Range 35 East. The sink is a roughly circular depression about 0.5 square mile in area and about 100 feet deep. It contains a secondary collapse structure within the larger sink and is about 35 feet deep. Nicholson and Clebsch (1961), Reeves (1972), and Lambert (1983) reported that subsidence was active in the sink from 1927 to the early 1930s. It is believed that the San Simon Swale and the San Simon Sink originated from dissolution of evaporites in the subsurface and are indicative of evaporite karst, but the exact formation mechanism is not known. Because the features overlie the Capitan Limestone, it is possible that water under artesian conditions breached the top of the reef and dissolved evaporites in the section above the reef.

The Bell Lake Sink, another karst feature in the area, is located within the 50-year mine area. The central part of the sink is primarily located in the northeast quarter of Section 9, Township 24 South, Range 33 East, but portions of Sections 3, 4, and 10 are within the sink area (**Figure 2-3**). Another sink close to the study area is located in Section 24, Township 24 South, Range 33 East (Nicholson and Clebsch 1961). The origin of the Bell Lake Sink and the unnamed sink is uncertain, but there would be no involvement with the Capitan Limestone because the sinks are 10 to 12 miles southwest of the subsurface trend of the Capitan. Given that fact, the origin of these sinks is attributed to deep dissolution of evaporites, but no conclusive evidence has been found (Lambert 1983). Both sinks contain abundant gypsum dune sand, which may be indicative of the upward movement of groundwater that resulted in the precipitation of gypsum. Because there is no surficial source of gypsum in the area, it most likely came from the

subsurface. Prevailing hydrostatic heads preclude such movement to the surface at present (Nicholson and Clebsch 1961).

Other sinks evidenced by closed depressions on topographic maps are located within or adjacent to the 50-year mine area (**Figure 2-3**). These depressions are not documented in the literature reviewed for this report, but given the nature of the area, these features have a high probability of being caused by dissolution and collapse. If dissolution at depth is responsible for these sinks, it is deeper than the Rustler Formation. Across the 50-year mine area, the Rustler is consistently about 500 feet thick (± 50 feet) (Crowl et al. 2011). Oil and gas wells around Bell Lake Sink show no thinning in the Rustler, and a well drilled in the SE1/4 SE1/4 of Section 9, Township 24 South, Range 33 East (close to the center of the sink) has a Rustler section of 520 feet.

Because there is no thinning in the Rustler, dissolution of Rustler evaporites does not appear to be the cause of these depressions in the 50-year mine area. However, it is possible the dissolution is deeper than the Rustler. **Table 6-1** lists the thicknesses of the geologic section from the top of the Rustler to the top of the Bell Canyon Formation from four oil or gas wells in the vicinity of the mine area. The table supports the contention that the thicknesses do not appreciably change from well to well. The thicker sections are found in wells that are in or adjacent to depressions where it would be expected that the sections would be thinner if the depressions were caused by dissolution of the Rustler.

Table 6-1 Thickness from Top of Rustler to Top of Bell Canyon Formation, Based on Local Oil/Gas Wells

	Harper Jackson #9 1	Marshall #3	Bell Lake Unit #2	Vaca Ridge 30 Fed Com 1
Location (Section-Township –Range)	SESE 9-24S-33E	SWSW 19-23S-33E	SESW 30-23S-34E	NESW 30-24S-34E
Top of Rustler to top of Bell Canyon (ft)	3,940	3,840	3,870	4,110
Comment	In Bell Lake Sink	Delaware Cruz Unit inside mine plan area	Approximately 0.25 mile east of mine plan area	Located adjacent to sink south of Highway 128

Similar surface depressions found at the WIPP site have been attributed by Hill (2003) to karst processes. However, according to Lorenz (2006), these features lack evidence of having originated by dissolution of subsurface evaporites. The San Simon Sink is probably a karst feature although there is no definitive explanation of its origin. A karst origin is supported by evidence of historic subsidence and the fact that it is similarly situated over the Capitan Reef as are other documented karst features. On the other hand, the origin of the depressions over the proposed mine area may not be the result of karst processes, but derived from surficial erosion processes.

Although caves are quite common to the west in the vicinity of Nash Draw, the potential for caves in the study area is low. The major reason for this is that the Rustler Formation (the primary formation that hosts caves in the Nash Draw area) is buried too deeply for caves to form. The Rustler Formation in the Nash Draw area is very shallow or outcrops on the surface, allowing dissolution of evaporites to occur from meteoric waters or shallow groundwater.

6.2 Anthropogenic Subsidence

Subsidence also can be caused by human activities. In the Delaware Basin, anthropogenic subsidence largely has occurred as a result of potash mining and activities involving the withdrawal or injection of fluids for oil and gas production and brine extraction.

6.2.1 General Principles of Mining Subsidence

Subsidence is the phenomenon or response that occurs when an underground opening is created. The overlying and surrounding rock or soil naturally deforms in an effort to arrive at a new and more stable overall equilibrium position. This equilibrium-seeking action can result in both vertical and horizontal ground movement, and, if not controlled or minimized, can cause damage to both surface and subsurface structures. It can result in the development of undesirable surface topography, such as surface cracking or collapse, sinkholes, blocking or changing stream channels, and modification of drainage pathways.

While the term “subsidence” usually refers to vertical displacement of a point, subsidence actually encompasses both vertical and horizontal displacements. Horizontal displacement can be greater than vertical displacement when subsidence is small in magnitude.

Room-and-pillar mining employs a regular grid pattern of passages and pillars (**Figure 6-1**). In this mining method, a substantial proportion of the target mineral is locked up in the pillars and is often removed during the latter stages of mining (e.g., on retreat, often referred to as “pillar robbing” or “second mining”), often to the extent that the number, size, or distribution of remaining pillars is insufficient to continue to support the roof. The surface effects of collapse of room-and-pillar workings depend on the depth and geometry of the workings, as well as the strength and integrity of the pillars and the surrounding and overlying strata.

The amount of subsidence realized at the surface is dependent on the depth, width, and thickness of the minerals extracted, on the ratio of the extracted void (mined out area) to the retained pillar area, and on the extent of area over which underground pillar failure takes place (**Figure 6-2**).

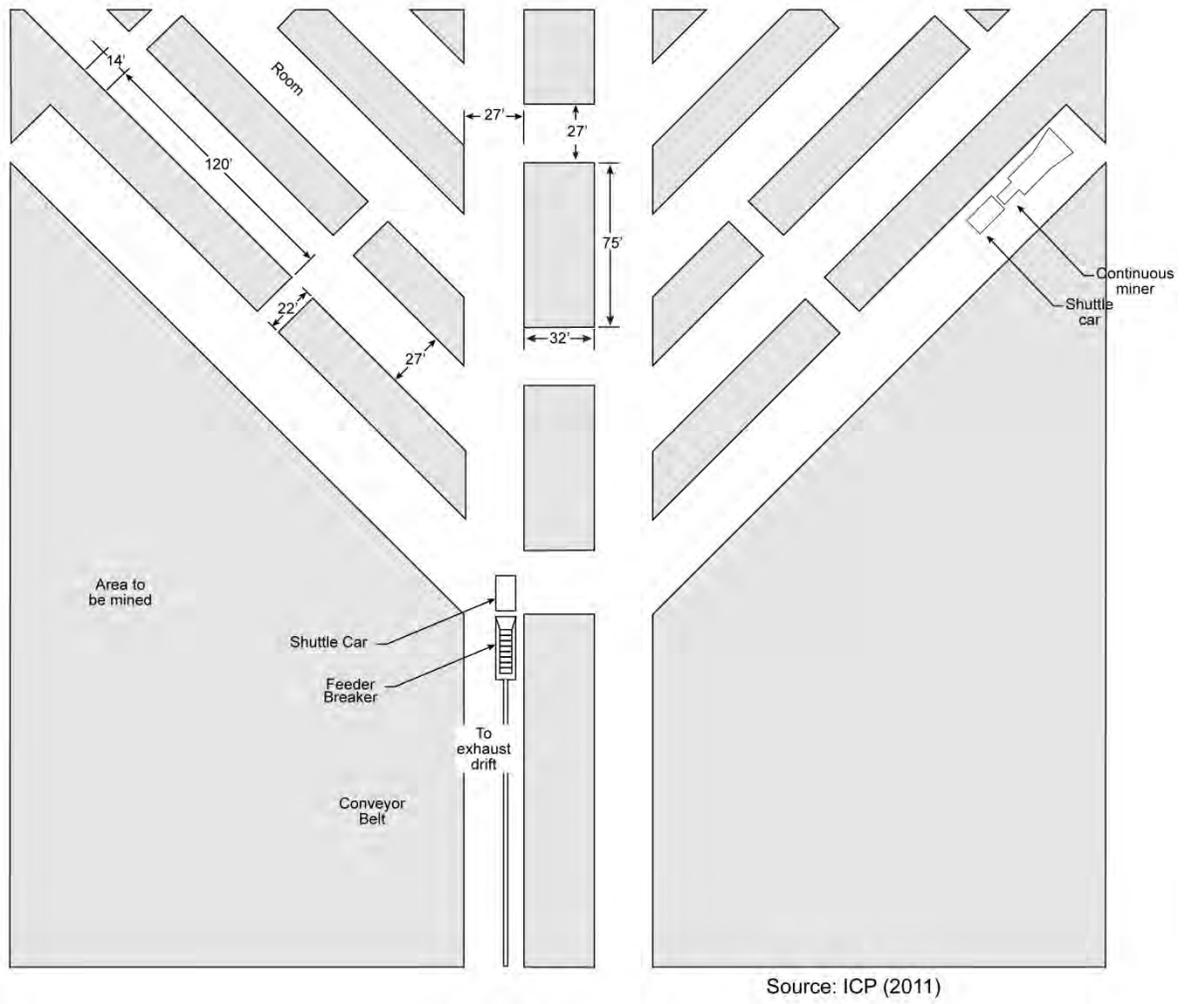
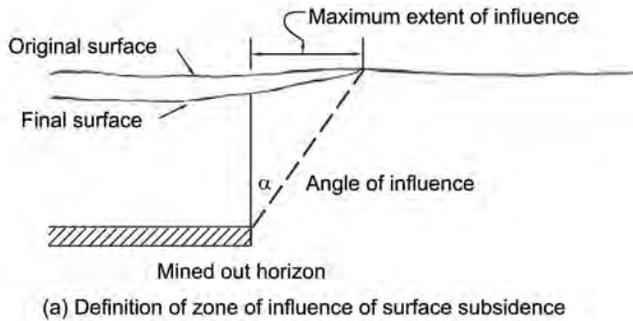
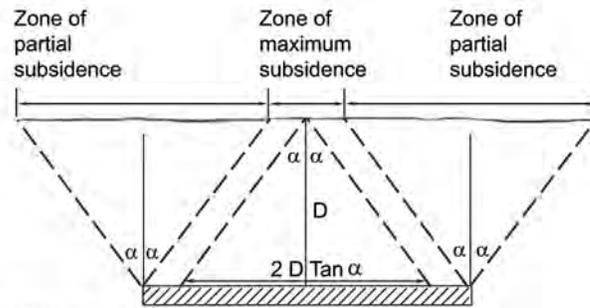


Figure 6-1 Plan View of Room-and-Pillar Mining



(a) Definition of zone of influence of surface subsidence



(b) Definition of zone of maximum subsidence

Source: Golder and Associates (1979)

Figure 6-2 Subsidence Effects Zones

The rate of subsidence is largely dependent on the type of material being mined. From a mine design and operations perspective, subsidence issues largely relate to the stability and safety of an excavation in rock as determined by:

- The extent to which disruptive displacements can be prevented; and
- The extent to which disruptive displacements can be controlled.

These same primary design objectives similarly influence the potential to affect the surface, and the degree of effect at the surface.

As a general rule, the amount of maximum subsidence (i.e., the depth of subsidence) that could occur cannot exceed the thickness of the zone of mineral extracted (the mining thickness) (Van Sambeek 2008, 2000). Maximum subsidence depth, however, is seldom observed, due to one or more of the following reasons:

- Because subsidence actually spreads over an area somewhat larger than the mined area, the subsidence is proportionally less.
- Convergence, or closure of the mined area, is never fully complete or total, so some voids inevitably remain, reducing the amount of subsidence.
- The overlying rocks expand slightly in volume due to breakage as the ground moves downward into the mined area, resulting in a “bulking” effect, which contributes to a reduction in subsidence volume and depth.
- The subsidence process can be slow for rocks that creep—several hundred (or more) years may be required for ultimate subsidence to occur.

It is important to note that both historic data and anecdotal evidence suggest that for the southeastern New Mexico potash mines, virtual completion of the maximum surface subsidence profile occurs within just a few years (5 to 7 years) after completion of second mining (Intrepid Potash/Shaw 2008). Minor, protracted subsidence or creep may continue to occur over an extended period of time thereafter. Potash, like salt, is classified as an elastoplastic rock, which is massive, homogeneous, and isotropic, but possesses load-deformation characteristics that deviate significantly from linearity, causing the rock to slowly flow or deform rather than break. However, catastrophic roof failure reportedly occurred at the Mosaic Potash mine located approximately 15 miles west of the 50-year mine area on March 18, 2012. While the event and its cause are still under investigation, it appears that the roof failure involved the collapse of an area 1,600 feet wide and 3,000 feet long (New Mexico Tech Seismological Observatory 2012), which triggered a magnitude 2.4 earthquake. The roof failure may be related to the type of mineral mined at the Mosaic Mine, which is predominantly langbeinite and sylvite, as opposed to the polyhalite to be extracted at the Ochoa Mine.

6.2.2 Expected Subsidence Due to Potash Mining

Subsidence is expected in areas where 90 percent extraction rates occur with the room-and-pillar mining technique to be used for the Ochoa Mine. Surface subsidence depth is expected to be approximately 4 feet, depending on the thickness of the seam removed (ICP 2011). Subsidence is not expected where 60 percent extraction rates are employed (proposed in the vicinity of oil or gas wells). The amount of subsidence is similar to findings concerning historic potash mining in the area where, given an average 6-foot mining extraction height, the maximum subsidence was found to be a nominal 4 feet. It should be pointed out though that the total extraction in the old mines may have been approximately 70 percent, rather than 90 percent. With a greater extraction, more subsidence may be expected, but the target polyhalite zone is deeper than the potash zones that are mined to the northwest of the proposed Ochoa Mine. It is likely that the thicker overburden would lessen the amount of subsidence that would be visible at the surface (Van Sambeek 2000). A one hundred-foot thick halite zone lies above the polyhalite zone

mined, so elastoplastic deformation of the halite into mining voids should lessen surface subsidence similar to what occurs in the historic potash mining area.

6.2.3 Effects of Subsidence

The effects of mining subsidence directly associated with the Ochoa Mine would generally be those related to surface topography changes and potential impacts to existing or new infrastructure such as structures, roadways, oil wells, pipelines, and other utility corridors. There are five major phenomena in the overburden above a mined out area that can result in damage to surface structures and resources (Van Sambeek 2000):

- Vertical displacement
- Horizontal displacement.
- Tilt or slope of ground surface
- Horizontal strain
- Curvature or flexure

Specific effects due to subsidence are the following (Van Sambeek 2000):

- Ground fissures
- Changes in ground slope
- Change in surface water flow direction
- Disruption of groundwater hydrology
- Sinkhole development at the surface

Given the current land use, potential subsidence is most likely to affect roads, pipelines and occasional structures, and diversion of surface water runoff with the greatest noticeable disruption occurring where tensile strains result in fissures. The following briefly describes what kind of damage could be expected.

Effects due to subsidence would be expected to occur at a distance defined by the angle of influence or angle of draw, which is the angle of inclination from the vertical of the line connecting the edge of the workings and the edge of the subsidence area (angle α in **Figure 6-2**). According to Golder and Associates (1979), "the zone of disturbance of strata above the mine workings extends beyond the limit of the mine workings and data from the southeast New Mexico potash fields suggest that a reasonable limit for defining this zone of disturbance would be an angle of 45 degrees from the vertical." If applied to the proposed project, mining would occur at a nominal 1,500-foot depth and would result in a subsidence effects area that would extend 1,500 feet beyond the edge of the mine workings.

6.2.3.1 Structures

Horizontal strain can be the most damaging to surface structures. Depending on the amount of strain, damage can range from slight and almost undetectable (hairline cracks in plaster) to serious structural damage (leaning walls, distorted window and door frames, and utility pipe damage).

6.2.3.2 Roads

Subsidence induced effects on roadways can range from minor to extreme. Minor effects can include slight heaving and dropping or lateral shifting of the roadway surface, creating an undulating or irregular horizontal alignment. More extreme effects can include pavement buckling or fracturing as well as failure of the roadway base, when subsidence undermines the soils and supporting embankments associated with roadway components.

6.2.3.3 Oil and Gas Wells

Subsidence induced deformations of the strata can damage oil and gas wells located within the zone of influence of the movements. Subsidence effects on such wells can include distortion of the boreholes, squeezing of casing, and shearing of casing. Experience and observations from historical potash mining in southeastern New Mexico indicates that subsidence strain in the overburden has little noticeable effect on oil and gas wells (Golder and Associates 1979). In the case of the Wills-Weaver Mine in Eddy County, three producing oil wells situated in an area of the mine with a 70 to 75 percent extraction ratio and centered within retained pillars of approximately a 150-foot radius, it was observed that “closures at the mine horizon level would have impacted the oil wells because of the limited pillar sizes, but the level of disturbance has evidently not been sufficient to cause problems” (Golder and Associates 1979).

6.2.3.4 Pipelines

The integrity of pipelines and their ability to withstand the effects of limited surface subsidence is largely based on inherent flexibility within the line and the manner in which pipe joints respond to angular and telescopic movements.

Buried pipelines effectively move when the ground moves, due to friction between the pipe (particularly at joint or flange locations) and the ground itself. Therefore, when the ground undergoes a curvature or horizontal change in length, a pipeline may fracture.

In the case of fixed anchorage aboveground pipelines, subsidence induced strain may be uniformly imposed at the support points; however, the degree of movement may not necessarily be equally distributed across the joints due to varying degrees of tightness or variances in mating surfaces, causing the pipe to crack or break.

6.2.3.5 Water

The development of tension cracks can cause disruption of surface water and groundwater resources that may be present in the overburden above the mining area. These effects can include lowering of groundwater levels, changes in surface water runoff direction and flow rate, and changes in water quality. Mining heights in bedded salt layers of less than 16 feet thick are not expected to have an effect on groundwater (Van Sambeek 2000). However, alteration of the ground surface can change surface water runoff quantity and flow direction.

6.2.4 Subsidence Due to Brine Mining and Oil and Gas Activities

6.2.4.1 Brine Mining and Subsidence

Salt can be extracted from subsurface formations by using wells that inject fresh water to dissolve the salt followed by extraction of the saturated water. In the Delaware Basin, these wells are referred to as brine wells. Brine wells in the Delaware Basin are used to extract saline water for use in oil and gas well drilling and workover fluids. Recently, a few brine wells in Eddy County that were 200 to 300 feet in diameter and 100 to 200 feet deep suffered catastrophic collapse causing sinkhole development at the surface. Each of the wells associated with the collapse were former oil and gas wells converted to brine wells. At one brine well in Carlsbad, New Mexico, geophysical surveys indicated the presence of subsurface fracturing, cavities, and collapse, but no surface manifestation of collapse has occurred other than tilting of the ground surface (Land and Veni 2011). No brine wells are located within or near the Ochoa 50-year mine area.

6.2.4.2 Oil and Gas Activities and Subsidence

Oil and gas exploration and production has been occurring since the 1920s in the Delaware Basin, which has been a prolific oil and gas producing area. Thousands of wells have been drilled through evaporite formations to explore for and produce oil and gas. Because of the extent of the evaporites (salt and

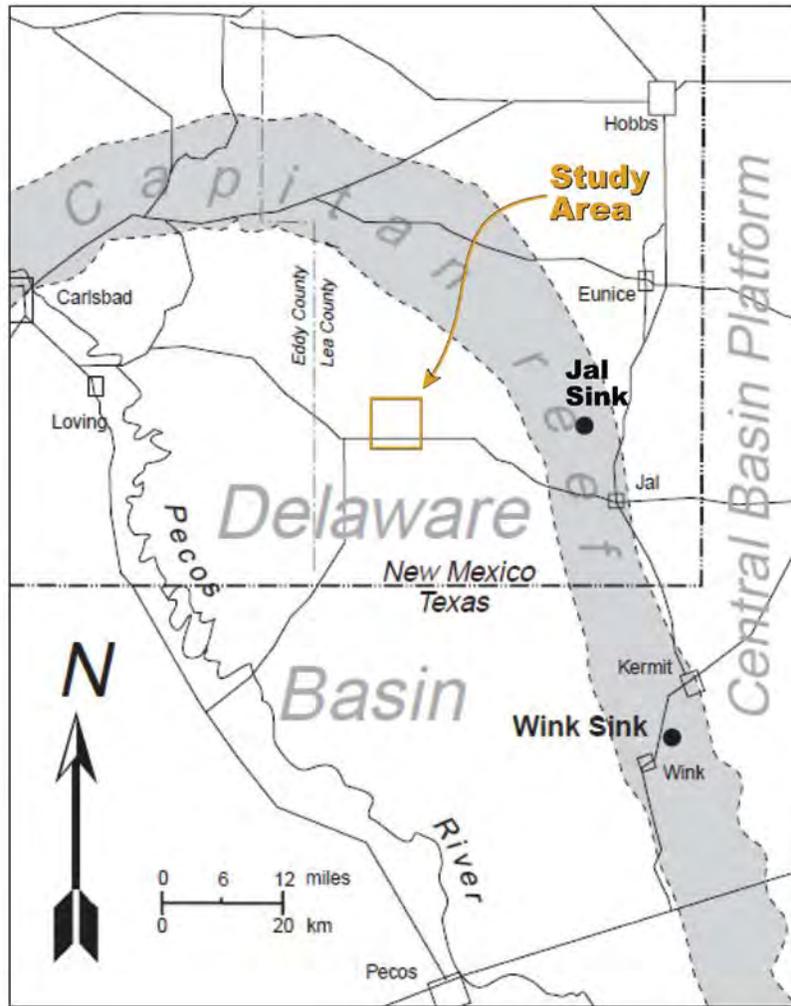
anhydrite), drilling and completion operations have to be conducted in a manner that prevents the dissolution of the salt and protects the well during drilling and through the productive lives of the wells, often 20 to 30 years or more.

From the 1920s until the 1950s, oil wells were commonly drilled with cable tool rigs (Cearley 2000). In cable tool drilling, the hole is advanced by pulling a weighted bit up and down with a cable. The method requires “bailing” the well occasionally to remove rock cuttings that accumulate in the bottom of the well. Drilling could not commence if the cuttings were not removed because the bit would pulverize the cuttings without deepening the bore. If water is encountered, the well must be cased through the water zone before drilling can resume. If hydrocarbons are encountered, drilling would have to stop for safety. In early cable tool practice, casing was pounded into the well, but not cemented. Cementing of casing strings started in California in the early 20th Century, but cementing did not come to the mid-continent area until the 1920s (Smith 1976). Although standardized cementing practices were developed in the 1930s, cementing was often based on guesswork, especially when determining proper setting times. As technology progressed, and cementing became more standardized, procedures and practices were codified into regulations to ensure that cement jobs were done properly. In the Permian Basin, completion practices even into the 1950s required cement at the bottom of intermediate and production casing strings, but allowed unprotected casing to be exposed to as much as 2,000 feet of salt formation (Giroux et al. 1988).

There are several examples in the Permian Basin of catastrophic subsidence as a result of suspected oil field casing corrosion and dissolution of salt. The examples of subsidence associated with oil and gas operations include the Wink Sinks I and II and the Jal Sink (Johnson et al. 2003; Powers 2003). There are other similar incidents that occurred in areas underlain by salt in Texas and in Kansas (Walters 1978). The Wink Sinks developed in the Hendrick oil field in Winkler County, Texas, near the town of Wink (**Figure 6-3**). Wink Sink I developed in 1980 and Wink Sink II occurred in 2002. The Jal Sink developed in 2001.

The Jal sinkhole is located about 8 miles northwest of Jal, New Mexico and about 12 miles east of the proposed 50-year mine area. The geologic settings of the Wink Sinks and the Jal sinkhole are similar as they occurred at the basin margin above the Capitan Reef. In each incident, sinkholes formed around a well location and the sinks had diameters ranging from 200 to over 700 feet (Johnson et al. 2003; Powers 2003). Although the exact cause of development of these sinkholes is not known, it is suspected that casing failure allowed unsaturated water to come into contact with, and subsequently dissolve, salt layers. **Figure 6-4** shows the postulated development of the Wink Sink showing cavitation and subsidence caused by leaking casing, with ultimate surface collapse not occurring until years after the well was plugged. It is not known if the sinkhole development was enhanced by upward movement of water from the Capitan Reef. Rising heads could have occurred in the Capitan Reef because of lower oil field demand for water in the 1980s and 1990s, but there is no definitive evidence that the reef was involved (Powers 2003)

A major concern regarding oil field cement is the potential vulnerability of cements to brine fluids (LaFleur and Lovelace 1969). The damage that brine can inflict is dependent on many variables, but if cement is vulnerable, deterioration can begin within 24 hours of exposure to brine. It can be readily surmised that, if casing were breached adjacent to an uncemented salt zone, the brine created by dissolution could attack the cement where it is present. Overall, cementing of casings in oil and gas wells that penetrate salt sections is often problematic and there is no general rule on how to deal with the problems (Hunter et al. 2009).



Source: Powers (2003)

Figure 6-3 Location of Jal and Wink Sinks

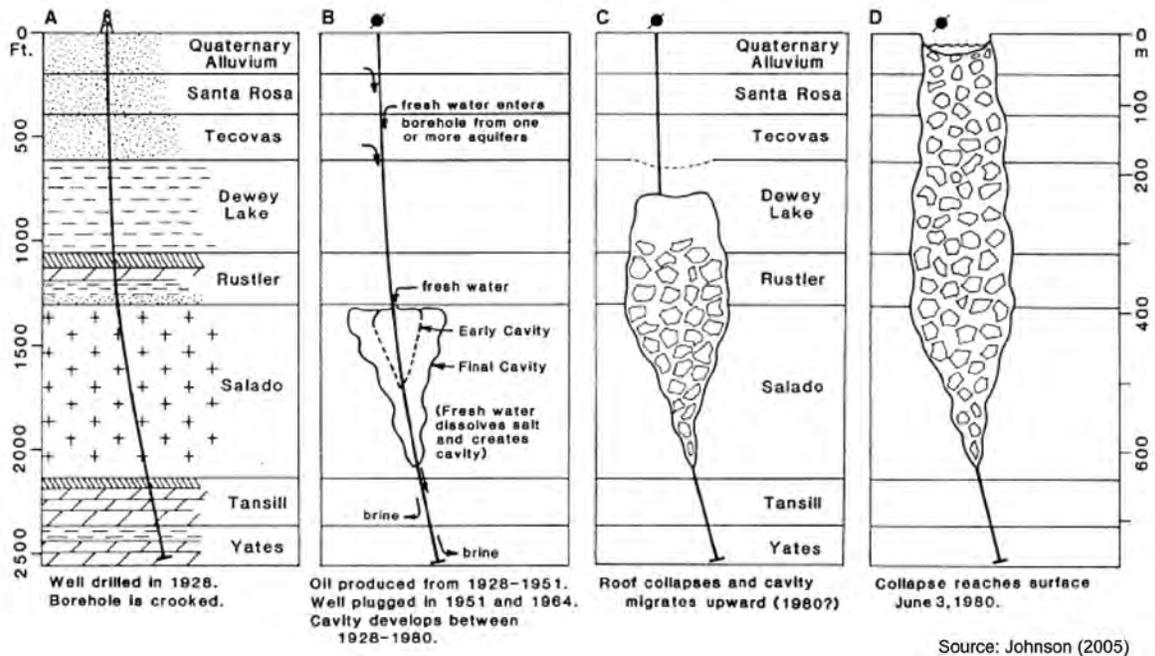


Figure 6-4 Development of Wink Sink

6.2.5 Oil and Gas and Proposed Polyhalite Mining

6.2.5.1 Mining and Oil and Gas Wells

Within the proposed 50-year mine area, there are 42 active gas wells, 37 active oil wells, 3 salt water disposal (SWD) wells, 2 pilot wells, 2 temporarily abandoned wells, and 49 plugged and abandoned (P&A) wells. To minimize the potential problems related to ground stability near the wells, the Ochoa Mine plan (ICP 2011) provides the following methodology to manage abandoned wells in the mine area because it may not be possible to determine whether cement plugs are present or where the plugs were placed.

- Locate the well.
- Install pressure valves.
- Run casing integrity logs in the well.
- Run cement bond logs in the well.

Several remedial actions may be necessary to stabilize P&A wells including the following procedures:

- Drill out cement plugs and replace plugs.
- Conduct remedial cement squeeze jobs where casing lacks sufficient cement or where there is no cement.
- Pull and replace the casing.

In addition to the procedures listed above, ICP proposes to mine at a 90 percent extraction rate beyond the 200-foot radius from a well and expects that subsidence would occur around the barrier pillar (ICP 2011).

For active oil and gas wells, ICP proposes the following procedures in the mine:

- A 200-foot radius barrier pillar would be left around the well.
- Beyond the barrier pillar, an extraction ratio of 60 percent would be conducted out to a radial distance of 1,500 feet from the well which would allow for no subsidence. Beyond the 1,500-foot radius, a 90 percent extraction rate would occur.

6.2.5.2 Oil and Gas Wells Within and Adjacent to the Proposed Mining Area

As described in the previous section, there are active and P&A gas, oil, and service wells within the 50-year mine area. All the wells were drilled since the 1950s when discovery of deep production of the Bell Lake Unit encouraged operators to develop into the deep basin. Well files and geophysical logs online at the New Mexico OCD were reviewed to determine if there are any wells within or closely adjacent to the 50-year mine area. The wells were reviewed for construction or integrity problems that could pose potential threats to underground safety and efficient mining of the polyhalite. Particular focus was on those wells drilled prior to the 1980s that produced oil and gas or had been productive at one time, but then were idle for an extended period.

Exploratory or development wells that had been drilled and subsequently abandoned within a few weeks or months were not evaluated because fairly immediate abandonment in accordance with drilling rules with plugs placed at intervals directed by the supervising agencies would be likely to avoid the development of unstable subsurface conditions. Wells drilled since the 1980s appeared to have casing strings and cement placement that would preclude the movement of fluids and minimize potential instability. SWD or injection wells were subject to scrutiny because the movement of large amounts of

fluids through them could lead to increased salt dissolution through casing leaks adjacent to uncemented zones.

Any condition that allows movement of unsaturated fluids between formations could result in the dissolution of evaporite layers and subsequent subsurface instability, possibly causing ultimate surface collapse (Walters 1978). The major purposes of cementing casing in place is to prevent the migration of fluids from one zone to another to protect water sources, prevent commingling of hydrocarbons from different zones, prevent the uncontrolled movement of hydrocarbons outside the production casing and tubing, and, where present, prevent the dissolution of evaporite layers.

In the study area, there are a number of aquifers that must be sealed off to prevent migration of fluids. These aquifers include sands in the Dewey Lake Formation and Triassic beds (Santa Rosa Formation) above the Rustler Formation, as well as the Magenta and Culebra zones within the Rustler Formation.

Oil and gas wells drilled in this area have similar casing and cementing programs. A typical well, regardless of ultimate depth, would have a surface casing string set at depths that vary from 300 to 800 feet below ground surface, with a requirement to have cement circulated to the surface to ensure that any aquifers behind the casing are sealed. After the surface casing is set, wells are typically drilled to the top of the Bell Canyon Formation of the Delaware Mountain Group at around 5,000 to 5,400 feet below the ground surface.

In the past, the wells were often drilled deep enough to test sands only in the upper Bell Canyon section, in which case the second casing string would have been the production casing. On the other hand, if the intent was to drill deeper, the second casing was set as an intermediate string in preparation to drilling to targets located at depths from 12,000 to 17,000 feet. In either case, if cement was not placed from the casing point to the surface or up into the surface casing, then there is the possibility that aquifers located below the surface casing may be in communication with salt or anhydrite zones (**Figure 6-5**).

Depending on groundwater flow potential, water could flow by gravity out of the aquifers and this hydrodynamic situation behind the uncemented casing could not only cause the dissolution of evaporite layers, but also contribute to casing corrosion. **Figure 6-5** shows an at-risk casing and cement configuration whereby unsaturated fluids from unsealed water-bearing zones can be in possible communication with evaporite layers susceptible to dissolution (A). This casing configuration could also allow injected or withdrawn fluids to come into contact with evaporites through casing and tubing leaks. A protective casing and cement configuration where cementing the long casing string to the surface would seal the aquifers and prevent communication between water-bearing zones and evaporites (B).

Of the many oil and gas wells that intercept the mining area, only a few of the wells appear to present a risk of unsealed aquifers and unprotected evaporite sections (**Table 6-2** and **Figure 6-6**). The wells listed on **Table 6-2** exhibit a casing-cement configuration as shown in **Figure 6-5 (A)**. These wells in some cases produced or were operated as injection wells for many years before finally being P&A. Over the course of several decades, it is not unreasonable to assume that salt zones in these wells could have been subjected to extensive dissolution and may pose as yet undiscovered hazards to mining, potentially limiting efficient ore recovery. Abandoned wells pose no less a hazard than active wells because annular flow behind production casings may not have been detected during the operational lives of the wells or when the wells were abandoned.

Data from the at-risk wells within 1,500 feet of the proposed 50-year mine boundary, were reviewed. This area within 1500 feet of the mine plan boundary is of concern because subsidence effects from potential voids caused by dissolution of evaporite rocks along the wellbores could extend into the mining area. Most of the wells in the unit had very similar casing and cementing programs that left potentially unsealed aquifers and large intervals of evaporites unprotected by cemented casing. Because of this aspect, these wells were included in **Table 6-2**.

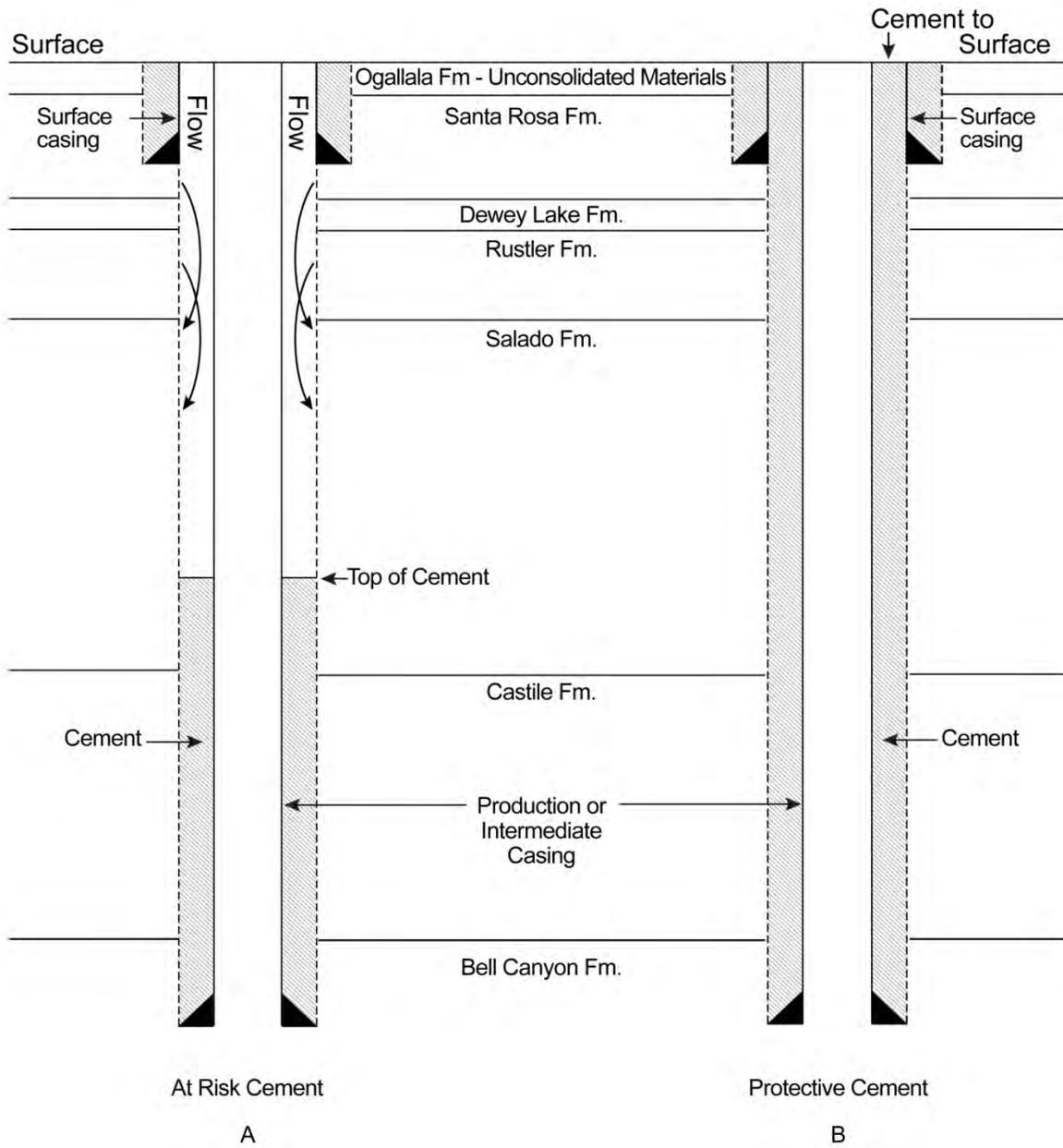
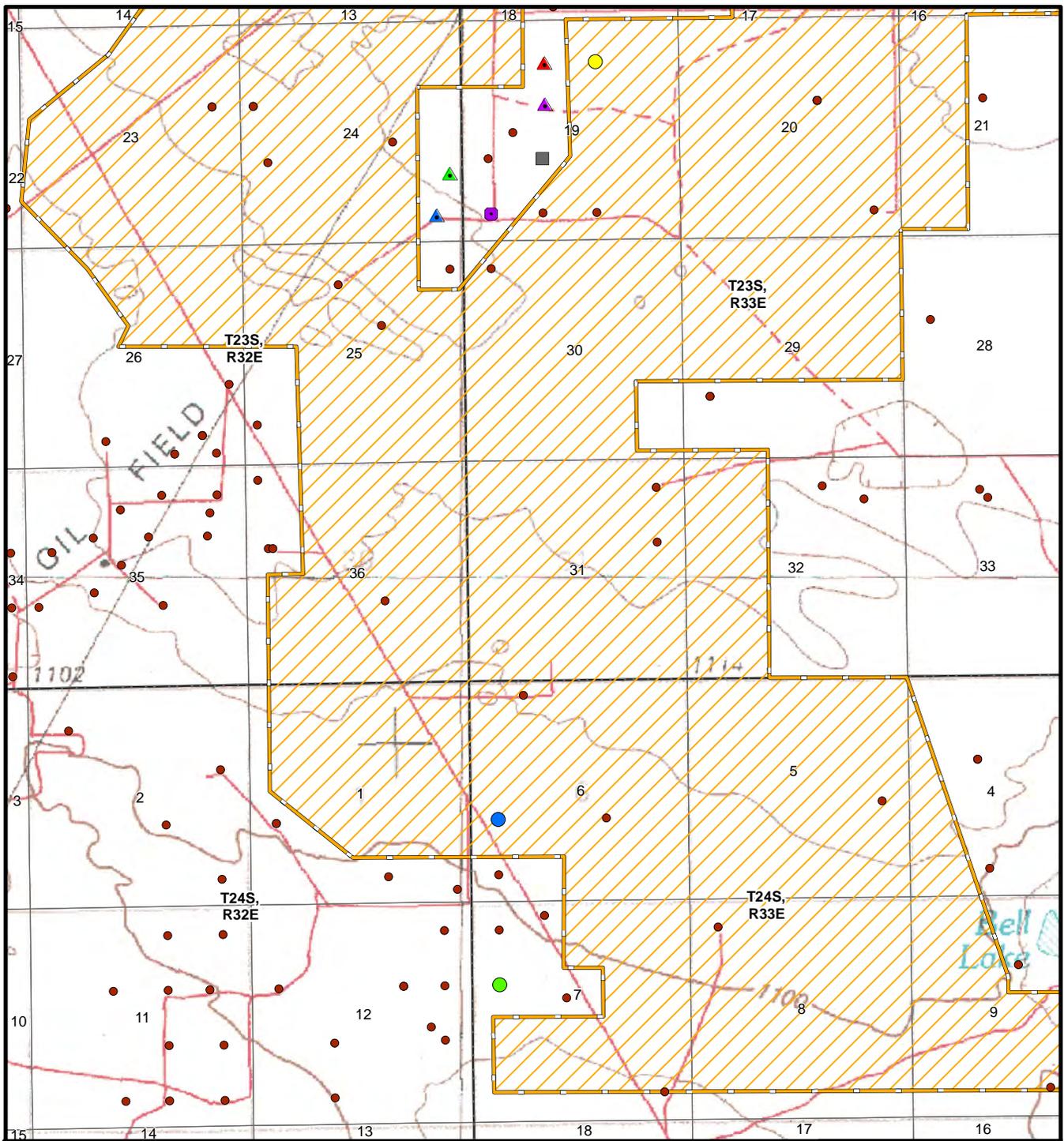


Figure 6-5 Typical Oil and Gas Well Casing and Cementing in Study Area



Legend

50-Year Mine Plan

Oil and Gas Wells

At Risk Wells and API #s

- | | | | |
|--|----------------|--|----------------|
| | 30025252010000 | | 30025244320000 |
| | 30025201530000 | | 30025251510000 |
| | 30025081190000 | | 30025243810000 |
| | 30025250000000 | | 30025083580000 |
| | 30025083590000 | | |



0 0.25 0.5
Miles



Figure 6-6. At Risk Wells Within and Adjacent to the 50-year Mine Plan Area

Table 6-2 List of Potential At-risk Wells Within and Adjacent to Proposed 50-Year Mine Area

API #	Location Sec-T-R	Original Operator	Well Name	#	Type ¹	TD ²	Year Comp	Status ³	Year P&A	Surface Casing Set (depth-feet)/Formation	Production/Intermediate Casing Set (depth-feet)/Formation	Reported TOC ⁴ (depth-feet)	Comment
30-025-25151	NWNE 19 T23S, R33E	Continental Oil Co.	Marshall	6	O	5,250	1975	P&A	2011	1,245/Rustler (based on offset well)	5,250/Bell Canyon	3,600	2,355 feet no cement.
30-025-24381	NWSW 6 24S 33E	Hondo Drilling Co.	Gulf NW State "L"	2	SWD	5,170	1973	P&A	2002	366/Santa Rosa	5,168/Bell Canyon	3,646	Casing cut at 1,370 feet during P&A, TOC not certain.
Wells Located Adjacent (less than 1,500 feet) to 50-Year Mine Plan Area													
30-025-08358	SWSW 19 23S-R33E	Continental Oil Co.	Marshall	1	O	5,237	1961	ACT	NA	381/Triassic (Santa Rosa?)	5,237/Bell Canyon	4,500	TOC Castile Formation, 4119 feet no cement. Casing leak at 660 and at unspecified depth. Repaired 1972.
30-025- 24432	SWNW 7 24S-33E	Continental Oil Co.	Ingram "O" State E	2	SWD	5,204	1973	ACT	NA	421/Santa Rosa	5,204/Bell Canyon	Reported circulated to surface, casing	Injection into perforations at 5012 to 5033 (Bell Canyon). Casing leaks at unreported depths repaired in 1977, 1983.
30-025-08359	NESW 19 T23S, R33E	Continental Oil Co.	Marshall	2	O	5,216	1961	P&A	2011	380/Triassic (Santa Rosa?)	5,216/Bell Canyon	4,408	TOC Castile Formation, 4,028 feet no cement. Converted to SWD 1985 after casing leaks repaired. Failed mechanical integrity test 2009.
30-025-25000	SENE 19 T23S-R33E	Continental Oil Co.	Marshall	5	O	5,180	1975	P&A	2011	527/Santa Rosa	5,180/Bell Canyon	2,500	TOC Salado, 1,973 feet no cement.
30-025-25201	NENW 19 T23S-R33E	Continental Oil Co.	Marshall	7	O	5,235	1976			1,287/Rustler	5,235/Bell Canyon	3,200	TOC in Salado, 1,913 feet no cement.
30-025-08119	SESE 24 T23S-R32E	Continental Oil Co.	Fields	1	O	5,217	1961	P&A	2006	386/Triassic (Santa Rosa?)	5,217/Bell Canyon	4,275	TOC in Castile Formation, 3,889 feet no cement.
30-025-20153	NESE 24 T23S-R32E	H.L. Johnson	Fields Federal	1	O	5,168	1963	P&A	1970	386/Triassic (Santa Rosa?)	5,168/Bell Canyon	4,650	TOC in Castile Formation, 4,264 feet no cement.

¹ O – Oil; G – Gas, SWD – Salt Water Disposal.

² TD – Total Depth, feet.

³ ACT – Active; P&A – Plugged and Abandoned; TA – Temporarily Abandoned.

⁴ TOC – Top of Cement.

7.0 Summary and Recommendations

7.1 Subsidence and Polyhalite Mining

A maximum of 4 feet of subsidence is expected where ore recovery is 90 percent. The depth of subsidence is well within observed historic ranges of subsidence for potash mines in southeastern New Mexico. Maximum subsidence may even be less than 4 feet because of bulking of rubble and greater depth of mining. Surface effects may be minimal, but have the potential to adversely impact mainly roads and pipelines. The Ochoa mine plan (ICP 2011) indicates that subsidence monitoring will occur, but does not provide details on where measurement stations would be placed, when measurements would periodically occur, or when monitoring would start. It is recommended that ICP set up the network and begin monitoring with enough lead time prior to mining to provide adequate baseline data for the area.

7.2 Oil and Gas Production and Proposed Polyhalite Mining

Wells having an at-risk casing and cement configuration may present a hazard to underground mining as well as the risk of development of sinkholes. The at-risk designation is not meant to indicate with certainty that problems exist or would occur, but is intended to identify a potential problem for planning purposes. It is based on a review of records available in the online OCD database and identification of casing and cementing configurations that may present problems. The movement of fluids out of a water-bearing zone is not likely if groundwater conditions or rock properties allow little or no fluid flow out of the rock. Identification of certain attributes of well construction that could allow migration of fluids is consistent with the observations and conclusions of workers who have studied the catastrophic subsidence associated with oil field practices (Johnson et al. 2003; Powers 2003) and provides the basis for the at-risk designation.

It is recommended that a monitoring plan be developed and implemented to assess potential ground instability in areas where the at-risk wells are located. The well monitoring could be done in conjunction with the subsidence monitoring network. However, monitoring for instability around at-risk wells might involve the use of additional equipment such as tiltmeters, aerial photography, and interferometric synthetic aperture radar (InSAR) to detect subtle changes in ground elevations. The specific survey methods would be determined by ICP in consultation with the BLM. The area around active wells also should be monitored for potential instability during and after mining.

ICP's recommended procedures to deal with abandoned wells may need to be modified to account for the actual condition of wells that have been P&A (Section 6.2.5.1). A common abandonment procedure is to salvage casing strings where they can be easily removed, except for surface casing. Because the surface casing is cemented to the ground surface, it is left in place and cut off below the ground. The intermediate or production strings are removed where they can be cut. In the case of an at-risk casing and cementing configuration, the top of the cement provides a convenient place at which to cut the casing. After the casing is cut and removed, cement plugs are then placed at discrete intervals. The cement plugs do not cover the entire hole but are placed strategically over intervals that need to be isolated to create a barrier to flow. Therefore, if an abandoned well is drilled out, there may be no casing to test or to run cement bond-detection tools, as proposed by ICP. If such an abandoned well has no long string casing to clean out and test, and if the well has been determined to pose a risk to mining, the only remedy is re-drilling and placing new plugs according to the regulatory agency.

P&A wells with intact casing, wells that are not abandoned but have been idle for extended periods of time, and active wells would be more amenable to the procedure proposed by ICP, as described in Section 6.2.5.1. Presumably the wells would be accessible and pressure testing and cement bond logs could be run to evaluate well integrity. However, re-entry into previously abandoned wells can involve a

high degree of risk because of undocumented junk left in the hole and collapsed casing if present (especially in salt intervals).

7.3 Potential Karst Features

There is a concern that the Bell Lake Sink and other depressions in the proposed 50-year mine area, described in Section 6.1, may be natural karst features indicative of potentially unstable subsurface conditions. However, review of selected well logs over the mine plan area did not indicate stratigraphic thinning in the Rustler, or thinning in the Rustler-Salado-Castile section. There is no strong evidence of these features having originated by dissolution of subsurface evaporites. Without a definitive explanation of the origin of these features, the presence of topographic depressions over the proposed mine area poses concerns for potentially adverse subsurface conditions.

It is recommended as a first step in analyzing possible karst features that a detailed correlation study be conducted of the geologic section from the surface to the top of the Bell Canyon Formation. Using information from wireline geophysical well logs, it would be possible to assess if there are any abrupt changes in thickness, the presence of intervals that may indicate breccia zones, and the continuity of the Dewey Lake and Santa Rosa formations.

Geophysical surveys are not recommended at this time. Various geophysical survey methods were evaluated extensively when planning the WIPP facility, but all were rejected due to limitations that resulted in unacceptably ambiguous results in an effort to detect karst features (USEPA 2006). It is assumed that, because the WIPP site has similar geology to the mine study area, geophysical surveys would not be able to reliably identify karst features.

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