

Mineral Resource Potential and Reasonably Foreseeable Development for Planning Units 1-5

FINAL REPORT

Prepared For:



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TABLE OF CONTENTS

SUMMARY AND CONCLUSIONS X

1.0 INTRODUCTION..... 2

1.1 Purpose of the Report..... 2

1.2 Lands Involved and Data Sources 2

 1.2.1 Lands Involved 2

 1.2.2 Data Sources 3

 1.2.2.1 Sources for Leasable Mineral Data 4

 1.2.2.2 Sources for Locatable and Salable Mineral Data 4

1.3 Organization of this Report 5

1.4 Definitions of Leasable, Locatable, and Salable Minerals..... 6

 1.4.1 Leasable Minerals 6

 1.4.2 Locatable Minerals 7

 1.4.3 Salable Minerals 7

2.0 GEOLOGY OF THE FIVE PLANNING UNITS..... 9

2.1 Physiographic Provinces 9

2.2 Rock Units 10

 2.2.1 Surface Geology 10

 2.2.2 Stratigraphic Sections 11

2.3 Historical Geology..... 13

2.4 Tectonic Features within the Planning Units 14

3.0 MINERAL RESOURCES..... 20

3.1 Leasable Minerals 23

 3.1.1 Oil and Natural Gas 23

 3.1.1.1 Geologic Setting 23

 3.1.1.2 Exploration, Development, and Production History 25

 3.1.1.3 Resource and Development Potential 30

 3.1.2 Coal 31

 3.1.2.1 Geologic Setting 32

 3.1.2.2 Exploration, Development, and Production History 35

 3.1.2.3 Resource and Development Potential 43

 3.1.3 Geothermal Resources and Hot Springs 46

 3.1.3.1 Geologic Setting 46

 3.1.3.2 Exploration, Development, and Production History 47

 3.1.3.3 Resource and Development Potential 50

 3.1.4 Sodium and Halite 51

 3.1.4.1 Geologic Setting 51

 3.1.4.2 Exploration, Development, and Production History 51

 3.1.4.3 Resource and Development Potential 51

 3.1.5 Sulfur 51

 3.1.5.1 Geologic Setting 52

 3.1.5.2 Exploration, Development, and Production History 52

 3.1.5.3 Resource and Development Potential 52

 3.1.6 Helium 52



TABLE OF CONTENTS (CONTINUED)

3.1.6.1	Geologic Setting.....	52
3.1.6.2	Exploration, Development, and Production History	53
3.1.6.3	Resource and Development Potential	53
3.1.7	Carbon Dioxide	53
3.1.7.1	Geologic Setting.....	53
3.1.7.2	Exploration, Development, and Production History	53
3.1.7.3	Resource and Development Potential	54
3.2	Locatable Minerals	55
3.2.1	Gold and Silver.....	55
3.2.1.1	Geologic Setting.....	55
3.2.1.2	Exploration, Development, and Production History	57
3.2.1.3	Resource and Development Potential	57
3.2.2	Base Metals and Fluorspar	58
3.2.2.1	Geologic Setting.....	58
3.2.2.2	Exploration, Development, and Production History	59
3.2.2.3	Resource and Development Potential	59
3.2.3	Gypsum.....	60
3.2.3.1	Geologic Setting.....	60
3.2.3.2	Exploration, Development, and Production History	61
3.2.3.3	Resource and Development Potential	62
3.2.4	Limestone	62
3.2.4.1	Geologic Setting.....	62
3.2.4.2	Exploration, Development, and Production History	62
3.2.4.3	Resource and Development Potential	63
3.2.5	Pumice	63
3.2.5.1	Geologic Setting.....	64
3.2.5.2	Exploration, Development, and Production History	65
3.2.5.3	Resource and Development Potential	66
3.2.6	Perlite.....	66
3.2.6.1	Geologic Setting.....	66
3.2.6.2	Exploration, Development, and Production History	67
3.2.6.3	Resource and Development Potential	67
3.2.7	Rare Earth Elements	67
3.2.7.1	Geologic Setting.....	68
3.2.7.2	Exploration, Development, and Production History	69
3.2.7.3	Resource and Development Potential	69
3.2.8	Uranium.....	69
3.2.8.1	Geologic Setting.....	70
3.2.8.2	Exploration, Development, and Production History	73
3.2.8.3	Resource and Development Potential	76
3.2.9	Semiprecious Stones and Miscellaneous Minerals.....	76
3.2.9.1	Geologic Setting.....	77
3.2.9.2	Exploration, Development, and Production History	77
3.2.9.3	Resource and Development Potential	77
3.2.10	Lithium	78
3.2.10.1	Geologic Setting.....	78
3.2.10.2	Exploration, Development, and Production History	78



TABLE OF CONTENTS (CONTINUED)

	3.2.10.3	Resource and Development Potential	78
3.3	Salable Minerals.....		79
	3.3.1	Aggregate, Sand, and Gravel	79
		3.3.1.1 Geologic Setting.....	79
		3.3.1.2 Exploration, Development, and Production History	80
		3.3.1.3 Resource and Development Potential	84
	3.3.2	Basalt, Diorite, Cinders, and Scoria	85
		3.3.2.1 Geologic Setting.....	85
		3.3.2.2 Exploration, Development, and Production History	86
		3.3.2.3 Resource and Development Potential	88
	3.3.3	Clay and Adobe	88
		3.3.3.1 Geologic Setting.....	89
		3.3.3.2 Exploration, Development and Production	89
		3.3.3.3 Resource and Development Potential	91
	3.3.4	Dimension Stone, Decorative Stone, and Travertine.....	91
		3.3.4.1 Geologic Setting.....	92
		3.3.4.2 Exploration, Development, and Production History	93
		3.3.4.3 Resource and Development Potential	94
	3.3.5	Humate	95
		3.3.5.1 Geologic Setting.....	95
		3.3.5.2 Exploration, Development, and Production History	96
	3.3.6	Resource and Development Potential.....	96
4.0	REASONABLY FORESEEABLE DEVELOPMENT.....		98
	4.1 Leasable Minerals.....		99
		4.1.1 Oil and Gas	99
		4.1.2 Coal.....	100
		4.1.3 Geothermal	100
	4.2 Locatable Minerals		102
		4.2.1 Gold and Silver	102
		4.2.2 Base Metals	102
		4.2.3 Gypsum.....	103
		4.2.4 Limestone	103
		4.2.5 Pumice and Perlite.....	103
		4.2.6 Rare Earth Elements	103
		4.2.7 Uranium.....	104
		4.2.8 Lithium	105
	4.3 Salable and other Industrial Minerals		106
		4.3.1 Aggregate, Sand, and Gravel, Stone and Cinders.....	106
		4.3.2 Clay.....	106
		4.3.3 Humate	106
5.0	CRITICAL MINERALS.....		107
6.0	REFERENCES.....		110



FIGURES

Figure 1	Regional Map
Figure 2	Physiographic Map
Figure 3	Geologic Map
Figure 3-1	Geologic Map: Legend
Figure 4	Representative Stratigraphic Sections of BLM Planning Units 1, 2, and 4
Figure 5	Stratigraphic Section of the Santa Fe Group, BLM Planning Units 2 and 5
Figure 6	Stratigraphic Section of Estancia Basin, BLM Planning Unit 3
Figure 7	Geologic Cross Section of the Albuquerque Basin
Figure 8	Tectonic Features Map
Figure 9	Index Map Locations
Figure 10	Mining Districts Within the BLM Rio Puerco Field Office Planning Units
Figure 11	Stratigraphic Section of the San Juan Basin Oil and Gas Producing Formations
Figure 12	Active Oil Wells Within BLM Planning Unit 4
Figure 13	Potential Coalbed Methane in BLM Planning Unit 4
Figure 14	Oil and Gas Exploration Wells in the Albuquerque Basin
Figure 14-1	List of Oil and Gas Exploration Wells in the Albuquerque Basin
Figure 15	Oil and Gas Exploration History of the Albuquerque Basin
Figure 16	Coal Fields Within BLM Rio Puerco Field Office Planning Units
Figure 17	Sequence of Cretaceous Coal-Bearing Sediments in BLM Planning Unit 1
Figure 18	Diagram of Coal-Bearing Rocks in New Mexico
Figure 19	Geothermal Resources in the United States
Figure 20	Volcanic Fields of New Mexico
Figure 21	Stratigraphic Section of the Laguna-Paguate Area, Valencia County, New Mexico
Figure 22	Uranium Deposits in the Grants Mineral Belt
Figure 23	Aggregate Production in BLM Planning Unit 5
Figure 24	Shakespeare and Other Gravel Pits in Albuquerque, New Mexico
Figure 25	Oil Projected Future Development
Figure 26	Natural Gas Projected Future Development
Figure 27	Coal Projected Future Development
Figure 28	Gold Production Trends
Figure 29	Silver Production Trends
Figure 30	Copper Production Trends
Figure 31	Gold, Silver, Copper, and Uranium Price Trends
Figure 32	Gypsum Production Trends
Figure 33	Limestone Production Trends
Figure 34	Pumice and Pumicite Production Trends
Figure 35	Uranium Production Trends
Figure 36	Aggregate, Scoria/Cinders, Ornamental Stone Production Trends
Figure 37	Example of Criticality Matrix



APPENDICES

Binder 1

Appendix A

Tables

Table 1 BLM Planning Unit Summary

Leasable Mineral Occurrence

Table 2 Oil Wells Index

Table 3 Natural Gas Wells Index

Table 4 Injection Wells Index

Table 5 Miscellaneous Site Released Oil and Gas Wells Index

Table 6 Coal Index

Table 7 Geothermal Wells Index

Table 8 Hot Springs Index

Table 9 Sodium Index

Table 10 Sulfur Index

Table 11 Helium Index

Table 12 Carbon Dioxide Index

Locatable Mineral Occurrence

Table 13 Precious Metals Index

Table 14 Base and Non-Precious Metals Index

Table 15 Halides and Miscellaneous Metals Index

Table 16 Gypsum Index

Table 17 Limestone and Travertine Index

Table 18 Pumice Index

Table 19 Perlite Index

Table 20 Rare Earth Elements Index

Table 21 Uranium Index

Table 22 Precious and Semiprecious Stones Index

Table 23 Miscellaneous Minerals Index

Salable Mineral Occurrence

Table 24 General Aggregate Index

Table 25 Aggregate Limestone Index

Table 26 Caliche Index

Table 27 Gravel Index

Table 28 Sand and Gravel Index

Table 29 Sand Index

Table 30 Basalt and Diorite Index

Table 31 Scoria and Cinders Index

Table 32 Clay Index

Table 33 Adobe Index

Table 34 Stone Index

Table 35 Humate Index

Table 36 References for Mineral Occurrence Tables



Binder 2

Appendix B Mineral Resource Maps

Leasable Minerals

Plate 1	Leasable Map Overview
Plate 2	Leasable Index Map 1
Plate 3	Leasable Index Map 2
Plate 4	Leasable Index Map 3
Plate 5	Leasable Index Map 4
Plate 6	Leasable Index Map 5
Plate 7	Leasable Index Map 6
Plate 8	Leasable Index Map 7
Plate 9	Leasable Index Map 8
Plate 10	Leasable Index Map 9
Plate 11	Leasable Index Map 10
Plate 12	Leasable Index Map 11
Plate 13	Leasable Index Map 12
Plate 14	Leasable Index Map 13
Plate 15	Leasable Index Map 14
Plate 16	Leasable Index Map 15
Plate 17	Leasable Index Map 16
Plate 18	Leasable Index Map 17

Locatable Minerals

Plate 19	Locatable Map Overview
Plate 20	Locatable Index Map 1
Plate 21	Locatable Index Map 2
Plate 22	Locatable Index Map 3
Plate 23	Locatable Index Map 4
Plate 24	Locatable Index Map 5
Plate 25	Locatable Index Map 6
Plate 26	Locatable Index Map 7
Plate 27	Locatable Index Map 8
Plate 28	Locatable Index Map 9
Plate 29	Locatable Index Map 10
Plate 30	Locatable Index Map 11
Plate 31	Locatable Index Map 12
Plate 32	Locatable Index Map 13
Plate 33	Locatable Index Map 14
Plate 34	Locatable Index Map 15
Plate 35	Locatable Index Map 16
Plate 36	Locatable Index Map 17

Binder 3

Salable Minerals

Plate 37	Salable Map Overview
Plate 38	Salable Index Map 1
Plate 39	Salable Index Map 2
Plate 40	Salable Index Map 3
Plate 41	Salable Index Map 4



Plate 42	Salable Index Map 5
Plate 43	Salable Index Map 6
Plate 44	Salable Index Map 7
Plate 45	Salable Index Map 8
Plate 46	Salable Index Map 9
Plate 47	Salable Index Map 10
Plate 48	Salable Index Map 11
Plate 49	Salable Index Map 12
Plate 50	Salable Index Map 13
Plate 51	Salable Index Map 14
Plate 52	Salable Index Map 15
Plate 53	Salable Index Map 16
Plate 54	Salable Index Map 17

Appendix C Point Density Mineral Potential Maps

Plate 55	Oil and Gas Potential Map
Plate 56	Coal and Humate Potential Map
Plate 57	Uranium Potential Map
Plate 58	Aggregate (Includes Sand and Gravel) Potential Map
Plate 59	Gypsum Potential Map
Plate 60	Limestone Potential Map
Plate 61	Basalt, Diorite, Cinders and Scoria Potential Map
Plate 62	Gold, Silver, and Copper Potential Map
Plate 63	Geothermal and Hot Springs Potential Map
Plate 64	Perlite and Pumice Potential Map
Plate 65	Clay Potential Map

Appendix D Generation of Point Density Mineral Resource Potential Maps



ACRONYMS AND ABBREVIATIONS

API	American Petroleum Institute
BCE	Before Common Era
BLM	United States Department of the Interior, Bureau of Land Management
BTU	British Thermal Units (heating value)
°	degrees
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
Field Office	Rio Puerco Field Office
GIS	Geographic information system
GRI	Gas Resources Institute
INTERA	INTERA, Incorporated
KGRA	known geothermal resource area
KGRF	known geothermal resource field
lb	pound
MMD	New Mexico Mining and Minerals Division
MRP	mineral resource potential
NMBGMR	New Mexico Bureau of Geology and Mineral Resources
NMEMNRD	New Mexico Energy, Minerals, and Natural Resources Department
NMOGA	New Mexico Oil and Gas Association
NMSHD	New Mexico State Highway Department
NURE	National Uranium Resource Evaluation
OCD	New Mexico Oil Conservation Division



ACRONYMS AND ABBREVIATIONS (CONCLUDED)

REE	rare earth elements
RFD	reasonably foreseeable development
RMP	Resource Management Plan
SOW	Statement of Work
Tscf	trillion standard cubic feet
U ₃ O ₈	uranium oxide
U.S.	United States of America
USGS	U.S. Geological Survey



SUMMARY AND CONCLUSIONS

Summary

This report presents the findings of an assessment of the mineral resource potential and reasonably foreseeable developments (RFD) for Rio Puerco Field Office Planning Units 1 through 5 for the United States (U.S.) Department of the Interior Bureau of Land Management (BLM), Rio Puerco Field Office, New Mexico. This project is based on a Statement of Work prepared by BLM (BLM, 2009) and was conducted by INTERA, Incorporated (INTERA) under GSA Contract No. GS-10F-0259P, Delivery Order L09PDO1833. The purpose of the report, according to the Statement of Work (SOW), is to “assess the mineral resource occurrence and development potential of the area defined for the Resource Management Plan.”

The information contained in this report is based on data gathered by INTERA from BLM, the New Mexico Bureau of Geology and Mineral Resources, the U.S. Geological Survey, other agencies and entities, and from interviews with key members of the geological and mineral resource communities in New Mexico. This report is intended to be an effective planning tool for the Field Office for use in the Rio Puerco Resource Management Plan (RMP) revision currently underway by BLM. This RMP is expected to be completed in 2011 and implemented in 2012.

The commodities of interest are divided into three categories as follows:

- **Leasable Minerals:** Federal leasable minerals are fluid or solid minerals that can be developed after obtaining a lease from BLM. Leasable fluid minerals include oil, gas, coalbed methane, geothermal, carbon dioxide and helium, oil shale, native asphalt, and oil-impregnated sands. Leasable solid minerals include coal, potash, phosphate, sulfur, and sodium. Of these, potash and phosphate are not found in the study area and are thus not addressed in this report.
- **Locatable Minerals:** Federal locatable minerals consist of metallic and non-metallic minerals. The metallic minerals include gold, silver, nickel, copper, lead, zinc, iron, uranium, vanadium, molybdenum, manganese, cobalt, beryllium, and tungsten. The non-metallic minerals include zeolites, silica, perlite, mica, block pumice, limestone of chemical or metallurgical grade, gypsum, barite, fluorspar, and gem minerals.
- **Salable Minerals:** Salable minerals include common variety of sand, stone, gravel, pumice, pumicite, basalt, clay, rock and petrified wood. Travertine is listed in this report as salable, although it is also considered to be locatable under some circumstances, because it is used as a form of decorative stone rather than as a chemical or “special” variety of limestone.

The five BLM planning units cross parts of the four major physiographic provinces shown: the Colorado Plateau, Southern Rocky Mountains, Basin and Range, and Great or High Plains provinces. Rock units in the five BLM planning units range in age from Precambrian to Recent and run the gamut from metamorphic greenstones, to granite intrusives, to Paleozoic and Mesozoic sedimentary formations, to Tertiary volcanics and rift basin sediments. The surface geology is described based on the mapped rock



units that lie within the five BLM planning units, while the subsurface geology is described in terms of stratigraphic sections that represent the rocks within the five planning units. In addition, distinctive tectonic features which fall within the planning units, such as the Zuni Mountains, the Jemez Caldera, the Sandia Mountains, the Estancia Basin, and others, are described to provide the reader with an introduction to the structure and tectonics within the study area.

This report consists of text, figures, tables and mineral resource maps. The text describes each commodity in terms of geologic setting, exploration, development, and production history, and their mineral occurrence potential, according to the guidance in BLM Manual 3031 (BLM, 1985). Tables which provide additional information on each commodity are presented in Appendix A and the table entries are tied to mineral resource maps. The mineral resource maps (Index Maps) are divided into leasable, locatable, and salable categories and are in Appendix B, in a separate binder. These maps show uniquely identified point locations which represent a particular mineral commodity. In addition, point density mineral resource potential maps (Appendix C, separate binder) are provided which define areas of low, moderate, and high mineral potential, according to a mineral commodity point-density method developed by INTERA in collaboration with BLM. A detailed discussion of the method used to create these point density mineral potential maps is presented in Appendix D.

The remainder of this Summary and Conclusion section provides a condensed discussion of the potential of the leasable, locatable, and saleable commodities. The levels of resource potential used in this report are high (H), moderate (M), and low (L). The levels of certainty used are D (abundant direct and indirect evidence of certainty), C (direct evidence of certainty), and B (indirect evidence of certainty). Please refer to Section 3 of the main body of this report for a more detailed explanation of the letters assigned for high, moderate, or low potential and the associated level of certainty. The potential assigned is the highest potential interpreted for a given commodity in a given area, and if the level is high, the potential also includes moderate and low on the margin of the high potential area. Likewise, if the highest potential is moderate, that potential is surrounded by low potential.

The following table presents the level of mineral potential and evidence of certainty for the commodities addressed in this report.

Summary of Mineral Potential and Level of Certainty

Commodity	Location	Potential	Certainty
Oil and Gas	San Juan Basin	H	D
	Albuquerque Basin	L	C
	Estancia Basin	L	C
Coal	Star Lake Coal Field	H	C
	La Ventana Coal Field	H	D
	Chacra Mesa Coal Field	H	C
	San Mateo Coal Field	H	C
	Mount Taylor Coal Field	L	B



Commodity	Location	Potential	Certainty
Coal	Crownpoint Coal Field	M	C
	Rio Puerco Coal Field	L-M	C
	Gallup Coal Field	H	C
	Zuni Coal Field	H	C
	Salt Lake Coal Field	H	C
	Datil Mountain Coal Field	M	C
	Hagan (Una del Gato) Coal Field	M	D
	Placitas Coal Field	M	D
	Tijeras Coal Field	M	D
Geothermal	Jemez Region/Valles Caldera/San Ysidro	H	D
	Albuquerque Basin	H	C
	San Juan Basin	L	C
Sodium and Halite	Laguna Salina and Laguna del Perro	H	C
Sulfur	Jemez Mountains	H	C
Helium	Nacimiento Mountains	M	C
	Near Mesita	M	C
Carbon Dioxide	North and South Estancia Fields	H	D
	Near Mesita	M	C
	Nacimiento Mountains	M	C
	Near Acoma Pueblo	M	C
	Jemez Springs region	M	C
Precious Metals	Cochiti District	H	D
	Placitas District	M	C
	Tijeras Canyon District	H	D
	Nacimiento District	M	C
	Coyote Canyon District	M	C
Base Metals	Cochiti District	H	D
	Placitas District	M	C
	Tijeras Canyon District	H	D
	Coyote Canyon District	M	C
	Scholle District	M	C
	Zuni Mountains District	M	C
Fluorspar	Zuni Mountains District	H	C
	Rio Grande Rift	L	C
Gypsum	White Mesa region	H	D
	North of Placitas	H	C
Gypsum	Nacimiento Mountains	M	C
	Tijeras Canyon	M	C



Commodity	Location	Potential	Certainty
Limestone	Tijeras Canyon	H	D
	Sandia Mountains	M	D
	Eastern Cibola/Western Valencia County	H	D
Pumice	Jemez Mountains	H	D
Perlite	Peralta Canyon (Jemez Mountains)	H	C
	Northwest of Grants	H	C
Rare Earth Elements	Throughout the study area	M	C
Uranium	Grants Mineral Belt	H	D
	Ojito Springs and La Ventana areas	H	C
	Hagen Basin area	M	C
	Scholle District	H	C
Semiprecious Stones	Throughout the study area	M	C
Miscellaneous Minerals	Throughout the study area	M	C
Lithium	Sandia Mountains	L	C
	Laguna Salina and Laguna del Perro	L	B
Aggregate	BLM Planning Unit 2	H	D
	BLM Planning Unit 5	H	D
	Throughout the study area	M-L	C
Basalt, Diorite, Cinders, Scoria	The Los Lunas Volcano northwest to I-40	H-M	C
	Southeast end of the Zuni Mountains	H	C
	Lava fields south of Mt. Taylor	H	C
Clay	Placitas region	H	D
	Eastern Sandia Mountains	M	C
	Manzanita Mountains	H	C
Dimension and Decorative Stone	Sandia Mountains	H	C
	Manzano Mountains	H	C
Travertine	Lucero Mesa	H	D
	Near San Ysidro	H	B
Humate	La Ventana Coal Field	H	D
	Rio Puerco Coal Field	M	C

This section of the summary presents more detail on the mineral potential and level of certainty for the commodities in the table above.



Oil and Gas Potential

San Juan Basin

The oil and gas occurrence potential in this area is high with abundant direct and indirect evidence to support the existence of the resource (H,D). This judgment is based on the abundant oil and gas currently being produced from the San Juan Basin in general, and also specifically from the portion of the basin which lies within BLM Planning Unit 4. The point density mineral potential map (Plate 55) reflects this assessment, showing a high resource potential in the South San Luis oil field. A region of moderate potential extends north through the San Luis oil field to just north of Cuba. Low potential extends across the entire northwestern half of Unit 4 from San Ysidro westward.

Albuquerque Basin

The oil and gas potential in the Albuquerque basin is judged to be low, with a direct evidence level of certainty (L,C). Exploratory drilling to date has encountered oil and gas shows, but no commercial production, according to available data. The sporadic nature of exploration in this region is reflected on the point density mineral potential map (Plate 55), which indicates low resource potential along the western edge of the basin.

Estancia Basin

Oil and gas potential in the Estancia Basin is judged to be low, with a direct evidence level of certainty (L,C). Numerous oil and gas shows have been reported from exploratory wells, but there has been no commercial production. The relative lack of exploration and development in the basin has resulted in a low point density from Mountainair north to Moriarty (Plate 55).

Coal Potential

Star Lake Coal Field

McLemore et al. (1984a) noted a high resource potential in this coal field based on outcrops, drill hole data, and continued interest; however, they also state that development potential will depend on the availability of railroads. INTERA has determined that the resource potential for the Star Lake field is high with direct certainty (H,C) even though the point density mineral potential map indicates low resource potential (Plate 56). This is because the databases used to generate the potential maps only cover mines and occurrences located within the BLM planning units, and therefore point density resource potential estimations for coal fields extending outside the study area will be artificially low. Thus the point density map for the Star Lake field (the majority of which is west of Unit 4) is not as reliable as it is for the La Ventana or Tijeras fields (both contained entirely within the BLM study area).

La Ventana Coal Field

McLemore et al. (1984a) assigned this field high mineral resource potential, and INTERA concurs that this field has high potential with abundant direct and indirect evidence of certainty (H,D). The point density mineral potential map also indicates that this field has high resource potential, with a cluster of



coal mines and occurrences south of Cuba (Plate 56). Lack of transportation has historically limited production at this coal field, although much of the area is conducive to strip mining.

Chacra Mesa Coal Field

The resource potential is high with direct evidence of certainty (H,C) (McLemore et al., 1984a) but resource potential as indicated by point density is low because most of the field lies outside the study area to the west.

San Mateo Coal Field

Although no mining activity has occurred within the portion of the field contained in the study area, active mining to the north and a favorable geologic environment (McLemore et al., 1984a) indicates high resource potential with direct evidence of certainty (H,C).

Mount Taylor Coal Field

The lenticular nature and thinness of the coal beds in the Mount Taylor field led McLemore (1984b) to assign it moderate to low resource potential, and thus INTERA has assigned it a low potential with indirect evidence of certainty (L,B). State databases consulted for this study did not report any occurrences or developments of coal in this field, and thus the resource potential indicated by point density does not apply.

Crownpoint Coal Field

The resource potential for this field is judged to be moderate with direct evidence of certainty (M,C) (Kirchbaum and Biewick, 2000). Resource potential based on point density is negligible because most of the Crownpoint Field is located to the north of the study area.

Rio Puerco Coal Field

Based on McLemore et al., 1984's assessment and point density measurements, INTERA rates the resource potential to be low to moderate with direct evidence of certainty (L,C to M,C). The point density resource potential map (Plate 56) assigns the southern portion of the Rio Puerco Field a low resource potential. However, point density resource potential is moderate to the southeast of San Ysidro, where several humate mines and coal occurrences are known to exist (McLemore et al., 1984a).

Gallup Coal Field

The resource potential for the Gallup field is rated as high with direct evidence of certainty (H,C) based on the presence of the geologic environment and geologic processes conducive to the presence of coal. Point density resource potential is low because most of the field lies to the north of the study area.



Zuni Coal Field

The resource potential of the Zuni field is rated as high with direct evidence of certainty (H,C) based on the presence of the geologic environment and geologic processes conducive to the presence of coal. The point density potential does not apply in this case because the state databases queried for this report do not provide comprehensive coverage of Indian reservations.

Salt Lake Coal Field

The resource potential of this field is high with direct evidence of certainty (H,C) based on the presence of the geologic environment and geologic processes conducive to the presence of coal. Point density resource potential is nonexistent because the field is on the southern edge of Planning Unit 1.

Datil Mountain Coal Field

The resource potential is judged to be moderate with direct certainty (M,C) based on the presence of the geologic environment and geologic processes conducive to the presence of coal. No mines are located in the study area, thus the point density resource potential is nil (Frost et al., 1979; Kirschbaum and Biewick, 2000).

Hagan (Una del Gato) Coal Field

McLemore et al. (1984a) determined that resource potential was moderate to low and the development potential was low. INTERA concurs that the resource potential is moderate with abundant direct evidence for the presence of coal (M,D). The point density map (Plate 56) indicates moderate resource potential due to the presence of several points of occurrence.

Placitas Coal Field

McLemore et al. (1984a) considered the resource potential of the Placitas field to be moderate to low and the development potential to be low because of the steeply dipping nature of the coal seams, which make it hard to access the coal. INTERA's assessment of current resource potential remains the same as that of McLemore et al. (1984a), moderate, with abundant direct and indirect evidence for the level of certainty (M,D). The point density mineral potential map (Plate 56) agrees with this assessment.

Tijeras Coal Field

McLemore et al. (1984a) determined that the Tijeras field had low resource and development potential because of the thinness of the coal beds and the impracticality of strip mining on the two synclines. However, INTERA's assessment of current resource potential is moderate with abundant direct and indirect evidence of certainty (M,D) based on the point density mineral potential map (Plate 56).



Geothermal

Jemez Mountains

INTERA judges the resource potential in these areas to be high with abundant evidence for the presence of the resource (H,D). The resource potential based on point density is low on the Pajarito Plateau and near San Ysidro (Plate 63), but this may reflect the cost of geothermal exploration rather than the lack of proven resources. Development potential is unlikely to be as high as was originally declared in these areas due to changes in economic conditions since the mid-1980s.

Albuquerque Basin

Geothermal energy is present at depth within the Albuquerque area, thus the potential for occurrence is judged by INTERA to be high, with direct evidence of certainty (H,C). However, the development potential fluctuates markedly with the price of more conventional, lower cost energy sources.

San Juan Basin

Although wells in the southern San Juan Basin have occasional elevated temperatures, the depth of these resources and the lack of nearby population centers keeps resource and development potential low. INTERA judges the resource potential to be low with direct evidence of certainty (L,C) and the sparse distribution of geothermal wells supports this assertion (Plate 63).

Sodium and Halite

The resource potential for sodium and halite at Laguna Salina and Laguna del Perro is high with direct evidence of certainty (H,C) due to a favorable geologic environment and past production. Based on the pattern of use at these lakes and the lack of current development, it is probably safe to say that halite mining interest here is purely historical. Furthermore, no sodium prospecting or development has occurred since the early 1900s. No other sodium or halite deposits are known in the study area.

Sulfur

Sulfur resource potential in the Sulfur Springs and San Diego areas are considered high with direct evidence of certainty due to a history of past production (H,C). However, the Jemez deposits will likely never be more than historical interest due to their small size and lack of recent production. Thus INTERA has determined that development potential is low for this commodity.

Helium

Helium is present in economical quantities in the Nacimiento Mountains and in a water well near the town of Mesita. These regions therefore have a moderate resource potential with direct evidence of certainty (M,C) for helium. Development potential is currently moderate due to ongoing helium production elsewhere in the state. However, if helium prices continue to rise and the other helium reservoirs become depleted, development potential can be expected to increase.



Carbon Dioxide

The resource potential for carbon dioxide in the Northern Estancia Field and the Southern Estancia Field is high with abundant direct and indirect evidence of certainty (H,D) due to the history of past production from the two fields. Demand for the gas is rising, and this may provide an incentive for renewed exploration and extraction in the area. Thus, development potential for the Northern Estancia Field and the Southern Estancia Field is also high. Other carbon dioxide occurrences are reported in the Nacimiento Mountains, in the Jemez Springs region, near the town of Mesita, and near Acoma Pueblo. These areas are assigned moderate potential with direct evidence of certainty (M,C) due to carbon dioxide measured in wells and springs.

Locatable Minerals

Precious Metals

The potential for the occurrence of gold and silver resources ranges from high to low with abundant direct to direct evidence for the level of certainty (H,D to H,C) in the study area due to the presence of numerous identified occurrences and prospects. The point density map (Plate 62) identifies the Cochiti and Tijeras Canyon districts as having high resource potential with abundant direct evidence of certainty due to the number of mines and prospects in these areas (H,D). The Placitas district shows moderate potential on the point density mineral potential map with direct evidence for the level of certainty (M,C). The Nacimiento and Coyote Canyon districts both have moderate potential based on point density with direct evidence for the level of certainty (M,C). The levels of certainty are based on the presence of significant past production (abundant direct evidence) or minor past production or only occurrences (direct evidence). However, the commercial development potential is judged to be low in all areas within the BLM planning units due to the apparently small size of the deposits, access difficulties, and environmental regulations governing extraction and reclamation.

Base Metals

The potential for the occurrence of base metal resources ranges from high to low, with the highest potentials in the identified metal mining districts (as shown on Figure 10). The point density map (Plate 62) identifies the Cochiti and Tijeras Canyon districts in particular as having high resource potential with abundant direct evidence of certainty (H,D). The Coyote Canyon, Placitas, and Scholle districts have moderate potential with direct evidence of certainty (M,C). The Zuni Mountains district has moderate potential for base metals based on the point density map with direct evidence of certainty (M,C). The development potential is judged to be low for all of these districts based on the low tonnage and grade of these deposits as well as access and environmental factors. The Zuni Mountains district has a high mineral potential for fluorspar with direct evidence of certainty (H,C) based on significant past production. Fluorspar potential in the Rio Grande Rift is judged to be low with direct evidence of certainty (L,C) due to the small, scattered nature of the deposits. Fluorspar development potential in the Zuni Mountains and the Rio Grande Rift is currently low. However, development could occur if uranium mining and milling were to resume in the Grants Mineral Belt, as fluorspar is used to make fluoric acid, an ingredient in the uranium milling process.



Gypsum

The potential for gypsum occurrence is high with abundant direct and indirect evidence of certainty (H,D) within BLM Planning Unit 4, in and around the operating White Mesa gypsum mine. Another area with high resource potential and direct evidence of certainty as indicated by point density (Plate 59) lies about five miles north of the town of Placitas (H,C). The point density map (Plate 59) also indicates moderate potential with direct evidence of certainty along the Nacimiento Mountains south of Cuba and in Tijeras Canyon (M,C). Development potential is high for the White Mesa Mine, but unlikely elsewhere due to the extent of the reserves at the White Mesa Mine. The White Mesa mine adequately meets the demand for wall board and other gypsum products within central New Mexico and southern Colorado.

Limestone

The limestone potential in Planning Units 2 and 5 (Tijeras Canyon area) is high with abundant direct and indirect evidence of certainty (H,D) due to the presence of the Tijeras limestone quarry and cement plant. The point density mineral potential map (Plate 60) also indicates that Tijeras Canyon has high resource potential for limestone based on current and past production in the area. The Sandia Mountains also have moderate potential as determined by point density, with abundant direct evidence of certainty (M,D). Travertine deposits (a variety of limestone) near the San Ysidro Anticline are shown as having high potential on the point density mineral potential map. These deposits are shown as having high potential because travertine is included with limestone in the databases queried for this study. However, these deposits are not similar to the Tijeras limestone deposits and are not likely to be developed as limestone for cement production. Scattered areas of moderate potential also exist in eastern Cibola and western Valencia Counties but these are also travertine deposits. These deposits are actually commercial and therefore may be classified as high resource potential with abundant direct evidence for certainty (H,D) even though the point density mineral potential map shows only moderate potential. Additional information on travertine is presented in this report under Dimension Stone, Decorative Stone, and Travertine.

Pumice

Because of the current abundant deposits and ongoing commercial operations INTERA judges the resource potential of pumice in Planning Unit 4 (in the Jemez Mountains area) to be high with abundant direct and indirect evidence of certainty (H, D). The point density map (Plate 64) agrees with this assessment.

Perlite

Perlite does not occur in the Jemez Mountains in sufficient quantity or purity to support a commercial operation. In addition, larger active operations in Taos, Cibola, and Socorro counties produce perlite of good quality and supply much of the domestic market for perlite, which makes development of new perlite mining operations difficult. Still, resource potential for perlite is judged to be high with direct certainty (H,C) in Peralta Canyon in the Jemez Mountains (Plate 64) due to notable occurrences and some small production. A concentration of perlite northwest of Grants has also been assigned high resource potential with direct evidence of certainty due to numerous map points in the area (H,C). Future development within



the five BLM planning units is expected to be minimal, due to the presence of more extensive, commercial-grade deposits elsewhere in the state.

Rare Earth Elements

The resource potential for rare earth elements (REE) is judged to be moderate with direct evidence of certainty (M,C) due to the presence of the requisite geologic environments and identified prospects. REE as critical minerals are discussed in more detail in Section 5 of this report.

Uranium

The uranium resource potential is judged to be high with abundant direct and indirect evidence of certainty (H, D) due to the presence of the necessary geologic environment and geologic processes for the formation of uranium deposits in the Grants Mineral Belt. This is supported by the point density mineral potential map for uranium (Plate 57), although much of the Grants Mineral Belt lies just to the north of the BLM Planning Unit 1 and there is not as high of a point density shown on the map as there would be if that area (primarily the Ambrosia Lake uranium district) were included in BLM Planning Unit 1. High potential with direct evidence of certainty (H,C) is also shown for the area that extends from south of Laguna in Unit 2 north to Cuba in Unit 4 (through the Ojito Springs and La Ventana areas). The Hagen Basin area is judged to have moderate potential with direct evidence of certainty (M, C) based on the presence of the Diamond Tail deposit, but no production. Another area of high resource potential with direct evidence of certainty (H,C) is the Scholle district near Mountainair. The development potential is judged to be moderate due to the large price fluctuations and uncertainties associated with uranium production in the U.S.

Semiprecious Stones and Miscellaneous Minerals

Examples of these commodities are mica, graphite, talc, opals, moonstone, topaz, garnets, tourmaline, and quartz. The semiprecious stones and minerals and miscellaneous minerals resource potential is judged to be moderate with direct evidence of certainty (M,C) throughout the study area due to the known occurrences but relatively small and non-commercial scale of production.

Lithium

The presence of lithium in a mine in the Sandia Mountains implies a low resource potential with direct evidence of certainty (L,C) for the entire mountain range. However, due to large brine operations domestically and abroad, it is very unlikely that lithium will be mined in this region. Thus, INTERA assigns a low development potential in the Sandia Mountains. Anomalous lithium in water samples taken near playa lakes in Torrance County may be from up to three sources, only one of which could represent an economically viable deposit. Thus, INTERA assigns a low resource potential with indirect evidence of certainty for lithium in the Estancia Basin (L,B). INTERA has determined that development potential in Torrance County will remain low unless high future prices encourage exploration in the region.



Salable Minerals

Aggregate, Sand, and Gravel

The resource potential for aggregate is judged to be high with abundant direct and indirect evidence of certainty (H,D) due to the extensive, ongoing commercial aggregate production, especially in BLM Planning Units 2 and 5. The point density mineral potential map (Plate 58) shows a 60 mile band of low to high resource potential along the Rio Grande Valley from Los Lunas to Cochiti Dam. The area from just south of Albuquerque to San Felipe Wash is a continuous swath of high resource potential for 40 miles along Interstate 25. Another region of moderate to high resource potential extends from Isleta eastward through Tijeras Canyon, a total distance of 30 miles. In addition, isolated point occurrences shown on the point density mineral potential map (Plate 58) indicate broad regions of low to moderate potential across much of the BLM study area.

Basalt, Diorite, and Scoria

Three major areas of high to moderate resource potential with direct evidence of certainty (H-M, C) extend in a line from the Los Lunas Volcano to a basalt quarry just east of the Interstate 40 bridge over the Rio Puerco (Plate 61). Other patches of high resource potential and direct evidence of certainty (H,C) occur at the southeastern end of the Zuni Mountains and in the lava fields south of Mount Taylor. Development of these resources is expected to continue to the extent that these materials are needed for construction and landscaping as a reflection of general economic conditions.

Clay and Adobe

The clay point density mineral potential map (Plate 65) shows an area of high potential to the northwest of Placitas and another small region of high potential on the east flank of the Sandia Mountains. The large gravel pits in the Placitas area do in fact report clay as one of their commodities, giving the region high potential with abundant direct and indirect evidence for clay occurrences (H,D). However, the points on the east slope of the Sandias represent clay sampling sites and not actual developments, thus INTERA assigns moderate potential with direct evidence of certainty (M,C) to this area. One of the two map points in the Manzanita Mountains is a clay quarry with a history of production, giving these mountains a designation of high potential with direct evidence of certainty (H,C) though the mineral potential point density map shows only moderate potential. In general, little development seems to have occurred in the Rio Puerco Field Office planning area since McLemore et al.'s 1984 report. Development potential appears to be limited due to moderate demand and the scattered locations of the clay deposits. Adobe production takes place in scattered locations throughout New Mexico and it is difficult to quantify the amount of production or the future potential. Adobe is a subset of clay in this report but it is not a regulated commodity and is thus not evaluated specifically for mineral potential.

Dimension Stone, Decorative Stone, and Travertine

The Sandia and Manzano Mountains contain potentially high-quality granites and gneisses so the resource potential is judged to be high, with direct evidence of certainty (H,C). But the presence of wilderness areas,



overburden, and lack of processing facilities make development impractical. Commercial development of other stone resources in the Rio Puerco planning area is unlikely due to the lack of processing facilities and low material prices.

The travertine resource potential is judged to be high with abundant direct and indirect certainty (H,D) in the Mesa Lucero and high with indirect certainty (H,B) for the other travertine deposits near San Ysidro. The future development potential is likely to reflect the general economic trends within the housing industry, which fluctuates periodically. Only the Lucero quarry is likely to continue producing, as opposed to new quarries starting elsewhere. Note that travertine is included here under salable minerals because it is utilized as a building stone and not a chemical grade limestone.

Humate

The humate resource potential is high with abundant direct and indirect evidence of certainty (H,D) in the La Ventana Coal Field and moderate with direct evidence of certainty (M,C) in the Rio Puerco Coal Field. The development potential is expected to increase as the product becomes better known within the agricultural community.

Reasonably Foreseeable Development

Reasonably foreseeable development (RFD) is the development potential for a mineral commodity. RFD for most of the commodities is provided in Section 4 of this report. Some commodities are excluded from the discussion due to a lack of production history and the judgment that future development for those commodities will be negligible. The RFD is for the next 20 years and is based on past production data, economic conditions, projected future economic conditions, projected future demand, and on the preparer's judgment. The commodities that are expected to continue to be produced from New Mexico are oil and gas, coal, and aggregate. Within the five BLM planning units, only oil and gas and aggregate have strong foreseeable futures. Coal mining is expected to remain steady but takes place in several locations just outside the planning unit boundaries. Oil development is projected to increase and then to flatten out over the 20 year period, as determined by the U.S. Department of Energy. Natural gas development is expected to increase over that period and there are interesting new sources (shale gas) elsewhere in the nation and also improved drilling techniques which could spur additional development. Aggregate mining is expected to remain steady from the major commercial operations north of Placitas and this production is anticipated to track national economic trends in housing and construction. Uranium development potential is only moderate in spite of the recent activity in the Grants Mineral Belt. This is due to the large fluctuation in price (currently down from record highs only two years ago) and the uncertainties associated with domestic uranium production.

Critical Minerals

Critical minerals are those minerals that are necessary to the provision of food, shelter, infrastructure, transportation, communications, health care, and defense. BLM Manual 3031 suggests that the mineral



potential report include a brief section on strategic and critical minerals, although this is not specifically required in the SOW for this project.

The criticality of the following minerals has been investigated by the National Academies: copper, gallium, indium, lithium, manganese, niobium, platinum group metals, REE, tantalum, titanium, and vanadium. Of these, platinum group metals, rare earth elements (REE), indium, manganese, and niobium were determined to be most critical. Their uses and applications, the difficulty in finding appropriate mineral substitutes for these applications, and the risk to their supply for any number of reasons were high enough to place these minerals in or near the critical zone of the criticality matrix (Figure 37).

Within the Rio Puerco Field Office planning units, copper and REE are present as occurrences or known deposits. As discussed in the section on base metals, copper is mined in large volume elsewhere in New Mexico, so it is not considered to have high development potential within the planning units. Although REE lack an actual production history in the planning units, these elements are reported to be present in multiple locations. REE are used in emission controls, magnets, electronics (notably cell phones) and there are few if any ready substitutes. Further, the supply of REE is potentially at risk because the U.S. is dependent on foreign suppliers and 76 percent of that supply is from China (National Academies, 2007).

Some exploration for REE has taken place in the planning units and additional exploration and potentially production could take place if the world supply were to be reduced or cut off.

Conclusion

This report and the associated figures, tables and maps provide a source of information that may be used by BLM planners to more effectively manage these mineral resources within the five BLM planning units. The BLM Rio Puerco Field Office planning area covers a large proportion of the state and contains an abundant supply of leasable, locatable, and salable minerals. The planning area has a rich mining and production history for coal, oil, natural gas, metals, uranium, aggregate, and other commodities. The San Juan Basin contains abundant oil, natural gas, and coal resources and BLM Planning Unit 4 covers a portion of this basin. BLM Planning Units 1 and 2 overlie portions of the Grants Mineral Belt and this area is second in the nation in past uranium production. Production could resume there under the right economic conditions. Planning Unit 5 encompasses some of the largest aggregate deposits in the state and the producing pits there face increasing pressure from nearby urbanization. Travertine quarries in Planning Unit 2 provide a product that is popular in New Mexico but that is also sold nation-wide. Critical rare earth elements and lithium are also potentially present within the BLM planning units and could become more important to the state and BLM managers within the foreseeable future.



SECTION 1.0 TABLE OF CONTENTS

1.0	INTRODUCTION.....	2
1.1	Purpose of the Report.....	2
1.2	Lands Involved and Data Sources.....	2
1.2.1	Lands Involved.....	2
1.2.2	Data Sources.....	3
1.2.2.1	Sources for Leasable Mineral Data.....	4
1.2.2.2	Sources for Locatable and Salable Mineral Data.....	4
1.3	Organization of this Report.....	5
1.4	Definitions of Leasable, Locatable, and Salable Minerals.....	6
1.4.1	Leasable Minerals.....	6
1.4.2	Locatable Minerals.....	7
1.4.3	Salable Minerals.....	7



1.0 INTRODUCTION

This report presents the findings of an assessment of the mineral resource potential (MRP) and reasonably foreseeable development (RFD) for Rio Puerco Field Office Planning Units 1 through 5 for the United States (U.S.) Department of the Interior Bureau of Land Management (BLM), Rio Puerco Field Office, New Mexico. This project is based on a Statement of Work (SOW) prepared by BLM (BLM, 2009) and was conducted by INTERA, Incorporated (INTERA) under Contract No. L09PDO1833. This effort is part of the Rio Puerco Field Office Resource Management Plan (RMP) revision currently being conducted by the Field Office. This RMP is anticipated to be completed in 2011 and implemented in 2012. The report is prepared as a “preliminary mineral assessment for use in the preparation of the Environmental Impact Statement as required by the National Environmental Policy Act for amending the existing Land Use Plans and the development of a new RMP for the Rio Puerco Field Office.” (BLM, 2009)

1.1 PURPOSE OF THE REPORT

The purpose of the report, according to the SOW, is to “assess the mineral resource occurrence and development potential of the area defined for the Resource Management Plan.” The Planning and Decision Area for the Rio Puerco RMP is defined in the Preparation Plan dated March 2008. This assessment includes an evaluation of leasable, locatable, and salable minerals. Mineral potential is evaluated based on the definitions provided in BLM Manual 3031 (BLM, 1985), and RFD is based on available market data and the professional opinion of the report preparer.

The BLM states: “The assessment involves reviewing published data and selecting pertinent data for use in the assessment.” (BLM, 2009). The content of the MRP report is governed by BLM Manual 3031 (BLM, 1985). According to Manual 3031, “the Bureau shall maintain a mineral assessment program to ensure the availability and consideration of mineral resources data in all public land management activities that may be affected by mineral resource exploration and development, or that may lead to limitations on the availability or use of the public lands for the exploration and development of mineral resources. Mineral resource assessments will be based to the maximum extent possible on evaluation of existing data.”

The quality standard for this report, as defined in the SOW, provides an intermediate level of detail for mineral assessment as prescribed in BLM Manual 3031 for planning documents and does not include field studies.

1.2 LANDS INVOLVED AND DATA SOURCES

1.2.1 Lands Involved

The study area comprises Rio Puerco Field Office Planning Units 1 through 5, located in northwestern New Mexico (Figure 1). All or parts of the following counties are present within the five planning units: Unit 1—most of Cibola County and a portion of McKinley County; Unit 2—a portion of eastern Cibola County, a portion of Bernalillo County, and Valencia County; Unit 3—Torrance County; Unit 4—



parts of Sandoval, Bernalillo, and McKinley Counties; Unit 5—portions of Sandoval and Bernalillo Counties.

Table 1 (Appendix A) presents a summary of the geographic, physiographic, and most significant mineral potential for the five planning units.

The units involve multiple land owners including BLM, Tribal, U.S. Forest Service, U.S. National Park Service, other federal agencies, state, and private land (see Table 1 for a description of BLM surface management in the study area). The mineral potential assessment is not limited to only the BLM land within the boundaries, but covers all lands within the units.

1.2.2 Data Sources

As stated in the SOW, the information contained in this report is based on data gathered by BLM, the New Mexico Bureau of Geology and Mineral Resources (NMBGMR), the U.S. Geological Survey (USGS), and other agencies and entities. The NMBGMR Open-File Reports that were prepared during the mid-1980s by Virginia McLemore et al., (McLemore et al., 1984a; McLemore et al., 1986a–1986f) were used as a basis for this report, and INTERA has made every effort to include all of the tabulated and mapped mineral resource data provided in those reports in the geographic information system (GIS) maps included in this document. In addition, Dr. Maureen Wilks, NMBGMR geologist and head librarian, provided access to the most recent NMBGMR minerals database (McLemore and Wilks, 2009). INTERA also met with Dr. Virginia McLemore to obtain the most recent updates to the mineral resource databases available from the NMBGMR for each of the mineral commodity groups. Ron Broadhead, petroleum geologist with NMBGMR, was consulted regarding oil and gas resources, particularly in the Estancia Basin and wildcat areas west of Los Lunas. Gretchen Hoffman, NMBGMR coal geologist, was consulted regarding coal resources within the planning areas. Sean Connell, NMBGMR geologist and Bureau Albuquerque Office Manager, was consulted regarding geology and mineral resources within the Albuquerque basin, primarily in Planning Unit 2.

BLM provided base maps for all of the planning units in GIS format. In addition, the BLM Rio Puerco Field Office GIS department and the BLM New Mexico State Office provided GIS-based access to the Land Rehost 2000 website so that, if needed, information presented there could be applied as a GIS layer to the maps prepared for this report.

INTERA consulted additional resources as follows:

- New Mexico Mining and Minerals Division (MMD), Mr. John Pfeil
- New Mexico Oil Conservation Division (OCD)
- USGS
 - Minerals Yearbook 2005 Area Reports: Domestic 2005 (USGS, 2009a)
 - Minerals Yearbook Metals and Minerals 2006, Volume 1 (USGS, 2009b)

- Society for Mining, Metallurgy, and Exploration, Inc.
 - Industrial Rocks and Minerals, Commodities, Markets, and Uses, 7th Edition (Kogel et al., 2006)
- Other sources
 - Uranium industry leader (confidential source) – uranium
 - Mr. Bruce Reid of Mesa Verde Resources, Inc. – humate
 - Mr. Jim Lardner of New Mexico Travertine, Inc. -travertine
 - Mr. Bob Gallagher, New Mexico Oil and Gas Association (NMOGA) – oil and gas

Also, several electronic databases were used in the compilation of this report; these include the ONGARD database (Petroleum Recovery Research Center, 2009), the OCD online well database (OCD, accessed 2009), the NMBGMR New Mexico Mines (minerals) database (Lucas-Kamat, 2009a) and the New Mexico Mines database (McLemore and Wilks, 2009).

1.2.2.1 Sources for Leasable Mineral Data

Oil and gas data were provided by the Petroleum Recovery Research Center ONGARD database and the OCD online well database. Although both databases have comprehensive coverage of oil and gas wells throughout New Mexico, there were some instances where one database contained data not included by the other. Thus both databases were combined and all repeat data were removed, giving a final data set that was more complete than either of its sources. Repeat well records were found by comparing the American Petroleum Institute (API) number of each well in the online well database with the API number of each well in the ONGARD database.

Coal data were collected from McLemore et al. (1984a), the BLM mine registry database, the NMBGMR New Mexico Mines database, and the New Mexico Energy, Minerals and Natural Resources Department (NMEMNRD) MMD online coal mines query (MMD, accessed 2009). This information was compiled and analyzed for duplicate records as described for the oil and gas data above.

Geothermal well and exploration data was collected from McLemore et al. (1984a) and the Western Geothermal Areas database maintained by the Southern Methodist University Geothermal Laboratory. Information on hot springs was compiled from the latter two sources as well as from an online list from the National Geophysical Data Center. This data set was visually inspected to ensure that repeat locations were not plotted. Information about carbon dioxide and helium was collected from data included with the Bureau of Geology and Mineral Resources Open-File Report 483 (Broadhead and Gillard, 2004).

1.2.2.2 Sources for Locatable and Salable Mineral Data

Most of the data on locatable minerals came from the NMBGMR New Mexico Mines database and the BLM mine registry database. The New Mexico Mines database covers historical data through 1990 and INTERA obtained an updated version of the database directly from the NMBGMR for use in this report.



The Mines database provides information on the mines, quarries, mineral deposits, mineral occurrences, and mills located in New Mexico. The term mine is used in the database to mean “any prospect, mineralized outcrop, altered area, quarry, mine working, mill, smelter, or other mining-related facility, including geothermal wells and other mineral wells, but excluding petroleum wells. Altered and mineralized areas are included where known even if never mined or developed because these areas have particular importance in terms of mineral resource development and/or environmental impacts” (Lucas-Kamat, 2009a).

The BLM mine registry database covers the time elapsed since 1989, when new mine registration regulations came into effect. In addition, mines and occurrences described in McLemore et al. (1984a) and Pfeil and Leavitt (2001) were included.

Location data collected for each mine or occurrence were reported in decimal latitude and decimal longitude. At times, this necessitated the conversion from the Township/Range/Section coordinate system to latitude and longitude. The latitude and longitude of the section centroid was found using Montana State University’s Graphical Locator Township/Range/Section to Lat/Lon converter (Gustafson, 2003). This converter does not convert Lat/Lon to Township/Range/Section. If quarter section, quarter-quarter section, or quarter-quarter-quarter section data were available, a custom Visual Basic script was used to further refine the calculated latitude and longitude. Results from the conversion formula were compared against values reported by the National Geospatial Agency to ensure precision. The precision of this script was further tested by looking at mines which had both Township/Range/Section and latitude/longitude reported in source literature. The distance between calculated and reported locations was measured using Google Earth. The error of the calculated location with respect to the reported location was less than a quarter mile for each record tested, and oftentimes less.

The sheer volume of mine data, and the often overlapping time coverage of individual databases, resulted in a large number of repeated records within the final data set. These repeated records were first removed by searching and removing exact matches using a Visual Basic script. Then, the records were sorted alphabetically and visually inspected for repeated values. Finally, a Visual Basic script was written to flag every mine that lay within an eighth of a mile of another mine. After this inspection for obvious double locations, the search radius was expanded to a quarter mile and the process was repeated. This resulted in a database of distinct mines and mineral occurrences and an accurate portrayal of their locations.

1.3 ORGANIZATION OF THIS REPORT

This report is intended to be an effective planning tool for use by the Rio Puerco Field Office. The five planning units span multiple physiographic and geologic provinces. To a reasonable extent, the report follows the format and outline required by the SOW, with minor exceptions as requested by BLM. *Section 2.0, Geology of the Five Planning Units* presents the physiographic, geologic and tectonic framework for understanding the occurrence of mineral resources in each planning area. Figures within the report sections illustrate locations or features of interest presented in the text.



In consultation with the BLM Field Office Technical Coordinator and Mineral Specialist, the information presented in *Section 3.0, Mineral Resources*, is organized according to three groups: leasable, locatable, and salable mineral commodities (see definitions of these groups in Section 1.4); discussions of mineral commodities include generic overviews of the commodity and its geologic setting for occurrences within the planning area, and, as appropriate, more detailed description of occurrences within specific geographic areas. For example, uranium deposits are described generically as they occur within the Grants Mineral Belt and then representative uranium deposits found in Planning Units 1, 2, and 4 are discussed in more detail. The section for each mineral also includes a discussion of mineral occurrence potential and classification of the mineral in terms of Low, Moderate, or High potential and the certainty qualifier, as defined by BLM (1985). RFD of the leasable, locatable, and salable minerals is presented in *Section 4.0* and is based on historical price and production data, as well as on the judgment of the report preparer. *Section 5.0* addresses the topic of critical minerals and their potential occurrence within the BLM planning units and references are presented in *Section 6.0*. Figures referenced throughout the text are presented together under a separate tab following the main body of the report. Appendix A presents all of the tables, including the mineral point data tables. The mineral potential data tables list the commodity, the Index Map number, a name for the entry, the location in latitude and longitude, the mineral product, the type of operation, and references. These references are a list of the data sources used to compile the points on the Index Map and are shown in Table 36 of this report. Appendix B, which is provided in a separate three-ring binder, presents all of the mineral commodity point location maps. These maps show the locations of point symbols which correlate with the table entries. All of the maps in this report are numbered as consecutive plates. A complete list of the plate numbers and map titles is provided in the Table of Contents. Appendix C presents the mineral potential maps for each group of commodities as regions containing low, medium, or high mineral potential for occurrence, in accordance with BLM definitions. Appendix D is a description of the methods used to create the point density mineral potential maps.

1.4 DEFINITIONS OF LEASABLE, LOCATABLE, AND SALABLE MINERALS

The following definitions are based on information presented in a brochure on the BLM website (BLM, 2006). This BLM publication provides a list and description of criteria for locatable, leasable, and salable minerals.

1.4.1 Leasable Minerals

Federal leasable minerals are fluid or solid minerals that can be developed after obtaining a lease from BLM. Leasable fluid minerals include oil, gas, coalbed methane, geothermal, carbon dioxide and helium, oil shale, native asphalt, and oil-impregnated sands. Leasable solid minerals include coal, potash, phosphate, sulfur, and sodium. Of these, potash and phosphate are not found in the study area and are thus not addressed in this report. Active oil and gas leases are shown on the maps for oil and gas point locations.



1.4.2 Locatable Minerals

Federal locatable minerals consist of metallic and non-metallic minerals. The metallic minerals include gold, silver, nickel, copper, lead, zinc, iron, uranium, lithium, vanadium, molybdenum, manganese, cobalt, beryllium, and tungsten. The non-metallic minerals include zeolites, silica, perlite, mica, block pumice, limestone of chemical or metallurgical grade, gypsum, barite, fluorspar, and gem minerals. Mining claims on federal land are an indication of activity or interest in a particular area, but they do not necessarily mean that mining is to take place in an area. Current mining claim maps are available on the BLM Land Rehost 2000 website and are not included in this report.

1.4.3 Salable Minerals

Salable mineral materials include common variety of sand, stone, gravel, pumice, pumicite, basalt, clay, rock and petrified wood. Travertine is listed in this report as salable, although it is also considered to be locatable under some circumstances, because it is used as a form of decorative stone rather than as a chemical or “special” variety of limestone. Travertine is combined with limestone on the point density mineral potential map for limestone (Plate 60).



SECTION 2.0 TABLE OF CONTENTS

2.0	GEOLOGY OF THE FIVE PLANNING UNITS.....	9
2.1	Physiographic Provinces	9
2.2	Rock Units	10
2.2.1	Surface Geology	10
2.2.2	Stratigraphic Sections	11
2.3	Historical Geology.....	13
2.4	Tectonic Features within the Planning Units	14



2.0 GEOLOGY OF THE FIVE PLANNING UNITS

This section presents a summary of the physiographic framework of the five BLM planning units followed by a summary of the geology of the entire study area, including specific tectonic features. The geologic summary is based on a review of the Geologic Map of New Mexico (Scholle, 2003) and on stratigraphic sections which represent the rocks in the five planning units.

2.1 PHYSIOGRAPHIC PROVINCES

The five BLM planning units cross parts of the four major physiographic provinces shown on Figure 2: the Colorado Plateau, Southern Rocky Mountains, Basin and Range, and Great or High Plains provinces. Unit 1 and the western parts of Units 2 and 4 lie within the Colorado Plateau physiographic province, which is characterized by relatively flat-lying, red, white, gray, green, and yellow sedimentary rocks that have been sculpted into mesas, buttes, and badlands. The southeast margin of the Colorado Plateau is covered by less than 5 million-year-old volcanic rocks (including Mount Taylor) that erupted along the Jemez lineament, a northeast-trending zone of weakness that likely developed about 1.6 billion years ago as the North American continent was forming (Cather, 2004).

The northeastern part of Unit 4 lies within the Southern Rocky Mountains province. The Southern Rocky Mountains province is a mountainous terrain that includes some of the highest peaks in New Mexico (e.g., Wheeler Peak at 13,161 feet). The mountain ranges that are considered to be part of the Southern Rocky Mountains include the Sangre de Cristo Mountains, the Tusas Mountains, and the Sierra Nacimiento. The Proterozoic rocks exposed in the cores of these uplifts preserve a remarkable record of the assembly of the North American continent 1.6 to 1.7 billion years ago. All three of these ranges were highlands during three younger mountain-building events that have affected New Mexico: Pennsylvanian Ancestral Rockies deformation, Late Cretaceous-early Tertiary Laramide compressional deformation, and Miocene to Pliocene Rio Grande extensional rift flank uplift. The northerly-trending Rio Grande rift bisects the Southern Rocky Mountains of northern New Mexico (Brister et al., 2004).

The southeast part of Unit 4 and all of Unit 5 lie within the Rio Grande rift within the Basin and Range province. The Basin and Range province is part of a larger geologic feature of the same name that also covers portions of west Texas, southern Arizona, western Utah, southern Idaho, eastern California, and most of Nevada and also extends into northern Mexico. The topography of the Basin and Range is characterized by northerly to northwesterly-trending narrow, rugged mountain ranges separated by broad basins and is the result of extension of the Earth's crust (Lawton, et al., 2000). The Rio Grande rift is a north-south trending zone of approximately east-west oriented extension that bisects the state of New Mexico. The northern part of the rift is relatively narrow, consisting of a series of westward-stepping, en echelon basins flanked by rugged mountains. The amount of extension increases toward the south. Rio Grande rift extension began earlier in southern New Mexico (approximately 36 million year ago) compared to the northern New Mexico (approximately 26 million years ago), with extension peaking 10 to 16 million years ago. The axial basins are in the form of half-grabens that are tilted strongly toward the east or the west, depending on the location of the master fault system on the margins of each basin. As



much as 15,000 feet of rift sediment has accumulated in the axial basins of the Rio Grande rift, forming important aquifers for some of the largest cities in our state (Keller and Cather, 1994). The Rio Grande flows through the rift.

Most of Unit 3 lies within the Great or High Plains physiographic province, although the western part of Unit 3 contains the eastern edge of the Manzano Mountains, which form part of the eastern margin of the Basin and Range province. The High Plains province covers the eastern quarter of the state of New Mexico. Mildly deformed Permian and Triassic sedimentary rocks capped by the late Miocene-Pliocene Ogallala Formation, an important aquifer, are exposed in the southeastern and east-central parts of the state. The northwest part of the Permian Basin, which is rich in oil and gas, underlies southeastern New Mexico (Muehlberger, et al., 2005).

Tectonic features within these physiographic provinces are described in more detail in Section 2.4.

2.2 ROCK UNITS

Rock units in the five BLM planning units range in age from Precambrian to Recent and run the gamut from metamorphic greenstones, to granite intrusives, to classic Paleozoic and Mesozoic sedimentary formations, to Tertiary volcanics and rift basin sediments. This section describes the rock units on a regional scale as depicted on the Geologic Map of New Mexico (Scholle, 2003) and on several stratigraphic sections that represent the sequences within the five BLM planning units.

2.2.1 Surface Geology

The surface geology shown in BLM Planning Unit 1 (Figures 3 and 3-1, a portion of the Geologic Map of New Mexico) includes Precambrian rocks in the core of the Zuni Mountains surrounded by Paleozoic and early Mesozoic (Triassic) rocks on the northern and southern mountain slopes. Volcanic rocks of the Malpais trend in a northeast to southwest band to the east of the Zunis. Triassic through Cretaceous sedimentary rocks crop out in the southwestern part of Unit 1 while Tertiary basalts cap the extensive Cebolleta Mesa in the eastern part of Unit 1.

Within Unit 2, the geologic map shows the transition from the southeastern San Juan Basin to the Rio Grande rift. The northwestern part of Unit 2 contains Mount Taylor and a portion of the Mesa Chivato volcanics. Rocks east of Mount Taylor consist of the Jurassic through Cretaceous section, from west to east, eventually transitioning to the Tertiary clay, sand, and gravel of the Santa Fe Group and Quaternary basalts within the Rio Grande rift near Albuquerque. Across the Rio Grande, on the east side of the rift, lie the Manzanita and Manzano Mountains. These mountains are cored by Precambrian granite and capped by Paleozoic sandstone and limestone. Proterozoic metamorphic rocks also crop out in this area in a northeast-southwest-trending band, north and south of the Interstate 40 corridor.

The geology of Unit 3 is dominated by the Estancia Basin. The Estancia Basin is surrounded by Paleozoic rocks but has Quaternary alluvium in the center. The playa lake known as Laguna del Perro also lies in the middle of the Estancia Basin. Near the center of the basin is an outcrop of Precambrian basement



rocks identified as Proterozoic granite and metasediments. These basement rocks, known as the Pedernal uplift, have been uplifted along two closely-spaced north-south trending faults. These faults and related structures form the Perro sub-basin which has been a target for petroleum exploration but to date lacks any production of oil or gas.

The outcrop pattern shown in Unit 4 on the geologic map reflects the north-south trending Nacimiento uplift, roughly bisecting the Unit. At the northern edge of this unit, near Cuba, red bed copper and uranium deposits occur in Paleozoic and Mesozoic sediments, respectively. West of this structure lies the Cretaceous and early Tertiary rocks of the eastern San Juan Basin. These rocks are a source of coal, oil, and natural gas, including coalbed methane. South of the Nacimiento uplift proper, the linear structure transitions from an up-to-the-east, high-angle reverse fault, to a down-to-the east series of normal faults with large displacement. These are the faults which form the boundary between the San Juan Basin and the Rio Grande rift. Rock units exposed by the Nacimiento uplift include Paleozoic and Mesozoic sediments with a core of Precambrian granite. Further east lies the Jemez volcanic center, located at the northern extent of the Jemez lineament. This area includes the Valles Caldera including the Bandelier and related tuff, a source of pumice and perlite. The relatively recent volcanic activity in this region makes the area a focus for potential geothermal energy development.

Unit 5 includes the northern tip of the Sandia Mountains. Rocks in this area include the Proterozoic metamorphics of the Rincon Ridge, the Precambrian Sandia Granite, and the faulted and fractured Paleozoic and Mesozoic rocks which overlie the northeastern part end of the mountain range around the town of Placitas. Bordering the Sandias within this planning unit are significant sand and gravel resources of the Santa Fe Group.

2.2.2 Stratigraphic Sections

Figure 4 contains the stratigraphic section for Units 1 and 4. Stratigraphic section 1 on this figure is generally representative of the rocks present in the northwestern part of New Mexico, although the units shown on the stratigraphic section are not necessarily present throughout Unit 1. Proterozoic rocks include older metamorphic and metavolcanic rocks, plutons, and younger plutons. Cambrian, Devonian, and Mississippian rocks include the Ignacio Quartzite, the Aneth Formation, the Elbert Limestone, the Ouray Limestone, the Arroyo Penasco Group, the Leadville Limestone, the Molas Formation, and the Pinkerton Trail Formation. These early Paleozoic formations do not figure prominently in the mineral resources within Unit 1.

Pennsylvania limestones in the section include the Hermosa Group, equivalent to the Madera Group in the southeastern part of the area. The Permian Abo Formation, Yeso Formation, Glorieta Sandstone, San Andres (Limestone) Formation, and the Chinle Group are present in this planning unit as well as within several of the other BLM planning units. This sequence, from Abo through Chinle, blankets the Precambrian core of the Zuni Mountains with the Permian Abo directly in contact with the Precambrian.

Above the Chinle Group lies the sandstone of the Jurassic Entrada Formation, which crops out along the north side of Interstate 40 just north of the northern boundary of Unit 1 near Gallup. Units above the



Entrada include the Todilto Formation, the Summerville Formation, Bluff Sandstone, and the Morrison Formation. Rocks within this Jurassic sequence contain significant mineral deposits within BLM Planning Units 1, 2, and 4. Commodities include gypsum (in the Todilto Formation) and uranium (in the Morrison Formation). The Morrison Formation is discussed in more detail in geologic setting section for uranium, Section 3.2.8.1. Lying unconformably above the Morrison are the Cretaceous Dakota Formation and a series of Cretaceous sediments which contain coal, oil, and natural gas. These include the Mancos Shale with its many records of transgression and regression of the Western Interior Seaway represented by sequences of sandstone and shale. Above the Mancos lies the Menefee Formation, a part of the Mesaverde Group. This formation represents a non-marine or near-shore marine depositional environment and is known for its coal beds. The Lewis Shale overlies the Menefee, which is overlain by the Pictured Cliff Sandstone and the coal and coalbed methane producing Fruitland Formation. Above the Fruitland is the Kirtland Formation, the youngest of the Cretaceous formations in the area.

Tertiary volcanics shown on the stratigraphic section are present in BLM Planning Units 1 and 2 and include primarily the Mount Taylor volcanics. The volcanics within the Malpais lava fields are of Quaternary age.

Stratigraphic Section 2 on Figure 4 represents the rocks within BLM Planning Unit 2. The geologic sequence in Stratigraphic Section 2 is quite similar to the sequence in Section 1 except that Section 2 contains a description of the Tertiary Santa Fe Group which crops out prominently within the Rio Grande rift. The Santa Fe Group is presented in more detail on Figure 5. This section also presents the Tertiary volcanics of the Jemez mountains, including the Bandelier Tuff and the Valles Rhyolite. Further, this section includes the basaltic lavas within the Albuquerque Basin. The Santa Fe Group sediments are an important source of aggregate within the Albuquerque basin while volcanics of the Jemez region are a source of pumice. The Jemez volcanics are also the location of epithermal gold and silver deposits.

The stratigraphic section for BLM Planning Unit 3 is shown on Figure 6 (Broadhead, 1997). This section shows that Pennsylvanian rocks unconformably overlie the Precambrian basement within the Estancia basin. The formations are similar to those described in Stratigraphic Section 2 on Figure 4 and include unnamed sediments in the Perro sub-basin, the Sandia Formation, the Los Moyos Limestone, and the Madera Group. Group, formation, and member designations are slightly different in the Estancia Basin compared to the rocks which directly overlie the Sandia Granite further to the west, but are similar in origin. Permian rocks include, from oldest to youngest, the Bursum Formation, Abo Formation, Yeso Formation, Glorieta Sandstone, San Andres (Limestone) Formation, and the Artesia Group. These rocks are overlain by the Upper Triassic Chinle Group, Jurassic Entrada Sandstone, Todilto Limestone (and gypsum), Morrison Formation, Cretaceous Dakota, Mancos Shale, Mesaverde Group, and Tertiary dikes and sills. Quaternary alluvium tops the section, including lacustrine deposits that were historically a source for salt. Oil and gas shows have been found within the Paleozoic section in the Estancia Basin but there has been no production to date. Carbon dioxide gas was produced from the Pennsylvanian Sandia Formation.



The rock sequence for Unit 5 is presented in Figure 5 in a detailed stratigraphic section of the Santa Fe Group and also in Figure 7, a cross section across the Albuquerque Basin. The stratigraphic section (Figure 5) gives a detailed picture of the Santa Fe Group and shows the evolution of nomenclature from 1937 to 1999. Based on Connel et al. (1999), the Santa Fe includes the older Zia Formation and the younger Arroyo Ojito Formation. The Arroyo Ojito contains the Ceja Member sand and gravel deposits, which are the source of significant aggregate production north of Placitas (Greer Price et al., 2009). The cross section on Figure 7 depicts the extensional rift basin block faulting of the Paleozoic and Mesozoic rocks from west to east within the Rio Grande rift.

In summary, the stratigraphic sections presented for the five BLM planning units show a relatively consistent sequence of Paleozoic, Mesozoic, and Cenozoic sedimentary rocks overlying basement Precambrian granite and metamorphic rocks. Tertiary and Quaternary volcanics occur in the Jemez region and Albuquerque basin, respectively.

2.3 HISTORICAL GEOLOGY

This historical geology section is based on the summaries by Hilpert (1969) and Chronic (1987). Precambrian metamorphic rocks consisting of gneiss, schist, and partly metamorphosed sedimentary rocks indicate that, 2 billion years ago, New Mexico was a marine environment where limestone, sandstone, and shale were deposited and volcanoes and other mountains were being formed. About 1.35 billion years ago, after millions of years of erosion, only the roots of the earlier mountains remained as metamorphic rocks. Masses of magma intruded the metamorphic rocks and cooled to form the pink Sandia Granite. The highlands were worn down by erosion and remained exposed until they were again covered by a marine depositional environment.

During the Paleozoic Era, North America was part of the megacontinent known as Pangea which included Europe, Asia, Africa, and Antarctica. About 570 million years ago, the western part of Pangea tilted west and the sea transgressed eastward, depositing a sequence of marine sandstone, siltstone, and limestone. These deposits were later removed by erosion. During the Pennsylvanian and Permian periods, the ancestral Rocky Mountains rose in north-central New Mexico and stretched into Colorado. In what is now southern New Mexico, a large barrier reef formed, resulting in embayments which eventually were cut off from the main sea. Deposits of salt, gypsum, and potash formed as these marine waters evaporated.

In the early and middle Mesozoic, non-marine sediments were deposited around the new mountains, consisting of alluvial fans, broad sheets of sand, sand dunes, floodplain and delta deposits. The rise of the ancestral Sierra Nevada far to the west caused a rain shadow effect, resulting in dry conditions in New Mexico. In Late Jurassic time the Zuni uplift was rejuvenated and a broad shallow basin and flood plain was formed to the north. This plain extended into Arizona, southeastern Utah, and southwestern Colorado. This basin was the location for deposition of the Entrada Formation, the Todilto Formation, the Summerville Formation, the Bluff Sandstone Formation, and the Morrison Formation. Structural flexures in the region may have formed local basins in which units like the Jackpile Member of the Morrison



Formation were deposited (Hilpert, 1969). Dinosaurs were prevalent in New Mexico during the upper Jurassic, as evidenced by the presence of dinosaur fossils in the Morrison Formation.

In the late Mesozoic, the sea transgressed, depositing thick sequences of marine shale and sandstone. The Late Cretaceous brought a series of marine and non-marine conditions, reflected in the deposition of shale, sandstone, and coal beds. At the end of the Mesozoic, North America broke away from Europe and the Atlantic Ocean basin opened. The westward moving north-American continent collided with the East Pacific plate resulting in a subduction zone on the western continental margin and uplift of the Rocky Mountains north of New Mexico.

Approximately 30 million years ago, the Rio Grande rift began to form in a north-south trending band from Texas to Colorado. About 15 to 18 million years ago, the earth's crust stretched and thinned, resulting in deep basins separated by the mountain ranges of the Basin and Range physiographic province.

In the late Tertiary, the Rio Grande began to deposit thick gravel layers in the Rio Grande rift. Only a million years ago, thick deposits of tuff were deposited in the Jemez Mountains and the Valles Caldera was formed through collapse. More recently, volcanoes within the rift have erupted, leaving the basalt flows seen on Albuquerque's west mesa (~160,000 years ago) and elsewhere in the Rio Grande valley (Baldrige, 2004, Chronic, 1987).

2.4 TECTONIC FEATURES WITHIN THE PLANNING UNITS

Prominent regional physiographic features within the five planning units reflect the tectonic and geologic framework of western and central New Mexico. These features are often the result of relatively recent tectonic history of the region, but they expose geologic units ranging in age from Precambrian to Recent. For example, Late Pliocene block-faulting in the Albuquerque Basin has exposed the Precambrian basement beneath the Pennsylvanian limestone and sandstone in the Sandia Mountains. A number of major identified tectonic and localized physiographic features within the planning units are shown on Figure 8 and described below. This description of tectonic features is based largely on Woodward (1982).

The Acoma sag, located within Unit 2, is a structurally low geologic embayment extending southward from the eastern portion of the San Juan Basin. The Acoma sag is about 50 miles long (north to south) and 35 miles wide (east to west) with the structurally deepest part along the gently north-plunging McCarty syncline. The sag is asymmetrical with a steep western limb that forms the boundary with the adjacent Zuni uplift. To the east, the sag merges with the Lucero uplift. The northern boundary of the sag is transitional with the gently north-dipping rocks of the San Juan Basin. The southern boundary of the sag merges with the Mogollon slope.

The Lucero uplift is located on the western margin of Unit 2 and consists of a west-tilted fault block about 35 miles long and 7 to 12 miles wide. The western flank of the uplift is transitional with the Acoma sag and is defined by northwesterly-dipping Pennsylvanian and Permian rocks. To the north the uplift merges through the Lucero anticline with the Ignacio monocline of the Rio Puerco fault zone. The eastern margin of the uplift is the boundary between the Colorado Plateau and the Rio Grande rift.



The Nacimiento uplift is located within Unit 4 and is about 50 miles long and 6 to 10 miles east to west. It consists of an uplifted block that is tilted eastward and bounded on the west by faults. In the northern part of the uplift, a thrust fault that is steep at depth but flattens near the surface has moved the block westward over the San Juan Basin. Further south the fault is a steeply east-dipping reverse fault.

The Rio Puerco fault zone is present in the northern part of Unit 2 and southern part of Unit 4. The fault zone is about 29 miles north to south and 8 to 19 miles wide. The structures in the zone consist of northwest-trending en echelon folds, northeast-trending en echelon normal faults, and the east-facing Ignacio-Lucero monocline. Major structural relief across the fault zone is down to the east for a maximum of about 3,300 feet.

The Rio Grande rift consists of north-trending grabens in New Mexico that extend into Colorado. Within and near the study area (Units 2, 4, and 5), the Santo Domingo and Albuquerque-Belen basins are considered as one tectonic feature and called the Albuquerque Basin (Woodward, 1982). Albuquerque Basin as used in this report includes the Albuquerque-Belen Basin of Bryan (Williams and Cole, 2007) and the Santo Domingo sub-basin as delineated by Kelley (1952). The Albuquerque Basin is one of a long line of basins or troughs which were designated by Bryan (Williams and Cole, 2007) as the Rio Grande depression. This depression was so named because the Rio Grande drainage system followed the intermontane basins through most of their known extent. The Albuquerque Basin is drained by two principal longitudinal streams, the Rio Puerco in the western part and the Rio Grande in the eastern part. Both streams are entrenched to several hundred feet into a former high level of basin filling still preserved in the long, narrow Ceja Mesa divide between the two valleys. Remnants of this formerly widespread surface are also preserved in the marginal strips of mesas elsewhere to the east and west of the two longitudinal valleys. The Rio Grande, which follows the length of the basin, descends from about 5,320 feet at the bounding La Bajada fault in White Rock gorge to 4,700 feet at the Rio Salado junction, an airline gradient of 5.9 feet per mile.

The Rio Grande rises in Colorado and empties into the Gulf of Mexico, flowing southward through the Albuquerque basin, which is surrounded by diverse Laramide and late Cenozoic uplifts. Several structural benches are delineated within the basin; fault scarps face the trough in most places. The Albuquerque Basin is about 102 miles long (north-south) and 25 to 40 miles wide (east-west) with the deepest part of the basin on the east side. Depth to Precambrian rocks may be as much as 18,000 feet below sea level in this part of the basin, yielding a maximum structural relief of about 28,000 feet against the front of the Sandia uplift. The ends of the basin open through narrow valleys and structural bedrock constrictions into the San Marcial Basin to the south and Española Basin to the north. The Hagan embayment (basin) is an eastward-tilted half-graben marking the northeastern margin of the Albuquerque Basin.

The basin fill consists of up to 12,000 feet of sandstone, mudstone, and gravel of the Santa Fe Formation or Group (Miocene–Pliocene). In the northern part of the basin, the fill is divided into units referred to as Zia, Middle red, and Ceja members (Williams and Cole, 2007). Elsewhere the fill generally is not divisible but may include equivalents of Zia and Ceja. Several facies of Santa Fe such as fanglomerates, playa, and river deposits and dunes are present. Upper Cenozoic basaltic volcanics occur in the



Albuquerque basin and basin sediments also interfinger with the Jemez volcanic field to the northwest. Late Pliocene deformation widened the basin, elevated the uplifts, and locally faulted and folded the Santa Fe Group sediments.

Along the eastern side of the basin, the Sandia-Manzano Uplift consists of a single, east-tilted fault block that includes the Sandia and Manzano mountains, as well as the Los Pinos mountains to the south. The Sandia Mountains are entirely within Unit 5 while a portion of the Manzano Mountains is within Unit 3. The fault block is about 75 miles long and up to 9 miles wide. Precambrian rocks crop out on the western side of the fault scarp and the dip slope is formed by Pennsylvanian rocks dipping about 15 degrees to the east. The principal uplift crests reach 10,678 feet at Sandia Crest. Altitudes and relief along the western side of the basin are much subdued by comparison, reaching 9,260 feet at one peak in the Ladron Mountains and 6,834 feet along the Lucero uplift. In a long stretch west of Albuquerque, there is no physiographic relief or rise at the structural edge of the basin. Absence of physiographic relief exists also locally along the eastern side of the basin north of the Sandia uplift (Kelley, 1977).

Tijeras Canyon, which separates the Sandia Mountains from the Manzano Mountains, is underlain by the Tijeras segment of the Tijeras-Canoncito fault system, a major, northeast-trending fault system that has undergone recurrent movement since Precambrian time. The Tijeras fault cuts rocks ranging in age from Precambrian to late Tertiary, with movement of left slip, right slip, and dip slip.

The Estancia Basin lies within planning Unit 3. Bedrock deposits include rocks of Pennsylvanian, Permian, and Triassic age. The western boundary of the basin is transitional with the eastern side of the Sandia-Manzano uplift while the eastern margin is bound by the Pedernal uplift. The northern end is arbitrarily located at the southern end of the Ortiz porphyry belt while the southern end is formed by an arch separating the Estancia from the Jornada basin.

The Jemez volcanic field in Unit 4 consists of a thick sequence of Pliocene and Quaternary extrusive rocks. Volcanic rocks of the Jemez field unconformably overlie rocks of the Nacimiento uplift to the west, the Chama basin to the north, and sediments of the Rio Grande rift to the south, east, and northeast. Volcanism began after initial development of the Rio Grande rift and continued with later stages of rifting. The Toledo and Valles calderas are the major structures within the field. These formed by collapse after extrusion of large volumes of the Bandelier Tuff.

The Mount Taylor volcanic field is a composite volcano within a volcanic area that trends to the northeast and is about 40 miles long and 21 miles wide. The southwestern and the northeastern flanks of the Mount Taylor volcanic field are located in Units 1 and 2, respectively. The initial volcanic cone was much larger than the present-day cone; erosion has worn it away. Radiometric ages of 1.1 to 3.8 million years are reported for these rocks; younger basalt flows exist along the margins of Mount Taylor, and one on the south side is as young as 700 A.D.

The Zuni Mountains are considered the southern boundary of the San Juan Basin. They form the core of an elongated structural dome created by regional compressional tectonics during the Cretaceous and early Tertiary periods (Hackman and Olson, 1977; Smith, 1954). The core of the structure is formed by



Proterozoic metamorphic and plutonic rocks, nonconformably overlain by Permian and Triassic rocks. The basal Permian rocks include a limestone that was originally included with the Abo Formation (Darton, 1928 cited in Krainer, et al., 2003 cited in Lucas et al., 2003) but has more recently been interpreted as the Bursum Formation (Krainer et al., 2003 cited in Lucas et al., 2003). These rocks are overlain by the Yeso Formation, the Glorieta Sandstone, and the San Andres Limestone, and the Moenkopi Formation. Overlying these Permian units is the Triassic Chinle Group, approximately 210 to 225 million years old. The Chinle Group consists of (in ascending order) unnamed basal strata, Shinarump Formation, Bluewater Creek Formation, Petrified Forest Formation, and Owl Rock Formation (Lucas et al., 1997). Plant fossils are locally common in the Chinle Group and include leaves, petrified wood, leafy shoots, stems, pollen, and woody debris. Chamberlin and Anderson (1989) proposed that the Zuni Uplift was caused by Eurasian-style indentation-extrusion tectonics during the late Laramide (Eocene).



SECTION 3.0 TABLE OF CONTENTS

3.0 MINERAL RESOURCES..... 20

3.1 Leasable Minerals..... 23

3.1.1 Oil and Natural Gas 23

3.1.1.1 Geologic Setting..... 23

3.1.1.2 Exploration, Development, and Production History 25

3.1.1.3 Resource and Development Potential 30

3.1.2 Coal..... 31

3.1.2.1 Geologic Setting..... 32

3.1.2.2 Exploration, Development, and Production History 35

3.1.2.3 Resource and Development Potential 43

3.1.3 Geothermal Resources and Hot Springs 46

3.1.3.1 Geologic Setting..... 46

3.1.3.2 Exploration, Development, and Production History 47

3.1.3.3 Resource and Development Potential 50

3.1.4 Sodium and Halite 51

3.1.4.1 Geologic Setting..... 51

3.1.4.2 Exploration, Development, and Production History 51

3.1.4.3 Resource and Development Potential 51

3.1.5 Sulfur 51

3.1.5.1 Geologic Setting..... 52

3.1.5.2 Exploration, Development, and Production History 52

3.1.5.3 Resource and Development Potential 52

3.1.6 Helium 52

3.1.6.1 Geologic Setting..... 52

3.1.6.2 Exploration, Development, and Production History 53

3.1.6.3 Resource and Development Potential 53

3.1.7 Carbon Dioxide 53

3.1.7.1 Geologic Setting..... 53

3.1.7.2 Exploration, Development, and Production History 53

3.1.7.3 Resource and Development Potential 54

3.2 Locatable Minerals 55

3.2.1 Gold and Silver 55

3.2.1.1 Geologic Setting..... 55

3.2.1.2 Exploration, Development, and Production History 57

3.2.1.3 Resource and Development Potential 57

3.2.2 Base Metals and Fluorspar 58

3.2.2.1 Geologic Setting..... 58

3.2.2.2 Exploration, Development, and Production History 59

3.2.2.3 Resource and Development Potential 59

3.2.3 Gypsum..... 60

3.2.3.1 Geologic Setting..... 60

3.2.3.2 Exploration, Development, and Production History 61

3.2.3.3 Resource and Development Potential 62

3.2.4 Limestone 62

3.2.4.1 Geologic Setting..... 62

3.2.4.2 Exploration, Development, and Production History 62



- 3.2.4.3 Resource and Development Potential 63
- 3.2.5 Pumice 63
 - 3.2.5.1 Geologic Setting..... 64
 - 3.2.5.2 Exploration, Development, and Production History 65
 - 3.2.5.3 Resource and Development Potential 66
- 3.2.6 Perlite..... 66
 - 3.2.6.1 Geologic Setting..... 66
 - 3.2.6.2 Exploration, Development, and Production History 67
 - 3.2.6.3 Resource and Development Potential 67
- 3.2.7 Rare Earth Elements 67
 - 3.2.7.1 Geologic Setting..... 68
 - 3.2.7.2 Exploration, Development, and Production History 69
 - 3.2.7.3 Resource and Development Potential 69
- 3.2.8 Uranium..... 69
 - 3.2.8.1 Geologic Setting..... 70
 - 3.2.8.2 Exploration, Development, and Production History 73
 - 3.2.8.3 Resource and Development Potential 76
- 3.2.9 Semiprecious Stones and Miscellaneous Minerals..... 76
 - 3.2.9.1 Geologic Setting..... 77
 - 3.2.9.2 Exploration, Development, and Production History 77
 - 3.2.9.3 Resource and Development Potential 77
- 3.2.10 Lithium 78
 - 3.2.10.1 Geologic Setting..... 78
 - 3.2.10.2 Exploration, Development, and Production History 78
 - 3.2.10.3 Resource and Development Potential 78
- 3.3 Salable Minerals..... 79**
 - 3.3.1 Aggregate, Sand, and Gravel 79
 - 3.3.1.1 Geologic Setting..... 79
 - 3.3.1.2 Exploration, Development, and Production History 80
 - 3.3.1.3 Resource and Development Potential 84
 - 3.3.2 Basalt, Diorite, Cinders, and Scoria 85
 - 3.3.2.1 Geologic Setting..... 85
 - 3.3.2.2 Exploration, Development, and Production History 86
 - 3.3.2.3 Resource and Development Potential 88
 - 3.3.3 Clay and Adobe 88
 - 3.3.3.1 Geologic Setting..... 89
 - 3.3.3.2 Exploration, Development and Production 89
 - 3.3.3.3 Resource and Development Potential 91
 - 3.3.4 Dimension Stone, Decorative Stone, and Travertine..... 91
 - 3.3.4.1 Geologic Setting..... 92
 - 3.3.4.2 Exploration, Development, and Production History 93
 - 3.3.4.3 Resource and Development Potential 94
 - 3.3.5 Humate 95
 - 3.3.5.1 Geologic Setting..... 95
 - 3.3.5.2 Exploration, Development, and Production History 96
 - 3.3.6 Resource and Development Potential..... 96



3.0 MINERAL RESOURCES

This section provides a discussion of mineral commodities that are known to occur within the five BLM planning units. Figure 9 is a map that shows the five BLM planning units and also the locations of the 17 mineral occurrence Index Maps that display mineral commodity point locations and identification numbers. Commodities are organized according to whether they are leasable, locatable, or salable minerals. A brief description of each commodity is given, followed by an overview of the geologic setting(s) within which the commodity occurs (in the five BLM planning units). Also, many of the commodities described are located in the commodity or mining districts illustrated on Figure 10. As applicable, a summary of the exploration, development, and production of the commodity is provided. Finally, based on geologic environment and inferred geologic processes the mineral occurrence potential is discussed, according to the BLM definition of mineral potential (BLM, 1985).

The reader is referred to tables and maps for information on the mineral occurrences. The tables in Appendix A list every point of occurrence within the database. The mineral occurrence maps in Appendix B are divided into leasable, locatable, and salable categories. Each category contains an Overview map at a scale of 1 inch to 10 miles (1:633,600) that covers the entire area of the five BLM planning units. On the Overview Maps for leasable, locatable, and saleable minerals are mineral occurrence points and the boundaries of the numbered mineral occurrence Index Maps that represent mineral commodity maps at a larger scale. To find information on a specific mineral occurrence, the reader selects the numbered Index Map and then refers to that map, which is at a scale of 1 inch to 2 miles (1:126,720), for the unique identifier for any particular point on the map. That identifier, for example, U153, is then cross-checked on the appropriate mineral occurrence table in Appendix A. Appendix C contains Mineral Potential maps at the same scale as the Overview maps.

Before addressing the presence of the various minerals within the study area, it is necessary to define several terms that are used in this report. According to the NMBGMR (McLemore and Wilks, 2009; Lucas-Kamat, 2009a) a “mineral occurrence” is any locality where a useful mineral or material occurs. A “mineral prospect” is any occurrence that has been developed by underground or above ground techniques or by drilling to determine the extent of mineralization. The terms mineral occurrence and mineral prospect do not have any resource or economic implications. A “mineral deposit” is any occurrence of a valuable commodity or mineral that is of a sufficient size and grade (concentration) that might under past, present, or future favorable conditions have potential for economic development. An “ore deposit” is a well-defined mineral occurrence that has been tested and found to be of sufficient size, grade, and accessibility to extract and process metals or other commodities at a profit at a specific time. Mineral deposits, especially ore deposits, are relatively rare and depend upon certain natural geologic conditions to form. The requirement that an ore deposit must be extracted at a profit makes them even rarer (McLemore and Wilks, 2009; Lucas-Kamat, 2009a). The points plotted on the mineral occurrence maps may consist of any of these types of occurrences.



This study uses a method which combines the historical approach of McLemore et al. (1984a), the BLM manual classification system, a geographical information system (GIS) mapping analysis method, and best professional judgment to arrive at a mineral resource potential value.

“Mineral potential” is used in this report according to the definitions presented in BLM Manual 3031 (BLM, 1985). The level of mineral potential is divided into none (O) low (L), moderate (M), and high (H), or not determined (ND) levels based on the geologic environment and on inferred geologic processes. In addition to these levels of potential for occurrence, a level of certainty is used as a modifier for the level of potential. These levels are: insufficient and/or cannot be considered direct or indirect (A), indirect (B), direct evidence but quantitatively minimal (C), or abundant direct and indirect evidence (D) to support or refute the possible existence of mineral resources. Potential refers to potential for the presence (occurrence) of a concentration of a mineral resource. It does not refer to or imply potential for development and/or extraction of the mineral resource. However, not all locations where a mineral has been reported to occur are considered to have high potential because the evidence for the presence of the geologic environment or inferred geologic processes may be poorly defined. Even where a mineral occurrence is identified as a point on the mineral occurrence Index Map, the point may be an isolated occurrence and may be considered as having moderate or low potential, depending on geologic factors and on the level of evidence for the occurrence.

Mineral potential maps based on occurrence point density are presented in Appendix C. These maps display colored regions of low, moderate, or high mineral potential for a specified commodity or group of related commodities. For evaluating relative mineral potential, we have used a GIS-based approach to calculate the relative density of mineral exploitation activity for each mineral of interest. Mineral exploitation activity is defined by the presence of mineral occurrences, mineral prospects, mineral deposits, mines, drill holes, wells, or other evidence of mineral exploration and/or extraction. Thus for this analysis, we have used the relative density of mineral exploitation activity as a proxy to evaluate mineral potential. Using a GIS-based method, the relative point density of mineral occurrence points was calculated and normalized (see Appendix D for the full methodology). This analysis assumes that mineral occurrence points are a good indicator of mineral potential, and that a high density of mineral occurrence points indicates a high level of activity, and thus a high potential. In addition, this method provides a transparent, unbiased, quantitative, and reproducible approach to quantifying mineral potential.

Point density is calculated by dividing the region of interest into a regular grid, and calculating, for each grid cell in the region of interest, the density of mineral occurrence points within the vicinity of each grid cell. The area over which to calculate the point density for each grid cell is circular, and is defined by a weighting function whose value is highest at the center of the grid cell and decreases with distance away from the center of the grid cell. The point density methodology is discussed in more detail in Appendix D.

Once the point density data set for each commodity was calculated, each point density data set was normalized by dividing by the highest point density for that commodity. The resulting point-density maps were then characterized by point-density values between 0 and 1, with 0 indicating no potential and 1



indicating high potential. Normalized point density ranges corresponding to low, medium, and high mineral potential were developed using a statistical method (see Appendix D).

Subsequent to this analysis, INTERA assigned a level of certainty to each potential. As discussed previously, the levels of certainty are A (insufficient evidence), B (indirect evidence), C (direct evidence), and D (abundant direct and indirect evidence).

As discussed above and in Appendix D, the GIS-based relative point-density method provides an unbiased, quantitative, and reproducible approach to quantifying mineral potential, since it applies the same methodology to all commodities. The assumption is that a high density of mineral occurrence points (representative of occurrences, prospects, and other evidence of mineral exploration and/or extraction) corresponds to a high mineral potential. This is based on the understanding that existing commodities have either been explored for or developed in areas where they are known to occur or are likely to occur. That is, the geologic environment and geologic processes have been studied by others, and those areas that have potential are characterized by some activity, as reflected in the presence of one or more mineral occurrence points.



3.1 LEASABLE MINERALS

The Mineral Leasing Act of February 1920 and subsequent regulations divide leasable minerals into solid (coal, oil shale, native asphalt, phosphate, sodium, potash, potassium, and sulfur) and fluid (oil, gas, and geothermal energy) minerals. Exploration, development, and extraction of these minerals from public lands can occur only through the acquisition of valid leases. Leasable minerals within the planning units include oil and gas, coal, carbon dioxide gas, helium, and sodium. Oil and natural gas (including coalbed methane) and coal are by far the most significant leasable minerals in the planning area, as these commodities are actively explored for and produced from the area, notably from Planning Unit 4. The geology, occurrences, exploration and development history, and potential development of each of these commodities are described in the following sections.

3.1.1 Oil and Natural Gas

Oil is an important resource in New Mexico. Ten of New Mexico's counties currently produce oil and/or natural gas—Chaves, Eddy, Lea, Roosevelt and Quay in the southeast, and McKinley, Rio Arriba, San Juan and Sandoval in the northwest and Colfax in the northeast. In 2007, over 1,200 new wells were drilled and the state produced over one trillion cubic feet of natural gas and approximately 60 million barrels of crude oil (NMOGA, 2009). According to the USGS (2002a), a mean of 50.6 trillion cubic feet of undiscovered natural gas, a mean of 19 million barrels of undiscovered oil, and a mean of 148 million barrels of natural gas liquids remain in the San Juan Basin province.

3.1.1.1 Geologic Setting

Known oil and gas reserves and prospects are largely confined to three geologic basins within the Rio Puerco planning area: the San Juan Basin, Albuquerque Basin, and Estancia Basin. The San Juan Basin has both conventional oil and gas as well as coalbed methane; the other two basins contain only (potential) oil and gas deposits. The geologic setting for petroleum resources is described below by basin.

3.1.1.1.1 San Juan Basin

The San Juan Basin petroleum province covers an area of about 23,700 square miles. About 42 percent of this area is administered by the U.S. government, mostly by BLM. The San Juan Basin has been classified as a craton-accreted margin basin (Klemme, 1986) and as a foredeep basin (Bally, 1975). A common characteristic of these types of basins is that they are filled by sequences comprising two or more cycles of deposition—a first cycle of carbonate shelf or platform sediments and a second cycle of orogenic clastics. The San Juan Basin contains two such sequences or megacycles: (1) Paleozoic carbonates and (2) Upper Cretaceous to Oligocene clastics. A stratigraphic section within the San Juan Basin is presented on Figure 11. Formations within the basin that crop out or are present in the subsurface of the study area, especially in Unit 4, are the Chinle Formation, Entrada Sandstone, Wanakah Formation (including the Todilto limestone and anhydrite beds), Morrison Formation, Dakota Sandstone, Lower Mancos Shale, Gallup Sandstone, Upper Mancos Shale, Mesaverde Group (including the Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone), Pictured Cliff Sandstone, Fruitland Formation, and the



Kirtland Shale (Huffman, 1996). Discussions related to the geologic setting for San Juan Basin oil and gas as well as coalbed methane are presented below.

Conventional Oil and Gas

Cretaceous age rocks have been important to the development of oil and gas in the Four Corners area of New Mexico and Colorado including the northwest portion of BLM Planning Unit 4. These stratigraphic horizons include the Morrison, Dakota, Mancos Shale, Lewis, Pictured Cliffs, Fruitland and Kirtland (Sandstone Member) Formations and the Mesaverde Group including the Point Lookout, Menefee, and Cliff House Formations. The principal petroleum source rocks in the San Juan Basin, and thus within BLM Planning Unit 4, are marine black shales of the Pennsylvanian Hermosa Formation and Upper Cretaceous Mancos and Lewis Shales; marine limestone of the Pennsylvanian Hermosa and Upper Jurassic Wanaka Formations; and coals of the Upper Cretaceous Dakota Sandstone, Menefee Formation, and Fruitland Formation (Huffman, 1987). Figure 12 shows the currently producing oil wells in BLM Planning Unit 4 according to the OCD database.

Coalbed Methane

Coalbeds, which both generate and store hydrocarbons, are considered unconventional gas reservoirs because they lack the production characteristics of conventional reservoirs such as sandstone porosity and permeability. The gas is produced from within the coal bed and this production is enabled or enhanced by the presence of fractures in the coal. Found locally in the Fruitland and Menefee Formations, coalbeds have played a significant role in the history of oil and gas development in the San Juan Basin. Figure 13 shows the extent of the Fruitland Formation within BLM Planning Unit 4.

3.1.1.1.2 Albuquerque Basin

The following information related to the geology of the Albuquerque Basin is derived from an article by Ron Broadhead (2009), the Principal Senior Petroleum Geologist for the NMBGMR.

The Albuquerque Basin, one of several north-south aligned basins in New Mexico that form the Rio Grande rift, was formed by extensive faulting during the Tertiary Period, and its thick fill of Tertiary-age sands, gravels, and clays reflect its history of faulting, subsidence, and sedimentary infilling. Beneath the Tertiary sediments lies a thick section of Cretaceous strata that is broadly similar in character to the Cretaceous strata that are prolific producers of natural gas in the San Juan Basin. Beneath the Cretaceous are 2,500 feet of Jurassic and Triassic strata, 2,000 feet of Permian sedimentary rocks, and almost 3,000 feet of Pennsylvanian-age sandstones, shales, and limestones. Cretaceous sedimentary rocks have been the objects of considerable oil and natural gas exploration since the 1950s. Some recently acquired data indicate that the deeper Paleozoic (Permian) section may have some intriguing natural gas possibilities as well (Broadhead, 2009). Figure 7 provides a geologic cross section across the Albuquerque Basin showing the subsurface structure and stratigraphy, including the Shell Santa Fe #1 exploration well drilled into the Ziana anticline.



3.1.1.1.3 Estancia Basin

The Estancia Basin is an asymmetric, north-south-trending structural depression that originated during Pennsylvanian time. The present day basin covers 1,500 square miles and is within BLM Planning Unit 3. It is bounded to the east by the Paleozoic Pedernal uplift, on the west by the Tertiary-age Sandia, Manzano, and Los Pinos Mountains, on the north by the Española Basin, and on the south by Chupadera Mesa. The thickness of sedimentary rocks in the basin ranges from 8,500 feet in the Perro sub-basin, a narrow graben in the eastern part of the basin, to less than 1,000 feet on a shelf to the west (Broadhead, 1997). Figure 6 is a stratigraphic section of the Estancia Basin showing the intervals where hydrocarbon shows have been found and reservoir characteristics.

3.1.1.2 Exploration, Development, and Production History

The majority of New Mexico oil and natural gas production takes place in either the San Juan Basin in the northwestern part of the state, or the Permian Basin in the southeastern part of the state. New Mexico's crude oil production in 2007, including condensate, was 59.1 million barrels while natural gas production was 1,528 billion cubic feet. Nearly a third of this gas production is coalbed methane. Oil and natural gas is produced in BLM Planning Unit 4 and oil exploration has taken place in Planning Units 1, 2, 3, and 4. Oil production during 2007 in Sandoval County, within or near BLM Planning Unit 4, was 90,583 barrels with natural gas production of 1,130,425 thousand cubic feet (NMEMNRD, 2008).

This section examines the exploration and production of oil and gas, including coal bed methane, in the Rio Puerco planning units. Most of the production activity has occurred in Sandoval County within BLM Planning Unit 4; additional information is provided for frontier exploration areas in the Albuquerque Basin and the Estancia Basin in Units 2 and 3, respectively.

3.1.1.2.1 San Juan Basin

Conventional Oil and Gas

Conventional gas exploration began in the early 1900s in the San Juan Basin. Early attempts were confined to completions in relatively shallow sandstones. The first recorded drilled well in the San Juan Basin reached to a depth of 200 feet penetrating the Kirtland Shale near Farmington, New Mexico. This discovery well began as a search for water but produced only gas (MacDonald and Arrington, 1970). A well drilled in Durango, Colorado in 1901 flowed natural gas, and no oil (Arnold and Dugan, 1971). The first commercially successful gas well in the region was drilled near Aztec, New Mexico in 1921, completed in the Farmington Sandstone Member of the Kirtland Shale Formation (Chafin, 1994). Additional development continued through the 1930s; another conventional prospect, the Pictured Cliffs Sandstone, was developed in the 1940s after gas was discovered in this horizon, also in the vicinity of Aztec, New Mexico. By the end of the 1940s deeper drilling proved that there were substantial resources of conventional gas located in the formations of the Mesaverde Group and in the Dakota Sandstone.

The 1950s ushered in another wave of gas development in the San Juan Basin. Thousands of wells were drilled in both Colorado and New Mexico. The construction of gas pipeline systems that delivered gas to the West Coast and southwestern U.S. encouraged this development. Development and exploration of

these conventional reservoirs continued through the 1970s with oversight by the oil and gas commissions of both New Mexico and Colorado. The accompanying strong economic market generated the next drilling boom for conventional gas production in the San Juan Basin. Drilling of conventional reservoirs for gas continued until 1982, when an over-supply of gas nationwide caused a decline in gas prices. Subsequent development of conventional gas reservoirs has been sporadic, with drilling and development dictated by pipeline capacity and prices.



Photograph: Sengebush, INTERA, 2008.

Drilling in the Rio Puerco valley.

Leasable Index Map 4 (Appendix B) shows the location of the majority of the oil and gas wells (both active and inactive) within Planning Unit 4. Most historical and current activity is in the southeastern part of the San Juan Basin oil and gas producing area, in Sandoval County, New Mexico, to the west/southwest of Cuba and to the north and south of New Mexico Highway 197. The area consists of remote high desert, most of which is administrated by BLM. All of the oil and gas wells identified in the OCD database are plotted on the leasable index maps (Appendix B) using a unique identification number that correlates to a specific well listed in the oil and gas well tables provided in Appendix A (for example, OIL395 or GAS110). **To find additional information on a particular well, the API number (shown on the oil well index table) associated with the well can be used to access the OCD well database on the OCD website (OCD, accessed 2009). Once the API number is entered in the blank field of that website, all available information on that well will be displayed.**



A well in the San Luis oil field may be used as an example of how this procedure works. The San Luis oil field is located approximately 9 miles northwest of San Luis, New Mexico and is actually two fields: San Luis and South San Luis. The field is shown on Leasable Index Map 4 (Appendix B) as two dense clusters of oil wells. Selecting active well OIL188 correlates with San Luis Federal 003 in the oil well table (in this report) and shows the API number of 3004320376. Once this API number is entered in the OCD well search data form on the OCD website, the following information is displayed.

<i>Well Name:</i>	San Luis Federal 003
<i>API Number:</i>	3004320376
<i>Lease Type:</i>	Federal
<i>Operator:</i>	Sagebrush Oil, Inc.
<i>Completion:</i>	Single
<i>Formation Tops:</i>	Cliffhouse: 0 feet, Menefee:41 feet
<i>Total Depth:</i>	606.5 feet below ground surface
<i>First Drilled:</i>	1978
<i>Last Inspection:</i>	11-12-2008
<i>Pits:</i>	No pits found
<i>Completion:</i>	San Luis Mesaverde (Menefee)
<i>Last Produced:</i>	7-1-2009
<i>Complaints, Incidents, Spills:</i>	No incidents found
<i>Cumulative Production through 2009:</i>	13,255 barrels
<i>Transporters:</i>	Giant Refinery
<i>Well Log :</i>	Click the well log tab at right on website page to view well log

Note that to display some of this information, it is necessary to click on the associated database heading (headings with more information to display have a downward-facing double caret sign to the left of the heading name). For example, to see the Lease Type, click on the heading “General Well Information.”

Coalbed Methane

In the early stages of natural gas exploration, San Juan Basin coal beds were penetrated in search of conventional gas reservoirs that lay beneath them. Problems associated with extraction of coal gas in comparison to conventional natural gas reservoirs, coupled with the fact that methane from coal seams typically has a lower heating value (BTU), made the Fruitland coal seam gas uneconomical to produce. Business risks were considerable due to high startup costs associated with pumping, storage, disposal, and corrosion potential (linked to a significant carbon dioxide content) of the produced water, coupled with a lack of sufficient historical data to establish production trends. With legislation (the production tax credit, a part of the Crude Oil Windfall Profits Tax Act of 1980) that offered lucrative tax incentives to explore unconventional fuel production, the potential for producing coal gas by water removal stimulated the oil and gas industry to invest in more research (BLM, 1999).

Estimates indicate that gas-in-place in the coalbeds may equal or exceed the amount of gas in conventional San Juan Basin reservoirs. Coalbed methane resources in the San Juan Basin are estimated



at 50 trillion standard cubic feet (Tscf) in the Fruitland Formation and 34 Tscf in the Menefee Formation (Mavor, 1997 as cited in BLM, 1999). Similar figures are quoted for the Fruitland (50-56Tscf) and the Menefee (34Tscf) by the Gas Resources Institute (GRI, 1997 as cited in BLM, 1999). Compared with other major U.S. coalbed methane reserves in the lower 48 states, the San Juan Basin ranks third in reserves: the Greater Green River Basin has 134 Tscf; Piceance Basin, 99 Tscf; San Juan Basin, 90 Tscf; Northern Appalachian Basin, 61 Tscf; Powder River Basin, 39 Tscf; Black Warrior Basin, 20-23 Tscf; Western Washington Basin, 24 Tscf; Illinois Basin, 21 Tscf; Raton Basin, 10 Tscf; Uintah Basin, 10 Tscf (Schwochow, 1997 as cited in BLM, 1999; Nelson, 1999 as cited in BLM, 1999). Huge coal reserves in Alaska have been identified with a gas-in-place content estimated at 1,000 Tscf (Smith, 1995 as cited in BLM, 1999), but no commercial exploitation has occurred to date (BLM, 1999).

In 1992, the American Gas Association reportedly predicted recoverable coalbed methane reserves in the Fruitland coalbeds of the Ignacio-Blanco Field (the northern portion of the San Juan Basin, located in La Plata County, Colorado) to be 1.5 Tscf. Actual production has already surpassed that estimate; by the end of 1998, 1.7 Tscf had been produced (Bell, 1999 as cited in BLM, 1999). When gas produced from the New Mexico portion of the San Juan Basin is included, the actual production to date exceeds 6 Tscf (Nelson, 1999 as cited in BLM, 1999). In 1998, coalbed methane production from the San Juan Basin was eight times that of the second-ranked Black Warrior Field (Nelson, 1999 as cited in BLM, 1999), which had a cumulative production of 1 Tscf at this time. Very little coal gas has been produced from the larger Greater Green River Basin shales and the Piceance Basin due to the extreme depth of burial and low permeability of the coals. Thus, coalbed methane production from the San Juan Basin rivals or exceeds such production from any U.S. basin to date.

3.1.1.2.2 Albuquerque Basin

The following is based on an article by Ron Broadhead (2009) in the *Water, Natural Resources, and the Urban Landscape* publication (Greer Price et al., 2009).

Exploration for oil and gas has taken place sporadically in the Albuquerque Basin since 1912. To date, there is no oil or gas production from this basin, which lies largely within BLM Planning Unit 4. Figure 14 and 14-1 show the locations and names of the exploratory wells in the Albuquerque Basin. Figure 15 shows the exploration history of the basin. Oil and natural gas have been the targets of exploratory drilling in the Albuquerque Basin since the Tejon Oil and Development Corporation No. 1 well was drilled to a total depth of 1,850 feet between July 1912 and July 1914. By 1952 a total of 36 exploration wells had been drilled in the basin, mostly to depths of less than 5,000 feet. The locations and depths of these early wells, drilled primarily into Tertiary-age strata, were based on concepts that lacked a modern understanding of the geology and geometry of the basin as well as of how oil and natural gas form and accumulate. Noncommercial “shows” of oil and gas were reported from many of the wells. However, because the nature of the shows was often not described, the authenticity of some of them may be in question.

The first well to penetrate and evaluate a significant thickness of Cretaceous strata was the Humble No. 1 Santa Fe Pacific well, drilled in 1953. Until this well was drilled, the presence of a deep rift basin filled



with Tertiary-age sands, gravels, and clays as much as 22,000 feet thick was unrecognized. This well marked the beginning of modern exploration the basin and provided the first geologic information on the depth, structure, and origin of the basin. However, a 19-year hiatus ensued before the next exploratory well was drilled in the Albuquerque Basin.

During the 1970s and early 1980s, the first sustained oil and natural gas exploration effort began in the basin (Figure 15). During this period, Shell Oil Company conducted extensive seismic reflection surveys and drilled seven unsuccessful deep exploratory wells, several of which encountered noncommercial shows of oil and natural gas. As expenses for the exploration program mounted without a return on investment, Shell partnered with other companies to drill an additional two wells. Natural gas was reportedly flowed and flared at the Shell No. 1 West Mesa Federal well (Map Point OIL16, Leasable Index Map 9, Unit 2), but large expenses associated with drilling this deep well (19,375 feet), combined with the low price of natural gas and the apparently limited flow rates, contributed to the reservoir encountered by the well being deemed noncommercial. The UTEX Oil No. 1 Westland Development, drilled by UTEX Oil Company in collaboration with Shell, represented the last unsuccessful gasp of the Shell effort. However, the wells drilled by Shell and its partners provided invaluable geologic information that has helped geologists develop an understanding of basin geology and has provided the foundation for all subsequent exploratory efforts in the Albuquerque Basin.

No further exploratory drilling was conducted in the basin until 1995, when Davis Petroleum, in conjunction with Vastar Resources, drilled two exploratory wells. The first well was drilled near the northern end of the Albuquerque Basin. This well penetrated the entire Cretaceous section but encountered only minor shows and was subsequently abandoned and converted to a water supply well. The second well was drilled at the southern end of the basin and was abandoned when it encountered volcanic rocks of Tertiary age. As with early wells drilled in the basin, the depth of this well was insufficient to penetrate Cretaceous strata, the primary exploration target in the basin.

Burlington Resources drilled two wells in the West Mesa area outside of Albuquerque in 1997. These wells were located in the relatively shallow western part of the basin. Again, no production of oil or natural gas ensued. The Burlington No 1Y Westland Development well was re-entered by Tecton Resources in 2007 and a test of the Jurassic-age Morrison Formation near the bottom of the hole apparently resulted in the recovery of water. Plans were announced to move uphole and test the Cretaceous-age Dakota Sandstone, but this work had not taken place as of 2009.

Further to the west but still on Albuquerque's West Mesa, XTO Energy drilled two wells during 2005 and 2006 to test the Cretaceous Menefee Formation, a known coal-bearing rock layer, for coalbed methane potential. After coring and extensive evaluation, the wells were plugged and abandoned without establishing production. Minor gas shows were recorded in at least one of the wells.

At the southern end of the basin, Twinning Drilling Corporation drilled a series of wells during late 1990s and early 2000s. Little data are available for these wells. Apparently most of the wells were drilled to an insufficient depth to penetrate Cretaceous strata. None of the wells established production (Broadhead,



2009; R.F. Broadhead, pers. comm.). These wells are shown on Leasable Index Map 13 (Appendix B) and are identified as Site on the map and in the associated table (Appendix A). Entry of the associated API numbers for these wells into the OCD database yields essentially no information; this implies that these wells were either not drilled or were drilled but the resulting well data was not released.

3.1.1.2.3 Estancia Basin

According to Broadhead (1997), 43 exploratory wells had been drilled in the basin prior to 1997. Most of the wells were drilled before 1950 and numerous oil and gas shows were reported. During the 1930s and 1940s, carbon dioxide gas was produced commercially from two small fields on the western flank of the basin.

3.1.1.3 Resource and Development Potential

3.1.1.3.1 San Juan Basin

The oil, conventional gas and coalbed methane occurrence potential in this area is high with abundant direct and indirect evidence to support the existence of the resource (H,D). This judgment is based on the abundant oil and gas (including coalbed methane) currently being produced from the San Juan Basin in general, and also specifically from the portion of the basin which lies within BLM Planning Unit 4 in Sandoval County. The coalbed methane potential is mainly from the Fruitland Formation coal gas pool as identified on Figure 13 of this report from the NMBMG Oil and Gas Pool Maps Circular 209 (NMBGMR, 2000). The point density map (Plate 55) reflects this assessment, showing a high resource potential in the South San Luis oil field. A region of moderate potential extends north through the San Luis oil field to just north of Cuba. Low potential extends across the entire northwestern half of Unit 4 from San Ysidro onward.

3.1.1.3.2 Albuquerque Basin

The oil and gas potential in the Albuquerque basin is judged to be low, with a direct evidence level of certainty (L,C). Exploratory drilling to date has encountered oil and gas shows, but no commercial production, according to available data. The sporadic nature of exploration in this region is reflected on the oil and gas potential map (Plate 55), which indicates low resource potential along the western edge of the basin.

3.1.1.3.3 Estancia Basin

Oil and gas potential in the Estancia Basin is judged to be low, with a direct evidence level of certainty (L,C). Numerous oil and gas shows have been reported from exploratory wells, but there has been no commercial production. The relative lack of exploration and development in the basin has resulted in a low point density from Mountainair north to Moriarty (Plate 55). A detailed treatment of the petroleum potential of the Estancia Basin is provided in New Mexico Bureau of Mines and Mineral Resources Bulletin 157 by Broadhead (1997).



3.1.2 Coal

Coal is one of the most valuable commodities in New Mexico and has been commercially extracted since the mid 19th century. Currently, New Mexico is 12th in the nation in terms of coal production. Coal is the third largest revenue generator among the state's mineral and energy resources and generates 46% of the state's electricity (Hoffman, 2002). The industry employed 1,445 personnel and generated 25.6 million short tons of coal at 5 mines in 2008 (EIA, 2009). Thus coal remains a very important component of the state's mineral resources, and will remain so for as long as the current energy paradigm lasts.

Roughly 3.7 billion short tons of coal exist in coal fields partly or wholly included in the Rio Puerco Field Office planning units. Coal is known to occur in all but Planning Unit 3, with the greatest potential in the western half of Unit 4 and the northwestern half of Unit 1. However, coal also lies beneath the southeastern corner of Unit 1, the center of Unit 2, and in isolated occurrences in Unit 5. A total of 87 coal occurrences, prospects, and mines are recorded in this report and plotted on the included maps. Key references in this section include McLemore *et al*, 1984, Hoffman, Campbell, and Beaumont, 1993, and Kirschbaum and Biewick, 2000.

The following provides an overview of coal resources in the Rio Puerco Field Office planning units.

Coal is categorized by metamorphic grade. The lowest grade (least metamorphosed) form is called lignite. The second grade is called bituminous and comprises the largest category of coals. The highest metamorphic grade is called anthracite (Press and Siever, 1982). The amount of heat generated per pound is a very important consideration in coal quantity. Therefore, bituminous coals have been subdivided according to the amount of volatiles released upon heating. The lower the level of volatiles, the more heat the coal can produce, and thus the higher the grade (Press and Siever, 1982). However, if sulfur is present, it causes coal to burn "dirtier" and thus creates more harmful emissions. Furthermore, a coal with a high ash content creates a large amount of byproduct (fly ash) when combusted, creating problems with corrosion and waste disposal. These three factors combine to determine the economic value of a particular coal deposit (Hoffman, 2002). Once a deposit has been characterized, the feasibility of extracting and then transporting the coal must be considered. This, combined with current market demand, will determine whether a coal deposit will be mined (Hoffman, 2002).



Photograph: Wikimedia, accessed 2009.

An active surface coal mine.

On a smaller scale, coal deposits can be characterized based on the presence or absence of resin and pyrite. Coals are also rated on quality of cleat. Cleat is a description of natural fracture in a given deposit and is an important consideration for coal bed methane flow (Lyons, 2003). New Mexico coals can contain clarain (a bright coal with a silky luster, no conchoidal fracture, occurs in thin bands), vitrain (bands of glossy, homogeneous material with a conchoidal fracture, usually less than an inch thick) and durain (gray to dull black, compact, structureless material) (Hambleton, 1953).

Areas of coal occurrences are called *coal fields*. A coal field is defined by coal outcroppings in a given geographic area (G.K. Hoffman, pers. comm.). Coal fields are often delineated in literature as extending from the base of an overlying barren unit, through the coal bearing unit, to the top of the underlying barren unit. However, some coal fields are arbitrarily broken up by township/range lines or other political and survey boundaries. There are a total of 14 coal fields in the Rio Puerco planning area. Please refer to Figure 16 for the locations of these coal fields within the five planning units.

The following discussion provides an overview of coal resources in the Rio Puerco planning area. First the formation and geologic setting for coal deposits in New Mexico is presented. This is followed by a discussion of the exploration, development, and production of the coal fields in the Rio Puerco planning units and an assessment of the potential for further coal development in these regions.

3.1.2.1 Geologic Setting

The majority of recoverable coal deposits in New Mexico are located in the San Juan Basin, a broad, gently-dipping Laramide structure comprising much of the northwest corner of New Mexico. The San Juan Basin is bounded on the east by the Nacimiento uplift, a Laramide-age deformational feature that has



been reactivated by the Rio Grande rift. The south boundary of the San Juan Basin is less well defined, approximately corresponding with the Zuni Mountains, also a reactivated Laramide structure.

Smaller coal deposits occur in structures associated with the Rio Grande rift and Laramide faulting. These deposits seldom produce economical quantities of coal because it is difficult (i.e. uneconomic) to produce from steeply dipping, heavily deformed coal beds.

Coal deposits in the Rio Puerco planning area are found in Cretaceous fluvial and nearshore sediments that were deposited during a series of transgressions and regressions of the Western Interior Seaway. The resulting strata are about 6,000 feet thick and represent a complicated interfingering of terrestrial and fluvial deposits in the south that merge with marine sediments in the north. Although many coal deposits are laterally extensive, they exhibit a complex local structure due to the varying depositional environments along this ancient shoreline. The largest and most economical deposits are typically found in regressive sequences or local standstills; coal deposits in transgressive sequences are generally thin and discontinuous (Hoffman et al., 1993).

There are five major coal-bearing formations in the Rio Puerco planning area. In stratigraphically descending order, they are the Fruitland Formation, the Menefee Formation, the Crevasse Canyon Formation, the Moreno Hill Formation, and the Dakota Sandstone. These formations and their stratigraphic relationships are presented on Figures 17 and 18.

The Fruitland Formation represents the last regression of the Western Interior Seaway from New Mexico. It is interpreted as representing a fluvial and shore marginal environment, and it contains the thickest coal beds in the region (Hoffman et al., 1993).

The Menefee Formation contains two coal-bearing members, the Upper Coal Member and the Cleary Coal Member of the Menefee (beneath the Upper Coal Member of the Menefee). The Upper Coal Member is considered transgressive; however, it also represents many instances of minor regressions. In the La Ventana region (Planning Unit 4), the shoreline stood still for a time, allowing a thick deposit of peat to form that later metamorphosed into a large coal deposit (Hoffman et al., 1993).

The Cleary Coal member is a regressive sequence with minor reversals. Local highs such as the San Miguel Creek dome affected sediment deposition in this member. Cleary coals tend to be patchy because of the presence of delta deposits and paleochannels (Hoffman et al., 1993).

In the southern San Juan Basin, the marine shales and nearshore sandstones separating the Menefee and Crevasse Canyon Formations become thin and eventually pinch out. The following unit is therefore a combination of the Cleary Coal Member of the Menefee Formation and the uppermost member of the Crevasse Canyon Formation, the Gibson Coal member. Since these two members are no longer distinguishable at this point, Hoffman et al. (1993) refer to them as the Cleary-Gibson Coal Members; this report does the same. The Cleary-Gibson Coal Members contain significant coal deposits, which were most likely deposited during a standstill between major transgressive and regressive phases (Hoffman et al., 1993).

The Gibson Coal Member of the Crevasse Canyon Formation contains both transgressive and regressive sequences, although it is never more than a few hundred feet thick (Hoffman et al., 1993). The Dilco Coal Member of the Crevasse Canyon Formation is a freshwater sequence of fine sandstones, siltstones, and shales associated with the regressive Gallup Sandstone. The contact between the Dilco Coal Member and the Gallup Sandstone is often unclear. Furthermore, previous investigators included a coal-bearing member with the marine Gallup Sandstone, adding to the confusion (see the Zuni coal field description in Section 3.1.2.1, below). Hoffman et al. (1993) note that this member should have been associated with the Dilco Coal Member rather than the marine Gallup Sandstone. In any case, data on these members are sparse (Hoffman et al., 1993).

The Salt Lake coal field (described in Section 3.1.2.1 below) contains the Moreno Hill Formation, which represents the tip of the transgression that produced the Gallup Sandstone. The Moreno Hill has three members, the Upper, Middle, and Lower. The Upper Member consists of siltstones, mudstones, and some coal near the base. The Middle Member is a sandstone thought to be a braided stream deposit. The Lower Member consists of fluvial sandstones and mudstones. Three coal zones, the Antelope, Cerro Prieto, and Rabbit, occur in the Lower Member. The coal-bearing Tres Hermanos Formation, a small transgressive sequence sometimes included with the underlying Dakota Sandstone, is discussed in the description of the Zuni coal field, below (Hoffman et al., 1993).



Photograph: Bowman, INTERA, 2009.

A thin coal seam in the Cretaceous Dakota Sandstone in the Rio Puerco Coal Field, near Cabezon Road and NM 550.

The lowest coal-bearing strata, the Dakota Sandstone, is a transgressive near-shore continental deposit that unconformably overlies the Jurassic Morrison Formation. The Dakota Sandstone consists of



sandstone beds separated by carbonaceous shales and small, discontinuous coal deposits. These deposits likely represent channel, swamp, and sandy marine environments (Kelley, 1963).

For a more exhaustive treatment of the geology of coal-bearing sediments in the southeastern San Juan Basin, see Hoffman et al. (1993) and Kelley (1963).

3.1.2.2 Exploration, Development, and Production History

This section describes the geographic extent, geology, coal resources, and production history of each of the fourteen coal fields wholly or partly included in the Rio Puerco Field Office.

3.1.2.2.1 Star Lake Coal Field

The Star Lake field is defined by the outcropping of the Fruitland Formation in Township 19 to 21 North, Range 1 to 9 West (Leasable Index Maps 1, 4, and 5). Its southern extent is marked by the southernmost outcrop of the Fruitland Formation and its eastern border is defined by thinning and a change in outcrop trend. The western edge is set as the border between Ranges 8 and 9 West (Kirschbaum and Biewick, 2000). The northern border is the contact with the Ojo Alamo Formation (McLemore et al., 1984a). The eastern half of this field is located in Planning Unit 4 in northern Sandoval County.

In this region, the Fruitland Formation consists mostly of sandstones that dip 1° to 5° to the northeast and northwest. Some normal faulting exists in the northeastern and eastern part of the field (Hoffman et al., 1993; McLemore et al., 1984a).

Coal beds average 6.5 feet thick and thicken towards the base of the section. The entire Fruitland Formation thins towards the southeastern end of the Star Lake Field. Eastern Star Lake coals also contain more shale partings. Coals vary from subbituminous A to high-volatile bituminous C and contain 15 to 20 percent ash, 0.4 to 0.7 percent sulfur, numerous bands of vitrain, and have good cleat. Heating values averages 8,636 BTU per pound (lb) with a standard deviation of 702 (Hoffman et al., 1993; Kirschbaum and Biewick, 2000).

Although leasing and exploration has been ongoing since the 1960s, no mines are currently active within this field (Kirschbaum and Biewick, 2000). Only one unnamed prospect exists in the Rio Puerco planning area (Map Point C77, Leasable Index Map 4, Unit 4).

3.1.2.2.2 La Ventana Coal Field

The La Ventana coal field is located in northern Sandoval County on the southwestern edge of the San Juan Basin in Planning Unit 4 (Leasable Index Maps 4 and 5). It consists of the Upper and Cleary Coal Members of the Menefee Formation and includes portions of Townships 16 to 21 North, Ranges 1 to 3 West. The north boundary of the field is defined by the outcrop of the La Ventana Tongue of the Cliff House Sandstone, and the south boundary of the field is marked by an outcrop of the Point Lookout Sandstone. The Menefee Formation dips steeply in the northeast portion of the field, and coal beds are further complicated by faulting and overturning associated with the Nacimiento uplift (Hoffman et al.,



1993). However, the southern portion of the field is much less deformed and has an average dip of 2° to the northeast (McLemore et al., 1984a).

Coal beds in the La Ventana field are 7 to 11.5 feet thick in the Upper Coal Member. Sections with fewer coal seams tend to have thicker deposits. Coals in the Cleary Coal Member are 1.4 to 3.3 feet thick and are separated by shale layers. The thickest coal layers are usually within 20 feet of the Point Lookout Sandstone contact. Coals in both members contain iron pyrite and the Upper Coal Member contains resin. A few Upper Coal Member samples smelled strongly of hydrogen sulfide. Coals in the Upper Coal Member have about 8 percent ash and 1 percent sulfur, whereas coals in the Cleary Coal Member have about 11 percent ash and 1 percent sulfur. Heat values for both members average 10,171 BTU/lb with a standard deviation of 696 BTU/lb. Upper Coal Member coals had medium to fine banding and calcite on cleat surfaces. Cleary Coal Member coals have fine to moderately thick banding. Both coals had moderate to high vitrain. Cleat is reported to be better developed in the La Ventana field than in the San Mateo and Chakra Mesa fields. However, cleat in the Cleary Coal Member ranges from poor to good (Hoffman et al., 1993; Kirschbaum and Biewick, 2000).

The La Ventana coal field was first mined in the 1880s to the 1890s to provide coal for local metal smelters. After a 30-year hiatus, mining resumed again in the 1920s, but the lack of railroads caused the last mine to close in 1969. The field's only strip mine, Arroyo #1 (Map Point C33, Leasable Index Map 4, Unit 4), opened in 1979 and was closed in 1984. A total of 34 coal mines have operated in this area during its 100-year lifespan with a total known production of 341,021 tons (Kirschbaum and Biewick, 2000; McLemore et al., 1984a).

3.1.2.2.3 Chacra Mesa Coal Field

The Chacra Mesa field is located in Township 17 to 19 North, Range 3 to 8 West in Planning Unit 4 (Leasable Index Map 4). The field consists of the Upper Coal Member and Cleary Coal Member of the Menefee Formation. The northern boundary of the field is marked by the Cliff House Sandstone and the southern boundary is defined by the southernmost outcrops of the Upper Coal Member of the Menefee Formation. The western and eastern boundaries are defined by the Chaco Canyon Field and the boundary at Range 3 West, respectively. The La Ventana field lies due east of this boundary. The Menefee Formation dips 1° to 5° to the north-northeast in this area, and there is some normal faulting present with downdrops to the north (Hoffman et al., 1993; Kirschbaum and Biewick, 2000).

Upper Coal Member coal seams are typically 1.25 to 5 feet thick in the Chacra Mesa field and are interbedded with sandy shales, shaly sandstones, and siltstones. These coals tend to be contaminated with silt because of the shaly nature of the host member. The Cleary Coal Member contains seams between 1.6 and 5.9 feet thick, with the thickest seams occurring to the west of the Rio Puerco planning area. Kirschbaum and Biewick (2000) report a maximum thickness of 13.7 feet in the Chacra Mesa field, but note that most seams are less than 6 feet thick. Coal beds are thickest within 20 feet of the contact with the Point Lookout Sandstone. Coal-bearing deposits lie between shale layers in the northeast, but the layers grow siltier and sandier to the west. Cleary Coal has moderate vitrain, fine to medium banding, and poor to good cleat. The coal tends to have a hackly fracture. Overall, Chacra Mesa coals have less pyrite



and resin than the coals in the San Mateo field to the south (see discussion below). Coals in the Chacra Mesa field are subbituminous A to high-volatile C bituminous. The Upper Coal Member averages 9.69 percent ash and 0.72 percent sulfur, with a heating value of 10,207 BTU/lb (standard deviation of 615 BTU/lb). The Cleary Coal Member has an average of 11.05 percent ash and 0.45 percent sulfur, and generates an average of 10,898 BTU/lb with a standard deviation of 1,605 BTU/lb (Kirschbaum and Biewick, 2000; Hoffman et al., 1993; McLemore et al., 1984a).

This field contains four small mines that were active between 1933 and 1958 with a total known production of 282 tons. Map Point C32 (Leasables Index Map 4, Unit 4) marks the location of at least three small coal prospects in the Chacra Mesa field that may represent the mines mentioned above.

3.1.2.2.4 San Mateo Coal Field

The San Mateo coal field lies south of the Chacra Mesa field, extending from the northern boundary of Township 16 North southward to the first outcrops of the Point Lookout Sandstone (Leasable Index Maps 4 and 8). This sandstone also separates the San Mateo field from the Crownpoint field to the west and from the South Mount Taylor field to the east. The San Mateo field is separated from the La Ventana field by the boundary between Ranges 2 and 3 West. The San Mateo field extends through portions of Cibola, Sandoval, and McKinley Counties in Planning Units 1, 2, and 4. The western portion of this field comprises north-south trending anticlines and synclines. The eastern side contains no significant structures. Two nearby domes, the San Mateo dome and the Miguel Creek dome, have affected coal deposits in the area (Kirschbaum and Biewick, 2000; McLemore et al., 1984a).

The only coal-bearing layer in the San Mateo coal field is the Cleary Coal Member of the Menefee Formation. Coal seams range from 1.6 to 5.9 feet thick (McLemore et al., 1984a), but at least one seam has been measured at more than 15 feet thick (Kirschbaum and Biewick, 2000). The two main coal seams within the Cleary Coal Member are named “blue” and “purple.” As in the Chacra Mesa field, coals in the San Mateo field are generally thickest to the west and directly above the contact with the Point Lookout Sandstone. Coals are more resinous and pyritic in the San Mateo than in the Chacra Mesa field, and lower coal seams are associated with high-gamma sandstones. All San Mateo coals are subbituminous A, averaging 13 percent ash and 1 percent sulfur. Heating values average 9,865 BTU/lb with a standard deviation of 1,088 BTU/lb.

The only mine of note in the San Mateo coal field is the Lee Ranch mine, north of the Rio Puerco planning area, which produced approximately 32 million short tons of coal between 1984 and 1995 (Kirschbaum and Biewick, 2000). The mine is still active as of 2009, with a total production of 3,334,698 short tons in 2008 (MSHA, 2009).

3.1.2.2.5 Mount Taylor Coal Field

The Mount Taylor coal field is located in Townships 11 to 15 North, Ranges 3 to 6 West, east of the Mount Taylor volcanic field in Planning Units 2 and 4 (Leasable Index Maps 4 and 8). This area covers parts of McKinley, Sandoval, and Cibola Counties. Kirschbaum and Biewick (2000) note that the historic



usage of the name “Mount Taylor Coal Field” included several adjacent fields such as the San Mateo and Rio Puerco fields. However, the current discussion is limited to the area noted above.

The underlying geologic structure is quite simple and contains few faults. Coal beds typically dip less than 5° to the north-northwest and are covered by Tertiary basalt that can reach thicknesses of up to 100 feet. However, the surface relief is very rugged, with canyons ranging between 500 and 1,000 feet deep (McLemore et al., 1984a).

The Mount Taylor coal field contains the Gibson and Dilco Coal Members of the Crevasse Canyon Formation in its southern region and only the Gibson in the eastern region. Coals are lenticular in nature and are typically between 2 and 7 feet thick. Spotty coal beds in the eastern portion of the field are up to 6.5 feet thick. Mount Taylor coals are subbituminous A to high-volatile C bituminous, but not many samples have been taken. The few analyses that do exist show an ash content of about 6 percent and a sulfur content of about 0.6 percent. Heating values average 11,738 BTU/lb (Kirschbaum and Biewick, 2000; McLemore et al., 1984a).

Four small mines or prospects were in operation between 1924 and 1954 in the eastern part of the field, but production and location data for these sites are unknown. Rekindled interest in the 1960s faded when drilling data indicated insufficient coal in the region.

3.1.2.2.6 Crownpoint Coal Field

Although the Crownpoint coal field is a major coal-bearing region, it only intersects the Rio Puerco planning units at its extreme southeastern end (Leasable Index Map 8) and has no coal prospects or mines in the study area. The Crownpoint field intersects Planning Unit 1 in Townships 12 and 13 North, Range 8 West, in McKinley and Cibola Counties near the town of San Mateo. The field itself is defined by outcrops of the Point Lookout Sandstone to the north and east and the southernmost outcrops of the Crevasse Canyon Formation to the south (Hoffman et al., 1993).

Strata dip gently to the north throughout most of the field, but the region near and within Planning Unit 1 is more complex. Faults are known to occur, but the subsurface is less well-defined due to the lack of drilling data. However, drilling to the northwest indicate a general change from sandstone to shale and siltstone towards the east (Hoffman et al., 1993).

The Crownpoint field contains the Dilco and Gibson Coal Members of the Crevasse Canyon Formation. The Dilco coal seams are thin but numerous. The Gibson coals are up to 6 feet thick and occur in zones of 3 to 13 beds. The coals have moderate clarain, fair to moderate cleat, and variable quantities of pyrite and resin. Coals are hard and rank subbituminous B-A, with about 12 percent ash and 1.4 percent sulfur. Heating value averages 10,037 BTU/lb with a standard deviation of 923 BTU/lb (Kirschbaum and Biewick, 2000; Hoffman et al., 1993).

Eleven mines were known to exist in this field from 1918 to 1963, but they likely lie north of the Rio Puerco planning units (Kirschbaum and Biewick, 2000).



3.1.2.2.7 Rio Puerco Coal Field

The Rio Puerco coal field lies within the Rio Puerco valley in Townships 8 to 14 North, Ranges 1 East, 1 to 3 West in Cibola, Sandoval, Bernalillo, and Valencia Counties (Leasable Index Maps 5, 8, 9, 13, and 14). This region extends through both the southwestern portion of Planning Unit 4 and the middle of Planning Unit 2. Faulting associated with the Rio Puerco fault zone has disrupted coal-bearing strata in a large portion of the field. The major coal-bearing member is the Gibson Coal Member of the Crevasse Canyon Formation; however Kirschbaum and Biewick (2000) also report occurrences of the Cleary Coal Member of the Menefee Formation and the Dilco Coal Member of the Crevasse Canyon Formation. Gibson Coal occurrences tend to be lenticular and are often steeply tilted due to fault activity. McLemore et al. (1984a) report an average bed thickness of 2.5 feet (beds less than 1.2 feet were not considered), but they note that beds up to 7.6 feet thick occur in the northern part of the field. Kirschbaum and Biewick (2000) report an average bed thickness of 3.8 feet with a maximum thickness of 9.6 feet, including two partings (Kirschbaum and Biewick, 2000; McLemore et al., 1984a).

Analytical data from this field is sparse due to a lack of samples. McLemore et al. (1984a) note that no exploratory drilling has been performed in the field. Kirschbaum and Biewick (2000) report analytical data from only four samples, all from the Gibson Coal Member. The coals are subbituminous A to high-volatile C bituminous, with an average ash content of about 8 percent and a sulfur content of about 0.9 percent (Kirschbaum and Biewick, 2000). McLemore et al. (1984a) note that Rio Puerco coals have 21 percent more sulfur than other Crevasse Canyon Formation coals. Heating values average 10,224 BTU/lb (McLemore et al., 1984a).

Despite the complicated geology and unfavorable coal occurrences, six small mines are reported to exist in the Sandoval County portion of the field (Map Points C22, C23, C25, C26, and C27, Leasable Index Map 9, Unit 4). These mines operated from the 1920s through part of the 1940s, producing a total of 3,069 tons and may have supplied a nearby railroad. Two mines, the Canoncito (Map Point C5, Leasable Index Map) and the Ferro (Map Point C3, Index Map 8, Unit 4), were located in extreme western Bernalillo County and produced a total of 30,987 tons (Kirschbaum and Biewick, 2000; McLemore et al., 1984a).

3.1.2.2.8 Gallup Coal Field

The Gallup coal field covers part of southwestern McKinley County (Leasable Index Maps 3 and 7). The southern portion of the field is included in Planning Unit 1 and the northern part of the field extends north of Interstate 40 into the Navajo Nation. The eastern edge of the field is defined by outcrops of the Gallup Sandstone along the Nutria monocline, and the western edge is marked by steeply dipping beds of Gallup Sandstone associated with the Defiance uplift. The southernmost extent of the field is delineated by the boundary between Townships 11 and 12 North. The interior of the coal field consists of the Gallup and Torrvio anticlines and the Gallup sag.

The Gallup coal field contains the Cleary-Gibson Coal Members of the Menefee and Crevasse Canyon Formations. In this area, the two coal members are considered one undivided member due to the pinching out of the sandstone and shale layers that separate them. The Gallup coal field also includes the Dilco



Coal Member of the Crevasse Canyon Formation. Sandstones and shales predominate in these members, along with some siltstone. Coal thickness is greatest north of the Rio Puerco planning area and thins to the south and west. The McKinley mine (north of the Rio Puerco planning area) produces all of its coal from the Cleary-Gibson Coal Member in four seams: the green, blue, fuchsia, and yellow. Cleary-Gibson Member seams are typically 2.5 to 3.5 feet thick and tend to be more continuous west of Highway 602 (formerly 666); however the drillings that established this fact were slightly north of Interstate 40 and thus outside the planning area. The Dilco Coal Member of the Crevasse Canyon Formation is a sequence of sandstones, shales, carbonaceous shales, and thin (1 to 2 feet) coal seams. However, two seams measured in Township 15 North, Range 18 West, Section 4 (just north of the Rio Puerco planning area) were approximately 8 and 8.5 feet thick, respectively. They may represent the previously mined Black Diamond and Otero coal seams. The thickest Dilco Coal Member seam south of Gallup was 5.85 feet (Kirshbaum and Biewick, 2000; Hoffman et al., 1993).

The Cleary-Gibson coals are hard with good cleat. They contain large to moderate amounts of vitrain interbanded with clarain and durain. Banding is fine to medium. Although some resin and pyrite was found, very few samples were shaly. Dilco coals tend to be pyritic and shaly with moderate vitrain. Banding is thicker in the deeper seams, and little to no resin is present. Cleat varies from poor to good (Hoffman et al., 1993). The rank of the Gallup Field coals ranges from subbituminous A to high-volatile C bituminous. The Cleary-Gibson coals have about 9 percent ash and 0.5 percent sulfur. The Dilco coals contain the same amount of ash but 0.8 percent sulfur. The heating value for Cleary-Gibson coals is 10,507 BTU/lb (standard deviation unknown) and the heating value for the Dilco coals is 10,343 BTU/lb with a standard deviation of 3,220 (Kirschbaum and Biewick, 2000).

Over 85 coal mines have operated in the Gallup coal field. Two of these, the Carbon #2 mine (Map Point C28, Leasable Index Map 7, Unit 1), and the Amcoal #1 mine (Map Point C24, Leasable Index Map 7, Unit 1), reside in Planning Unit 1, southeast of Gallup. Both are inactive and have been reclaimed (Lucas-Kamat, 2009). As mentioned above, the McKinley mine is currently extracting coal north of Planning Unit 1 and appears to be the only active mine in the region (Kirshbaum and Biewick, 2000; EPA, 2009).

3.1.2.2.9 Zuni Coal Field

The Zuni coal field is a continuation of the Gallup coal field onto the Zuni Indian Reservation (Leasable Index Maps 7 and 12). This field lies within the Zuni Basin, a northwest-trending syncline. The northern extent of this coal field is the boundary with the Gallup field proper at the line between Townships 11 and 12 North. The field is in Cibola and McKinley County and lies within Planning Unit 1.

Coals are found in the Dilco Coal Member of the Crevasse Canyon Formation, the Ramah Unit of the Gallup Sandstone, and the Carthage Member of the Tres Hermanos Formation. Carthage Member coals are 3 to 4 feet thick and Gallup Sandstone coals seams can be up to 7 feet thick. Coals in this field are ranked high-volatile C bituminous. Analyses are only available for the Ramah Unit of the Gallup Sandstone, which has an ash content varying from 8.8 to 36 percent and a sulfur content varying from 0.6 to 1.5 percent. Heating values for this coal ranges from 10,470 to 11,250 BTU/lb.



Three small mines operated in the area between 1905 and 1958, but their locations are unknown (Kirshbaum and Biewick, 2000).

3.1.2.2.10 Salt Lake Coal Field

The Salt Lake field is delineated by outcrops of the Cretaceous Moreno Hill Formation, a package of sandstones, siltstones, mudstones, and coal. The field extends from the western border of New Mexico to Range 15 West, and from Township 6 North to Township 1 North in southern Planning Unit 1 (Leasable Index Maps 11 and 12). The field extends through both Cibola and Catron Counties. The dip of the Moreno Hill Formation in this area is generally between 3° and 5° to the southeast, with a few minor variations (Kirshbaum and Biewick, 2000).

Coals in the Salt Lake field exist in four zones within the Moreno Hill Formation: the Antelope, the Cerro Prieto, the Rabbit, and the Twilight. Small amounts of coal are also present in the underlying Dakota Sandstone. These coals lie within 260 feet of the surface and are usually about 5 feet thick, although layers as thick as 14 feet have been noted. The frequency of coal seams increases as one approaches the Atarque Sandstone contact. Coals lower in the section tend to be associated with shales; sandstones become more common upsection. Two noteworthy coal seams (5.4 and 7.4 feet thick, respectively) are reported to occur in the lower member of the Moreno Hill Formation at Township 3 N, Range 17 West, Section 1 and Township 5 N, Range 16 West, Section 30 (Kirshbaum and Biewick, 2000; Hoffman et al., 1993).

Moreno Hill Formation coals are subbituminous A and have abundant vitrain with moderate banding and good cleat. Some pyrite has been noted in samples, and thicker coals tend to have a thin parting of claystone or tonstein. Ash content is about 17 percent and sulfur content is about 0.7 percent. Heating value averages 9,166 BTU/lb with a standard deviation of 837 BTU/lb (Kirshbaum and Biewick, 2000; Hoffman et al., 1993).

The Salt Lake Field has been the focus of leasing and exploration in the 1980s, and the Fence Lake #1 mine south of the Planning Unit 1 produced about 100,000 short tons of coal before closing in 1987 (Kirshbaum and Biewick, 2000). No mines or prospects are known to occur in the Rio Puerco planning area portion of the Salt Lake coal field.

3.1.2.2.11 Datil Mountain Coal Field

The Datil Mountain coal field extends from Township 1 North to Township 9 North and from Range 3 West to Range 11 West and crosses Socorro, Cibola, and Valencia Counties (Leasable Index Maps 13, 14, and 16). The northern half of the field is located in Planning Unit 1, but a small section intersects the extreme southwestern corner of Planning Unit 2. The Datil Mountain field is defined by the Lucero uplift and the Ladron Mountains to the east and the Malpais to the west. The northern edge of the field is marked by erosion and the northern portion of the field consists of the McCarty syncline; the southern portion is complicated by Tertiary volcanic deposits, dikes, and faulting (Frost et al., 1979). The northern part of the field typically has dips of less than 10° while the more deformed southern part can have dips of up to 45°.



Coals in the Datil Mountain field are found in the Dilco Coal Member of the Crevasse Canyon Formation. Coal seams are typically less than 3 feet thick, although seams up to 4.5 feet thick have also been reported. They have an average rank of subbituminous A, with an ash content of about 13 percent and a sulfur content of about 0.7 percent. Average heating value is 11,465 BTU/lb with a standard deviation of 869 BTU/lb. Four small mines or prospects have operated in this field, none of which are located within the Rio Puerco planning units (Frost et al., 1979; Kirshbaum and Biewick, 2000).

3.1.2.2.12 Hagan (Una del Gato) Coal Field

The Hagan coal field (also known as the Una del Gato coal field) is a small coal occurrence along the axis of a syncline in Planning Unit 5 (Sandoval County). The field runs north-south through Townships 12 to 13 North, Range 6 East (Leasable Index Map 9) and is correlated with the Menefee Formation. The coal beds typically dip less than 20°, but faulting complicates parts of the field (McLemore et al., 1984a).

Coal seams in this field tend to be thin, though some are up to 5 feet thick. The coals average 8.3 percent ash and 0.66 percent sulfur, which is low for Menefee Formation coals. Heating value averages 10,508 BTU/lb (McLemore et al., 1984a).

Mining began in 1903 in the Hagan coal field with the opening of the Hagan mine (Map Point C14, Leasable Index Map 9, Unit 5). Several other mines, including the Sloan (Map Point C19, Leasable Index Map 9, Unit 5), Pina Vititos (Map Point C20, Leasable Index Map 9, Unit 5), and Tejon (Map Point C17, Leasable Index Map 9, Unit 5) operated during this time period. No mining activity is reported after 1939. In total, the Hagan field produced 115,465 tons of coal (McLemore et al., 1984a).

3.1.2.2.13 Placitas Coal Field

The Placitas field is a small series of coal outcrops in Planning Unit 5 (Sandoval County) near the Hagan coal field. The field lies within Township 13 North, Range 5 East (Leasable Index Map 9). The coal occurs in the Menefee Formation and dips 45° to 70° to the northeast. Three coal prospects are known to have existed in this area. One, the Taraddei prospect (Map Point C12, Leasable Index Map 9, Unit 5), produced 265 tons (McLemore et al., 1984a).

3.1.2.2.14 Tijeras Coal Field

The Tijeras coal field is located in Townships 10 to 11 North, Ranges 5 to 6 East in Bernalillo County (Planning Unit 5, Leasable Index Map 9). The field consists of two synclines with dips of up to 30°. Although the precise formation is not known, the coals are within the Mesaverde Group and are found in two zones. The upper zone is reported to be higher quality. Coal seams are up to 3 feet thick, but tend to be highly deformed. Only one sample of Tijeras coals was analyzed for rank, and it was found to be of high volatile B bituminous. Average sulfur content was 1.53 percent and average ash content was 20 percent from three samples. The one sample analyzed for heating value generated 10,293 BTU/lb (McLemore et al., 1984a).



Coal mining was underway in the Tijeras field in 1898 and the Tocco Mine (Map Point C9, Leasable Index Map 9, Unit 5) produced 350 tons of coal in 1910 and 160 tons in 1911. Production figures for other mines are not available, and no mining is reported after 1911 (McLemore et al., 1984a).

3.1.2.3 Resource and Development Potential

This section describes coal resource and development potential. The reader is referred to Figure 16 for the locations of the coal fields.

3.1.2.3.1 Star Lake Coal Field

McLemore et al. (1984a) note a high resource potential in the Star Lake Coal Field based on outcrops, drill hole data, and continued interest, however they also state that development potential will depend on the availability of railroads. Kirschbaum and Biewick (2000) report demonstrated surface-mineable coal reserves of 946 million short tons; this represents material in coal seams greater than 2.5 feet thick with less than 200 feet of overburden. McLemore et al. (1984a) report a value of about 1,065 million tons of coal reserves with less than 250 feet of overburden. However, coals in this field are the poorest quality of all the Fruitland Formation fields (Kirschbaum and Biewick, 2000; McLemore et al., 1984a). Overall, INTERA has determined that the resource potential for the Star Lake field is high with direct certainty (H,C) even though the point density mineral potential map indicates low resource potential (Plate 56). This is because our databases only cover mines and occurrences located within the five planning units, and therefore point density resource potential estimations for coal fields extending outside the study area will be artificially low. Thus the point density map for the Star Lake field (the majority of which is west of Unit 4) is not as reliable as it is for the La Ventana or Tijeras fields (both contained entirely within the study area).

3.1.2.3.2 La Ventana Coal Field

The Upper Coal Member contains about 130 million short tons of coal, with an estimated 75 million with less than 200 feet of overburden (Kirschbaum and Biewick, 2000). Therefore, McLemore et al. assigned this field high resource potential, and INTERA concurs with this assessment, high potential with abundant direct evidence (H,D). The point density map also indicates that this field has high resource potential, with a cluster of coal mines and occurrences south of Cuba (Plate 56). However, lack of transportation has historically limited production at this coal field, although much of the area is conducive to strip mining (McLemore et al., 1984a).

3.1.2.3.3 Chacra Mesa Coal Field

There are an estimated 269 million short tons of demonstrated underground reserves in the Chacra Mesa coal field, and the area is conducive to strip mining (Kirschbaum and Biewick, 2000). McLemore et al. (1984a) assigns a high level of potential to the Chacra Mesa field but notes that the area is difficult to develop due to the lack of transportation (McLemore et al., 1984a). INTERA considers the resource potential to be high with direct certainty (H,C) but resource potential as indicated by point density mineral potential map is low because most of the field lies to the west of the study area.

3.1.2.3.4 San Mateo Coal Field

With the exception of the Lee Ranch mine, little activity has been reported in the San Mateo Coal Field, however McLemore et al. (1984a) assigns it a high resource potential due to favorable geology. INTERA concurs, with direct certainty (H,C) though the lack of data within the study area precludes the use of the point density mineral potential map. The field contains a demonstrated reserve of about 450 million short tons of coal with less than 200 feet of overburden. However, like other nearby coal fields, the San Mateo field suffers from lack of adequate transportation (Kirschbaum and Biewick, 2000; McLemore et al., 1984a).

3.1.2.3.5 Mount Taylor Coal Field

About 14 million short tons of coal under 200 feet of overburden and 37 million tons under 1,000 feet of overburden and in beds greater than 3.5 feet thick exist in the Gibson Coal Member in the southern part of the Mount Taylor field (Kirschbaum and Biewick, 2000). However, the lenticular nature and thinness of the coal beds in the Mount Taylor field led McLemore (1984b) to assign it moderate to low resource potential, and INTERA concurs, low with indirect certainty (L,B). State databases consulted for this study did not report any occurrences or developments of coal in this field so there is no potential shown on the point density mineral potential map. Development potential is low because of the rough terrain and massive basalt capping units (McLemore et al., 1984a).

3.1.2.3.6 Crownpoint Coal Field

There are an estimated 663 million short tons of coal within the Gibson Coal Member with overburden of less than 200 feet. Other estimates put 15 million short tons of strippable Gibson Coal Member coal in this field (Kirschbaum and Biewick, 2000). The resource potential for this field is judged to be moderate with direct certainty (M,C). There is no resource potential based on point density because most of the Crownpoint Field is located to the north of the study area.

3.1.2.3.7 Rio Puerco Coal Field

The estimated reserves for the Sandoval County portion of the Rio Puerco coal field are 184.6 million short tons. The southern portion of the Rio Puerco field is believed to contain about 175 million tons of coal (not including seams less than 1.2 feet thick), but the presence of faults precluded reserve calculations (McLemore et al., 1984a). Kirschbaum and Biewick (2000) report a demonstrated coal resource of 25 million short tons for the entire field. McLemore et al. (1984a) considered the resource potential for this field to be low because of the presence of numerous high-angle faults and the general lack of data. However, they considered the northern region to have the highest resource potential because of its smaller number of faults and higher quality of coal outcrops. Based on McLemore's assessment and point density measurements, INTERA rates the resource potential to be low up to moderate with direct certainty (L,C to M,C). The point density resource potential map (Plate 56) assigns the southern portion of the Rio Puerco Field a low resource potential. However, point density mineral potential is moderate to the southeast of San Ysidro, where several humate mines and coal occurrences are known to exist. Development potential is very low because of complications associated with faulting and lenticular beds combined with the lack of transportation in the region (McLemore et al., 1984a).

3.1.2.3.8 Gallup Coal Field

An estimated 449 million short tons of demonstrated coal resources remain in the Cleary-Gibson Coal Member of the Gallup field. The Dilco Coal Member contains demonstrated coal resources of 161 million short tons under less than 200 feet of overburden (Kirschbaum and Biewick, 2000). The resource potential for the Gallup field is rated as high with direct certainty (H,C), but point density resource potential is low because most of the field lies to the north of the study area.

3.1.2.3.9 Zuni Coal Field

About 6 million short tons of strippable coal are reported to exist in three areas in the middle of the field (Kirschbaum and Biewick, 2000). Another study cited by Kirschbaum and Biewick estimated 49 million short tons in the Gallup Sandstone to the southeast (Kirschbaum and Biewick, 2000). The resource potential of the Zuni field is rated as high with direct certainty (H,C). The point density mineral resource potential does not apply in this case because the state databases queried for this report do not provide comprehensive coverage of Indian reservations.

3.1.2.3.10 Salt Lake Coal Field

Within the Salt Lake field, the Cretaceous Moreno Hill Formation is estimated to have 323 million short tons of coal under less than 200 feet of overburden, assuming a seam thickness of greater than 2.5 feet (Kirschbaum and Biewick, 2000). The resource potential of this field is high with direct certainty (H,C). Point density resource potential is nonexistent because the field is on the southern edge of Planning Unit 1.

3.1.2.3.11 Datil Mountain Coal Field

About 47 million short tons of coal are thought to exist in this field (Frost et al., 1979; Kirschbaum and Biewick, 2000). The resource potential is judged to be moderate with direct certainty (M,C) due to a relative lack of exploration and production in this coal field. There are no coal point occurrences on the coal mineral Index Map in this field, thus the point density resource potential is nil.

3.1.2.3.12 Hagan (Una del Gato) Coal Field

Estimated reserves in the Hagan field are 17.3 million tons, but the coal is difficult to extract due to faulting, steeply dipping beds, and the thinness of the coal seams. McLemore et al. (1984a) determined that resource potential was moderate to low, and the development potential was low. INTERA concurs that the resource potential is moderate with abundant direct evidence (M,D). The point density map (Plate 56) indicates moderate resource potential due to the presence of several points of occurrence.

3.1.2.3.13 Placitas Coal Field

McLemore et al. (1984a) considered the resource potential of the Placitas field to be moderate to low and the development potential to be low because of the steeply dipping nature of the coal seams, which make it hard to access the coal. Our assessment of current resource potential remains the same as that of McLemore et al (1984a), moderate, with abundant direct evidence for the level of certainty (M,D). The point density mineral potential map (Plate 56) agrees with this assessment.

3.1.2.3.14 Tijeras Coal Field

McLemore et al. (1984a) determined that the Tijeras field had low resource and development potential because of the thinness of the coal beds and the impracticality of strip mining on the two synclines. However, INTERA's assessment of current resource potential is moderate with abundant direct evidence for the level of certainty (M,D) based on the point density mineral potential map (Plate 56).

3.1.3 Geothermal Resources and Hot Springs

A geothermal resource is a reservoir of heat within the Earth's crust. Geothermal resources are grouped into three categories: high temperature, moderate temperature, and low temperature. The highest temperature (vapor-dominated) geothermal resources are used to generate electricity. This energy typically is produced in the form of steam at greater than 455 °F. Lower temperature fluids (300 to 700 °F) are used in flash-steam power plants, which use the transition from high-pressure liquid to steam in order to generate power. The lowest temperature usable for power plants is about 212 °F. These plants use a heat exchanger to volatilize a fluid with a low boiling point in order to drive a turbine (Hulen and Wright, 2001).

Low to moderate temperature geothermal fluids (95 to 300 °F) can be used for a variety of purposes. Traditionally, fluids in the comfortable swimming range have been used for medicinal and recreational bathing. However, other uses for moderate and low temperature waters have dramatically increased in the last decade. Geothermal fluids are now being used in aquaculture, greenhouses, building heat, leaching of metal ores, and drying.

Geothermal energy currently produces about 2,600 megawatts of electric power in the U.S., ranking third behind hydroelectric and biomass power in the list of renewable energy utilization in our nation (Hulen and Wright, 2001; Geothermal Resources Council, 2005).

New Mexico has more acreage devoted to geothermal greenhouses than any other state. Uses of low and moderate temperature geothermal resources in New Mexico include aquaculture and space heating. A variety of hot springs and spas throughout the state also cater to tourists. However, no geothermal power plants are presently operating or being developed in New Mexico despite a period of intense high-temperature geothermal resource exploration during rising energy prices in the 1970s and 1980s (Witcher, 2002; Wentz, 2002; Fleischmann, 2006).

The USGS uses criteria set forth by the *Geothermal Steam Act of 1970* to designate certain areas as Known Geothermal Resource Areas (KGRAs). The New Mexico State Land Office has also created the category of Known Geothermal Resource Fields (KGRFs) to delineate regions in the state where geothermal energy could potentially occur (McLemore et al., 1984a). Both designations are used in this report to discuss geothermal resources in the Rio Puerco planning area.

3.1.3.1 Geologic Setting

Geothermal heat is associated with areas of recent volcanism and is most visibly expressed by hot springs, fumaroles, geysers, and other hydrothermal features. Figure 19 shows the potential geothermal resource



areas within the U.S. and Figure 20 shows the volcanic fields (in pink) in New Mexico. These resources have been used throughout history as a source of hot water for cooking and bathing. Such phenomena are the surface representation of a vast underground system of hot, convecting fluids. Some of these systems are completely sealed off from the surface and require more sophisticated methods of exploration to discover. These heat reservoirs are commonly associated with volcanism, young intrusive rocks, and highly permeable fracture systems in regions with a high geothermal gradient. Other geothermal resources are located in deep sedimentary basins. Finally, some young igneous intrusions are theoretically capable of producing vast amounts of energy (Hulen and Wright, 2001).

Within the Rio Puerco planning area geothermal resources exist in the Jemez Mountain area within Planning Unit 4 where a KGRF is designated due to the presence of the Jemez volcanic field. Geothermal resources are also present within Planning Unit 2, where a KGRF has been defined due to Quaternary volcanism, high measured heat flows, and geothermal wells. Another KGRF is present in Planning Unit 1, in the southern San Juan Basin.

3.1.3.2 Exploration, Development, and Production History

The Valles Caldera is home to the Baca #1 KGRA inside the Jemez Mountains KGRF within BLM Planning Unit 4. This KGRA was extensively drilled during the 1970s and 1980s. The Baca Demonstration Project developed out of a partnership between the Union Oil Company of New Mexico, the Public Service Company of New Mexico, and the U.S. Department of Energy (DOE) to explore the possibility of a geothermal power plant north of Jemez Springs. The first four wells produced 320,000 pounds of steam per hour from geothermal fluids. After these encouraging results, more wells were drilled to produce steam for a proposed power plant. However, only 268,000 pounds of steam were being produced from the well field three years later, far short of the 900,000 lbs needed for the power plant. The project languished due to the high cost of further drilling and the poorly characterized nature of the initially promising reservoir (McLemore et al., 1984a).

The Baca well field consists of 23 wells. The deepest reaches a total depth of 8,284 feet below ground surface (Map Point GTW100, Leasable Index Map 5, Unit 4). This well also attained the highest temperature of all the wells, reaching 649 °F at the bottom of the hole (Richards, 1999).

The Fenton Lake Hot Dry Rock project was conducted by the Los Alamos National Laboratory in the Baca #1 KGRA from 1971 to 1995. The project planned to demonstrate the feasibility of drilling an injection well into hot rocks at depth, creating a fracture field by the application of pressurized water, and then drilling a second well a short distance away. The idea was to inject water into the first well and extract the (now superheated) water from the second well. The Fenton Lake project proceeded in two stages. The first stage created a fracture field in jointed granite 9,200 feet below ground level with a mean temperature of 383 °F. These wells produced water between 313 to 300 °F at a rate of 90 gallons per minute during final flow testing. Well GT-2 (Map Point GTW114, Leasable Index Map 5, Unit 4) was the extraction well for this project, and well EE-1 (Map Point GTW116, Leasable Index map 5, Unit 4) was the injection well (Duchane and Brown, 2002).



The second stage of the project was intended to create multiple reservoirs in deeper and hotter rocks (14,000 feet below ground level, 455 °F). Initial efforts failed at creating a hydraulic connection between the injection and recovery wells, but re-drilling finally allowed circulation to commence. A small surface plant was constructed and several long-term flow tests were conducted, the longest being 112 days. Water was produced at about 361 °F at about 95 gallons per minute during these tests (McLemore et al., 1984a; Duchane and Brown, 2002; Brown, 2009).

McLemore et al. (1984a) mentions another project conducted by Los Alamos National Laboratory to extract geothermal energy for space heating on the Pajarito Plateau. A reservoir was found 1,970 feet underground containing waters between 86 to 95 °F with predicted deeper reservoirs having temperatures over 194 °F. However, an attempt to reach this reservoir was unsuccessful (McLemore et al., 1984a).

McLemore et al. (1984a) also notes that the southern Valles Caldera region is geologically favorable for the existence of additional geothermal resources. Industry watchers surveyed by Fleischmann (2006) believe that the entire region would benefit from a new geothermal resource potential survey. Some respondents also mentioned that new technology could revitalize and render economical the principles behind the Fenton Hill experiment. However, the federal government recently purchased the Valles Caldera Baca Grant and restrictions now stand in the way of future development in this area (McLemore et al., 1984a; Fleischmann, 2006).

Numerous hot springs in the area, including San Antonio Hot Spring (Map Point HS31, Leasable Index Map 5, Unit 4), Spence and Little Spence Springs (Map Points HS27 and HS30, Leasable Index Map 5, Unit 4), Sulfur Springs (point HS28, Leasable Index Map 5, Unit 4), and Alamo Canyon Spring (Map Point HS29, Leasable Index Map 5, Unit 4), underscore the numerous geothermal reservoirs in the Baca #1 KGRA and surrounding Jemez KGRF.

The San Ysidro/Jemez Springs area (San Ysidro KGRA) contains hot and warm springs. In addition, the town of Jemez Springs has at least two geothermal bath houses. The area's most famous geothermal landform is the Soda Dam, a feature formed by travertine deposited by a series of hot springs (Map Point HS25, Leasable Index Map 5, Unit 4). McLemore et al. (1984a) mention that geothermal waters are used for a greenhouse and to heat the Jemez Springs town hall (McLemore et al., 1984a). The Pueblo of Jemez researched geothermal space heating opportunities in 2004 and found some potential, but further drilling is required before this potential can be realized (Fleischmann, 2006). Resistivity surveys in the early 1980s found evidence of small geothermal fluid reservoirs along the Jemez Fault (McLemore et al., 1984a).

A series of tepid to warm springs with temperatures around 70 °F exist along the axis of the San Ysidro anticline and on the west side of the Nacimiento Mountains (Map Points HS15-17, HS19, Leasable Index Map 5, Unit 4), and a cluster of wells in the southwest corner of Sandoval County (Map Points GTW41-46, Leasable Index Map 4, Unit 4) contain fluids at about 60 °F, much too low for geothermal energy purposes (McLemore et al., 1984a; Richards, 1999).



Photograph: Bowman, INTERA, 2009.

A tepid spring near San Ysidro (0.5 miles southeast of Map Point HS15, Leasable Index Map 5).

The New Mexico State Land Office has defined a KGRF in western Bernalillo County, western Valencia County, and eastern Cibola County within BLM Planning Unit 2. The presence of Quaternary volcanoes, high measured heat flows, and geothermal wells has contributed to this decision. A well about 2 miles west of the Rio Puerco River along Interstate 40 (Map Point GTW15, Leasable Index Map 9, Unit 2) encountered waters up to 235 °F (McLemore et al., 1984a). A well just west of Isleta Volcano (point GTW7, Leasable Index Map 14, Unit 2) yielded geothermal fluids up to 433 °F, but this well was over 21,000 feet deep (McLemore et al., 1984a).

The Sandia Savings Building in Albuquerque was being heated using a geothermal heat pump system as early as 1979 (Rodriguez et al., 1979; McLemore et al., 1984a). Fleischmann (2006) notes the potential for other direct geothermal use applications in the metro area along with the existence of significant temperatures detected in natural gas wells throughout the Albuquerque Basin. In fact, Fleischmann mentions that developers were considering using geothermal space heating in the new Mesa del Sol development in South Albuquerque.

A series of salt springs occur along the Rio Puerco near Highway 6. These springs have temperatures of around 77 °F. They are part of a line of springs located in western Valencia County in Planning Unit 2 (Map Points HS1-HS3, HS5-HS8, HS10, Leasable Index Map 13, Unit 2) (Fernandez, accessed 2009).



Wells in the southern San Juan Basin sometimes contain abnormally warm waters that may represent fluids rising from the deep subsurface along fractures. A number of these wells are scattered across Unit 1, especially south of Gallup. A 1,059-foot-deep well south of the town of Black Rock (Map Point GTW16, Leasable Index Map 7, Unit 1) had a bottom temperature of 93 °F, but most wells in the area found lower temperatures (McLemore et al., 1984a; Richards, 1999).

3.1.3.3 Resource and Development Potential

McLemore et al. (1984a) assigned a high resource potential to the Baca #1 KGRA in the Jemez Mountains for low through high temperature geothermal resources. They also assigned a high potential for hot dry rocks, and recent articles by Los Alamos National Laboratory tend to support that conclusion (Brown, 2009). The point density map (Plate 63) notes an area of high potential that extends from the western half of the Valles Caldera south along the Jemez River. The resource potential near Jemez Springs was deemed high for low to moderate temperatures (McLemore et al., 1984a). McLemore et al. (1984a) assigned a moderate resource potential to the San Ysidro area, and moderate to low potential to the Pajarito Plateau (McLemore et al., 1984a). However, INTERA judges the resource potential to be high throughout these areas with abundant direct and indirect evidence for the level of certainty (H,D) due to the presence of the known resource, especially in the center of the Valles Caldera area. This is supported by point density mineral resource potential map in that area. The resource potential based on point density is low on the Pajarito Plateau and near San Ysidro, but this likely reflects the high cost of geothermal exploration rather than lack of resources. Development potential is unlikely to be as high as was originally declared in these areas due to changes in economic conditions since the mid-1980s.

Geothermal resource potential and development potential was judged to be high by McLemore et al. (1984a) in the Albuquerque area. The lack of exploration in the area has resulted in low to nonexistent point density resource potential, but the presence of hot wells in the region indicates that there is no need to change McLemore et al.'s (1984a) assessment. However, Southwestern Bernalillo County and a series of salt springs along Highway 6 between Los Lunas and Interstate 40 also have low potential as determined by point density. Geothermal resource potential was declared to be low, moderate, or unknown in the rest of the Rio Grande rift (McLemore et al., 1984a); however, recent natural gas exploration indicates that geothermal resource potential may be higher than previously thought in the Albuquerque Basin (Fleischmann, 2006). McLemore et al. (1984a) noted that development potential was highest in the Albuquerque area and decreased away from the city. Again, the resource is known to be present to some extent at some depth within the Albuquerque area, thus the potential for occurrence is judged by INTERA to be high, with direct evidence for the level of certainty (H,C), even though the point density mineral potential map indicates the potential is low. However, the development potential fluctuates markedly with the price of more conventional, lower cost energy sources.

Although wells in the southern San Juan Basin have occasional elevated temperatures, the depth of these resources and the lack of nearby population centers keeps resource and development potential low (McLemore et al., 1984a). INTERA judges the resource potential to be low with direct evidence for the level of certainty (L,C) and the sparse distribution of geothermal wells supports this assertion (Plate 63).



Although the geologic conditions are favorable for the presence of geothermal energy in many parts of the study area, the actual development potential is judged to be low due to high development costs and the availability of abundant lower cost alternatives. The price of conventional energy (i.e. primarily fossil fuels and nuclear power) would have to increase drastically for a sustained time period, or a vast improvement in technology for harnessing geothermal energy would need to occur to cause a significant shift toward the development of geothermal energy.

3.1.4 Sodium and Halite*

Salt lakes in Torrance County have occurrences of the minerals blödite, glauberite, and halite. Both blödite and glauberite contain sodium (Ralph and Chau, 2009), but the economic viability of extracting this resource is unknown.

3.1.4.1 Geologic Setting

Only two known occurrences of sodium exist in the planning area, both in Torrance County. These deposits consist of evaporates in Laguna del Perro (Map Point NA1, Leasable Index Map 15, Unit 3) and Laguna Salina (point NA2, Leasable Index Map 15, Unit 3), two large playa lakes.

3.1.4.2 Exploration, Development, and Production History

Historical halite mining in this area dates back to 1660, when salt was shipped to silver mines during the Spanish colonial period. More recently, considerable interest in salt and blödite resources was expressed in the 1904 publication *New Mexico Mines and Minerals* (Jones, 1904). This book mentions plans for a salt production and purification facility to be constructed near Laguna Salina, apparently to refine the lake brines for use as table salt. Some salt mining did occur at Laguna del Perro between 1915 and 1933 (McLemore and Wilks, 2009; McLemore, 1984b) and this may be the facility referred to by Jones (1904). Jones also reported that chunks of blöderite weighing several hundred pounds existed on the bottom of Laguna Salina. In 1904, this was the only known blöderite deposit in the United States (Jones, 1904).

3.1.4.3 Resource and Development Potential

The resource potential for sodium and halite at Laguna Salina and Laguna del Perro is high (H,C) based on the presence of a favorable geologic environment. Based on the pattern of use at these lakes and the lack of current development, it is probably safe to say that halite mining interest here is purely historical. Furthermore, no sodium prospecting or development has occurred since the early 1900s. Therefore, INTERA concludes that the development potential is low for both resources. No point density mineral potential map was prepared for these commodities because of this lack of development potential.

3.1.5 Sulfur

Sulfur occurs as a native element in nature, oftentimes associated with hydrocarbons and volcanic activity. A great deal of sulfur is used for sulfuric acid, but it has several other uses as well. Sulfur is

* The Bureau of Land Management classifies halite as a salable mineral, but it is included in this section due to its association with sodium-bearing minerals.



occasionally mined from surface or subsurface deposits. However, the vast majority of the world's sulfur is produced as a byproduct of hydrocarbon extraction and processing, and there are no currently operating sulfur mines in the United States (Geotimes, 2003).

3.1.5.1 Geologic Setting

Small, subeconomic deposits of sulfur are present in the Jemez region (Planning Unit 4, index map 5) associated with hot spring activity. These deposits occur in fissures and as thin bands (McLemore et al., 1984a).

3.1.5.2 Exploration, Development, and Production History

The presence of sulfur in this region has been common knowledge since it was first discovered by Don Juan de Oñate in 1598, but sulfur production has never been extensive. About 100 tons of sulfur was extracted from the area around Sulfur Springs (Map Point S2, Leasable Index Map 5, Unit 4) between 1902 and 1904. The sulfur content is 60 percent but the deposit itself is only a few inches thick. Small scale mine workings at this site represent the only sulfur development in the Rio Puerco Field Office. Another thin, laterally extensive sulfur deposit occurs at the San Diego site (Map Point S1, Leasable Index Map 5, Unit 4) in limestone bedrock. This deposit is about 700 feet long, 150 feet wide, and 2 to 4 inches thick, with 15 to 39 percent sulfur (McLemore et al., 1984a).

3.1.5.3 Resource and Development Potential

Sulfur resource potential in the Sulfur Springs and San Diego areas are considered high due to a history of past production (H,C). However, the Jemez deposits will likely never be more than historical interest due to their small size and lack of recent production. Thus INTERA has determined that development potential is low for this commodity. No point density mineral potential map was prepared for this commodity because of this lack of development potential.

3.1.6 Helium

Helium occurs naturally in the Earth, and it can become concentrated in sufficient quantities to allow for commercial extraction. Once extracted, helium has a wide range of uses. Helium is used in cryogenics (it has the lowest boiling point of any element), fiber optics manufacturing, welding, synthetic breathing and inert atmospheres, and leak detection. Perhaps its most well known use is to provide lift for balloons and blimps (Broadhead et al., 2009). Several occurrences of helium are present in the Rio Puerco Field Office, but none of them have been developed.

3.1.6.1 Geologic Setting

Helium consists of two isotopes. ^3He rises up from the mantle, and ^4He is derived from the radioactive decay of uranium and thorium in granites and uranium ore. Once the helium has been produced, it rises through fractures in the host rock until it encounters an impermeable barrier or is lost to the atmosphere. Due to the small size of the helium atom, most rocks are not able to act as traps because the gas easily diffuses through even the smallest pore spaces. Halite and gypsum, however, make good helium traps because they typically do not have a system of interconnected pores through which it can escape (Broadhead and Gillard, 2004).



3.1.6.2 Exploration, Development, and Production History

Helium production in New Mexico began in 1943 and was first driven by the need for blimps in World War II. After the war, production continued in and near Shiprock, New Mexico until 1990. During the 1990s, production halted due to low gas yields and the opening of more productive fields elsewhere. However, production resumed in northwestern New Mexico in 2001, and continues through the present. No helium production is currently occurring in the Rio Puerco Field Office area, but two occurrences of economical (>0.3 mole percent) concentrations of helium exist in the study area (Broadhead and Gillard, 2004). Gas from an oil test on the west side of the Nacimiento Mountains (Map Point HE8, Leasable Index Map 5, Unit 4) contained 1 percent helium. Gas from a water well in Mesita, New Mexico (Map Point HE3, Leasable Index Map 8, Unit 2) has over 2 percent helium. Given that United States helium reserves are rapidly diminishing and helium prices have risen more than 50 percent in the past two years (ScienceDaily, 2008), these occurrences may represent fields worthy of commercial exploration and development

3.1.6.3 Resource and Development Potential

Helium is present in economical quantities in the Nacimiento Mountains and in a water well near the town of Mesita on Laguna Pueblo. These regions therefore have a moderate resource potential with direct evidence for the level of certainty (M,C) for helium. Development potential is currently moderate due to ongoing helium production elsewhere in the state. However, if helium prices continue to rise and the other helium reservoirs become depleted, development potential can be expected to increase.

3.1.7 Carbon Dioxide

Carbon dioxide has a range of uses, ranging from the mundane to the surprising. For example, carbon dioxide is used to make dry ice, which is essential for long term refrigeration and storage. Carbon dioxide is also used as a propellant in aerosol cans and fire extinguishers, to shred tires, and to provide a noncombustible atmosphere in potentially explosive objects such as grain silos (Broadhead, 2008). However, over 99 percent of all carbon dioxide is used in the oil extraction process (Broadhead et al., 2009).

3.1.7.1 Geologic Setting

Carbon dioxide is a ubiquitous chemical in natural gas, but it rarely constitutes more than 1 percent of the total gas volume. However, some gas reservoirs are almost pure carbon dioxide. This carbon dioxide may come from a variety of sources, including magma, metamorphism (especially of carbonate and carboniferous rocks) and microbial activity. It then rises until it encounters a trap or enters the atmosphere (Broadhead et al., 2009).

3.1.7.2 Exploration, Development, and Production History

Carbon dioxide was produced in small quantities in the Rio Puerco Field Office in the early part of the 20th century. Two small fields in Tarrant County, the northern Estancia field and the southern Estancia field, extracted carbon dioxide for a small dry ice manufacturing facility from 1934 to 1942. These fields are located in Planning Unit 3 (Leasable Index Map 14). Wells J. B. Witt Text (Map Point CDOX4,



Leasable Index Map 14, Unit 3) and DeHart No. 2 (Map Point CDOX3, Leasable Index Map 14, Unit 3) are located in the northern Estancia Field, and well No. 1A Pace (Map Point CDOX2, Leasable Index Map 14, Unit 3) is located in the southern Estancia field. The northern and southern Estancia fields are associated with the Wilcox anticline, which probably serves as a trap for the carbon dioxide (Broadhead, 1997).

Carbon dioxide was not a major commodity before 1970 because the supply in natural gas wells far exceeded the demands of society. However, when it was discovered that the carbon dioxide injection process greatly increased the amount of recoverable petroleum in oil wells, demand for the gas increased. Carbon dioxide reservoirs in the Bravo Dome of northeastern New Mexico and Sheep Mountain in southern Colorado were developed to meet this demand, and these produced enough gas to meet demand until about 2000. Recently, demand has begun to outstrip supply, and interest in new carbon dioxide reservoirs has increased (Broadhead et al., 2009).

A handful of wells and springs in the Rio Puerco Field Office area have economical quantities of carbon dioxide. Gas from an oil test on the west side of the Nacimiento Mountains (Map Point CDOX10, Leasable Index Map 5, Unit 4) contained 86 percent carbon dioxide. Gas from a water well in Mesita, New Mexico (Map Point CDOX8, Leasable Index Map 8, Unit 2) has around 50 percent carbon dioxide, and a well near the Pueblo of Acoma (Map Point CDOX6, Leasable Index Map 13, Unit 2) has about 98 percent carbon dioxide. The previously mentioned wells in the Estancia fields all produced 99 percent carbon dioxide, and an unnamed spring in southwest Valencia County (Map Point CDOX1, Leasable Index Map 13, Unit 2) gives off 98 percent carbon dioxide. Numerous springs in the Jemez and Nacimiento Mountains (Planning Unit 4) are known to produce carbon dioxide, but in such low quantities that McLemore et al. deemed them uneconomical (McLemore et al., 1984a).

3.1.7.3 Resource and Development Potential

The resource potential for carbon dioxide in the Northern Estancia Field and the Southern Estancia Field is high with abundant evidence for the level of certainty (H,D) due to the history of past production from the two fields. Demand for the gas is rising, and this may provide an incentive for renewed exploration and extraction in the area. Therefore, INTERA assigns a high development potential for the Northern Estancia Field and the Southern Estancia Field.

Demonstrated occurrences in the Nacimiento Mountains, near the town of Mesita, and near Acoma Pueblo indicate that resource potential is moderate with direct evidence for certainty (M,C) for carbon dioxide in these regions. The development potential is moderate due to lack of previous production and higher gas concentrations elsewhere in the state. Springs in the Jemez Springs region contain carbon dioxide and therefore have moderate resource potential with direct evidence for certainty (M,C). However, INTERA concurs with the McLemore et al. (1984a) analysis which assigned a low development potential to these springs because they produce so little gas.



3.2 LOCATABLE MINERALS

Locatable minerals can be prospected for, developed, and extracted on federal lands open to mineral entry by the location (staking) of lode or placer mining claims as authorized under the General Mining Law of 1872 (as amended). Locatable minerals known to exist in the planning area include precious and base metals, gypsum, limestone, pumice, rare earth elements (REE), uranium, limestone, pumice, and semiprecious stones. Of these, limestone and gypsum are actively produced. Uranium has been produced in significant quantities in the recent past and could be produced again with an increase in price. Each of the locatable minerals is described in the following sections. Source locations or mining districts for many of the commodities discussed here are shown on the mining district map (Figure 10).

3.2.1 Gold and Silver

This section on gold and silver is based primarily on Resource Map 21 and the associated report by Virginia McLemore of the NMBGMR (McLemore, 2001). Additional data is provided from the NMEMNRD 2008 Annual Report and the NMBGMR minerals database.

Gold is known as a *precious metal*. The combination of gold's relative scarcity and its beauty has made it a valuable commodity throughout human history. Gold does not corrode or rust and its physical and chemical properties make it ideal for a number of industrial applications.

Silver has also been known and used since ancient times. Silver is found combined with a number of different elements to form a variety of minerals and ores. It is also found in trace amounts in gold, lead, zinc, and copper ores.

There are 108 occurrences of gold and silver within the five BLM planning units plotted on the Locatable Index Maps. Gold and silver are combined in the table under the term PREC (precious metals) because many localities have yielded both gold and silver.

3.2.1.1 Geologic Setting

Gold and silver deposits in New Mexico typically occur in rocks formed during five major metal-forming periods: late Tertiary through Quaternary, middle to late Tertiary, Laramide (Late Mesozoic through early Tertiary), late Paleozoic through Mesozoic, and Proterozoic. Some of the state's largest gold deposits occur in a belt that roughly coincides with the boundaries between the Great Plains and Southern Rocky Mountains and Basin and Range (Rio Grande rift) physiographic provinces. These types have also been characterized as alkalic-gold or alkaline-igneous-related gold deposits, porphyry-gold deposits, and Rocky Mountain gold deposits. Examples are the Old Placers district (in the Ortiz Mountains) and the New Placers district (also known as the San Pedro district). Although these deposits are located just east of Planning Unit 5, associated placer gold derived from these deposits could be present in gravels within Planning Unit 5 in the drainages of arroyos with their source in the Ortiz Mountains. Refer to Figure 10 for the locations of the metal mining districts in New Mexico.



The majority of primary gold and silver deposits and occurrences within the Rio Puerco planning area occur in the Cochiti/Bland mining district in Tertiary andesite flows, rhyolite, and a quartz monzonite stock on the southern flank of the Jemez Caldera; in granite and Paleozoic sediments along the west sides of the Sandia and Manzano Mountains; or in veins in Proterozoic metamorphic rocks near Tijeras. Of these, only the Cochiti district has produced significant quantities of non-placer gold and silver. Placer gold in Tertiary and Quaternary gravel deposits in arroyos is related to these primary deposits. These locations correlate with the metal mining districts on Figure 10.

The gold and silver deposits in the Cochiti district (Map Points PREC71-103, Locatable Index Map 5, Unit 4) and on Figure 10 are known as volcanic-epithermal deposits and they are of Eocene to Pliocene age. These deposits are interpreted to have been formed at temperatures between 122 to 572 °F and at pressures of a few thousand pounds per square inch. There is a recognized association between epithermal mineral deposits and active geothermal or hot spring systems. Many volcanic-epithermal deposits are found along the margins of calderas, although not all calderas are mineralized.

The volcanic-epithermal deposits in New Mexico, including those in the Cochiti district, formed largely as siliceous vein fillings, breccia pipes, disseminations, and replacement deposits along faults and fissures in rhyolitic ashflow tuffs and andesites of Oligocene to Miocene age. Ore textures include open-space and cavity fillings, drusy cavities, comb structures, crustifications, colloform banding, brecciation, replacements, lattice textures, and irregular sheeting.

Other types of deposits in which gold and silver occur are sedimentary-copper deposits, Rio Grande rift barite-fluorite-galena and Mississippi Valley-type deposits, and vein and replacement deposits in Paleozoic carbonate rocks and in or associated with contacts with Proterozoic granite and metamorphic rocks. Sedimentary-copper deposits include the Jemez Springs deposit (Map Points PREC67 and PREC68, Locatable Index Map 5, Unit 4) which reportedly produced 1 ounce of gold and 159 ounces of silver and the Nacimiento district (Map Points PREC105-108, Locatable Index Map 2, Unit 4), which produced a trace of gold and 76,000 ounces of silver. The Nacimiento district sedimentary-copper deposit occurs in the Agua Zarca sandstone of the Triassic Chinle Formation. An example of the Rio Grande rift barite-fluorite-galena and Mississippi Valley-type deposits is the Coyote Canyon district (Map Points PREC11-17, Locatable Index Map 14, Unit 2) which consists of veins filling faults and fissures in Proterozoic rocks. The Placitas district (Map Point PREC45, Locatable Index Map 9, Unit 5) is another example of the base-metal and barite-fluorite vein deposit associated with the Sandia granite and overlying Sandia and Madera Formations.

The Tijeras Canyon (Map Points PREC21-25, PREC27-34, Locatable Index Map 9, Unit 2) and the Hell Canyon districts, located in and south of Tijeras Canyon, are vein and replacement deposits in Proterozoic rocks. An additional example of this type of deposit is in the Zuni Mountains (Map Points PREC42-44, Locatable Index Map 7, Unit 1) where gold, silver, and copper occur in quartz veins in shear zones in Proterozoic granite and metamorphic rocks.



3.2.1.2 Exploration, Development, and Production History

Gold and silver are reported in 163 mining districts and other areas of New Mexico. From 1848 through 2000, almost 3.2 million ounces of gold worth more than \$393 million and 117 million ounces of silver worth more than \$252 million were produced in New Mexico (McLemore, 2001).

Of the 108 localities plotted on the Locatable Index Maps, 45 are in the Cochiti/Bland mining district on the southern flank of the Jemez Caldera (Planning Unit 4, Locatable Index Map 5), while 35 are located on Locatable Index Maps 9 and 12 and on Locatable Index Map 14 along the west side of the Sandia and Manzano Mountains. Together these deposits represent the majority of gold and silver occurrences within the BLM planning units.

Table 4 in McLemore (2001) provides the name, location, type of deposit, and production data for many of the deposits in New Mexico. Among those present within the Rio Puerco planning area, only the Cochiti district has had significant gold and silver production. It is described as having produced approximately 42,000 ounces of gold and 208,923 ounces of silver between 1880 and the present (McLemore, 2001).

Placer gold deposits were an important source of gold in New Mexico before 1902, but placer production since then has been minor. The earliest placer mining was in the early 1600s along the northern Rio Grande. In 1828 large placer deposits were found in the Ortiz Mountains of Santa Fe County (the Old Placers district).

There is currently no gold or silver production taking place in any of the five BLM planning units, in spite of record gold prices as of the date of this report (NMEMNRD, 2008).

3.2.1.3 Resource and Development Potential

The potential for the occurrence of gold and silver resources ranges from high to low with abundant direct and indirect evidence to direct evidence for the level of certainty (H,D to H,C) in the study area due to the presence of numerous identified occurrences and prospects. The point density map (Plate 62) identifies the Cochiti (Unit 4) and Tijeras Canyon (Unit 2) districts as having high potential due to the number of mines and prospects in these areas and INTERA judges the level of certainty in these areas as based on abundant direct and indirect evidence of certainty (H,D). The Placitas area (Unit 5) shows moderate potential on the point density mineral potential map and INTERA judges the level of certainty to be based on direct evidence (M,C). The Nacimiento (Unit 4) and Coyote Canyon (Unit 2) both have moderate potential based on point density mineral potential map with direct evidence of for the level of certainty (M,C). The levels of certainty are based on the presence of significant past production (abundant direct evidence) or minor past production or only occurrence (direct evidence). However, the development potential is judged to be low in all areas within the BLM planning units due to the apparently small size of the deposits, access difficulties, and environmental regulations which govern extraction and reclamation.



3.2.2 Base Metals and Fluorspar

The term base metal refers to industrial non-ferrous metals excluding precious metals. These include copper, lead, zinc, nickel, tin, and aluminum. Fluorite and barite, although not base metal minerals, are included in the base metal group of commodities within the NMBGMR Mines database (McLemore and Wilks, 2009; Lucas-Kamat, 2009a) and the base metal tables (BASE and HALK) in this report.

3.2.2.1 Geologic Setting

Base metals in New Mexico occur in a variety of geologic environments. They are known to occur along with gold and silver in geologic settings equivalent to those described for precious metals in Section 3.2.1. These include the stratabound sedimentary copper deposits in the Nacimiento and Jemez areas, the epithermal deposits in the Cochiti district, base and precious metals veins in the Placitas district, and base and precious metals in the Tijeras Canyon, Coyote Canyon, and Hell Canyon districts. Refer to Figure 10 for the locations of the metal mining districts, which include base metals. The most significant base metal deposit within the five BLM planning units is the Nacimiento sedimentary-copper deposit, located within Planning Unit 4 (Locatable Index Map 5), a few miles east of Cuba. The Nacimiento mine (Map Point BASE161, Locatable Index Map 5, Unit 4) is used here as an example of the sedimentary copper deposits that occur in Planning Units 2, 4, and 5. The following discussion of the geologic setting of and production from the Nacimiento copper mine is from Woodward, et al. (1974), Talbott (1974) and McLemore et al. (1984a).

The Nacimiento mine is a stratabound, sedimentary-copper deposit, a type of deposit that is numerous and widespread in the western U.S. and is often associated with gold, silver, lead, zinc, uranium, and vanadium. Such deposits are typically associated with red-bed sedimentary sequences and have been called red-bed copper deposits even though mineralization occurs in gray or green beds within the red-bed sequences. The copper and related mineralization typically occurs in bleached or gray to green sandstone, conglomerate, siltstone, shale, and limestone. In Planning Unit 4, these types of deposits occur in mainly in Permian and Triassic sediments in the Nacimiento Mountains, Jemez Springs, Coyote, Gallinas, Placitas, and Tijeras Canyon districts. Copper and the associated metals were probably transported in solution at low temperatures through the permeable sediments and along faults.

The Nacimiento copper mine is in the Agua Zarca member of the Triassic Chinle Formation. The Agua Zarca is a white, kaolinized, poorly cemented, fine to conglomeritic quartzose sandstone with abundant carbonaceous material. The Agua Zarca is reported to be 75 to 100 feet thick in the mine area and dips westward at 30° to 50°. The Agua Zarca is underlain by the Permian Yeso Formation, a reddish orange shale and mudstone with occasional lenticular sandstone beds. The Agua Zarca is overlain by the Salitral Shale member of the Chinle Formation.

Fluorite (often denoted by the mining term “fluorspar”) occurs with some of the metal deposits in the mining districts described above associated with the base metals in the fissure vein and breccia filling deposits along the Rio Grande rift in BLM Planning Units 2 and 5. It also occurs in the Zuni Mountains of BLM Planning Unit 1. A classic reference on fluorspar in New Mexico by Rothrock et al. (1946) described the geology, mining, milling, uses and marketing of fluorspar in New Mexico. Within that



report, fluorite deposits in Bernalillo County include the Capulin Peak prospect, the Schmidt prospect, the Darrel prospect, the Blackbird mine, the Red Hill Prospect, the Eighty-five prospect, an unnamed prospect, and the Galena King prospect. In the Zuni Mountains, fluorspar occurs in an area about 20 miles long and 3 miles wide in the southeastern Zuni Mountains. All of the mines and prospects are in the Precambrian granitic and metamorphic rocks in the core of the Zunis. Fluorite occurs in fissure veins which contain purple or green coarse-grained, high-grade fluorspar (Rothrock et al., 1946).

3.2.2.2 Exploration, Development, and Production History

New Mexico ranks third in the nation in copper production, but the producing copper mines are located in Grant County in the southwestern corner of the state, far from the BLM Rio Puerco field office planning area. There are 166 base metal occurrences within the five planning units but there is no base metal production. Sedimentary copper deposits occur in the areas shown on Figure 10 as metal-producing, although none of the deposits shown are producing at this time.

Early mining of stratabound sedimentary deposits was conducted by the Indians and the Spanish, but significant mining did not occur until the 1880s. In 1971, Earth Resources Company began production after extensive exploration and construction of a 3,000 tons/day flotation mill. Reserves were estimated at 9.6 million tons of 0.071 percent copper (Woodward et al., 1974). Mining ended after a tailings dam broke. Later efforts to in-situ acid leach the copper resulted in an acid plume in groundwater and no copper production. The U.S. Forest Service undertook efforts to investigate and remediate this plume under the Comprehensive Environmental Restoration, Compensation, and Liability Act in the early 2000s.

In the Zuni Mountains, fifteen fluorspar prospects or mines are listed and described in some detail in the report. The Mirabal Mine was operated underground and in open cuts during the early 1940s. There is no fluorspar production currently in the area.

3.2.2.3 Resource and Development Potential

The potential for the occurrence of base metal resources in the planning area has a range from high to low, with the highest potential in the metal mining districts (as shown on Figure 10). The point density mineral potential map (Plate 62) identifies the Cochiti and Tijeras mining districts as having high potential and INTERA assigns a high level of certainty to these areas due to abundant direct evidence of favorable geologic environment and processes (H, D). The Placitas district has moderate resource potential based on the point density mineral potential map and we assign it direct certainty (M, C) based on historical prospecting and mining in the area. The Coyote Canyon and Scholle districts have moderate potential according to the point density mineral potential map, with direct evidence of certainty (M,C), again based on mining history. The Zuni Mountain district has moderate potential for base metals based on the point density and direct certainty (M,C) but in the Zuni Mountains the potential for fluorspar deposits is high with direct certainty (H,C) based on significant past production.

Despite the base metal occurrences in these areas, the development potential is judged to be low, based on the low tonnage and grade of these deposits and on access and environmental factors. The presence of



large, open pit copper mining operations near Silver City, New Mexico make the development of base metal deposits in the five BLM planning units highly unlikely. Fluorspar occurs in the mines and prospects along the east side of the Rio Grande rift, but development is unlikely because of the low tonnage and due to military and Indian reservation closures and because there has been no production from these deposits for many years. Development could occur if uranium mining and milling were to resume in the Grants Mineral Belt, as fluorspar is used to make fluorine acid, a constituent in the uranium milling process.

3.2.3 Gypsum

Gypsum is hydrous calcium sulfate. It is found in nature in mineral and rock form, typically in thick sedimentary layers. It forms in lagoons where ocean waters high in calcium and sulfate content can slowly evaporate and be regularly replenished with new sources of water. The result is the accumulation of large beds of sedimentary gypsum. In 2003, about 90 percent of the total gypsum produced in the U.S. was used in wallboard and construction plasters (Kogel et al., 2006).

3.2.3.1 Geologic Setting

Gypsum is present in both Paleozoic and Mesozoic rocks in New Mexico. There are 13 gypsum localities plotted within the five BLM planning units, but the Jurassic Todilto Formation is the only gypsum-producing unit. The location of the White Mesa district gypsum deposits on Figure 10 correlates with the Todilto outcrop. The Todilto is composed of two members, a basal limestone member that is from 0 to 40 feet thick and an upper gypsum-anhydrite member that is up to about 125 feet thick. The gypsum-anhydrite member occupies the central area of Todilto deposition. The Todilto is generally considered an evaporite, but the environment of deposition is uncertain. The Todilto crops out north of Interstate 40 in the Laguna Pueblo area and along the eastern edge of the San Juan Basin. Notable and easily accessible outcrops are present between the south and north intersections between Highway 550 and Cabezon Road. The White Mesa mine is located within this section of the Todilto (Hilpert, 1963).



Photograph: Bowman, INTERA, 2009.

The gypsum-bearing Todilto Formation caps this mesa near San Ysidro.

3.2.3.2 Exploration, Development, and Production History

Gypsum is surface-mined from several deposits in BLM Planning Unit 4, with major production from the White Mesa mine west of San Ysidro. Three deposits in Sandoval County in BLM Planning Unit 4 have been commercially active: the White Mesa mine, the San Felipe deposit, and the G & W mines (McLemore et al., 1984a). American Gypsum LLC operates the White Mesa gypsum mine (Map Point GYPS11, Locatable Index Map 5, Unit 4) near San Ysidro. The mine has estimated reserves of more than 48 million tons that is expected to last more than 50 years (Harben et al., 2008). The deposit was first developed in 1959 by a small group of investors that obtained mining rights to the White Mesa gypsum deposit under the name American Gypsum Company. Company ownership and the company name changed repeatedly through the 1960s, 1970s, and 1980s. In 1985 the company was renamed Centex American Gypsum. Early in 2004 the Centex Corporation divested its remaining stake in the Centex Construction Products Company. In 2004 Centex Construction Products Company was spun-off and renamed Eagle Materials Company. Information on the White Mesa mine may be found on the website for American Gypsum.

There are five gypsum points located northeast of Bernalillo on the San Felipe Indian Reservation (Map Points GYPS3-7, Locatable Index Map 9, Unit 5). The G & W deposit is on BLM land along Cabazon Road south of the White Mesa mine (Map Point GYPS8, Locatable Index Map 5, Unit 4).



3.2.3.3 Resource and Development Potential

The potential for gypsum occurrence is high with abundant direct and indirect certainty (H,D) within BLM Planning Unit 4, in and around the operating White Mesa gypsum mine. Another area with high resource potential as indicated by point density (Plate 59) lies about five miles north of the town of Placitas, with direct evidence of certainty (H,C). Along the Nacimiento Mountains south of Cuba and in Tijeras Canyon, the point density mineral potential map indicates moderate potential and INTERA assigns the certainty based on direct evidence of the presence of gypsum in these areas (M,C).

Development potential is high for the White Mesa Mine, but lower elsewhere due to the extent of the reserves at the White Mesa Mine. The White Mesa mine adequately meets the demand for wall board and other gypsum products within central New Mexico and southern Colorado.

3.2.4 Limestone

Limestone is used to make Portland cement, crushed stone, agricultural products, and limestone specialty products such as fillers, extenders, and whiting materials (Kogel et al., 2006). Some travertine deposits have been identified as limestone in the NMBGMR Mines database but these are used primarily as decorative stone, a saleable mineral.

3.2.4.1 Geologic Setting

The Pennsylvanian-age Madera Formation limestone, which crops out along both the eastern and western margins of the Rio Grande rift, is a ready source of raw material primarily for the production of Portland cement. The Madera Formation forms the crest and part of the eastern dip slope of the Sandia, Manzano, and Manzanita Mountains, east and southeast of Albuquerque. The formation consists of a lower cliff-forming interval composed predominantly of limestone and an upper interval of interbedded sandstone, limestone, and shale. The Madera Formation in this region was deposited on a west-sloping ramp within an epicontinental sea along the margin of the ancestral Rocky Mountains. Clastic sediment in the Sandia Mountains was apparently derived from the Pedernal uplift, 37 miles to the east (Smith, 1999). The limestone producing area in Tijeras Canyon is shown on Figure 10.

3.2.4.2 Exploration, Development, and Production History

In 2007, New Mexico produced 1,170,069 short tons of limestone (NMEMNRD, 2008). Within the Rio Puerco planning area, Portland cement is produced at the Tijeras cement plant from limestone mined from the on-site quarry in the Madera Formation. The Tijeras cement plant began in 1959 and the current owner, Grupos Cementos de Chihuahua, took over operations in 1994. The estimated annual capacity of the plant was 500,000 short tons per year of cement in 2005 (USGS, 2005).

There are 47 limestone localities plotted on the Locatable Index Maps. The Tijeras deposit is located at Map Point LIM19 (Locatable Index Map 9, Unit 2). A group of six localities, including LIM24 identified as an open pit, are located near Sedillo Hill, east of Tijeras (Locatable Index Map 9, Unit 2).



Several localities are shown on Locatable Index Map 13. Two of these, identified as the Lucero Quarry Mine and Lucero, are on or near BLM land along Mesa Aparejo (Map Points LIM2 and LIM3, Locatable Index Map 13, Unit 2). These are travertine quarries but they are also identified as limestone in the NMBGMR minerals database. Thirteen of the limestone localities within the five planning units are listed in the limestone table as New Mexico State Highway Department (NMSHD) pits. The Tinaja pit (Map Point LIM15, Locatable Index Map 7, Unit 1) is located on the south flank of the Zuni Mountains east of Ramah.

3.2.4.3 Resource and Development Potential

The limestone potential in Planning Units 2 and 5 (Tijeras Canyon area) is high with abundant direct and indirect evidence of certainty (H,D) due to the presence of the Tijeras limestone quarry and cement plant. The point density mineral potential map (Plate 60) indicates that Tijeras Canyon has high resource potential for limestone based on current and past production in the area. The Sandia Mountains also have moderate potential as determined by point density, with abundant direct evidence of certainty (M,D). Travertine deposits (a variety of limestone) near the San Ysidro Anticline are shown as having high potential on the point density mineral potential map. These deposits are shown as having high potential because travertine is included with limestone in the databases queried for this study. However, these deposits are not similar to the Tijeras limestone deposits and are not likely to be developed as limestone for cement production. Scattered areas of moderate potential also exist in eastern Cibola and western Valencia Counties but these are also travertine deposits. These deposits are actually commercial and therefore may be classified as high resource potential with abundant direct evidence for certainty (H,D) even though the point density mineral potential map shows only moderate potential. Additional information on travertine is presented in this report under Dimension Stone, Decorative Stone, and Travertine. Limestone mining on a major scale in New Mexico is done only in association with cement production, and cement production is economic only within a limited range of conditions, including high tonnage and grade of material and proximity to a large volume demand. Given these conditions, it is likely that the existing Tijeras limestone quarry will remain the only limestone-producing site within any of the five BLM planning units, and within the state, for years to come. Therefore, only the Tijeras Canyon area has a high development potential, while the other limestone-bearing regions have low development potential.

3.2.5 Pumice*

Pumice, pumicite, and volcanic cinder are volcanic rocks that form as gases are released from molten rock, generating a froth that cools and solidifies into rigid foam. These rocks are characterized by their cellular structure. The cells, referred to as vesicles, may range in size from a few thousandths of a millimeter to several centimeters. As the vesicle walls of pumice and cinder are broken, sharp cutting edges are created. These properties are the basis for the commercial value of such rocks as lightweight aggregates, insulators, abrasives, and absorbents (Presley, 2006).

* This section describes both locatable pumice (high quality stone used in bath products, stone washing, etc) and salable pumice (lower quality pumice used as aggregate and in cement). These two minerals are described together because they occur in geologically identical environments.



Pumice may be used as a lightweight aggregate in both cast concrete and concrete block units. Lightweight concrete reduces the total weight of the structure in which it is used and reduces bearing strength requirements of the supporting members while contributing thermal and acoustical insulating qualities. Decorative and structural concrete block units made of pumice are easily handled, reducing construction time and worker fatigue. The large volumes and low cost of this type of pumice has contributed to its status as a salable mineral.

Pumice abrasive products are sawn and shaped blocks, granules, and powders. Sawn and shaped blocks and irregular lumps of pumice are used in applications requiring handheld abrasives for scouring various surfaces, and coarse granular pumice is most often used for stonewashing of fabric, though ground pumice is also compounded in such products as hand soaps, rubber erasers, and polishing compounds. Processing pumice and pumicite for abrasives involves drying, crushing, milling, air flotation, screening, and blending. Abrasive pumice prices of up to 100 times aggregate pumice prices reflect the rarity of suitable deposits, the higher capital and operating costs of processing plants, and the higher product tolerances required for pumice abrasives. The higher quality, rarity, and production price of this type of pumice contributes to its definition as a locatable mineral.

The high porosity, large surface area, and low chemical reactivity of pumice make it suitable for many absorbent applications as well, ranging from floor-sweep products used in machine shops to catalyst carriers. Finer granular pumice is also used in potting soils and as a hydroponic growth medium, where it is sometimes compounded with pesticides, herbicides, and fungicides.

Because of the many diverse applications of pumice products, deposits are continually mined today throughout the western U.S. National pumice and pumicite production in 2006 of 1.74 short tons was valued at about \$50 million. In New Mexico, the principal pumice deposits occur within the volcanic units related to the Valles Caldera in the Jemez Mountains in BLM Planning Unit 4. This area is shown on Figure 10 as an area of industrial mineral mining.

3.2.5.1 Geologic Setting

The Jemez region of north-central New Mexico represents a complex intersection of several geologic and geographic provinces, including the Colorado Plateau, the Rio Grande rift, and the Jemez volcanic field. The bulk of the Jemez Mountains is composed of Miocene to Early Quaternary volcanic rocks that fill in much of the western Rio Grande rift, but also spill westward onto the Colorado Plateau to the northwest (Kempter et al., 2007). The huge mass of volcanic rocks that constitute the Jemez volcanic field is often attributed to the intersection of the Rio Grande rift and the SW-NE-trending Jemez lineament (Goff and Grigsby, 1982). This boundary is defined by several faults, and tectonic activity along the intersection has migrated over space and time (Koning et al., 2007). Pre-Quaternary volcanism of basalt-andesite-dacite-rhyolite association formed the constructional phase of the Jemez Mountains, and the Valles Caldera later formed from explosive Quaternary rhyolitic volcanism.

Chamberlin and McIntosh (2007) proposed that a dilatant shear zone may have formed during the late Miocene, as crustal extension dragged a rigid ENE-trending crustal margin of the Colorado Plateau



obliquely westward away from relatively mobile lithosphere under the Rio Grande rift. This dilatant shear zone presumably made room for the rise of late Miocene igneous intrusions under the southern Jemez volcanic field, resulting in the Chamisa Mesa Basalt flows, followed by the ash flows and pumice falls of the ± 9.5 million year old Canovas Canyon Rhyolite. These units are exposed northeast of the village of San Ysidro in the southern Jemez Mountains.

Relatively small-volume mafic eruptions then covered these volcanoclastic sediments at approximately 7.2 million years, which had been faulted and tilted in response to further oblique extensional shear in the late Miocene. These flows are expressed at Mesita Cocida, which juts up east of Canovas Canyon. They are blanketed by the Peralta Tuff, a series of light gray to white, glassy to lithoidal pumiceous bedded tuffs and intercalated fall deposits. Chamberlin and McIntosh (2007) used unaltered sanidine crystals present in these rhyolitic deposits to infer an age of 6.89 ± 0.14 million years, which implies a lull in volcanic activity in the region of about 1.4 million years before deposition of the overlying Puye Formation. This formation is a volcanoclastic alluvial-fan sequence that developed in response to the growth and erosion of dacite domes (Waresback, 1986; Waresback and Turbeville, 1990). The coarse-grained volcanoclastic sediments of the Puye Formation were derived from the Jemez highlands from approximately 5 to 1.8 million years, and are found well-exposed in Guaje Canyon, on the eastern flank of the Jemez mountains (Slate et al., 2007).

Younger igneous units exposed in the Jemez are comprised mainly of the Bandelier Tuff, a sequence of pyroclastic flows and ashfall units deposited from a series of caldera eruptions between approximately 1.7 million years and approximately 1.2 million years. The oldest of these units is the Otowi Member of the Bandelier Tuff, which includes the basal Guaje pumice-fall deposit. This lower member consists of pumice within the Guaje unit. The Otowi member is overlain by the upper Bandelier Tuff, the Tshirege Member, which contains a deposit of pumice at its base, referred to as the Tsankawi pumice-fall deposit (Slate et al., 2007).

The most recent volcanic deposits in the region include the Pleistocene Valles Rhyolite, forming approximately 50 to 60 thousand years before the present. This formation includes the El Cajete Pumice, a depositional unit of high-silica rhyolitic composition (Slate, et al., 2007).

3.2.5.2 Exploration, Development, and Production History

The uses of pumice aggregate in construction were first recognized by the New Mexico Bureau of Mines and Mineral Resources in 1947. This report predicted that the state had sufficient pumice to supply plants producing concrete products and satisfy the state's building needs for decades to come (Clippinger and Gay, 1947). Since then, several companies have begun pumice mining operations throughout the state, including the Española-based Copar Pumice Company, which has been in the pumice mining industry in New Mexico for more than 40 years (USGS, 2005).

In the 1990s, pumice production for four companies in New Mexico was nearly 2,500 cubic yards per day from two units: the El Cajete Pumice and the Guaje Pumice Bed. The Copar Pumice Company currently operates the El Cajete mine, located in section 5, T. 18 N., R. 4 E (Map Point PUM33, Locatable Index



Map 5, Unit 4). This mine is just north of NM Highway 4, along the southern rim of the Valles Caldera, and is in the northeastern portion of Planning Unit 4. It produces both locatable and salable pumice. In 2004, three other active mines were operated by Copar Pumice Company, Inc., CR Minerals Company, and Utility Block Company (Presley, 2006) and all produced from the Guaje Pumice Bed.

The Guaje Canyon Mine of Copar Pumice is in section 31, T. 20 N, R. 7 E, and the Rocky Mountain Mine of CR Minerals is in section 33, T. 21 N, R. 7 E. Both operations are located on the eastern flank of the Valles Caldera. They are just east of the boundary of Planning Unit 4, though extractable Guaje Pumice deposits may extend further westward, within the study area. The U.S. Forest Service mine operated by Utility Block Company is in section 3, T. 17 N, R. 3 E (Map Point PUM26, Locatable Index Map 5, Unit 4). According to the USGS, this mine was active in 2006 (Harben et al., 2008). However, Google Earth images indicate that this mine has undergone or is undergoing complete remediation.

3.2.5.3 Resource and Development Potential

The physical properties of the New Mexico pumiceous materials indicate they are most suitable for use in concrete aggregate, in Portland-pozzolan cements, and as abrasives. The coarser-particle pumice deposits of the El Cajete pumice are also promising for laundry use (Harben et al., 2008). Because of the current abundant deposits and ongoing commercial operations INTERA judges the resource potential of pumice in Planning Unit 4 (in the Jemez Mountains area) to be high with abundant direct and indirect evidence of certainty (H,D). The point density mineral resource map (Plate 64) agrees with this assessment. Rhyolitic volcanism is rare or absent elsewhere in the other BLM planning units. The development potential will likely track the economics of the construction industry, which is the major user of pumice products.

3.2.6 Perlite

Perlite is a natural volcanic glass defined as having 2 to 5 percent (by weight) combined water; it generally occurs in young, high-silica extrusive igneous rocks. It becomes hydrated as a result of the chemical weathering of obsidian, a process that can take several million years (Barker and Santini, 2006).

Perlite's chemical resistance and porosity make it useful in horticulture, and because of its brightness, finely ground perlite is also sometimes applied to the surfaces of seed blocks to reflect light to the underside of seedlings, which promotes rapid and sturdy growth. However, perlite is primarily used in the construction industry. In the U.S. in 2004, perlite end uses were construction products, 62 percent; horticultural aggregate, 13 percent; fillers, 10 percent; filter aids, 9 percent; and other uses, 6 percent (Bolen, 2005). Perlite construction applications include insulating board, ceiling tile, plaster aggregate, paint coatings, and several other products (Barker and Santini, 2006).

3.2.6.1 Geologic Setting

Perlite deposits are located in Planning Unit 4 on the southern flank of the Jemez Mountains in Peralta Canyon. These deposits are derived from the high-silica, glassy flows of the Valles Caldera eruptions in the early Pleistocene. Perlite is a secondary igneous product, and the perlite in the Jemez region likely formed as meteoric or thermal spring water gradually diffused into the obsidian present in these flows.



Jemez volcanic glass deposits are mainly characterized by interbedded flow-banded rhyolite and pumiceous perlite (McLemore et al., 1984a), which suggests a diverse Quaternary volcanic history in the Valles Caldera region. This diversity makes the Jemez deposits largely unsuitable for commercial production. Though crude perlite is widely distributed in the Jemez region, individual perlite masses are generally small and exposures are limited.

3.2.6.2 Exploration, Development, and Production History

New Mexico continues to be a major producer of perlite in the United States. Dicaperl operated two mines in the state until the El Grande mine at No Agua Peaks was placed on standby in 2006. The company currently maintains a large perlite operation just southwest of Socorro, which produces about 150,000 short tons/year. Harborlite operates the other large perlite mine in New Mexico at No Aguas Peaks, north of Tres Piedras in Taos County, producing more than 250,000 short tons/year (Harben, et al., 2008).

Prospected locatable perlite deposits found in Peralta Canyon are referenced on Locatable Map Index 5 in Planning Unit 4 (Map Point PER5, Locatable Map Index 5, Unit 4). Although the canyon was intensely explored in the 1950s, its relatively remote location and the presence of impurities in deposits have discouraged mining. Only one small open pit mine in the canyon is known to have produced, and this mine managed just a few small shipments before stopping production (McLemore et al., 1984a). Other referenced deposits reflect perlite observed in outcrop at isolated locations throughout the canyon.

3.2.6.3 Resource and Development Potential

Perlite does not occur in the Jemez Mountains in sufficient quantity or purity to support a commercial operation. In addition, larger active operations in Taos, Cibola, and Socorro counties produce perlite of good quality and supply much of the domestic market for perlite, which makes development of new perlite mining operations difficult. Still, resource potential for perlite is judged to be high with direct evidence of certainty (H,C) in Peralta Canyon (Plate 64) due to notable occurrences and some small production. A concentration of perlite northwest of Grants has also been assigned high resource potential with direct evidence of certainty due to numerous map points in the area (H,C). Future development within the five BLM planning units is expected to be minimal, due to the presence of more extensive, commercial-grade deposits elsewhere in the state.

3.2.7 Rare Earth Elements

The last 40 years have seen an ever-increasing demand for REE, which include lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium ytterbium, lutetium, and yttrium (USGS, 2002b). These elements are used in applications such as cathode ray tubes, liquid crystal displays, fiber optic cables, glass polishing, hybrid vehicle engines, specialized batteries, high-temperature superconductors, wind turbines, missiles, and many others. There is often no substitute for the specific element or group of elements required in each of these applications. Therefore, the REE are essential for the continued production and advancement of



modern day technology, and a reliable supply must always be on hand to meet these needs (V.T. McLemore, pers. comm.; Bradsher, 2009; USGS, 2002b).

The U.S. was largely self-sufficient in REE production until the mid 1980s, when China began flooding the market with REE. The subsequent reduction in prices drove many domestic REE producers out of business. Recently, however, China has threatened to freeze its REE exportation. This has caused an increasing interest in developing (and redeveloping) existing REE deposits in the U.S. (V.T. McLemore, pers. comm.; Bradsher, 2009).

3.2.7.1 Geologic Setting

In New Mexico, REE deposits are typically found in pegmatites, carbonatites, alkaline igneous rocks, and heavy metal beach placer deposits (McLemore, pers. comm.).

No REEs have been produced for sale in the Rio Puerco Field Office planning units. However, there are eight distinct REE occurrences that may represent future opportunities for commercial development. These eight locations, all of which are plotted on the corresponding maps in Appendix B, are in the following regions: the Torreon Wash area in the western portion of Unit 4 (Sandoval County); near the Herrera town site in Unit 4 (Bernalillo County); west of Gallup in Unit 1 (McKinley County); along the west side of the Manzanita Mountains in Unit 2 (Bernalillo County); northwest of Cañoncito in Unit 5 (Bernalillo County); just below the mountain front of the northeastern section of the Sandia Mountains in Unit 5 (Bernalillo County); and in the Pedernal Mountain area in Unit 3 (Torrance County). REE are also known to occur in alkaline igneous intrusions and possible carbonatites in the Gallinas Mountains in extreme southern Unit 3. A mine in the Gallinas area produced 146,000 lbs of bastnäsite, a REE-bearing mineral, from a location south of the Planning Unit 3 border. REEs may also be present in economic quantities in Proterozoic syenites of the Zuni Mountains in Unit 1 (McLemore, pers. comm.).

The Torreon Wash occurrence (Map Point REE8, Locatable Index Map 4, Unit 4) consists of beach placer deposits associated with the Cretaceous Point Lookout Sandstone (McLemore et al., 1984a). These deposits are heavy metal lags formed on beaches or longshore bars. These low-grade deposits are typically 3 to 5 feet thick, a few tens of feet wide, and a few hundred feet long (McLemore, pers. comm.). A similar deposit is found near the Herrera town site (Map Points REE5 and REE6, Locatable Index Map 8, Unit 4).

REEs were also found in samples of the Cretaceous Gallup Sandstone collected during drilling west of the town of Gallup (Map Point REE7, Locatable Index Map 7, Unit 1). The deposit is reported to be a lenticular, dense olive green sandstone trending North 25° West (McLemore, written communication, 2009). McLemore et al. (1984a) describe a REE occurrence in the Precambrian Sandia Granite along the western slope of the Manzanita Mountains (Map Point REE2, Locatable Index Map 9, Unit 2) as a pegmatite or a fault zone.

One instance of REE-bearing radioactive carbonatite is known to occur northwest of the town of Cañoncito (Map Point REE3, Locatable Index Map 9, Unit 5). Carbonatite is an intrusive or extrusive



igneous rock containing over 50 percent carbonate minerals and is commonly associated with continental rifting. This occurrence consists of dikes of Cambrian-Ordovician age and is called the Monte Largo Carbonatite. The dikes intrude a suite of Proterozoic metamorphic and igneous rocks and are about 1 to 2 feet wide. No production or workings are reported (McLemore, 2009; McLemore et al., 1984a; V.T. McLemore, pers. comm.).

The La Quava and La Madera mines (also known as Quartz #1) in the northeastern Sandia Mountains (Map Point REE4, Locatable Index Map 9, Unit 5) contain REE along with quartz, precious metals, uranium, halides, and copper in pegmatites of the Precambrian Juan Tabo sequence. Cambrian-Ordovician syenite dikes in the Pedernal Mountain area in Torrance County (Map Point REE1, Locatable Index Map 15, Unit 3) were found to contain REE. The REE occurred in fluorite veins in association with uranium. The syenite dikes cut Proterozoic rocks and are about 1.5 to 2 feet thick (McLemore and Wilks, 2009, V.T. McLemore, pers. comm.).

3.2.7.2 Exploration, Development, and Production History

No production is recorded from the beach placer deposits in the Torreon Wash area in Unit 4, and the small extent and poor grade of the deposits make them difficult to mine economically (McLemore, pers. comm.). Another beach placer deposit occurs in the Cretaceous Gallup Sandstone near the town of Herrera in Unit 4, just north of the border between Bernalillo and Sandoval County. Prospect pits were dug in this area, but no further activity is reported (McLemore et al., 1984a; McLemore, pers. comm.). Prospect pits were also dug along the western slope of the Manzanita Mountains, but no production is reported (McLemore, 2009; McLemore et al., 1984a).

The La Quava and La Madera mines never entered production (McLemore et al., 1984a). Ten pits are reported to exist in the syenite dikes within the Pedernal Mountain area, but no REE or uranium production occurred at this site (McLemore, 2009; McLemore et al., 2002; McLemore, pers. comm.).

3.2.7.3 Resource and Development Potential

The resource potential in the study area for REE is judged to be moderate with direct evidence of certainty (M,C) due to the presence of the requisite geologic environments and the identified REE prospects. There is no point density mineral potential map for REE because all eight occurrences are scattered and all would show as having low potential on the map. It seems unlikely that these deposits will be developed in the near future unless the world supply of REE is disrupted. REE as critical minerals are discussed in more detail in Section 5 of this report.

3.2.8 Uranium

Uranium is a radioactive element that occurs naturally in low concentrations (a few parts per million) in soil, rock, and surface and groundwater. It is the heaviest naturally occurring element, with an atomic number of 92. Uranium in its pure form is a silver-colored heavy metal that is nearly twice as dense as lead. Since the development of the first atomic bomb in the 1940s by the U.S. government, uranium has become a critical energy source. Concerns over shortage of oil and gas and environmental issues



regarding greenhouse gas emissions have fuelled a new interest in nuclear energy as the source of power to meet current and future global demand for electricity (Encyclopedia of Earth, accessed 2009). Nuclear power provides nearly 17 percent of the world's total annual electricity generation and 34 percent of the European Union's needs. France receives 78 percent of its electricity from nuclear, Belgium almost 56 percent, Sweden close to 50 percent, South Korea 40 percent, Switzerland 40 percent, Japan 25 percent and the United States 20 percent. The International Atomic Energy Agency expects 168 new nuclear reactors to be built within the next 15 years. As of 2008, China had plans to build 40 nuclear reactors within the next 15 years to increase the proportion of its electricity generated by nuclear power from the current 2.4 percent to 4 percent (Global Infomine, 2009).

As of 2003, New Mexico was estimated to have 15 million tons of ore reserves with a grade of 0.280 weighted average percent of uranium oxide concentrate (U_3O_8) per ton of ore, equivalent to 84 million pounds of ore at a uranium price of \$30 per pound, or 102 million tons of ore reserves with a grade of 0.167 weighted average percent U_3O_8 per ton of ore, equivalent to 341 million pounds of ore at a price of \$50 per pound (DOE, 2004).

Key references for uranium in New Mexico used in this study are Kelley (1963), Rautman (1980), McLemore and Chenowith (1989) and McLemore (2007). There are 335 uranium localities plotted on the resource maps for this study. Most of these are located within BLM Planning Units 1 and 2 in the Grants Mineral Belt in McKinley and Valencia Counties; other occurrences are located in the Ojito Springs area (southwest of San Ysidro) and the La Ventana area along NM Highway 550 between San Ysidro and Cuba in Sandoval County.

3.2.8.1 Geologic Setting

Uranium deposits within the Rio Puerco planning units are located primarily within the Grants Mineral Belt. This uranium-rich zone extends from several miles east of Laguna to the Gallup area, a length of 100 miles, and is about 25 miles wide, located primarily north of Interstate 40 (Fitch, 1980). The Grants Mineral Belt (and other uranium districts) is depicted in red on Figure 10. The area is flanked on the north by the San Juan Basin, and on the south and west by the Acoma sag and the Zuni uplift. Sedimentary rocks in the area range in age from Pennsylvanian to Cretaceous and rest on the Precambrian core of the Zuni uplift. Intrusive and extrusive rocks in the area include the Mount Taylor volcanic center and the Zuni volcanic fields of Tertiary and Quaternary age. The regional dip of the sedimentary rocks is to the north into the San Juan Basin. The gently dipping structure is interrupted locally by folds and faults. The Ambrosia Lake area, among others, is located just north of the Planning Unit 1 boundary, while other areas are located within the boundaries of Planning Units 2 and 4. Examples of areas within Units 2 and 4 are the Jackpile mine (Map Point U77, Locatable Index Map 8) and the Saint Anthony mine (Map Point U89, Locatable Index Map 8) in Unit 2 and the Marquez mine (Map Point U187, Locatable Index Map 8) in Unit 4. Additional examples are the undeveloped smaller deposits the La Ventana area between San Ysidro and Cuba.

The rocks containing the uranium deposits are primarily in the Jurassic-age Morrison Formation. The most common ore zones are in fluvial sandstones containing mudstone interbeds of the Westwater Canyon Member and the Jackpile Member of the Morrison.

The stratigraphic nomenclature for the Jackpile is controversial. In 1984, Owen et al. (1984) defined the Jackpile Sandstone Member as a formal member of the Morrison Formation, but still many geologists consider it a part of the Brushy Basin Member and they designate it as the Jackpile sandstone of economic usage. The USGS did not recognize it as a separate member in 1986 (Condon and Peterson, 1986), but Aubrey (1986, 1988) did recognize Owen et al (1984) but did not specify which usage was preferred. For the purpose of this report, the Jackpile will be identified as a formal member of the Morrison Formation. Figure 21, the stratigraphic column for the rocks in the Laguna-Paguete area, identifies the Jackpile Sandstone as a member of the Morrison (the “Jackpile Ss bed” is positioned in the “Member” column of the diagram) although the controversy is suggested by the box outlining the Jackpile within that column.

Other host rocks of lesser importance for the presence of uranium are the Todilto Limestone, Summerville Formation, and Entrada Sandstone (all Jurassic) and the Dakota Sandstone (Cretaceous). The Jackpile uranium mine (reclaimed) is located in the Laguna-Paguete area within BLM Planning Unit 2.



Photograph: Sengebush, INTERA, 2007.

Uranium ore in the Morrison Formation.



The Westwater Canyon member of the Morrison Formation produced more than 340 million pounds of U_3O_8 from 1948 to 2002. In contrast, the other sandstone uranium deposits produced around 503,000 pounds. There are three types of deposits in the Westwater Canyon Member: primary (trend or tabular), redistributed (stack), and remnant-primary sandstone deposits. These are described briefly below.

Primary sandstone-hosted uranium deposits—also known as pre-fault, trend, blanket, and black-band ores—are found as blanket-like, roughly parallel ore bodies along trends, mostly in sandstone of the Westwater Canyon Member of the Morrison Formation. These deposits are typically less than 8 feet thick, average more than 0.20 percent U_3O_8 , and have sharp ore-to-waste boundaries.

Redistributed sandstone-hosted uranium deposits are also known as post-fault, stack, secondary, and roll-type ores and are younger than the primary sandstone-hosted uranium deposits. They are discordant, asymmetrical, irregularly shaped, characteristically more than 8 feet thick, have diffuse ore-to-waste contacts, and cut across sedimentary structures. The average deposit contains approximately 18.8 million pounds of U_3O_8 with an average grade of 0.16 percent. Some of these are vertically stacked along faults.

Remnant sandstone-hosted uranium deposits were preserved in sandstone after oxidizing waters that formed redistributed uranium deposits had passed. These deposits are difficult to find because they occur sporadically within the oxidized sandstone. The average size is approximately 2.7 million pounds of U_3O_8 at a grade of 0.20 percent.

Bleaching in the Morrison sandstone and the geometry of the tabular uranium-vanadium bodies in sandstone beds supports the reaction of two chemically different waters, most likely a dilute meteoric water and saline brine from deeper in the basin. The intimate association of uranium-vanadium minerals with organic material further indicates that they were deposited at the same time. Cementation and replacement of feldspar and quartz grains with uranium-vanadium minerals are consistent with deposition during early diagenesis (McLemore, 2007).

Many of the ore bodies in the Grants Mineral Belt are primary, tabular deposits that range in size from a few tons to several million tons. They are irregular in shape, are roughly tabular and elongate, and range from thin pods a few feet in width and length to bodies several tens of feet thick, several hundred feet wide, and several thousand feet long (Fitch, 1980). These deposits are not classical roll-front uranium deposits, although, as described above, they are associated with organic materials that can serve as a reductant in groundwater. These organic materials are sometimes referred to as “humate.” (Note: This humate coats sandstone grains and is not present in the massive form that characterizes “humate deposits” described under salable minerals in this report.)

Redistributed or secondary deposits may have formed by remobilization of the primary deposits by groundwater along faults and fractures. Chemical oxidation and reduction play a part in the formation of these deposits. They form when groundwater in permeable sandstone or conglomerate encounter the interface between oxidizing and reducing conditions and the uranium in solution (in the oxidized condition) was precipitated and concentrated at the reducing front (Heylman, 2003). The Diamond Tail



uranium deposit, located northeast of Bernalillo (and technically outside the Grants Mineral Belt) is identified as a roll-front-sandstone-type deposit (McLemore, 2007). Coffinite is a common ore mineral in the region, although other uranium minerals occur in these deposits.

3.2.8.2 Exploration, Development, and Production History

The Grants uranium district of the Grants Mineral Belt is located within BLM Planning Units 1, 2, and 4 and is the second largest uranium producing area in the United States (second to Wyoming). By the late 1970s, this region had produced 40 percent of domestic uranium and was known to contain 53 percent of all U.S. uranium reserves. Although none of the mines are operating today, significant uranium reserves remain in place and these mines could reopen with an increase in uranium demand and price.

The discovery of uranium in the Grants Mineral Belt area is attributed to Paddy Martinez in 1950, although uranium minerals were known to occur in the area as early as the 1920s. In 1951 the Denver Exploration Branch of the U.S. Atomic Energy Commission mapped the Jurassic-age outcrops and the published results of this study were available for use by 1952 (Melancon, 1963).

Uranium production from the Grants Mineral Belt through 1978 was about 254 million pounds of U_3O_8 . The published reserves were 735 million pounds of U_3O_8 at a forward cost up to \$30 per pound. Average grade of produced ore was 0.21 percent (Fitch, 1980). Figure 22 shows the locations and names of 34 uranium deposits in the Grants Mineral Belt.

Representative examples, characteristics, and exploration and production history of uranium deposits within the planning area are presented below.

The Jackpile-Paguete deposit is on Locatable Index Map 8, Map Point U77, within BLM Planning Unit 2, on the Laguna Indian reservation. This deposit is hosted in the Jackpile Member of the Morrison Formation. Uranium was produced here from an open pit mine from uranium-bearing carbonaceous material in lenses and horizons which were elongate and subparallel to the Jackpile sandstone channel outline. The ore zones were up to 30 feet thick and 100 feet across with a roughly flat or planar upper surface. The major ore mineral was coffinite. The mine ceased operations in 1982 and reclamation of the mine site has been completed (Beck et al., 1980 in Rautman, 1980).



Photograph: Sengebush, INTERA, 2007.

The Saint Anthony open pit uranium mine (Map Point U89, Locatable Index Map 8).

The Marquez Uranium mine is located in BLM Planning Unit 4, on Locatable Index Map 5, Map Point U187. This deposit is in the Jackpile, Westwater Canyon, and Recapture Members of the Morrison Formation. The Westwater Canyon Member is the target zone and contains three ore horizons. The ore is dark brown to black and is present at a depth of 1,800 feet. The ore occurs in tabular and lenticular forms that are grossly concordant with bedding. As with other deposits in the area, humates are thought to have exerted a major influence on the fixation of hexavalent uranium from solution. Coffinite is the major ore mineral with some uraninite and the mill feed is estimated at 0.12 percent U_3O_8 (Livingston, 1980 in Rautman, 1980). This deposit is currently undergoing renewed development by Neutron Energy.

The Bernabe Montaña uranium deposit is located in BLM Planning Unit 2, on Locatable Index Map 8, Map Points U111, U112 and on Locatable Index Map 9, Map Points U104, U106, U107. Map Points U111 and U112 are plotted on BLM land, while some of the other points are on the Laguna Indian reservation. This deposit occurs predominantly in the Westwater Canyon Member of the Morrison, but includes some uranium shows in the Jackpile sandstone. The deposit occurs as tabular, concordant lenses or blankets, a few inches to over 10 feet thick, 1,500 to 2,000 feet wide, with a combined length of nearly 9 miles. The deposit is defined by approximately 2000 drill holes at depths ranging from 1,000 to 2,500



feet. Reserves are documented at 10 to 20 million pounds of uranium oxide. This deposit is currently dormant (Kozusko and Saucier, 1980 in Rautman, 1980).

The La Jara Mesa uranium deposit is located in BLM Planning Unit 1, on Locatable Index Map 8, Map Point U153 and other map points in a tight cluster. The deposit is currently under development by Laramide Resources, Ltd. This is a primary sandstone-hosted uranium deposit (McLemore, 2007) in the Poison Canyon trend within the Westwater Canyon Member of the Morrison Formation. It contains tabular deposits and also c-shaped roll fronts associated with humate or “carbon trash.” The ore is coffinite with an estimated 3.9 million pounds of proven U_3O_8 (Laramide Resources, Ltd., 2007) although McLemore (2007) documents 8 million pounds of ore averaging 0.25 percent. The estimated uranium, based on measured and indicated deposits, at La Jara Mesa is 7,257,817 pounds U_3O_8 contained in 1,555,899 tons of ore at an average grade of 0.23 percent; an additional inferred resource of 3,172,653 pounds of U_3O_8 contained in 793,161 tons of ore at an average grade of 0.20 percent is thought to be present. Laramide Resources, LTD plans to develop the deposit as a small underground mine. The project is located on public land administered by the U.S. Forest Service but is near land administered by BLM in Planning Unit 1 (Reuters, 2009).

There are 27 uranium localities plotted within the Ojito Springs area within BLM Planning Unit 4, Locatable Index Map 5. An example of a point location is Map Point U226. These prospects are in the Jackpile sandstone north of Cabezon Road and southwest of San Ysidro, and are identified as radioactive anomalies or other occurrences in the NMBGMR Mines database. The actual extent of exploration in this area is not known. Many of these locations are on and near BLM land and some are in the Ojito Wilderness Area (McLemore and Wilks, 2009; Lucas-Kamat, 2009a; Santos, 1975).

The La Ventana uranium prospects are somewhat unusual in that they occur in the La Ventana tongue of the Cliff House Sandstone, of Late Cretaceous age. They occur within BLM Planning Unit 4, on Locatable Index Map 5; an example of a point location is Map Point U310. This deposit is documented to contain 132,000 short tons (120,000 metric tons) of coal and carbonaceous shale, which are estimated to contain an average of 0.10 percent uranium. Uranium anomalies also occur in carbonaceous shale of the Dakota Sandstone east of La Ventana Mesa and in a peat bed containing 1.4 percent uranium at the base of the Dakota Sandstone. In a deposit more typical of the Grants Mineral Belt, 30 tons of ore averaging 0.12 percent U_3O_8 was mined from the Brushy Basin Member, the only production recorded from the Morrison Formation in the La Ventana area (Santos, 1975).

The Diamond Tail uranium deposit in the Hagan Basin is located in the north end of BLM Planning Unit 5, on Locatable Index Map 9, at Map Point U199 and other map points nearby. The uranium in the Hagan Basin was first discovered in 1954 by an AEC aerial radiometric survey. It occurs in several roll-front-sandstone bodies within high energy, braided stream deposits of a complex alluvial fan sequence in the Eocene-age Galisteo Formation. These rocks rest unconformably on the Cretaceous Mancos Shale. The uranium is associated with selenium, pyrite, and carbonaceous material in bleached, fine- to coarse-grained quartz sandstones. The uranium deposits are typically within bleached, gray-green-white sandstones and conglomerates with interbedded green mudstones and are surrounded by red sandstones



and conglomerates. Urananite, coffinite, and uranophane occur as sand coatings in the roll-type bodies (McLemore and Chenoweth, 1989).

Active uranium mining ceased in New Mexico in 1998, although Rio Algom continued to recover uranium dissolved in water from its flooded underground mine workings at Ambrosia Lake until 2002.

As of 2008, there were only two uranium mining operations permitted by the Mining Act Reclamation Program in the state: Rio Grande Resources' Mount Taylor Mine and Rio Algom's Old Stope mining properties. The Mount Taylor Mine is a flooded underground mine (Map Point U195, Locatable Index Map 8, Unit 1) that was on standby status and would need an amended permit before mining could commence. The Old Stope mines are undergoing reclamation.

Due to the rapid escalation in the price of uranium that began in 2003, New Mexico experienced a significant increase in uranium exploration activity. In January 2006, the MMD received the first uranium exploration application since 1998. Twenty-two uranium exploration applications were submitted between 2006 and 2008. As of November 2008, eight applications had been approved, one was pending, and thirteen had been denied, withdrawn, or were in enforcement.

3.2.8.3 Resource and Development Potential

The rise in uranium prices in 2003 led to renewed interest in uranium mining and production in New Mexico. The spot price of U_3O_8 was \$6.50 per pound in 2000 but rose to \$60 per pound in the fall of 2006. By July of 2007, the price had peaked at \$138 per pound, then fell to approximately \$55 per pound in November 2008. The current price is \$44.50 per pound (January, 5 2010). The uranium resource potential is judged to be high with abundant direct and indirect evidence of certainty (H,D) due to the presence of the necessary geologic environment and geologic processes for the formation of uranium deposits in areas of BLM Planning Units 1 and 2 within the Grants Mineral Belt. The level of certainty (D) is based on the extensive commercial uranium production from this area. The north-south trending belt known as the Ojito Springs and La Ventana areas in Unit 4 is assigned high potential with direct evidence of certainty (H, C) because uranium is known to occur there but production has been very limited. This is supported by the point density mineral potential map in these areas (Plate 57). The Hagen Basin area, north of Placitas, is assigned moderate potential with direct evidence of certainty (M,C), based on the presence of the Diamond Tail deposit, but no production. Another area of high resource potential is the Scholle district near Mountainair where uranium is known to occur in multiple prospects, although there has been no production from that area. The potential there is judged to be high with direct evidence of certainty (H,C). The development potential is judged to be moderate due to the large price fluctuations and uncertainties associated with the future of nuclear power in the U.S. Additional discussion of uranium development potential is presented in Section 4 of this report.

3.2.9 Semiprecious Stones and Miscellaneous Minerals

Semiprecious stones such as opals, moonstone, topaz, garnets, and tourmaline, are generally collected by hobbyists and not by commercial operations. Readers interested in learning more about concentrations of



semiprecious and collectible minerals are encouraged to download the New Mexico Bureau of Geology and Mineral Resources' free *Rockhounding Guide to New Mexico* for more information on the subject (Scholle, 2002). Miscellaneous minerals are those resources that are too minor or scattered to merit anything more than cursory interest. These minerals include mica, roofing sand (classified as miscellaneous by McLemore et al., 1984a), talc, and graphite.

3.2.9.1 Geologic Setting

Minor occurrences of opals, orthoclase, moonstone, tourmaline, and quartz crystals occur in the Jemez Mountains (Unit 4), Placitas (Unit 5), and Tijeras Canyon (Units 2 and 5). The Jemez region is known to contain hyalite, orthoclase, moonstone, obsidian, and precious opals (McLemore et al., 1984a; Freed and Vaskys, 2008). Opals can be found in volcanic tuffs near Battleship Rock (Map Point GEM13, Locatable Index Map 5, Unit 4). Moonstones, wood opals, and obsidian can also be found in road cuts along Highway 4 (Map Point GEM14, Locatable Index Map 5). An occurrence of topaz, garnets, and obsidian can be found along Highway 547 north of Grants (Map Point GEM9, Locatable Index Map 8, Unit 1). Muscovite, tourmaline, and feldspar occur in Tijeras Canyon (point GEM5, Locatable Index Map 9, Unit 5) and are also reported to occur in Placitas and near Cochiti (McLemore et al., 1984a).

A variety of other minor mineral occurrences exist in the Rio Puerco Field Office. A talc deposit is located in the eastern foothills of the Manzano Mountains (Map Point MISC1, Locatable Index Map 14, Unit 3, McLemore, 2009). Four mica occurrences are reported in the study area (Map Points MISC2, MISC 5, and MISC 7, Locatable Index Maps 7 and 5, Units 1 and 4). Two graphite outcrops have been reported in the study area. The one in Tijeras Canyon (Map Point MISC3, Locatable Map Index 9, Unit 5) may have been initially mistaken for coal. The second graphite occurrence is located within the Albuquerque metropolitan area, near Interstate 25 between San Antonio Boulevard and Paseo del Norte Boulevard (Map Point MISC4, Locatable Index Map 9, Unit 5). However, this data is based on an unpublished map and may not be reliable.

3.2.9.2 Exploration, Development, and Production History

Because most semiprecious stones and miscellaneous minerals are collected by hobbyists, it is difficult to accurately ascertain the amount produced per year in the Rio Puerco planning area. Three mines have produced quartz crystals from Precambrian quartzite; this was likely used as ornamental quartz as the deposits were unsuitable for more technical uses. Quartz Mines #1 and #2 (Map Point GEM8, Locatable Index Map 9, Unit 5) are located about a mile and a half north of Sandia Casino, and the Isleta Quartz Mine lies on the northeast slopes of the Manzano Mountains (McLemore et al., 1984a). Roofing sand was mined from a Quaternary eolian deposit in an open pit immediately adjacent to the Jemez River south of Indian Road 74 (Map Point MISC6, Locatable Map Index 9, Unit 4, McLemore et al., 1984a). There is no record of mica, graphite, or talc production in the study area.

3.2.9.3 Resource and Development Potential

The semiprecious stones and miscellaneous minerals resource potential is judged to be moderate with direct evidence of certainty (M,C), due to the known occurrences but relatively small and non-commercial



scale of production. Mica deposits are unlikely to be developed due to the patchy nature of the deposits and the rigorous standards required for industrial muscovite (McLemore et al., 1984a; McLemore, 2009). Other miscellaneous minerals occur in such small concentrations as to render their production uneconomical. No point density mineral potential map was prepared for this category because there are only a 19 scattered points of occurrence and this group represents widely variable mineral types.

3.2.10 Lithium

Lithium is a highly reactive alkali metal that never naturally occurs in its elemental form. Lithium is an important component of many batteries due to its high electronegativity. Other uses for lithium include as an antidepressant, ceramics, fuel cells, and rocketry. There is also a slight possibility that lithium may also have a future as fuel in fusion reactors (Kogel et al., 2006; McLemore, pers.comm.; SME preprint, 2010).

3.2.10.1 Geologic Setting

Lithium was historically mined from pegmatites, but in the last 60 years production has shifted to brine extraction. These brines are generally located in playa lakes adjacent to volcanic fields. Lithium carbonate is harvested from these lakes and then purified for later use. World supplies of brine lithium are currently being produced from the state of Nevada as well as Chile and Argentina, whereas Australia, Canada, Zimbabwe, Brazil, Russia, Portugal, and China mine lithium from pegmatites. Playa lakes in China, Bolivia, Argentina, and Tibet are currently the focus of lithium exploration (Kogel et al., 2006).

Recently, water samples taken near a playa lake in the Estancia Basin (Unit 3) indicate an unusually high concentration of lithium (up to 624 parts per billion). This lithium could be derived from uranium-bearing waters from the Pedernal or Manzano Mountains or perhaps from alkaline granite and syenite basement rock. However, the lithium anomaly could also be due to the presence of enriched brines similar to the ones currently under production elsewhere in the world.

3.2.10.2 Exploration, Development, and Production History

The La Quava/La Madera Mine (Map Points BASE88, HALK74, PREC46, REE4, Locatable Index Map 9, Unit 5) reportedly contains lithium, probably in a pegmatite deposit. However, no lithium production is recorded for this locality (McLemore et al., 1984a). The National Uranium Resource Evaluation (NURE) water samples taken from the Estancia Basin playa lakes indicate the only other possible lithium resource in the study area.

3.2.10.3 Resource and Development Potential

The presence of lithium in a nearby mine represents a low resource potential in the Sandia Mountains (L,C). However, due to large brine operations domestically and abroad, it is very unlikely that lithium will be mined in this region. Thus, INTERA assigns a low development potential in the Sandia Mountains. Lithium near playa lakes in Tarrant County may be from up to three sources, only one of which could represent an economically viable deposit. Thus, INTERA assigns a low resource potential for lithium with indirect evidence in the Estancia Basin (L,B). No point density mineral potential map was prepared for lithium because of the scarcity of occurrence. INTERA has determined that development potential in Tarrant County will remain low unless high future prices encourage exploration in the region.



3.3 SALABLE MINERALS

Salable minerals located on public lands can be sold by the federal agency directly to the public at prices determined by the administering agency. These minerals include aggregate, decorative and building stone, clay, and other mineral materials.

3.3.1 Aggregate, Sand, and Gravel

Aggregate, which includes sand, gravel, and some varieties of limestone, is a subset of industrial minerals. Aggregate is invaluable in almost all construction projects, being used for cement, fill, and landscaping. Furthermore, construction sand and gravel is one of the most accessible natural resources in the Albuquerque area, and a major basic raw material.

3.3.1.1 Geologic Setting

The information provided in this section is based largely on the USGS Geologic Map of the Albuquerque 30' × 60' quadrangle and accompanying report, compiled by Paul Williams and James Cole (Williams and Cole, 2007) and the New Mexico Bureau of Geology and Mineral Resources' Geologic Map of New Mexico (Scholle, 2003)

The oldest aggregate-producing deposits in the planning area are Pennsylvanian-age limestones laid down by a warm, shallow sea near the shore of the Ancestral Rocky Mountains. These limestones, known as the Madera and San Andres Formations, are present in many places throughout the Rio Puerco Field Office planning area, extending from western Cibola and McKinley Counties in Unit 1 to northeastern Torrance County in Unit 3. Major outcrops are also found in the Zuni Mountains and along the crest of the Sandia and Manzano Mountains. Smaller, isolated occurrences exist in the Jemez Mountains (Unit 4) and southern Valencia County (Unit 2).

The gravel and sand resources were generated much later, during the formation of the Rio Grande rift in mid- to late-Cenozoic time. The earliest fluvial sediments attributed to extension of the rift in the Albuquerque area are found in the Hagan Basin, to the north of the Sandia uplift. These deposits indicate that extension was underway by the late Oligocene. Farther west, the oldest rift-filling sediments are eolian sand and interdunal deposits of the Zia Formation of the Santa Fe Group.

Major extension occurred during the Miocene, but subsidence and sedimentation rates were highly irregular from place to place throughout the Albuquerque Basin. Late Miocene and early Pliocene uplift and erosion were widespread in the region, as evidenced by channeled and local angular unconformities at the bases of all Pliocene units, especially prominent along basin margins. Generally coarser-grained late Miocene and early Pliocene rift-fill deposits that overlie the older Zia Formation were broadly grouped into the Arroyo Ojito Formation of the Santa Fe Group by Tedford and Barghoorn (1999). These sediments indicate the beginning of high energy, fluvial-dominated depositional regimes in the basin, in contrast to the eolian deposits of the Zia Formation.



Pliocene units of the Santa Fe Group form relatively thin, blanketing deposits within and marginal to the Rio Grande rift. They are channeled into the underlying Miocene units, and are much coarser-grained, especially near the rift-marginal source areas. Pliocene units conceptually represent local alluvial-fan and braided-stream deposits that covered a landscape that was eroded locally in latest Miocene time, in response to increased precipitation and stream power. These increases were likely related to the Pliocene onset of cooler, wetter global climates.

Sand and gravel mining operations in the BLM planning units that extract material from Santa Fe Group sediments are located primarily along the central axis of the rift structure, where the layers of interest are found exposed near the modern Rio Grande. The largest aggregate operations in the Albuquerque area today are located just north of Placitas in upper Santa Fe Group deposits. These areas are outlined on Figure 10, although they extend north of Placitas. These pits utilize the uppermost unit of the Santa Fe Group, the Ceja Formation, which consists of consolidated, moderately cemented, sandy, pebble to boulder conglomerate, coarse pebbly sand, and sparse interbeds of reddish-brown silty mudstone. This unit is thick and laterally extensive, which contributes to the production value (Greer Price et al., 2009).

Many operations in the area, however, utilize younger material. Quaternary alluvium forms alluvial-slope deposits, major stream deposits, and several localized deposits that resulted from other processes during Pleistocene and Holocene time. These sediments are widespread in the region, and likely formed in response to late Pliocene incision of the rift valley by the Jemez River and contributing arroyos (Koning and Personius, 2002).

Alluvial slope deposits consist of lower Pleistocene to Holocene piedmont-slope gravels, sand, and conglomerates, composed of sandstone, limestone, and granite clasts. Although cycles of downcutting and backfilling along the Rio Grande inner valley are not clearly reflected in piedmont areas away from the modern valleys, many major stream deposits did accumulate along floodplains of the Rio Grande and its major tributaries during the Pleistocene. These are preserved as fluvial terrace deposits, ranging in height from about 60 to 370 feet above the modern floodplain. The highest of these Quaternary river terraces has been called the Sunport surface (Williams and Cole, 2007), because it underlies the runways of Albuquerque International Airport. NMSHD oversees several major aggregate mining operations along Interstate 25 south of the airport, where Quaternary terrace gravel and sand is extracted for use in construction.

Some quarries in the eastern portion of the Rio Puerco Field Office planning units mine caliche, a crust that often forms in soil in arid areas. This crust is generated by the precipitation of calcium carbonate dissolved in water just below ground level (Desert Processes Working Group, accessed 2009).

3.3.1.2 Exploration, Development, and Production History

In 2007, there were 200 active and 16 standby stone and aggregate operations in New Mexico. Production value for stone and aggregate set a new record high of \$140.2 million in the state, with 5.3 million tons of gravel being produced at a value of \$56 million, and 1.4 million tons of sand produced at a value of \$13.7 million (NMEMNRD, 2008).

All five planning units contain numerous aggregate pits, but the largest and most extensive operations occur in BLM Planning Units 2, 4, and 5. These units encompass the inner portions of the Albuquerque Basin within the Rio Grande rift valley, and have the thickest accumulations of late Tertiary rift-fill sand and gravel deposits. In addition, Quaternary alluvial sediments and fluvial terrace deposits were deposited in the inner valley at the distal end of a large alluvial fan system, and often meet construction-grade sand and gravel specifications because of their generally smaller clast size and higher degree of sorting.

The New Mexico State Highway Department (NMSHD) is responsible for the majority of aggregate pits in the Rio Puerco Field Office planning units. These pits are usually developed to supply aggregate for nearby road construction, and then closed when the project is complete (Bland, 2009).

Several large pits in the study area are operated by corporations. For example, Lafarge North America maintains one of the largest aggregate production operations in the region at the Placitas Pit (Map Point SG141, Salable Index Map 9, Unit 5) (Figure 23). Western Mobile New Mexico also maintains several aggregate and gravel operations throughout Bernalillo, Sandoval, and Santa Fe counties, including the Santa Ana gravel pit (Map Point SG149, Salable Index Map 9, Unit 5) and the Baca Pit (Map Points AGG49, SG150, Salable Index Map 9, Unit 5) located along Interstate 25 north of Bernalillo. Vulcan Materials Company operates the Shakespeare pits, which mine sand and gravel within the Albuquerque metropolitan area (Map Points SG104 and AGG49, Salable Index Map 9, Unit 5) (Figure 24).



Photograph: Sengebush, INTERA, 2009.

The Shakespeare Pit (Map Points SG104 and AGG49, Salable Index Map 9) is located in the Albuquerque city limits. It is operated by Vulcan Materials Co.

This report divides the aggregate resources of the Rio Puerco planning area into six categories: general aggregate, caliche, aggregate limestone, gravel, sand and gravel, and sand. General aggregate pits (designated AGG on Salable Index Maps) are pits for which specific materials information was not available. They are most likely sand or gravel pits. Caliche is a calcium carbonate deposit formed in arid soils and crushed for aggregate use. Aggregate limestone is limestone used in crushed stone applications



(as opposed to chemical or metallurgical grade limestone, which is locatable). Gravel denotes a location where only gravel is present. Sand and gravel is a location with both sand and gravel. Sand only contains only sand, sometimes as an eolian “blow sand” deposit.

General aggregate pits (designated AGG on the Salable Index Maps) are usually owned by private companies rather than the NMSHD. These corporations seem more likely to report their commodity as general aggregate without specifying what kind they are mining. Like most aggregate developments, general aggregate pits tend to occur along highways and near cities and towns, where transport costs are low. For example, the Red Mesa Sand Pit (Map Point AGG79, Salable Index Map 3, Unit 1) operates just south of Gallup, and the Mountainair Gravel Products Pit (Map Point AGG7, Salable Index Map 14, Unit 3) is a little ways north of Mountainair, on the east side of New Mexico 542. A large general aggregate quarry complex is located east of Los Lunas (Map Points AGG16-20, Salable Index Map 14, Unit 2). Shakespeare Pit is located right in the middle of Albuquerque (Map Point AGG49, Salable Index Map 9, Unit 5), and the Placitas area contains the Baca Pit complex (Map Points 68, 70, and 71, Salable Index Map 9, Unit 5). A few general aggregate pits operated by the NMSHD are also located within the study area. One highway pit just west of Belen (Map Point AGG12, Salable Index Map 14, Unit 2) and two highway pits on the west side of Interstate 25 between Albuquerque and San Felipe Pueblo (Map Points AGG69 and AGG74, Salable Index Map 9, Unit 5) were estimated to contain unlimited quantities of aggregate.

Caliche (CAL) pits are mostly concentrated in Unit 3 along Interstate 40 and also in the southeastern corner of Torrance County. All but one of the caliche pits are highway pits. Only one caliche pit exists outside of Unit 3: a NMSHD pit in eastern Valencia County (Map Point CAL12, Salable Index Map 14, Unit 2). The only pit not operated by the State Highway Department is Loyd’s Pit, located in the northwestern corner of Torrance County (Map Point CAL19, Salable Index Map 9, Unit 3).

The Pennsylvanian Madera and San Andres Limestones are the sources for aggregate limestone (AGLIM) for Units 2, 3, and 5. Aggregate limestone production is thus restricted to areas where these two formations outcrop or are readily available in the subsurface. Major aggregate limestone production regions include the Zuni Mountains (Map Point AGLIM41, Salable Index Map 7, Unit 1), the Tijeras Canyon region (Map Point AGLIM56, Salable Index Map 9, Unit 2), northern Torrance County along Interstate 40 (Map Point AGLIM36, Salable Index Map 15, Unit 3), near Mountainair (Map Point AGLIM12, Salable Index Map 16, Unit 3) and southeastern Torrance County (Map Point AGLIM13, Salable Index Map 17, Unit 3). Most of these pits are operated by NMSHD, probably for crushed stone. However, some locations, such as the Abo Viejo Quarry (Map Points LIM1 and AGLIM12, Locatable/Salable Index Map 16, Unit 3) produce both aggregate limestone and chemical/metallurgical grade locatable limestone.

Pits with an estimated unlimited quantity of aggregate limestone are located in the Zuni Mountains (Map Point AGLIM41, Salable Index Map 7, Unit 1), southwestern Torrance County (point AGLIM1, Salable Index Map 16, Unit 3), east of Mountainair (Map Point AGLIM15, Salable Index Map 14, Unit 3), south of Tijeras in the Manzanita Mountains (Map Point AGLIM49, Salable Index Map 9, Unit 2), southwest of

Milan in Cibola County (Map Point AGLIM73, Salable Index Map 8, Unit 2) and on the northern flank of the Sandia Mountains (Map Point AGLIM90, Salable Index Map 9, Unit 5).

A collection of NMSHD pits along Highway 44 produce only gravel (Map Points GRA28 and GRA30-33, Salable Index Maps 5 and 2, Unit 4). A scattering of other exclusively gravel (GRA) pits occur throughout Torrance County (Unit 3) and a few pits exist in Valencia, Cibola, and Bernalillo Counties (Units 1, 2 and 5). Most of these quarries were operated by NMSHD. One highway pit along Highway 60 southeast of Mountainair contains a virtually unlimited supply of gravel (Map Point GRA4, Salable Index Map 16, Unit 3).

Numerous pits producing sand and gravel (SG) exist in the Rio Puerco planning area. Many of them are highway pits, but some are operated by large, multinational corporations. These pits range from active aggregate production to complete remediation. They are also enormous: the Placitas Pit (Map Point SG141, Salable Index Map 9, Unit 5) is 4,200 by 3,700 feet across, and the Santa Ana pit (Map Point SG149, Salable Index Map 9, Unit 5) is 4,700 feet by 3,700 feet across. These pits in the Placitas area mine the fluvial deposits of the Upper Santa Fe Group (Bland, 2009).



Photograph: Sengebush, INTERA, 2009.

The Placitas Pit (Map Point SG141, Salable Index Map 9) mines sand and gravel from the Santa Fe Group. It is operated by LaFarge North America.

The greatest concentrations of sand and gravel pits occur along Interstate 25 in Unit 5. A total of six highway pits in that area have unlimited reserves (Map Points SG147, SG152, SG159, SG160, SG161,



SG162, Salable Index Map 9, Unit 5). A pit on the western flank of the Manzano Mountains (Map Point SG4, Salable Index Map 14, Unit 2) and two pits on the south side of Tijeras Canyon (Map Points SG45 and SG46, Salable Index Map 9, Unit 2) also have unlimited reserves.

Sand and gravel pits in the Rio Puerco Field Office are almost always located near roads. A good example of this is along Interstate 25 north of Albuquerque, where favorable geology and proximity to a major metropolitan area has stimulated aggregate production. Other lines of sand and gravel pits can be seen along Highway 44 in Sandoval County (Unit 4) especially near the town of Cuba. There are also a number of pits near Highway 4 in the town of San Ysidro (Unit 4).

Some aggregate pits produce only sand (SND). Eolian sand is especially favorable because it is often quite homogeneous. A good example of an economic eolian sand deposit is found in southern Tarrant County along New Mexico 42 (Map Points SND3-5, Salable Index Map 17, Unit 3). Other sands appear to be arroyo deposits, or arroyo deposits remobilized by wind (Map Point SND27, Salable Index Map 9, Unit 5). A highway pit across the Rio Grande from Isleta (Map Point SND14, Salable Index Map 14, Unit 2) is estimated to contain unlimited sand reserves. Two other highway pits, one near Laguna (Map Point SND20, Salable Index Map 8, Unit 4) and another on the banks of the San Felipe Wash just south of Interstate 25 (Map Point SND27, Salable Index Map 9, Unit 5) have virtually limitless sand.

3.3.1.3 Resource and Development Potential

The most significant resource and development potential for aggregates in the Rio Puerco Field Office area exist in sedimentary units of late Tertiary to Quaternary age along Interstate 25 north of Bernalillo, NM. These include abundant deposits of aggregate material consisting mainly of loosely-consolidated alluvial gravel and sand. A series of large, actively producing sand and gravel pits attest to the availability and quality of aggregate resources in this area. However, residential developments threaten to curtail mining activity in portions of the region. The Tijeras area is very favorable to aggregate limestone production due to limitless resources and proximity to Albuquerque. Other regions in the Rio Puerco Field Office area contain massive amounts of aggregate resources, but the lack of nearby metropolitan areas makes large scale development unlikely. The resource potential for aggregate is judged to be high with abundant direct and indirect evidence of certainty (H,D) due to the extensive, ongoing commercial aggregate production, especially in BLM Planning Units 2 and 5. The point density mineral potential map (Plate 58) shows a 60 mile band of low to high resource potential along the Rio Grande Valley from Los Lunas to Cochiti Dam. The area from just south of Albuquerque to San Felipe Wash is a continuous swath of high resource potential for 40 miles along Interstate 25. Another region of moderate to high resource potential extends from Isleta eastward through Tijeras Canyon, a total distance of 30 miles. In addition, isolated point occurrences shown on the point density mineral potential map indicate broad regions of low to moderate potential across much of the BLM study area. Development potential is discussed in more detail in Section 4 of this report.



3.3.2 Basalt, Diorite, Cinders, and Scoria

Basalt is a dark colored, mafic extrusive igneous rock composed of calcic plagioclase and clinopyroxene, with occasional olivine, nepheline, and other mafic minerals. Diorite is a plutonic igneous rock with intermediate silica content and is the equivalent of the volcanic rock andesite. Diorite contains amphiboles and sodic plagioclase with pyroxene and occasional quartz (Bates and Jackson, 1980).

Volcanic cinders are volcanic rocks formed from the violent degassing of highly fluid lava. This magma foam cools and solidifies into lightweight vesicular fragments that accumulate around the volcanic vent, oftentimes forming a structure called a cinder cone. Cinders are distinguished from pumice by their greater weight and strength as well as their darker color. Industrial terminology reserves the term “cinder” for fragments smaller than about 1 inch, and scoria for the larger fragments. The specific density, color, and hardness characteristics of cinders depends on many factors within the volcanic eruption itself, and therefore cinder characteristics can vary from volcano to volcano and even within a single deposit (Kogel et al., 2006).

Basalt, especially relatively young basalt, is excellent for crushed stone uses. However, excessively vesicular or weathered basalt lacks the strength and abrasion resistance of fresh, massive basalt. Jointed or brecciated basalt is also less effective as a crushed stone resource. Thus, the best basalt for crushed stone is found in young, massive lava flows. Diorite is also a potentially useful crushed stone product so long as grain size is not excessively large. Like basalt, weathered diorite is less useful as it may contain a higher proportion of soft minerals (Kogel et al., 2006).

Basalts are also highly desirable decoration stone because of its durability and hardness. Basaltic building stone is sometimes known as “black granite” or “traprock.” Basalts have also been used as flux rocks in the production of rock wool insulation (Kogel et al., 2006).

Cinders and scoria can be used in concrete manufacturing, road and railroad construction, and landscaping. Cinders continually generate sharp edges as they are crushed, making them especially useful as absorbents and abrasives. However, cinders are also a good source of lightweight aggregate and insulators. Cinders are also commonly used for landscaping in the Albuquerque area. Crushed cinders are also used to improve road traction during and after a snowfall. Larger pieces of scoria are commonly used as an absorbent bed in gas grills (Kogel et al., 2006).

3.3.2.1 Geologic Setting

New Mexico’s basalt and cinder resources are concentrated in the numerous small volcanic fields scattered about the state. Volcanic fields are areas that ideally contain volcanoes related both in time and source material. However, volcanic fields are sometimes simply a geographic relationship that has little or no bearing on age or composition (Dunbar, pers. comm.). New Mexico volcanic fields are often monogenetic and consist of cinder cones, small shield volcanoes, domes, and lava flows. These fields typically range from Pliocene to Quaternary in age. Two larger volcanoes, Mount Taylor and the Valles Caldera, have also produced basalts and related rocks in New Mexico.



There are six volcanic fields in the Rio Puerco Field Office planning units with potential or demonstrated occurrences of basalt and cinders (see Figure 20). Many of these occurrences are the location of NMSHD resource pits. NMSHD is not obligated to report its aggregate pits, so there may be more cinder and basalt occurrences not covered by this map.

The Zuni-Bandera volcanic field is located in southwestern McKinley and northwestern Cibola Counties (Planning Unit 4, Salable Index Maps 3, 7, 8, 12, and 13). The field consists of monogenetic cinder cones and basaltic lava flows. These volcanoes range in age from over 500,000 to 3,000 years old. The field is famous for its lava tubes with year-round deposits of ice (Baldrige, 2004).

The Mount Taylor volcanic field lies within southeastern McKinley and northern Cibola Counties (Unit 1, Salable Index Maps 3, 4, 7, and 8). It includes Mount Taylor, a large composite volcano, and associated dikes, lava flows, and subsidiary cones. This volcanic field also includes the Puerco necks, a series of volcanic necks along the Rio Puerco northwest of Mount Taylor. Lavas from Mount Taylor itself were rhyolitic and latitic whereas rocks in the Puerco necks range from basaltic to basanitic. The field is between 4.49 and 1.5 million years old (Baldrige, 2004).

The Lucero Volcanic Field, Isleta Basalt, Cat Hills, and Las Lunas Volcanoes lie within Planning Unit 2 in Cibola, Valencia, and Bernalillo Counties (Salable Index Maps 8, 9, 13, and 14). These volcanoes range in age from 8.3 million years to less than a few tens of thousands of years old. Volcanoes in this region are scattered cinder cones and small shields of basaltic rock (Baldrige, 2004).

The Albuquerque Volcanoes include at least 15 eruptive centers and 8 basalt flows that erupted on the West Mesa about 160,000 years ago. They are located in western Bernalillo County (Unit 2, Salable Index Map 9). These cinder and spatter cones consist of basalt and lie along a north-south fissure about 10 kilometers long (Baldrige, 2004). Although the Albuquerque Volcanoes may contain significant amounts of basalt and cinders, they are included in Petroglyph National Monument and are thus off-limits to development.

The Jemez and Cerros del Rio volcanic fields are included together because of their geographic proximity. The Cerros del Rio volcanics are 13.1 to 2.2 million years old and consist of basalts, andesites, and latites, probably erupted from shield volcanoes and fissures. The Jemez volcanic field is dominated by the Valles Caldera, a massive resurgent dome that has generated a series of tuffs and rhyolitic lava flows. Volcanism in the Jemez field began as much as 14 million years ago and ended less than 55,000 years ago. This long lived field contains some basalt, but predominantly consists of silicic rocks (Baldrige, 2004; Goff and Gardner, 2004).

3.3.2.2 Exploration, Development, and Production History

One basalt highway pit exists near the town of Black Rock (Map Point BSLT13, Salable Index Map 7, Unit 1) and another just west of Gallup (Map Point BSLT19, Salable Index Map 7, Unit 1). NMSHD reports over 100,000 cubic yards of fair quality rock near Black Rock and over 100,000 cubic yards of good quality rock in the pit near Gallup (Barker et al., 2006). One other basalt quarry owned by Hamilton

Brothers, Inc. lies west of Gallup, just south of Interstate 40 (Map Point BSLT20, Salable Index Map 7, Unit 1; Orris, 2000). Nothing is known about the quality or quantity of basalt extracted from this quarry.

A cluster of cinder quarries occurs in the southeastern part of the Zuni-Bandera field. The Candelaria Pits (Map Points CIND8 and CIND9, Salable Index Maps 12 and 7, Unit 1) extract cinders from a series of pits along Highway 53 (McLemore et al., 1984a; Orris, 2000). Three other pits are located in the same cluster of cinder cones.



New Mexico Resource Geographic Information System: Earth Data Analysis Center.

The Candelaria Pit (Map Point CIND9, Salable Index Map 13) mines cinders and scoria that were probably deposited by the cinder cone to the west (across the road).

Several highway pits have extracted basalt from lava flows east of Grants along Interstate 40 and the southeastern flanks of Mount Taylor. Highway pits near Acomita Lake (Map Point BSLT11 and BSLT12, Salable Index Map 8, Unit 2) contain over 500,000 cubic yards of Quaternary basalt (Barker et al., 2006). A highway pit west of the town of Encinal contains 500,000 cubic yards of excellent quality basalt (Map Point BSLT14, Salable Index Map 8, Unit 2, Barker et al., 2006).

Two basalt pits and one cinder pit lie close to where Interstate 40 crosses the Rio Puerco River. One basalt highway pit contains an estimated 100,000+ cubic yards of basalt (Map Point BSLT10, Salable Index Map 9, Unit 2; Barker et al., 2006). The cinder pit is located near Cerro Colorado, a small hill south of the interstate (McLemore et al., 1984a). A number of cinder pits are located on the mesa between



Highway 6 and Interstate 40 east of the Rio Puerco. These pits mine a series of cinder and spatter cones (see Map Points CIND1-CIND5, Salable Index Map 14, Unit 2). The Isleta and Los Lunas volcanoes are both sources of basalt. The Los Lunas Volcano pits contain 150,000 cubic yards of good quality basalt along with eolian sand deposits (Map Points BSLT4 and BSLT5, Salable Index Map 14, Unit 2; Barker et al., 2006).

A large basalt quarry is located on the Santa Ana Reservation just east of the Jemez Canyon Dam, and a highway pit on the Santa Ana Mesa (Map Point BSLT18, Salable Index Map 9, Unit 4) contains essentially unlimited quantities of good quality basalt (Barker et al., 2006). Two highway pits are located on the Pajarito Plateau. One pit contains basaltic andesite (Map Point BSLT21, Salable Index Map 5, Unit 4) and the other contains over 200,000 cubic yards of basalt and other Tertiary volcanic (Map Point BSLT22, Salable Index Map 5, Unit 4; McLemore et al., 1984a). Two pits are located within the Valles Caldera itself along Highway 4. Both contain Tertiary basalt (Map Points BSLT23 and 24, Salable Index Map 5, Unit 4), and one is estimated to have over 300,000 cubic yards of good quality rock (McLemore et al., 1984a; Barker et al., 2006).

Two highway pits occur in eastern Torrance County (Map Points BSLT1 and 2, Salable Index Maps 15 and 17, Unit 3). Both contain fair to poor quality diorite (Barker et al., 2006). The Quail Lode just east of the Manzanita Mountains (Map Point CIND7, Salable Index Map 14, Unit 2) is reported to have scoria, but nothing else is known about it (McLemore et al., 1984a).

3.3.2.3 Resource and Development Potential

Basalt, diorite, and cinders are abundant throughout the BLM planning units, especially in BLM Planning Unit 2. Three major areas of high to moderate resource potential with direct evidence of occurrence (H,C to M,C) extend in a line from the Los Lunas Volcano to a basalt quarry just east of the Interstate 40 bridge over the Rio Puerco (Plate 61). Other patches of high resource potential with direct certainty occur at the southeastern end of the Zuni Mountains, and in the lava fields south of Mount Taylor (H,C). Areas of low potential surround these high and moderate regions. The point density mineral potential map shows moderate and low potential around single points of occurrence. This is due to the overall relatively low point density for these materials in the area and the fact that these volcanic materials are the entire actual resource that could be exploited. Development of these resources is expected to continue to the extent that these materials are needed for construction and landscaping as a reflection of general economic conditions. INTERA has determined that development potential is moderate near the city of Albuquerque, decreasing to low elsewhere due to distance from major urban areas.

3.3.3 Clay and Adobe

Clay is one of the oldest and most used resources by cultures the world over. In New Mexico, clays have been used for brick, tile, pipes, fire brick, and general lightweight aggregate (McLemore et al., 1984a; McLemore, 2009). In addition, Native Americans have used clay in pottery in the area for thousands of years.



The economic viability of a given clay deposit is strongly influenced by its mineralogy. Since a wide variety of clay minerals exists, this means that each clay deposit must be carefully examined to determine whether or not it is economic. For this reason, a series of tests were conducted in the early and mid 20th century to characterize the clays in New Mexico (McLemore et al., 1984a). The sampling sites for these tests as well as clay pits are plotted on the index maps and the clay point density mineral potential map (Plate 65).

Clay is also an important constituent of adobe. Adobe bricks consist of a mixture of sand and clay (55 to 75 percent sand, the remainder clay). The sand is typically medium-to coarse-grained with clay as a binder. Clay composition is highly variable between production sites, but a typical adobe brick in New Mexico contains roughly equal proportions of expansive and non-expansive clay minerals. Asphaltic emissions are sometimes added as a stabilizer. The use of adobe and related earthen building materials dates back to at least 7,000 years before common era (BCE). Even today, adobe and related construction materials continue to be popular because they are cheap, environmentally friendly, and plentiful.

3.3.3.1 Geologic Setting

Clay deposits are fairly common in the Rio Puerco planning area. Shales from the Mesaverde Group, the Santa Rosa, Chinle, Morrison, and Abo Formations, the Mancos Shale, and the Fruitland Formation have been analyzed for usefulness. These clays are composed mostly of smectite with lesser amounts of kaolinite. Clay is also present in Rio Grande floodplain deposits (McLemore et al., 1984a). Despite the apparently vast resources in the study area, relatively few deposits have been developed. Most of the clay pits that do exist are operated by brick, tile, and Portland cement manufacturers, although the NMSHD does list clay as a commodity in a few of its pits (McLemore et al., 1984a; Barker et al., 2006; McLemore, 2009; Lucas-Kamat, 2009).

Adobe production in the Rio Puerco Field Office planning area is confined to Planning Units 2 and 4 (Sandoval and Bernalillo Counties, Salable Index Maps 5, 9, and 14). Preferred source materials for adobe include recent fluvial deposits or any soil with a wide range of grain sizes. In New Mexico, the best adobe material is typically found in Quaternary and Tertiary terrace deposits near the Rio Grande.

3.3.3.2 Exploration, Development and Production

The majority of recognized clay occurrences cited in recent literature occur in Bernalillo and Sandoval Counties (Units 2, 3, and 4), with two occurrences in Cibola County and none at all in the rest of the counties included in the study area. However, 12,000 tons of semi-refractory clays were being produced annually in the Gallup Region (Unit 1) at the turn of the 20th century. This clay was being sold to the United Verde Copper Company in Arizona to line their copper converters (Reis and Leighton, 1909).

More recently, NMSHD developed a burned shale deposit in eastern Cibola County that contains over 300,000 cubic yards of good quality material (Map Points CLAY2 and CLAY3, Salable Index Map 13, Unit 2; Barker et al., 2006).



Several clay pits and one clay sample was taken in or near the Albuquerque metropolitan area. The New Mexico Clay Products Co pit (Map Point CLAY5, Salable Index Map 9, Unit 2) mined Holocene floodplain clays in the Rio Grande valley. A test on the western edge of the city (Map Point CLAY10, Salable Index Map 9, Unit 2) revealed clay suitable for red brick and tile manufacture (McLemore et al., 1984a).

The Manzanita Mountains and the Tijeras area are home to significant clay deposits. The Kinney Brick Company takes its raw material from the Pine Shadow Member of the Wild Cow Formation (Madera Group). As of 1984, the company had been mining from its pits on the eastern slopes of the Manzanita Mountains for over 30 years (Map Point CLAY4, Salable Index Map 9, Unit 2). The company also works another nearby occurrence (Map Point CLAY1, Salable Index Map 14, Unit 2). Clay produced from these pits is used primarily in brick manufacture (McLemore et al., 1984a). As of 2010, the Kinney Brick Company continues to mine from the Hattie Pit (CLAY4) (pers. comm.. Hoffman).

Several clay occurrences were tested east of the Sandia Mountains (Map Points CLAY12-14, Salable Index Map 9, Unit 5). These clays range from poor to fair quality and could be used in lightweight aggregate and tile manufacture (McLemore et al., 1984a) but no development is reported.

A handful of pits produce clay near Placitas, and numerous tests have been conducted in that area. The Placitas Pit (Map Point CLAY19, Salable Index Map 9, Unit 5) mines clay as well as sand and gravel. The Tongue Clay Pit (Map Point CLAY23, Salable Index Map 9, Unit 5) produced raw material for the Albuquerque Brick and Tile Company from the Mancos Shale. This pit produced from the early 1930s to the mid 1940s (McLemore et al., 1984a; Lucas-Kamat, 2009).

Clays have been investigated along the southern edge of the Jemez River Valley, southwest of San Ysidro. Clays from the Mancos Shale (Map Point CLAY32, Salable Index Map 5, Unit 4) and bentonites from the Dakota Sandstone (Map Point CLAY33, Salable Index Map 5, Unit 4) are reported to be marginal for light aggregate. A deposit of gray shale shows some potential as fireclay (Map Point CLAY34, Salable Index Map 5, Unit 4; McLemore et al., 1984a).

All but one adobe producer is within or very close to the Albuquerque city limits. The remaining adobe brickyard (Map Point ADOB3, Salable Index Map 5, Unit 4) is located near the town of Peña Blanca in west-central Sandoval County (McLemore et al., 1984a). Adobe production facilities operate during the summer months only, as freezing weather interferes with brick making (Kogel et al., 2006; McLemore et al., 1984a). Traditionally, adobe was produced on a small scale at or near a construction site. However, with the rise of a distinctively New Mexican architecture, adobe buildings are increasingly sought after by middle and upper class homeowners. This has given rise to large scale commercial adobe operations producing a cumulative value of over \$1 million in the year 1980. Undoubtedly the value is even higher today (Kogel et al., 2006; McLemore et al., 1984a).

New Mexico Earth Adobes, Inc (Map Point ADOB7, Salable Index Map 9, Unit 2) produces about 400,000 bricks in a typical year for a total value of about \$316,000 at its brickyard in North Albuquerque.



Other adobe producers, such as the Lawrence Tenorio brickyard (Map Point ADOB5, Index Map 9, Unit 2), continue to operate on a smaller scale (Levine, pers. comm.).

3.3.3.3 Resource and Development Potential

McLemore et al. (1984a) reported high mineral resource potential in Tijeras Canyon and southeast Bernalillo County (Unit 2, Salable Index Maps 9 and 14), moderate potential in the Placitas region (Unit 5, Salable Index Map 9), and low to moderate potential in other clay occurrences in the Rio Puerco planning area. Development potential was considered high in Tijeras Canyon and southeast Bernalillo County, most likely because of existing industry in the area (McLemore et al., 1984a). The point density mineral potential map (Plate 65) shows an area of high potential to the northwest of Placitas and another small region of high potential on the east flank of the Sandia Mountains. The gravel pits in the Placitas area do in fact report clay as one of their commodities, giving the region high potential with abundant direct and indirect evidence for clay occurrences (H,D). However, the points on the east slope of the Sandias represent test sites and not actual developments, thus INTERA assigns moderate potential with direct certainty (M,C) to this area. One of the two map points in the Manzanita Mountains is a clay quarry with a history of production, giving these mountains a designation of high potential with direct certainty (H,C) though the mineral potential point density map shows only moderate potential. In general, little development seems to have occurred in the Rio Puerco Field Office planning area since McLemore et al.'s 1984 report. Development potential appears to be limited due to only moderate demand and the small and scattered locations of the clay deposits.

The resource potential for adobe is considered to be high with direct certainty (H,C). With an essentially unlimited supply of raw materials in the Rio Puerco planning units (McLemore et al., 1984a), the adobe industry is subject only to the fluctuations of the housing market.

3.3.4 Dimension Stone, Decorative Stone, and Travertine*

Stone is an attractive and durable building material, and trends in modern architecture have increasingly relied on stone to build long lasting, aesthetically pleasing structures. This trend has been driven by price drops due to the development of efficient quarrying technology and an increase in cheap imports from the developing world (Lardner, pers. comm.).

Classification of stone resources depends on the use of the particular occurrence. Dimension stone is produced in specific shapes. The stone is often cut into large rectangular blocks and then processed into its final form at a later date. Building stone is not cut to specific measurements and can be used for erosion control, rough walls, or paving. Decorative stone has a broader definition and includes any stone used to enhance the appearance of a given location. Decorative stone can come in any size, shape, or quantity, from small samples of valuable minerals to large slabs of rough stone (Kogel et al., 2006). Fieldstone is a subset of decorative stone and consists of slabs harvested off the ground surface. New Mexico builders and landscapers particularly value a certain type of fieldstone called *moss rock* (Tracy,

* Although travertine is technically a locatable mineral, we have included it in this section due to its use as decorative and dimension stone.

Rocky Mountain Stone, pers. comm.). Moss rock consists of lichen-covered boulders harvested directly off the ground surface. Flagstones (thin slabs of fissile sandstones) are also common building materials in the state, especially for use in patios and walkways. Aggregates are also sometimes used for decorative stone, and are particularly useful in xeriscaping (Kogel et al., 2006).

Dimension stone production technology is often cutting edge, employing computer controlled equipment and specialized abrasives. Even stone cut to less exact specifications still requires a great deal of physical labor to produce. Because of this, the dimension stone industry is capital intensive. However, due to the numerous and sometimes conflicting definitions of stone resources and the difficulty in determining how much stone is quarried, sold, and used, accurate production statistics are hard to come by. Furthermore, industry definitions of certain stone types can conflict with accepted geologic definitions (Kogel et al., 2006).

3.3.4.1 Geologic Setting

Travertine is a stone created by the deposition of calcium carbonate usually by a spring. The numerous active and inactive mineral springs in New Mexico have created extensive, though spotty, occurrences of travertine. Commercially viable deposits are hard and crystalline, although they may contain vugs and impurities that give the stone a unique character. Travertine occurrences are limited to two regions in the Rio Puerco Field Office planning units. The first region is west of San Ysidro near Highway 44 in Unit 4. This area contains many active and extinct soda springs and their resulting travertine deposits. Most or all of these travertines were noted by uranium prospectors (for example, Map Point LIM39, Locatable Index Map 5, Unit 4) and none of them have been quarried (McLemore et al., 1984a; McLemore, 2009). The other travertine deposit is located west of Los Lunas in BLM Planning Unit 2, at Map Points LIM2-8, Locatable Index Map 5. The point source mineral resource potential map for limestone (Plate 60) includes travertine in its assessment, and thus acts as a guide to travertine potential in the areas mentioned above.



Photograph: Bowman, INTERA, 2009.

Active travertine deposition in the San Ysidro Anticline (Map Point LIM37, Locatable Index Map 5).



Other stone resources in the Rio Puerco planning area are vast and varied, encompassing everything from Precambrian crystalline igneous rocks through Quaternary volcanics and even decorative aggregate gravel.

3.3.4.2 Exploration, Development, and Production History

The most important stone in the Rio Puerco Field Office planning units is arguably the travertine deposits currently being mined from the Lucero Quarry in western Valencia County (points LIM2 and STONE9, Salable and Locatable Index Maps 13, Unit 2; Lucas-Kamat, 2009; Lardner, pers. comm.) by New Mexico Travertine, Inc. New Mexico Travertine, Inc. quarries most of the travertine produced in the U.S. from this quarry (Kogel et al., 2006). This travertine is typically used for dressed veneer stone (Lardner, pers. comm.). The Haskani Mine in eastern Cibola County is also reportedly mining travertine (Map Point LIM6, Locatable Index Map 13, Unit 2; Lucas-Kamat, 2009) but the operating company is unknown.

Small-scale production of flagstone and other miscellaneous resources occurs elsewhere in the planning units. Some local collection and sale of moss rock may occur in the higher, wetter elevations of the study area, but development and production data for this resource is nonexistent.

Many quarries are operated by NMSHD, especially in Cibola and McKinley Counties (BLM Planning Unit 1). These pits produce conglomerates (Map Points STONE13 and STONE14, Salable Index Map 12, Unit 1; Barker et al., 2006) and andesite (point STONE25, Salable Index Map 7, Unit 1; Barker et al., 2006). A series of highway pits along Highway 53 at the extreme southern tip of the Zuni Mountains produce granite (Map Points STONE17-19, STONE21, Salable Index Map 13, Unit 1). The New Mexico State Highway Department reports that Map Points STONE17, STONE19, and STONE21 contain virtually unlimited amounts of granite (Barker et al., 2006, McLemore, 2009).

The Valles Caldera/Jemez region in Planning Unit 4 (Sandoval County) also contains many highway pits. These produce andesites and rhyolites (Map Points STONE36-40, Salable Index Map 5, Unit 4; McLemore et al., 1984a; Barker et al., 2006). The Atkinson Company quarry extracted stone, sand, and gravel from a location near Cochiti Dam (Map Points STONE35, Salable Index Map 5, Unit 4), but the type of stone product is unknown (McLemore et al., 1984a). The Eureka Mesa Quarry of northern Sandoval County also produced unspecified stone (Map Point STONE41, Salable Index Map 2, Unit 4; McLemore et al., 1984a). One highway prospect pit in southeastern Sandoval County reported unlimited quantities of rhyolite (Map Point STONE33, Salable Index Map 9, Unit 5; Barker et al., 2006).

The Sandia Mountains contain gneisses and granites (Map Point STONE27, Salable Index Map 9, Unit 5). Point STONE27 is a highway pit (McLemore et al., 1984a) and thus probably represents road aggregate exploration rather than an occurrence of building stone quality granite. However, the Great Combination Mine (Map Point STONE28, Salable Index Map 9, Unit 5) was reported to have building stone along with gold, copper, and silver (McLemore et al., 1984a). The type of building stone is not specified, but given the mine's location it is probably granite or limestone.

The Pohl and Abo Viejo quarries (Map Points STONE4 and STONE5, Salable Index Map 16, Unit 3) produce flagstone, dimension stone, and limestone in the southwest corner of Torrance County (Lucas-



Kamat, 2009). Other highway pits and quarries are scattered across Unit 3. Precambrian crystalline rocks and Paleozoic sandstones and limestones in the Manzano Mountains are also suitable for dimension and aggregate stone (McLemore et al., 1986b) but do not appear to be developed. A highway pit along the west side of the Manzano Mountains in Valencia County (Map Point STONE10, Salable Index Map 14, Unit 2) contains unlimited amounts of granitic schist, and another highway pit south of the Pederal Mountains in Torrance County reported unlimited amounts of granitic gneiss (Map Point STONE11, Salable Index Map 13, Unit 3). A pit southeast of the town of Willard in Torrance County also reported unlimited amounts of granite (Map Point STONE6, Salable Index Map 15, Unit 3; Barker et al., 2006).

3.3.4.3 Resource and Development Potential

McLemore et al. (1986b) report high resource potential for travertine along Mesa Lucero in Valencia County. Past history indicates that other travertines outside the Mesa Lucero area are probably too poor quality for use in building, and future development is unlikely unless these deposits are found to be unique and easily extractable (Lardner, pers. comm.). Furthermore, the housing recession of 2008 significantly affected travertine production in the area, causing New Mexico Travertine Inc to produce only 340 tons, about half of their typical yearly output. Finally, cheap imports from overseas continue to undercut the economic viability of the New Mexico travertine industry. The point density mineral potential map for travertine is included in the map for limestone (Plate 60). The travertine resource potential is judged to be high with abundant direct and indirect evidence of certainty (H,D) in the area of the Lucero quarry and high with indirect evidence of certainty (H,B) for the other travertine deposits near San Ysidro. The future development potential is likely to reflect the general economic trends within the housing industry, which fluctuates periodically. Only the Lucero quarry is likely to continue producing, as opposed to new quarries starting elsewhere. Therefore, the Mesa Lucero has high development potential, and the San Ysidro travertines have low development potential. Note that travertine is included here under salable minerals because it is utilized as a building stone and not a chemical grade limestone.



Photograph: Sengebush, INTERA, 2009.

Blocks of travertine from the Lucero Quarry for sale at Rocky Mountain Stone, Inc.

The Sandia and Manzano Mountains contain potentially high-quality granites and gneisses so the resource potential is judged to be high, with direct evidence of certainty (H,C) due to the abundance of granite rocks in the area, but there is no specific point density mineral potential map for this commodity. The presence of wilderness areas, overburden, and lack of processing facilities make development impractical. Commercial development of other stone resources in the Rio Puerco planning area is unlikely due to the lack of processing facilities and low material prices (Lardner, pers. comm.).

3.3.5 Humate

Humate is a broad term encompassing oxidized coals, carbonaceous shales and mudstones, and organic-rich sandstones (Kogel et al., 2006). The chemicals of interest in humate include humic acid, fulvic acid, ulvic acid, humins, and humic mineral salts. These chemicals act as soil conditioners to improve water absorption and retention, capture essential plant nutrients, and stimulate microbial activity (Roybal and Barker, 1987; Pettit, accessed 2009). Other uses for humate include animal feed additives and hydrocarbon spill remediation (Reid, pers. comm.) and even as a drilling fluid additive (Roybal and Barker, 1987). New Mexico humate is exported domestically to every state except Alaska, and internationally to Central America, the Caribbean, Taiwan, and South Korea (Kogel et al., 2006; Reid, pers. comm.).

3.3.5.1 Geologic Setting

In New Mexico, humate occurs as oxidized coals and carbonaceous shales (McLemore et al., 1984a). Within the planning area, humate is found in the Cretaceous Fruitland, Menefee, and Crevasse Canyon



Formations of the San Juan Basin in proximity to coal seams. These deposits represent both clayey organic matter and weathered coal. Humates in the Fruitland Formation often have less than 20 feet of overburden, making them amenable to strip mining. Humate layers 4 to 6 feet thick are reported in the Fruitland Formation north of the Rio Puerco planning area, and laterally persistent layers averaging 1 to 2 feet thick are reported in the Menefee Formation. Menefee humates tend to occur in the upper 30 to 90 feet and lower 240 to 300 feet of the formation. Menefee and Fruitland humates are less dense than coal and will not combust (Reid, pers. comm.; Roybal and Barker, 1987; McLemore et al., 1984a).

3.3.5.2 Exploration, Development, and Production History

Humate has been produced in New Mexico since at least 1965. Known humate operations in the Rio Puerco planning area are located exclusively in Sandoval County (Planning Unit 4, Salable Index Maps 2, 4, 5, and 9). Eight humate mines were reported in 1984. The Tenorio mine (Map Point HUM1, Salable Index Map 9, Unit 4) was open from approximately 1966 to 1980. The Clod Buster mine (Map Point HUM6, Salable Index Map 5, Unit 4) was a strip mine with a maximum capacity of 100 tons per day. This facility was shut down sometime after 1984, but a new pit may now be producing in a different location. As of 2008, humate production was also occurring at the San Luis mine (Map Point HUM3, Salable Map Index 4, Unit 4).

3.3.6 Resource and Development Potential

Because of the vast coal deposits of the Fruitland, Menefee, and Crevasse Canyon Formations, humate resources may number in the millions to even billions of tons in northwestern New Mexico. Therefore, the humate supply in the Rio Puerco planning area is essentially unlimited (Reid, pers. comm.; Roybal and Barker, 1987; McLemore et al., 1984a). Humate is combined with coal to create the point density mineral potential map (Plate 56). The humate resource potential is high with abundant direct and indirect evidence of certainty (H,D), especially in the La Ventana coal field area, based on geologic environment and the point density mineral potential map. The level of potential is moderate with direct evidence of certainty (M,C) in the northern Rio Puerco coal field. The development potential is expected to be steady at current levels, or increasing as the product becomes better known within the agricultural community (Reid, pers. comm.).



SECTION 4.0 TABLE OF CONTENTS

4.0	REASONABLY FORESEEABLE DEVELOPMENT	98
4.1	Leasable Minerals	99
4.1.1	Oil and Gas	99
4.1.2	Coal.....	100
4.1.3	Geothermal	100
4.2	Locatable Minerals	102
4.2.1	Gold and Silver.....	102
4.2.2	Base Metals	102
4.2.3	Gypsum.....	103
4.2.4	Limestone	103
4.2.5	Pumice and Perlite.....	103
4.2.6	Rare Earth Elements	103
4.2.7	Uranium.....	104
4.2.8	Lithium	105
4.3	Salable and other Industrial Minerals	106
4.3.1	Aggregate, Sand, and Gravel, Stone and Cinders.....	106
4.3.2	Clay.....	106
4.3.3	Humate	106



4.0 REASONABLY FORESEEABLE DEVELOPMENT

Reasonably foreseeable development (RFD) is defined as the “potential for the occurrence and likelihood for future development of mineral resources” (BLM, 2009). The evaluation of RFD includes two component analyses: (1) an evaluation of the potential for the occurrence of a resource based on geologic factors and (2) an evaluation of the potential for future exploitation of that resource based on economic factors. Geologic factors might include lithologic, structural, geochemical and other factors that, when considered together in a qualitative and/or quantitative fashion, comprise an occurrence model that may be used to evaluate potential for occurrence of a particular resource. Economic factors might include future price projections for the resource, as well as consideration of changes (typically decreases) in mining or extraction costs based on development of new technologies. In the absence of readily-available data for projecting potential future exploitation, evaluation factors may also include an analysis of historical economic trends. Thus the evaluation of RFD is based both on where the resource is predicted to occur as well as how great future demand (or lack thereof) is expected to be. This section focuses on economic factors, and presents an evaluation of potential future exploitation based on an analysis of both historical production as well as projections of future production.

The discussion is organized in terms of leasable (oil, gas, and coal, geothermal), locatable (gold and silver, base metals [copper is used to represent the base metal group as a whole], gypsum, limestone, pumice and perlite, REE, and uranium, and lithium), and salable (aggregate/sand/gravel, ornamental stone, basalt-diorite-scoria [cinders] and humate). In general, INTERA’s approach was to acquire New Mexico production data, and compare those to historical U.S. production data and projected U.S. production data (when available) to get a sense of potential future trends. The historical data generally start in 1970 and continue through the present. The start date of 1970 was chosen based on data availability as well as the fact that time series starting with 1970 should provide a solid historical baseline to evaluate. For future projections, we have attempted to find projected data to 2030, where available. This data was available from the DOE (2009) for oil, natural gas, and coal. Commodities not addressed in this section, due to the absence of any significant quantity within the BLM planning units, a lack of production data, or an apparent lack of demand (with the associated total lack of production), include the following: semiprecious minerals and stone, sodium, sulfur, halite, carbon dioxide and helium.



4.1 LEASABLE MINERALS

The RFD potential for leasable minerals occurring in the Rio Puerco planning area is discussed below. Leasable commodities include oil, natural gas, and coal.

4.1.1 Oil and Gas

New Mexico historical oil production data (DOE, 2009a) are presented on Figure 25, along with historical (DOE, 2009b) and projected (DOE, 2009c) U.S. oil production. New Mexico oil production generally mirrors U.S. oil production, showing a downward trend since 1970. However, projections of future oil production indicate an increase in U.S. production starting in 2015 then leveling off from about 2025 to 2030 (DOE, 2009c). Therefore we may infer that New Mexico may see a similar production trend.

New Mexico historical natural gas production data (DOE, 2009d) are presented on Figure 26, along with historical (DOE, 2009e) and projected (DOE, 2009f) U.S. gas production. Similar to oil, New Mexico gas production generally mirrors U.S. gas production, with a trough in production in the mid-1980s, followed by generally increasing production after that time. DOE (2009f) projects a dip in production through 2015 followed by a strong increase in natural gas production between about 2015 and 2030. New Mexico production is expected to follow a similar trend. Over the last decade, average annual price for natural gas rose from less than \$2 per MCF to more than \$5 per MCF, with prices in 2008 exceeding \$10 per MCF. As a result, interest in exploration for natural gas and associated natural gas liquids and light oils increased but then fell as the price decreased in late 2009 to around \$3.00 per MCF at the wellhead. According to the Wall Street Journal and National Public Radio, new technologies of recovering natural gas from shale have helped production rise 11% in the past two years (Casselman, 2009).

This shale gas was previously considered unreachable, but advances in drilling techniques have changed that assessment (Gjelten, accessed 2009).

According to DOE (DOE, 2009) large decline in electric power sector consumption of natural gas in 2010 is projected to more than offset natural gas consumption growth in the residential, commercial, and industrial sectors. The anticipated addition of new coal-fired generating capacity combined with higher natural gas prices should reverse the coal-to-natural-gas switching trend that accounted for the large increase in electric-power-sector natural gas consumption this year.

As indicated by Broadhead (2009) rising prices for natural gas have generally resulted in increased exploration in the Albuquerque Basin. Wells drilled as part of Shell's exploration program in the 1970s and post Shell exploration that began in the 1990s have yielded geologic information that previously did not exist and have provided invaluable information with which to understand the geology and petroleum potential of the basin (Broadhead, 2009). However, the depth of the drilling targets in the Albuquerque basin and the associated cost suggest that development will occur elsewhere before additional exploration efforts resume in the Albuquerque basin.



4.1.2 Coal

Lower total electricity generation combined with increases in generation from natural gas, nuclear, hydropower, and wind led to an 11-percent decline in coal consumption by the electric power sector in the first half of 2009. A projected continuation of these trends for the remainder of the year leads to an annual decline in electric power sector coal consumption of more than 9 percent. Projected increases in electricity demand and natural gas prices will contribute to coal regaining a larger share of baseload generation in 2010. Nearly 4,300 megawatts of new coal-fired generation, online by the end of 2010, will add to the demand for coal. Projected coal consumption in the electric power sector increases by almost 5 percent in 2010 but it remains below 1 billion short tons for the second consecutive year. Coal consumption for steam in the retail and general industry and coke (coal from which the volatile constituents have been driven off by heat) for the smelting industry declined by 21 percent in the first half of 2009 compared with the first half of last year. In the forecast, consumption of coal for coke plants rises in the second half of 2009. Improved economic conditions in 2010 are forecast to lead to an increase of almost 3 million short tons (17 percent) of coal consumed in the coke sector. DOE projects 6-percent growth in 2010 for coal consumption in the retail and general industry sectors (DOE, 2009g).

Historical New Mexico coal production (Hoffman, 2009) is compared to historical Western U.S. (DOE, 2009g) and projected Western U.S. (DOE, 2009h) coal production on Figure 27. The Western U.S. data were used for comparison because the DOE-reported data were subdivided by Eastern and Western U.S., and the Western U.S. data should be more indicative of New Mexico coal production. The historical and projected data generally trend moderately upward through 2030 and thus based on projected Western U.S. coal production, New Mexico coal production is expected to increase in the future.

According to an industry publication (Pay Dirt, 2009), coal will maintain its position as the largest fuel provider for U.S. electricity and the nation is expected to add 184 gigawatts of coal capacity by 2030. We expect this increase to be reflected in the coal mines of New Mexico, although not necessarily by development of any of the deposits within the Rio Puerco Field Office planning units.

4.1.3 Geothermal

Resources of geothermal energy range from the shallow ground to hot water and hot rock found a few miles beneath the Earth's surface, and down even deeper to the extremely high temperatures of molten rock called magma. Major exploration efforts for geothermal resources have taken place in New Mexico within the Jemez mountains region, yet to date there has been no commercial production of geothermal energy. Nationwide, geothermal energy for the production of electricity has remained flat from 2004 (14,810,975 thousand kilowatt hours) through 2008 (14,859,238 thousand kilowatt hours) (DOE, 2009). DOE does not predict the growth of geothermal energy from 2010 through 2030 as they do for oil, natural gas, and coal.

Direct use of geothermal energy via steam generation of electricity seems unlikely in New Mexico within the next 20 years, based on the difficulties encountered during the Fenton Lake Hot Dry Rock project and the Baca Demonstration project. However, newer geothermal technologies, such as the geothermal heat



pump, could be used to exploit the resource in a more economical fashion. A geothermal heat pump is an electric heat pump that exchanges heat with the ground or ground water at relatively shallow depth. According to DOE, geothermal heat pump sales increased 250 percent from 2003 to 2008 (DOE, 2009). This suggests that new technology could significantly change the outlook of geothermal energy use but in ways that would not require exploitation of the deep, volcanic heat sources that have been explored in the past.



4.2 LOCATABLE MINERALS

The RFD for locatable commodities gold and silver, base metals (copper is used to represent the group as a whole), gypsum, limestone, and pumice and perlite, rare earth elements, uranium, and lithium are discussed below.

4.2.1 Gold and Silver

Precious metals gold and silver are both characterized by volatile production histories, primarily tied to market price. Figure 28 presents gold production data for New Mexico (Lucas-Kamat, 2009). The production trend generally follows the spike in price during the early 1980s (Figure 31) (Global Infomine, 2009a) and decreases after that. There appears to be a small uptick in production in the last few years, probably coincident with the recent increase in gold prices (near \$1,200 per Troy ounce as of December 2009). Trends in the precious metals markets are notoriously difficult to predict, but it appears that future gold production in New Mexico might be characterized as flat to slightly increasing. The only gold produced commercially in New Mexico at this time is as a byproduct recovery from copper refining from the open pit copper mines in the southwestern part of the state (USGS, 2009). Even the commercial deposits in the Ortiz mountains east of BLM Planning Unit 5 are idle. We believe that potential gold production from any of the BLM planning units would be from the Cochiti district in Unit 4, although this is unlikely due to the relatively small size of the deposits and the environmental hurdles of opening a mine. Silver follows a very similar pattern (Figure 29), with production peaking in the early 1980s and dropping off steeply after that period reflecting the silver price (Figure 31). We might conservatively state that future silver production in New Mexico could be characterized as flat to slightly increasing, but not from any sources within the five BLM planning units.

4.2.2 Base Metals

Historical production data for copper in New Mexico are presented on Figure 30 (Lucas-Kamat, 2009). Production in New Mexico peaked in the late 1980s and has generally declined since. There was a brief spike in the price during the run-up to the worldwide economic collapse of 2008 (Figure 31), followed by a sharp drop. However, in the wake of the economic collapse copper prices have been slowly edging back up (Figure 31). As large potential market countries like China transition towards a more westernized consumer culture, worldwide demand for copper may very well be expected to increase. Thus we have conservatively estimated that future copper production in New Mexico could be characterized as flat to slightly increasing.

There is no copper or other base metals production in any of the five BLM planning units. The occurrences and deposits that occur in the study area are essentially non-commercial by comparison to the major operations at the Chino and Tyrone pits in the southwest part of the state. It is highly unlikely that this will change within the next 20 years. Fluorite deposits in the Zuni mountains could attract renewed interest if uranium milling were to resume in the Grants Mineral Belt (Erskine, pers. comm.).

4.2.3 Gypsum

The production of gypsum (used primarily for wallboard) and limestone (used primarily for manufacture of Portland cement) are both tied strongly to the construction industry. Historical data for gypsum are not available due to New Mexico state statutes which prohibit publication of production data for industries with less than three producers (New Mexico has one producing gypsum mine, the White Mesa mine). Gypsum production data for the U.S. are presented on Figure 32 (USGS, 2009c). These data show a general increasing trend, characterized by a more recent downturn likely related to the downturn in the U.S. housing market. Based on these figures and the known deposits, we think gypsum production within the BLM planning units will increase moderately from the current level and reflect the recovery in the housing and construction industry as the U.S. economy recovers from the 2008 recession. The gypsum production is expected to track the national economy, both up and down, over the next 20 years.

4.2.4 Limestone

Historic limestone production in New Mexico is presented on Figure 33 (Hoffman, 2009). These figures indicate variable, but generally trending upward production within New Mexico from the mid-1990s through 2005, followed by a sharp downturn in about 2005. These data include public, private, institutional, infrastructure, and transportation, and thus they are representative of a broad range of activities. Although there was a significant downturn in many areas of the construction industry during and following the recession of 2008, based on data from the U.S. Census Bureau, it appears that infrastructure and transportation spending funded by stimulus funding allowed for continued growth in the industry. Based on these data, the construction industry continues to trend upward overall, and thus limestone demand and production is expected to do the same. Limestone production within BLM Planning Unit 2 (the Tijeras plant) is expected to remain the only operating source for the next 20 years due to the extensive size of the deposit and the existing cement plant infrastructure.

4.2.5 Pumice and Perlite

Pumice and perlite are related to a variety of industries due to its broad spectrum of uses (construction, clothing manufacture, abrasives, and personal care products, among others). For pumice, we have evaluated historical U.S. production (New Mexico production data are not readily available), shown on Figure 34. U.S. pumice production is variable, but generally trending upward since about 1990. Perlite production figures were not available but development is expected to be minimal over the next 20 years due to the low tonnage and variable quality of the perlite deposits within the BLM study area.

4.2.6 Rare Earth Elements

There is no REE production in the five BLM planning units, but there are several identified occurrences and some exploration has taken place. According to McLemore (pers.comm. 2009), REE exploration could increase in New Mexico due to increased demand for these materials and a potential reduction in the supply from overseas.



According to a recent article on the New Tang Dynasty Television network website (New Tang Dynasty Television, 2009), annual worldwide sales of the 17 rare earth metals are less than \$2 billion, but their impact on trillion-dollar industries is huge. This article, which summarized some of the information discussed at the fifth international Metal Events Rare Earths conference, was used for the following information.

By 2015, industry experts predict an annual shortage of REE on the order of 44,000 tons. Over-production and low prices during the 1990s and early 2000s resulted in many rare earth producers shutting down their operations. By 2008, China REE production increased to about 97 percent of world supplies; however, soaring domestic demand has led the Chinese to control mining, production and exports, leaving room for producers in other parts of the world, including the U.S., to fill the likely gap between supply and demand.

We believe that exploration for REE could increase significantly over the next 20 years within the BLM planning units. Production could also begin, given sufficient grade and reserves, if demand continues to rise and world supplies remain uncertain.

4.2.7 Uranium

Figure 35 presents some historical data on production of uranium in New Mexico (Lucas-Kamat, 2009) compared to the number of nuclear power plants in the U.S. (DOE, 2009i). It is apparent that New Mexico production has dropped precipitously since the late 1970s, and that few, if any, new nuclear power plants are being built in the U.S. at present. Projections of future production were not readily available from DOE. Increases in the price of uranium from 2003 to 2007 translated into current activity in the Grants Mineral Belt. However, the uranium price fell sharply in 2008 (Figure 31) resulting in stagnation with the uranium industry. Several companies are actively pursuing licenses to mine uranium in that area. Given these factors, the future of uranium remains unknown, but might be characterized as flat to slightly increasing. An industry source who requested to remain unnamed, predicted minimal uranium development in the near future. Clearly, the development is tied directly to price, and the rapid price increase starting in 2003 did lead to a flurry of activity which has decreased significantly over the past year as the price has fallen to near \$40 per pound.

In September 2009 the International Atomic Energy Agency released the latest update of its annual projections for the future of nuclear power, projected to 2030. The following excerpt may shed light on the future of nuclear power and in turn the development of uranium resources:

“The financial crisis that started in late 2008 has affected the prospects of some projects, but its impact has been different in different parts of the world. The regional pattern of revisions in the projections reflects, in part, the varying impacts of the financial crisis in different regions. The general upward revision in both the low and high projections reflects the experts’ judgment that the medium- and long-term factors driving rising expectations for nuclear power have not changed substantially. The performance and safety of nuclear power plants continue to be good. Concerns persist about global



warming, energy supply security, and high and volatile fossil fuel prices. All studies still project persistent energy demand growth in the medium and long term.

The low projection foresees an installed global nuclear power capacity of about 510 gigawatts (GW(e)) in 2030, a 40% increase over the 370 GW(e) currently installed in 2009. The high projection foresees 810 GW(e), well more than a doubling. These revised projections for 2030 are 8% higher than last year's projections.

The upward shift in the projections is greatest for the Far East, a region that includes China, Japan and the Republic of Korea. Modest downward shifts in the projections were made for North America and for Southeast Asia and the Pacific. For all other regions there is a generally modest upward shift. The one exception is a higher upward shift in the high projection for the Middle East and South Asia, which includes India and Pakistan. There the high projection for 2030 shifted upward by 15 GW(e)." (IAEA) 2009

4.2.8 Lithium

RFD for lithium within the BLM planning areas is judged to be low due to its low level of occurrence and the presence of existing sources outside the planning areas. As a potential critical mineral, lithium could become a more important commodity and exploration and/or development could arise within the BLM planning areas if the existing supply were to be reduced over the next 20 years.

4.3 SALABLE AND OTHER INDUSTRIAL MINERALS

The RFD for the saleable minerals of aggregate (with sand, gravel, stone and cinders), clay, and humate is discussed below.

4.3.1 Aggregate, Sand, and Gravel, Stone and Cinders

The salable commodities aggregate/sand/gravel, ornamental stone, and cinders (scoria) are all also used to supply the construction industry, and are expected to following the general upward trend in this industry. Historical production data for aggregate/sand/gravel, ornamental stone, and scoria are presented on Figure 36 (Hoffman, 2009). Historical New Mexico production of these commodities is variable, but generally increasing slightly, thus the RFD potential for these commodities is considered to be flat to slightly increasing. The production graph for travertine shows an extreme upward spike in about 2004, followed by a radical decline in 2005 and another upsurge in about 2008. Travertine production is expected to remain variable but with a general increase over the next 20 years, as long as economic conditions are no worse than at the present time because of the quality and popularity of New Mexico travertine in the local and national markets. Since 1990 (when records were first maintained), scoria production has remained steady with only one spike in 2006. INTERA projects a flat but steady market for scoria over the next 20 years based on past production trends.

4.3.2 Clay

Clay production in New Mexico was essentially steady from 2003 through 2005, averaging 35 thousand metric tons (USGS, 2009c). It seems unlikely that any major increase in clay production will occur over the next 20 years within the BLM planning units.

4.3.3 Humate

Humate has been produced in North America for several decades. In New Mexico, it is mined by front-end loaders and stockpiled to dry before crushing and screening. For some uses, the material is custom blended to obtain a specific humic acid content. After the material is crushed, it is shipped in bulk, bagged, or liquefied (Reid, pers. comm.). No rigorous evaluation of humate resources is available. Resources in the San Juan Basin, New Mexico, are 4.5 to 6.8 Mt and production is about 18.1 ktpy. Potential or emerging uses for humate are neutralization of herbicides and pesticides, livestock feed supplement, soil stabilization, or feedstock for synfuels (Hoffman et al., accessed 2009). INTERA projects humate production to be steady to increasing over the next 20 years, due to demand in the agricultural market in the U.S. and in various world markets. The potential environmental remediation uses described above suggest an additional untapped market.



5.0 CRITICAL MINERALS

As suggested by BLM Manual 3031, this section presents a brief discussion of critical minerals and the potential presence of such minerals within the BLM planning area.

Critical minerals are those minerals that are necessary to the provision of food, shelter, infrastructure, transportation, communications, health care, and defense. Every year, over 25,000 pounds of new minerals must be provided for every person in the U.S. to make items that we use every day, and a growing number of these minerals are imported (National Academies, 2007). The criticality of a mineral is determined by a matrix (“criticality matrix”) which presents the supply risk on the x-axis and the impact of supply restriction on the y-axis (i.e. the difficulty of finding a substitute for that mineral). For example, platinum group metals and rare earth elements are fundamental to the construction and function of catalytic converters. At present, there are no viable substitutes for these minerals in this application and a restriction of these minerals would result in a “no-build” situation for catalytic converters. An example of a criticality matrix for a group of minerals is presented as Figure 37.

The criticality of the following minerals has been investigated by the National Academies (2007): copper, gallium, indium, lithium, manganese, niobium, platinum group metals, rare earth elements, tantalum, titanium, and vanadium. This list could be changed in the future. Of these, platinum group metals, rare earth elements, indium, manganese, and niobium were determined to be most critical. Their uses and applications, the difficulty in finding appropriate mineral substitutes for these applications, and the risk to their supply for any number of reasons were high enough to place these minerals in or near the critical zone of the criticality matrix.

Within the Rio Puerco Field Office planning units, copper and REE are present as occurrences or known deposits. As discussed in the section on base metals, copper is mined in large volume elsewhere in New Mexico, so it is not considered to have high resource or development potential within the planning units. However, REE elements, although lacking an actual production history, are known to be present in multiple locations in the planning unit. REE are used in emission controls, magnets, electronics (notably cell phones) and there are few if any ready substitutes. Further, the supply of REE is potentially at risk because the U.S. is dependent on foreign suppliers and 76 percent of that supply is from China (National Academies, 2007).

Some exploration for REE has taken place in the planning units and additional exploration and potentially production could take place if the world supply were to be reduced or cut off.

Lithium is identified in several locations in the BLM planning units and it has some characteristics of a critical mineral in terms of the criticality matrix (supply risk and potential supply restriction). Thus, it could become a more important resource within the BLM planning units in the future.

6.0 REFERENCES

- American Gypsum, 2009, accessed at <http://www.americangypsum.com/about/history.cfm>.
- Arnold, E.C., and Dugan, T.A., 1971, Wildcat Near Durango Before 1900 Was First San Juan Basin Activity, *in* Western Oil Reporter, August issue.
- Aubrey, W.M., 1986, The nature of the Dakota-Morrison boundary, southeastern San Juan Basin *in* A basin analysis case study: Morrison Formation Grants uranium region, New Mexico: American Association of Petroleum Geology, Special volume SG22, p. 93-104.
- Aubrey, W. M., 1988, Measured sections of the Jackpile sandstone of the Morrison Formation, the Burro Canyon Formation, and the Encinal Canyon Member of the Dakota sandstone on the eastern side of the San Juan Basin, New Mexico: U.S. Geological Survey, Open-file Report 85-35, 54 p.
- Austin, G.S., 1994, Clay deposit adjacent to NM-44 north of Bernalillo: New Mexico Bureau of Mines and Mineral Resources, Open-File Report 404.
- Baldrige, W.S., 2004, Pliocene-Quaternary volcanism in New Mexico and a model for genesis of magmas in continental extension *in* The Geology of New Mexico: A Geologic History: New Mexico Geologic Society, p. 313-330.
- Bally, A.W., 1975, A geodynamic scenario for hydrocarbon occurrences: Ninth World Petroleum Congress, Proceedings, v. 2, p. 33-44.
- Barker, J.M., and Santini, K., 2006, Perlite *in* Industrial Minerals & Rocks: Commodities, Markets, and Uses, 7th ed., Washington, D.C., Society for Mining, Metallurgy, and Exploration, Inc., p. 685-670.
- Barker, J., Wilks, M., Jones, G., Read, A., Frisch, K., Vaiza, J., Hemenway, L., Gonzales, T., Schwartzberg, D., 2006, Construction Aggregate on State Trust Lands: New Mexico Bureau of Geology and Mineral Resources, Open-File Report 462 a, b, c, v. 5.0.
- Bland, D., 2009, Mineral resources and urban growth in the Albuquerque Region *in* Water, Natural Resources, and the Urban Landscape, The Albuquerque Region, Decision-Makers Field Conference: New Mexico Bureau of Geology and Mineral Resources.
- Bolen, W.P., 2005, Perlite *in* Mineral Commodity Summaries 2005. Reston, VA: U.S. Geological Survey, p. 120-121.
- Bradsher, K., 2009, China's Threat Revives Race for Rare Minerals: The New York Times Business, Energy & Environment, 25 September 2009, accessed November 13, 2009, at http://www.nytimes.com/2009/09/26/business/energy-environment/26rare.html?_r=1&partner=rss&emc=rss.
- Brister, B., Bauer, P. W., Read, A. S., eds., 2004, Geology of the Taos Region: New Mexico Geological Society Guidebook, New Mexico Geological Society 55th Annual Field Conference, September 22-25, 2004, 440 pages.



References (Continued)

- Broadhead, R.F., 1997, Subsurface geology and oil and gas potential of Estancia Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 157.
- Broadhead, R.F., and Gillard, L., 2004, Helium in New Mexico, Geologic distribution and Exploration Possibilities: New Mexico Bureau of Geology and Mineral Resources, Open-File Report 483.
- Broadhead, R.F., 2008, Natural accumulations of carbon dioxide in New Mexico and adjacent parts of Colorado and Arizona: New Mexico Bureau of Geology and Mineral Resources, accessed November 16, 2009, at <http://geoinfo.nmt.edu/staff/broadhead/CO2.html>.
- Broadhead, R.F., 2009, Oil and Natural Gas Potential in the Albuquerque Basin, *in* Water, Natural Resources, and the Urban Landscape, The Albuquerque Region, Decision-Makers Field Conference: New Mexico Bureau of Geology and Mineral Resources, p. 80-86.
- Broadhead, R.F., Mansell, M., and Jones, G., 2009, Carbon dioxide in New Mexico: Geologic distribution of natural occurrences. New Mexico Bureau of Geology and Mineral Resources, Open-File Report 514.
- Brown, D.W., 2009, Hot dry rock geothermal energy: Important lessons from Fenton Hill: Thirty-Fourth Workshop on Geothermal Reservoir Engineering Proceedings, Stanford University, Stanford, California, February 9-11, SGP-TR-187.
- Bureau of Land Management, 2009, Rio Puerco Field Office RMP/EIS: Analysis of the Management Situation.
- Casselman, 2009, Wall Street Journal, U.S. Gas Fields Go From Bust to Boom, Wall Street Journal, April 30, 2009.
- Cather, S.M., 2004, The Laramide orogeny in central and northern New Mexico and southern Colorado, *in* The Geology of New Mexico, A Geologic History: New Mexico Geological Society Special Publication 11, p. 203-248.
- Chafin, D.T., 1994, Sources and migration pathways of natural gas in near-surface ground water beneath the Animas River valley, Colorado and New Mexico: U.S. Geological Survey Water-Resources Investigations Report 94-4006, p. 1-2.
- Chamberlin and Anderson, 1989, The Laramide Zuni Uplift, Southeastern Colorado Plateau: A Mircocosm of Eurasian-Style Indentation-Extrusion Tectonics?, New Mexico Geological Society Guidebook, 40th Field Conference, Southeastern Colorado Plateau.
- Chamberlin, R.M., and McIntosh, W.C., 2007, Chronology and Structural Control of Late Cenozoic Volcanism in the Loma Creston Quadrangle, Southern Jemez Volcanic Field, New Mexico, Geology of the Jemez Mountains Region I *in* New Mexico Geological Guidebook, New Mexico Geological Society 25th Annual Field Conference, p. 248-261.



References (Continued)

- Chronic, H., 1987, *Roadside Geology of New Mexico*, Mountain Press Publishing Company, Missoula, Montana, 255 p.
- Clippinger, D.M., and Gay, W.E., 1947, *Bulletin 28–Pumice Aggregate in New Mexico—Its Uses and Potentialities*: New Mexico Bureau of Mines and Mineral Resources, Supplement to Bulletin 24.
- Condon, S.M. and Peterson, F., 1986, *Stratigraphy of Middle and Upper Jurassic rocks of the San Juan Basin: Historical perspective, current ideas, and remaining problems; in A basin analysis case study: Morrison Formation Grants uranium region, New Mexico*: American Association of Petroleum Geology, Special volume SG22, p. 7-26.
- Connell, S.D., Koning, D.J., and Cathier, S.M., 1999, *Revisions to the Stratigraphic Nomenclature of the Santa Fe Group, Northwestern Albuquerque Basin, New Mexico* in *Albuquerque Geology*, New Mexico Geological Society, p. 337-354.
- Desert Processes Working Group; Knowledge Sciences, Inc. Summary: Duricrusts, Caliche, accessed November 20, 2009, at http://www.agc.army.mil/research/products/desert_guide/lmsheet/lscal.htm.
- Duchane, D., and Brown, D., 2002, *Hot dry rock (HDR) geothermal energy research and development at Fenton Hill, New Mexico*: Geo-Heat Center Quarterly Bulletin, vol. 23, no. 4, accessed November 17, 2009, at <http://geoheat.oit.edu/bul23-4/bull23-4-all.pdf>.
- Encyclopedia of Earth, Supported by the Environmental Information Coalition and the National Council for Science and the Environment, accessed November 2009, at <http://www.eoearth.org/>.
- Energy Information Administration (EIA), 2009, *Coal: U.S. Data: United States Department of Energy, Official Energy Statistics from the U.S. Government*, accessed November 12, 2009, at <http://www.eia.doe.gov/fuelcoal.html>.
- ESRI, 2009a. ArcGIS 9.3 software.
- ESRI, 2009b, *ArcGIS Desktop Help: How Kernel Density Works*, accessed December 31, 2009, at <http://webhelp.esri.com/arcgisdesktop/9.3/index.cfm?TopicName=How%20Kernel%20Density%20works>.
- Fernandez, L., *Hot Springs Enthusiast: New Mexico*, accessed October 2, 2009, at <http://www.hotspringsenthusiast.com/newmexico.asp>.
- Fitch, D.C., 1980, *Exploration for Uranium Deposits, Grants Mineral Belt, in Geology and mineral technology of the Grants uranium region 1979*, New Mexico Bureau of Mines and Mineral Resources, Memoir 38, p. 40-51.
- Fleischmann, D., 2006, *Geothermal Resource Development Needs in New Mexico: A Publication by Geothermal Energy Association (GEA) for the U.S. Department of Energy*.



References (Continued)

- Freed, M., and Vaskys, R., 2008, Rockhounding in New Mexico: A Guide to the State's Best 140 Rockhounding Sites, Connecticut: Morris Book Publishing, LLC.
- Frost, S.J., Tabet, D.E., and Campbell, F.W., 1979, Coal exploratory drilling in the Datil mountain coal field: New Mexico Bureau of Mines and Mineral Resources, Open-File Report 111.
- Geothermal Resources Council, 2005, What is Geothermal?, accessed November 18, 2009, at <http://www.geothermal.org/what.html>.
- Geotimes, 2003, Mineral Resource of the Month: Sulfur, American Geological Institute Energy and Resources, accessed November 17, 2009, at <http://www.agiweb.org/geotimes/july03/resources.html>.
- Gjelten, accessed 2009, Rediscovering Natural Gas By Hitting Rock Bottom, National Public Radio, September 22, 2009
<http://www.npr.org/templates/story/story.php?storyId=113043935>
- Global InfoMine, 2009a, Dynamic Charting Tool: Gold, accessed December 1, 2009, at <http://www.infomine.com/investment/charts.aspx?c=Gold&r=15y#chart>.
- Global InfoMine, 2009b, Dynamic Charting Tool: Silver, accessed December 1, at <http://www.infomine.com/investment/charts.aspx?c=Silver&r=15y#chart>.
- Global InfoMine, 2009c, Dynamic Charting Tool: Copper, accessed November 25, at <http://www.infomine.com/investment/charts.aspx?mv=1&f=f&r=15y&c=ccopper.xusd.ulb#chart>.
- Global InfoMine, 2009d, Dynamic Charting Tool: Uranium, accessed December 1, at <http://www.infomine.com/investment/charts.aspx?c=Uranium&r=15y#chart>.
- Goff, F., and Grigsby, C.O., 1982, Valles Caldera geothermal systems, New Mexico: Journal of Hydrology, v. 56, p. 119-136.
- Goff, F., and Gardner, J., 2004, Late Cenozoic geochronology of volcanism and mineralization in the Jemez Mountains and Valles Caldera, north central New Mexico *in* The Geology of New Mexico: A Geologic History: New Mexico Geologic Society, p. 295-312.
- Greer Price, L., Bland, D., Johnson, P.S., and Connell, S.D., 2009, Water, Natural Resources, and the Urban Landscape, The Albuquerque Region, Decision-Makers Field Conference: New Mexico Bureau of Geology and Mineral Resources, p. 75-107.
- Gustafson, D.L., 2003, TRS-data: Graphical locator, accessed <date>, at <http://www.esg.montana.edu/gl/trs-data.html>.
- Hackman, R. J., and Olson, A.B., 1977, Geology, structure, and uranium deposits of the Gallup 1 x 2 degree quadrangle, New Mexico and Arizona: U.S. Geological Survey, Miscellaneous Field Investigations Map I-981, scale 1:250,000, in Bluewater Lake State Park, New Mexico Bureau of Geology and Mineral Resources, NMBGMR Geologic Tour: Bluewater Lake, http://geoinfo.nmt.edu/tour/state/bluewater_lake/home.html.

References (Continued)

- Hambleton, W. W., 1953, Petrographic Study of Southeastern Kansas Coals: Kansas Geological Society Bulletin 102, Part 1 (out of print), accessed November 30, 2009, at http://www.kgs.ku.edu/Publications/Bulletins/102_1/index.html.
- Harben, P., Austin, G., Hoffman, G., McLemore, V., Caledon, M., and Barker, J., 2008, Industrial minerals, a staple in the economy of the Land of Enchantment *in* Proceedings of the 43rd Forum on the Geology of Industrial Minerals, Resource Series 46, Forum sponsored by the Colorado Geologic Survey, May 20-25th, 2007.
- Heylmun, E.B., 2003, Roll-Front Uranium Deposits: Mining Journal, October, accessed at <http://www.icmj2.com/03Oct/03OctFeature.htm>.
- Hilpert, L.S., 1963, Regional and local stratigraphy of uranium-bearing rocks, *in* Geology and Technology of the Grants Uranium Region: New Mexico Bureau of Mines and Mineral Resources, Memoir 15, p. 6-18.
- Hilpert, L.S., 1969, Uranium resources of northwestern New Mexico, U.S. Geological Survey Professional Paper 603, Prepared on behalf of the U.S. Atomic Energy Commission, United States Government Printing Office, Washington, p. 27.
- Hoffman, G.K., Campbell, F.W., and Beaumont, E.C., 1993, Quality assessment of strippable coals in northwestern New Mexico: Fruitland, Menefee, and Crevasse Canyon coals in San Juan Basin, and Moreno Hill Formation coals in Salt Lake Field: New Mexico Bureau of Mines and Mineral Resources, Bulletin 141.
- Hoffman, G.K., 2002, New Mexico's Coal Industry: Resources, Production, and Economics *in* New Mexico's Energy: Present and Future, Policy, Production, Economics, and the Environment, Decision-Maker's Field Conference 2002: New Mexico Bureau of Geology and Mineral Resources, p. 65-70.
- Hoffman, G., 2009, Spreadsheet of compiled data on New Mexico coal production: New Mexico Bureau of Geology.
- Hoffman, G.K., Barker, J.M., and Austin, G.S., Over view of Humate Production in North America: New Mexico Bureau of Geology and Mineral Resources, Campus Station, Socorro, New Mexico, accessed December 3, 2009, at <http://geoinfo.nmt.edu/staff/hoffman/humateforum.html>.
- Huffman, A.C., Jr., 1987, Petroleum Geology and Hydrocarbon Plays of the San Juan Basin Petroleum Province: U.S. Geological Survey Open-File Report 87-450 B.
- Huffman, A.C., Jr., 1996, San Juan Basin Province (022) *in* 1995 National assessment of United States oil and gas resources--Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series DDS-30, Release 2, one CD-ROM, accessed November 2009, at <http://certmapper.cr.usgs.gov/data/noga95/prov22/text/prov22.pdf>.
- Hulen, J.B., and Wright, P.M., 2001, Geothermal Energy, The University of Utah: Energy and Geoscience Institute.

References (Continued)

- International Atomic Energy Agency (IAEA) 2009, IAEA Revises Nuclear Power Projections Upward, Shift Greatest in Far East, Staff Report, accessed January 9, 2010, at <http://www.iaea.org/NewsCenter/News/2009/nprojections.html>.
- Jenks, G. and Caspall, F.C., 1971. Error on choroplethic maps: Definition, measurement, reduction, *Annals of the Association of American Geographers*, 61:217-244.
- Jones, F.A., 1904, *New Mexico mines and minerals*. Santa Fe: The New Mexico Printing Company
- Keller, G.R., and Cather, S.M., 1994, Basins of the Rio Grande rift: Structure, stratigraphy, and tectonic setting: *Geological Society of America Special Paper 291*, 304 pp.
- Kelly, T.D. and Matos, G.R., 2009, Historical Statistics for Mineral and Material Commodities in the United States: U.S. Geological Survey Data Series 140, Supersedes Open-file Report 01-006, v. 3.0, accessed November 25, 2009, at <http://minerals.usgs.gov/ds/2005/140/>.
- Kelley, 1952, Tectonics of the Rio Grande depression of central New Mexico: *New Mexico Geological Society Guidebook 3*, p. 93-105.
- Kelley, V.C., 1963, Geology and Technology of the Grants Uranium Region: *New Mexico Bureau of Mines and Mineral Resources, Memoir 15*, p. 3-5.
- Kelley, V.C., 1977, Geology of Albuquerque Basin, New Mexico: *New Mexico Bureau of Geology and Mineral Resources, Memoir 33*.
- Kempton, K.A., Kelley, S.A., and Lawrence, J.R., 2007, Geology of the Northern Jemez Mountains, North-Central New Mexico: Geology of the Jemez Mountains Region II, *in New Mexico Geological Guidebook, New Mexico Geological Society 25th Annual Field Conference*, p. 155-168.
- Kirschbaum, M.A. and Biewick, L.R.H., 2000, Chapter B: A summary of the coal deposits in the Colorado Plateau: Arizona, Colorado, New Mexico, and Utah *in Geologic Assessment of Coal in the Colorado Plateau: Arizona, Colorado, New Mexico, and Utah*. U.S. Geological Survey, Professional Paper 1625-B.
- Klemme, H.D., 1986, Field size distribution related to basin characteristics, *in Oil and gas assessment – methods and applications: American Association of Petroleum Geologists Studies in Geology 21*, p. 85-99.
- Kogel, J.E., Trivedi, N.C., Barker, J.M., and Krukowski, S.T., eds., 2006, *Industrial Minerals & Rocks: Commodities, Markets, and Uses*, 7th ed., Washington, D.C., Society for Mining, Metallurgy, and Exploration, Inc.
- Koning, D.J., and Personius, S.F., 2002, Geologic Map of the Bernalillo NW Quadrangle, Sandoval County, New Mexico. U.S. Geological Survey, Miscellaneous Field Studies Map, MF-2404.

References (Continued)

- Koning, D.J., Kelley, S.A., and Kempter, K.A., 2007, Geologic structures near the boundary of the Abiquiu embayment and Colorado Plateau – a long history of faulting *in* Geology of the Jemez Region II, New Mexico Geological Society Fifty-eighth Annual Field Conference, September 19-22, 2007, p. 43-45.
- Laramide Resources, LTD, 2007, accessed at <http://www.sedar.com/CheckCode.do?sessionId=0000Q4I0ifaFTslDvHGP5z-iI0E:-1> from <http://www.wise-uranium.org/uousanm.html#LAJARAMESA>.
- Lawton, T.F., McMillan, N.J., and McLemore, V.T., 2000, Southwest passage: A trip through the Phanerozoic: *in* New Mexico Geological Guidebook, New Mexico Geological Society 51st Annual Field Conference, Guidebook, 281 pp.
- Lucas, S. G., Heckert, A. B., and Anderson, O.J., 1997, Triassic stratigraphy and paleontology on the For Wingate quadrangle, west-central New Mexico: *New Mexico Geology*, v. 19, no. 2, pp. 33-42 in *Bluewater Lake State Park, New Mexico Bureau of Geology and Mineral Resources, NMBGMR Geologic Tour: Bluewater Lake*, http://geoinfo.nmt.edu/tour/state/bluewater_lake/home.html.
- Lucas-Kamat, S., 2009a, The New Mexico Mines Database: New Mexico Mines and Minerals Division.
- Lucas-Kamat, S., 2009b, Spreadsheet of compiled data on New Mexico mineral production: New Mexico Mining and Minerals Division.
- Lucas, S. G., Semken, S. C., Berglof W. R., Ulmer-Scholle, D., S., 2003, Geology of the Zuni Plateau, New Mexico Geological Society Fifty-fourth Annual Field Conference.
- Lyons, P.C., 2003, Coalbed methane potential in the Appalachian states of Pennsylvania, West Virginia, Maryland, Ohio, Virginia, Kentucky, and Tennessee-An overview. U.S. Geological Survey Open-File Report 96-735: U.S. Geological Survey, accessed November 30, 2009, at <http://pubs.usgs.gov/of/1996/of96-735/index.htm>.
- MacDonald, E.D., and Arrington, J.B., 1970, The San Juan Basin: My Kingdom Was a County.
- Mavor, Matt, and Nelson, C.R., 1997, Coalbed Reservoir Gas-In-Place Analysis, Gas Research Institute Report No. GRI-97/0263; Chicago, Illinois.
- McLemore, V.T., Roybal, G.H., Broadhead, R.F., Chamberlin, R., North, R.M., Osburn, J.C., Arkell, B.W., Colpitts, R.M., Bowie, M.R., Anderson, K., Barker, J.M., and Campbell, F., 1984a, Preliminary report on the geology and mineral resource potential of the northern Rio Puerco Resource area in Sandoval and Bernalillo Counties and adjacent parts of McKinley, Cibola, and Santa Fe Counties, New Mexico: New Mexico Bureau of Mines and Minerals Resources, Open-File Report 211.
- McLemore, V.T., 1984b, Preliminary report on the geology and mineral-resource potential of Torrance County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-File Report 192.



References (Continued)

- McLemore, V.T. and others, 1986a, A preliminary mineral-resource potential of Northwestern New Mexico; Introduction: New Mexico Bureau of Mines and Mineral Resources, Open-File Report 228.
- McLemore, V. T., Broadhead, R.F., Barker, J.M., Austin, G.S., Klein, K., Brown, K.B., Murray, D., Bowie, M.R., and Hingtgen, J.S., 1986b, A preliminary mineral-resource potential of Valencia County, Northwestern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-File Report 229.
- McLemore, V. T., Broadhead, R.F., Roybal, G.H., Chenoweth, W.L., Barker, J.M., North, R.M., Bowie, M.R., Hingtgen, J.S., Murray, D., Klein, K., Brown, K.B., and Austin, G.S., 1986c. A preliminary mineral-resource potential of Cibola County, northwestern New Mexico (2 vol): New Mexico Bureau of Mines and Mineral Resources, Open-File Report 230.
- McLemore, V.T.; Roybal, G.H.; Birdsall, K.; Broadhead, R.F.; Chenoweth, W.L.; North, R.M.; Barker, J.M.; Copeland, P.; Bowie, M.R.; Hingtgen, J.S.; Brown, K.B.; Klein, K., 1986d. A preliminary mineral-resource potential of McKinley County, northwestern New Mexico (2 vol): New Mexico Bureau of Mines and Mineral Resources, Open-File Report 231.
- McLemore, V.T.; Broadhead, R.F.; Cook, K.; Chenoweth, W.L.; Barker, J.M.; Roybal, G.H.; North, R.M.; Copeland, P.; Bowie, M.R.; Hingtgen, J.S.; Klein, K.; Brown, K.B., 1986e. A preliminary mineral-resource potential of San Juan County, northwestern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-File Report 232.
- McLemore, V.T.; Broadhead, R.F.; Cook, K.; Roybal, G.H.; Chenoweth, W.L.; Barker, J.M.; Copeland, P.; Klein, K.; Brown, K.B.; Bowie, M.R.; Hingtgen, J.S., 1986f. A preliminary mineral-resource potential of western Rio Arriba County, northwestern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-File Report 233.
- McLemore, V.T., and Chenoweth, W.L., 1989, Uranium Resources in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Resource Map 18.
- McLemore, V.T., 2001, Silver and Gold in New Mexico, Resource Map 21: New Mexico Bureau of Geology and Mineral Resources.
- McLemore, V.T., Donahue, K., Krueger, C.B., Rowe, A., Ulbricht, L., Jackson, M.L., Breese, M.R., Jones, G., and Wilks, M., 2002, Database of Uranium Mines, Prospects, Occurrences, and Mills in New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-File Report 461.
- McLemore, V.T., 2007, Uranium resources in New Mexico *in* Proceedings of SME Annual Meeting, February 25-28, Denver, Colorado.
- McLemore, V.T., and Wilks, M., 2009, The New Mexico Mines Database: New Mexico Bureau of Geology and Mineral Resources.



References (Continued)

- Melancon, P.E., 1963, History of Exploration, *in* Geology and Technology of the Grants Uranium Region, New Mexico Bureau of Mines and Mineral Resources, Memoir 15, p. 3-5.
- Mine Safety and Health Administration (MSHA), 2009, Mine Yearly Production Information: Lee Ranch Mine, United States Department of Labor: Mine Safety and Health Administration-Mine Data Retrieval System, accessed November 30, 2009, at <http://www.msha.gov/drs/ASP/MineAction70002.asp>.
- Mining and Minerals Division (MMD), New Mexico Coal Mines Query: New Mexico Energy, Minerals and Natural Resources Department, accessed October 1, 2009, at <http://www.emnrd.state.nm.us/mmd/CoalMinesQuery/default.aspx>.
- Molenaar, C.M., 1995, Albuquerque – Santa Fe Rift (023), Conventional Plays, U.S. Geological Survey National Oil and Gas Assessment, accessed <date>, <http://certmapper.cr.usgs.gov/data/noga95/prov23/text/prov23.pdf>.
- Muehlberger, W.R., Muehlberger, S.J., and Price, L.G, 2005, Scenic Trips to the Geologic Past #19, High Plains of northeastern New Mexico: a guide to geology and culture: New Mexico Bureau of Geology and Mineral Resources, 102 pp.
- National Academies, 2007, Report in Brief: Minerals, Critical Minerals, and the U.S. Economy: National Academy of Sciences.
- New Mexico Energy, Minerals and Natural Resources Department (NMEMNRD), 2008, 2008 Annual Report: New Mexico Energy, Minerals and Natural Resources Department.
- New Mexico Oil and Gas Association (NMOGA), 2009, Industry Impact, accessed at <http://nmoga.org/industry.asp?CustComKey=361961&CategoryKey=361962&pn=Page&DomName=nmoga.org>.
- New Tang Dynasty Television, 2009, Rare Earths Shortage Expected by 2015 – Experts Gather in Hong Kong, accessed November 25, 2009, at http://english.ntdtv.com/ntdtv_en/ns_china/2009-11-19/606769525339.html.
- New Mexico Oil Conservation Division (OCD), OCD Permitting–Well Search: New Mexico Energy, Minerals, and Natural Resources Department, accessed October 7, 2009, at <http://www.emnrd.state.nm.us/OCD/OCDPermitting/Data/Wells.aspx>.
- Orris, G.J., 2000, Dataset of Aggregate Producers in New Mexico: U.S. Geological Survey, Open File Report 00-11B, accessed October 15, 2009, at <http://geopubs.wr.usgs.gov/open-file/of00-011/>.
- Owen, D.E, Walters, L.J., and Beck, R.G., 1984, The Jackpile Sandstone Member of the Morrison Formation in west-central New Mexico--a formal definition: *New Mexico Geology*, v. 6, no. 3, p. 45-52.
- Pay Dirt, 2009, Coal going through contraction but future still appears bright, *PayDirt*, May.



References (Continued)

- Petroleum Recovery Research Center, 2009, All Wells Data–The ONGARD Database: New Mexico Institute of Mining and Technology, accessed 10/7/2009, at http://octane.nmt.edu/gotech/Petroleum_Data/allwells.aspx.
- Pettit, R.E., Organic matter, humus, humate, humic acid, fulvic acid, and humin: Their importance in soil fertility and plant health, accessed November 12, 2009, at http://www.triganic.com/organic_matter.htm.
- Pfeil, J.J., 2005, Economic Impact of Mining on New Mexico, *in* Mining in New Mexico, The Economic, Water, Economics, and Sustainable Development: Decision-Makers Field Conference 2005, Taos Region, New Mexico Bureau of Geology and Mineral Resources, p. 90-95.
- Pfeil, J.J., and Leavitt, A.J., 2001. Mines, Mills, and Quarries in New Mexico: New Mexico Bureau of Geology and Mineral Resources.
- Presley, G.C., 2006, Pumice, Pumicite, and Volcanic Cinder, in *Industrial Minerals & Rocks: Commodities, Markets, and Uses*, 7th ed., Washington, D.C., Society for Mining, Metallurgy, and Exploration, Inc., p. 743-753.
- Press, F., and Siever, R., 1982, *Earth*, 3rd Edition, W. H. Freeman and Company: San Francisco.
- Ralph, J., and Chau, I., 2009, Mindat.org database, accessed November 17, 2009, at <http://www.mindat.org/loc-48743.html>.
- Rautman, C.A., 1980, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources, Memoir 38.
- Read, A., Broadhead, R., Lopez, A., Fleming, E., and Watrous, J., 2000, *New Mexico Oil and Gas Pool Maps*: New Mexico Bureau of Geology and Mineral Resources, Circular 209, v.1.0.
- Reis, H., and Leighton, H., 1909, *History of the Clay-Working Industry in the United States*, First Edition, London: Chapman and Hall, Ltd.
- Reuters, T., 2009, Laramide Reports on La Jara Mesa Permitting: U.S. Department of Agriculture Forest Service Commences Environmental Impact Statement and Public, accessed at <http://www.reuters.com/article/pressRelease/idUS149556+19-May-2009+MW20090519>.
- Richards, M., 1999, The Western Geothermal Areas Data Base: The Southern Methodist University Geothermal Laboratory, accessed October 2, 2009, at <http://smu.edu/geothermal/georesou/nmexico.htm>.
- Rodriguez, P., Scudella, G., and Fedor, D., 1979, *New Mexico geothermal commercialization planning. Semi-annual progress report, January 1, 1979-June 30, 1979*, New Mexico Energy and Minerals Department, Report No. DOE/ID/12017-1.

References (Continued)

- Rothrock, H.E., Johnson, C.H., and Hahn, A.D., 1946, Fluorspar Resources of New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 21.
- Roybal, G.H., and Barker, J.M., 1987, Geology and production of humate and weathered coal in New Mexico: in Transactions, Society of Mining and Engineers of AIME, vol. 280, p. 2105-2110.
- Santos, E.S., 1975, Lithology and Uranium Potential of Jurassic Formations in the San Ysidro-Cuba and Majors Ranch Areas, Northwestern New Mexico: U.S. Geological Survey Bulletin 1329.
- Scholle, P., 2002, Rockhounding in New Mexico: New Mexico Bureau of Geology and Mineral Resources.
- Scholle, P.A., 2003, Geologic Map of New Mexico, 1:500,000: New Mexico Bureau of Geology and Mineral Resources.
- ScienceDaily, 2008, Science News: Helium supplies endangered, threatening science and technology, ScienceDaily, 5 January 2008, accessed November 17, 2009, at <http://www.sciencedaily.com/releases/2008/01/080102093943.htm>.
- Seimers, C. T., ed., 1974, Ghost Ranch Central-Northern New Mexico: New Mexico Geological Society, New Mexico Geological Society 25th Annual Field Conference.
- Silverman, B.W., 1986, Density Estimation for Statistics and Data Analysis. New York: Chapman and Hall, 1986.
- Slate, J.L., Sarna-Wojcicki, A.M., Wan, E., Dethier, D.P., Wahl, D.B, and Lavine, A., 2007, A Chronostratigraphic Reference Set of Tephra Layers from the Jemez Mountains Volcanic Source, New Mexico in Geology of the Jemez Region II, New Mexico Geological Society Fifty-eighth Annual Field Conference, September 19-22, 2007, p. 239-243.
- SME, 2010 (preprint), Use of the New Mexico Mines Database and Arcmap in Uranium Reclamation Studies, Society for Mining, Metallurgy, and Exploration, Inc.
- Smith, C. T., 1954, Geology of the Thoreau quadrangle, McKinley and Valencia Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 31, 36pp, in Bluewater Lake State Park, New Mexico Bureau of Geology and Mineral Resources, NMBGMR Geologic Tour: Bluewater Lake, http://geoinfo.nmt.edu/tour/state/bluewater_lake/home.html.
- Smith, G., 1999. The nature of limestone-siliciclastic “cycles” in middle and upper Pennsylvanian strata, Tejano Canyon, Sandia Mountains, New Mexico, *in* Albuquerque Geology: New Mexico Geological Society, p. 269-280.
- Smith, Goodchild, and Longley, 2009, Geospatial Analysis-a Comprehensive Guide (3rd edition), accessed December 30, 2009, at <http://www.spatialanalysisonline.com/output/>.



References (Continued)

- Talbot, L.W., 1974, Nacimiento Pit, A Triassic Stratabound Copper Deposit, *in* New Mexico Geological Guidebook, New Mexico Geological Society 25th Annual Field Conference.
- Tedford, R.H., and Barghoorn, Steve, 1999, Santa Fe Group (Neogene), Ceja del Rio Puerco, northwestern Albuquerque basin, Sandoval County, New Mexico, *in* Albuquerque Geology: Socorro, New Mexico Geological Society Guidebook 50th Field Conference, p. 327-335.
- U.S. Bureau of Land Management (BLM), 1985, 3031 – Energy and Mineral Resource Assessment: Bureau of Land Management Manual, Rel. 3-115.
- U.S. Bureau of Land Management (BLM), 1999, Coalbed Methane Development in the Northern San Juan Basin of Colorado, A Brief History and Environmental Observations, A Working Document: The Bureau of Land Management San Juan Field Office, accessed at http://oil-gas.state.co.us/Library/sanjuanbasin/blm_sjb.htm.
- U.S. Bureau of Land Management (BLM), 2006, Locatable Minerals, Minerals Locatable Under the General Mining Law on Public Lands in New Mexico, accessed November 2009, at http://www.blm.gov/nm/st/en/prog/energy/solid_minerals/mining_law/mining_claims_and/locatable_minerals.html.
- U.S. Bureau of Land Management (BLM), 2007, Solid Minerals Brochure, accessed September 23, 2009, at http://www.blm.gov/wo/st/en/prog/more/non-energy_minerals/solid_minerals_brochure.html
- U.S. Bureau of Land Management (BLM), 2009, Statement of Work for the Minerals Potential Report for the Rio Puerco Field Office RMPR Planning Area.
- U.S. Census Bureau, 2009, Value of Construction Put in Place Statistics: U.S. Census Bureau, accessed November 25, 2009, at <http://www.census.gov/const/C30/oldtc.html>.
- U.S. Department of Energy (DOE), 2004, U.S. Uranium Reserves Estimates: Energy Information Administration, accessed November 25, 2009, at <http://www.eia.doe.gov/cneaf/nuclear/page/reserves/ures.html>.
- U.S. Department of Energy (DOE), 2009a, Petroleum Navigator: New Mexico Crude Oil Estimated Production from Reserves, accessed November 25, 2009, at http://tonto.eia.doe.gov/dnav/pet/hist/rcrr10snm_1a.htm.
- U.S. Department of Energy (DOE), 2009b, Petroleum Navigator: Crude Oil Production, accessed November 25, 2009, at http://tonto.eia.doe.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_a.htm
- U.S. Department of Energy (DOE), 2009c, Table 11. Liquid Fuels Supply and Disposition: Annual Energy Outlook 2009 with Projections to 2030, Updated Annual Energy Outlook 2009 Reference Case with ARRA: Energy Information Administration, accessed November 25, 2009, at <http://www.eia.doe.gov/oiaf/servicerpt/stimulus/aeostim.html>.



References (Continued)

- U.S. Department of Energy (DOE), 2009d, Natural Gas Navigator: New Mexico Natural Gas Marketed Production, accessed November 25, 2009, at <http://tonto.eia.doe.gov/dnav/ng/hist/n9010nm2a.htm>.
- U.S. Department of Energy (DOE), 2009e, Natural Gas Navigator: U.S. Natural Gas Gross Withdrawals and Production, accessed November 25, 2009, at http://tonto.eia.doe.gov/dnav/ng/ng_prod_sum_dcu_nus_a.htm
- U.S. Department of Energy (DOE), 2009f, Table 13. Natural Gas Supply, Disposition, and Prices: Annual Energy Outlook 2009 with Projections to 2030, Updated Annual Energy Outlook 2009 Reference Case with ARRA: Energy Information Administration, accessed November 25, 2009, at <http://www.eia.doe.gov/oiaf/servicerpt/stimulus/aeostim.html>.
- U.S. Department of Energy (DOE), 2009g, Table 7.2 Coal Production, 1949-2008, accessed November 25, 2009, at <http://www.eia.doe.gov/emeu/aer/txt/ptb0702.html>.
- U.S. Department of Energy (DOE), 2009h, Table 15. Coal Supply, Disposition, and Prices: Annual Energy Outlook 2009 with Projections to 2030, Updated Annual Energy Outlook 2009 Reference Case with ARRA: Energy Information Administration, accessed November 25, 2009, at <http://www.eia.doe.gov/oiaf/servicerpt/stimulus/aeostim.html>.
- U.S. Department of Energy (DOE), 2009i, Table 9.1, Nuclear Generating Units, 1955-2008, accessed November 25, 2009, at <http://www.eia.doe.gov/emeu/aer/txt/ptb0901.html>
- U.S. Environmental Protection Agency (EPA), 2009, Fact Sheet: Chevron Mining, Inc.- McKinley Mine, Proposed July, 2009: CWA Standards and Permits Office, accessed November 12, 2009, at <http://www.epa.gov/region09/water/npdes/pdf/navajo/McKinleyMineFactSheetDraft.pdf>.
- U.S. Geological Survey, 2002a, Fact Sheet FS-147-02, accessed at <http://pubs.usgs.gov/fs/fs-147-02/FS-147-02.pdf>.
- U.S. Geological Survey, 2002b, Rare earth Elements: critical resources for high technology: U.S. Geological Survey Fact Sheet 087-02, 4 p.
- U.S. Geological Survey, [year of last update, e.g., 2005], [Mineral commodity, e.g., Gold] statistics, in Kelly, T.D., and Matos, G.R., comps., Historical statistics for mineral and material commodities in the United States: U.S. Geological Survey Data Series 140, accessed November 25, 2009, at <http://pubs.usgs.gov/ds/2005/140/>.
- U.S. Geological Survey, 2009a, Area reports – Domestic: U.S. Geological Survey Minerals Yearbook 2005, vol. II, 414 p.
- U.S. Geological Survey, 2009b, Minerals Yearbook, Metals and Minerals 2006, vol. 1.
- U.S. Geological Survey, 2009c, Historical Statistics for Mineral and Material Commodities in the United States, accessed November 25, 2009, at <http://minerals.usgs.gov/ds/2005/140/>.



References (Concluded)

- Waresback, D.B., 1986, The Puye Formation, New Mexico: analysis of a continental rift-filling, volcanoclastic alluvial-fan sequence [M.S. thesis]: Arlington, University of Texas, 269 p.
- Waresback, D.B. and Turbeville, B.N., 1990, Evolution of a Plio-Pleistocene volcanogenic-alluvial fan: the Puye Formation, Jemez Mountains, New Mexico: *Geological Society of America Bulletin* March 1990, v. 102, p. 298-314, doi:10.1130/0016-7606(1990)102<0298:EOAPPV>2.3.CO;2.
- Wentz, C.J., 2002, Renewable Energy in New Mexico: Current Status and Future Outlook *in* New Mexico's Energy, Present and Future: New Mexico Bureau of Geology and Mineral Resources, Decision-Maker's Field Conference 2002.
- Wilks, M. E., compiler, 2005, New Mexico Geologic Highway Map: New Mexico Geological Society and New Mexico Bureau of Geology and Mineral Resources, 1 sheet containing text and figures, scale 1:1,000,000.
- Williams, P.L., and Cole, J.C., 2007, Geologic map of the Albuquerque 30' x 60' Quadrangle, North-Central, New Mexico: U.S. Geologic Survey Scientific Investigations Map 2946, scale 1:100,000.
- Witcher, J.C., 2002, Geothermal energy in New Mexico: New Mexico Geothermal Resources and Utilization: *Geo-Heat Center Quarterly Bulletin*, vol. 23, no. 4, accessed November 17, 2009, at <http://geoheat.oit.edu/bul23-4/bull23-4-all.pdf>.
- Woodward, L.A., 1982, Tectonic Framework of Albuquerque Country *in* Albuquerque Country II: New Mexico Geological Society Guidebook, New Mexico Geological Society 33rd Annual Field Conference, New Mexico Geological Society, Albuquerque, New Mexico.
- Woodward, L.A., Kaufman, W.H., and Schumacher, O.L., 1974, Sandstone copper deposits of the Nacimiento region, New Mexico, Ghost Ranch, Central-Northern New Mexico: *New Mexico Geological Guidebook*, New Mexico Geological Society 25th Annual Field Conference, p. 295-299.
- World Coal Institute, 2009, What is Coal? The Coal Resource: A Comprehensive Overview of Coal, p. 4.
- Wright, R.J., 1980, Grants and World Uranium, *in* Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources, Memoir 38, p. 22-35.

FIGURES

Figures 3 and 3-1 are located in the map pocket at the end of this section.

Appendix A

Tables

Table 1 - BLM Planning Unit Summary
Leasable Mineral Occurrence Tables
Locatable Mineral Occurrence Tables
Salable Mineral Occurrence Tables

Appendix B

Mineral Resource Occurrence Maps

Leasable Minerals
Locatable Minerals
Salable Minerals

List of Mineral Resource Occurrence Maps

Plate 1	Leasable Map Overview
Plate 2	Leasable Index Map 1
Plate 3	Leasable Index Map 2
Plate 4	Leasable Index Map 3
Plate 5	Leasable Index Map 4
Plate 6	Leasable Index Map 5
Plate 7	Leasable Index Map 6
Plate 8	Leasable Index Map 7
Plate 9	Leasable Index Map 8
Plate 10	Leasable Index Map 9
Plate 11	Leasable Index Map 10
Plate 12	Leasable Index Map 11
Plate 13	Leasable Index Map 12
Plate 14	Leasable Index Map 13
Plate 15	Leasable Index Map 14
Plate 16	Leasable Index Map 15
Plate 17	Leasable Index Map 16
Plate 18	Leasable Index Map 17
Plate 19	Locatable Map Overview
Plate 20	Locatable Index Map 1
Plate 21	Locatable Index Map 2
Plate 22	Locatable Index Map 3
Plate 23	Locatable Index Map 4
Plate 24	Locatable Index Map 5
Plate 25	Locatable Index Map 6
Plate 26	Locatable Index Map 7
Plate 27	Locatable Index Map 8
Plate 28	Locatable Index Map 9
Plate 29	Locatable Index Map 10
Plate 30	Locatable Index Map 11
Plate 31	Locatable Index Map 12
Plate 32	Locatable Index Map 13
Plate 33	Locatable Index Map 14
Plate 34	Locatable Index Map 15
Plate 35	Locatable Index Map 16
Plate 36	Locatable Index Map 17
Plate 37	Salable Map Overview
Plate 38	Salable Index Map 1
Plate 39	Salable Index Map 2
Plate 40	Salable Index Map 3
Plate 41	Salable Index Map 4
Plate 42	Salable Index Map 5
Plate 43	Salable Index Map 6
Plate 44	Salable Index Map 7
Plate 45	Salable Index Map 8
Plate 46	Salable Index Map 9
Plate 47	Salable Index Map 10
Plate 48	Salable Index Map 11
Plate 49	Salable Index Map 12
Plate 50	Salable Index Map 13
Plate 51	Salable Index Map 14
Plate 52	Salable Index Map 15
Plate 53	Salable Index Map 16
Plate 54	Salable Index Map 17

Appendix C
Mineral Potential Maps

List of Mineral Potential Maps

Plate 55	Oil and Gas Potential Map
Plate 56	Coal and Humate Potential Map
Plate 57	Uranium Potential Map
Plate 58	Aggregate (Includes Sand and Gravel) Potential Map
Plate 59	Gypsum Potential Map
Plate 60	Limestone Potential Map
Plate 61	Basalt and Cinders (Scoria) Potential Map
Plate 62	Gold, Silver, and Copper Potential Map
Plate 63	Geothermal and Hot Springs Potential Map
Plate 64	Perlite and Pumice Potential Map
Plate 65	Clay Potential Map

Appendix D

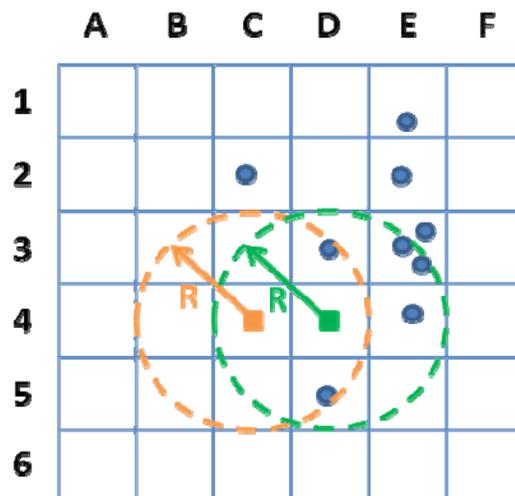
Generation of Point Density Mineral Resource Potential Maps

GENERATION OF POINT DENSITY MINERAL RESOURCE POTENTIAL MAPS

Eleven point density mineral resource potential maps are presented in Appendix C of this report. The purpose of these maps is to define the mineral resource potential for each mineral commodity or each group of related mineral commodities for use by BLM planners. The BLM would like to know the mineral resource potential for any given location and any given mineral commodity.

In previous resource studies (predating 1985), mineral resource potential was assigned based on a set of criteria consisting of the presence or absence of mines, deposits, mineral occurrences, and mineral exploration, as well as geologic environment. BLM Manual 3031 (BLM, 1985) provides a specific classification system that can be used to assign mineral potential, although these criteria may be difficult to apply uniformly for all commodities over varying geologic terrain. This study uses a method which combines the historical approach of McLemore et al. (1984a), the BLM manual classification system, a geographical information system (GIS) mapping analysis method, and best professional judgment to arrive at a mineral resource potential value. The GIS mapping system utilizes the mineral occurrence point location maps (Index Maps) provided in Appendix B which are based on the presence of a particular mineral commodity occurrence, then applies a mathematical formula to those points to calculate the density of a certain level of mineral resources at any given location on the map.

The point density mineral resource potential maps were developed by dividing the study area into a rectangular grid with a resolution of 450 x 450 meters. The point density method calculates the density of point features around each grid cell. Conceptually, a “neighborhood” is defined around each grid cell center, and the number of points that fall within the neighborhood is totaled and divided by the area of the neighborhood. For this analysis, a circular neighborhood was used, defined by a radius, R . The figure below illustrates the neighborhood concept.



For grid cell C4, the neighborhood is defined by the orange circle. Likewise, for grid cell D4, the neighborhood is defined by the green circle.

The figure also illustrates how point density is calculated. For grid cell C4, there are two points within the neighborhood defined by the orange circle, and thus the point density is two divided by the area of the circle. Likewise, for grid cell D4, there are five points within the neighborhood defined by the green circle, and thus the point density is five divided by the area of the circle. This calculation is repeated for each grid cell to arrive at a point density for each grid cell. In the example illustrated, all of the points have been weighted equally, and are given the same value (1). Alternatively, a weighting scheme can be used where the relative value of points diminishes as the distance from the grid cell center approaches the radius of the neighborhood, R.

For this study, a weighting function was used to calculate the point density for each grid cell. This weighting function, known as the Epanechnikov (or quadratic) kernel, has the following form

$$K(t) = \left(\frac{3}{4}\right)(1 - t^2), |t| \leq 1$$

$$K(t) = 0, |t| > 1$$

and

$$t = \frac{d_{ij}}{h}$$

where d_{ij} is the distance from a grid cell to a particular commodity point, and h is the bandwidth, or the sensitivity of the function to distance. The Epanechnikov kernel is a smoothing function for numerous statistical applications and is used in ArcGIS (ESRI, 2009a), the GIS software used for this study (Smith et al. 2009). The ArcGIS implementation of the Epanechnikov kernel was used in the preparation of the point density mineral resource potential maps in this report. The motivation for using the kernel smoothing function is to more highly weight the points in the immediate vicinity of a given grid cell center, but also consider points distal from the grid cell center albeit with a lower weighting. This has the effect of smoothing the data to make it easier to interpret.

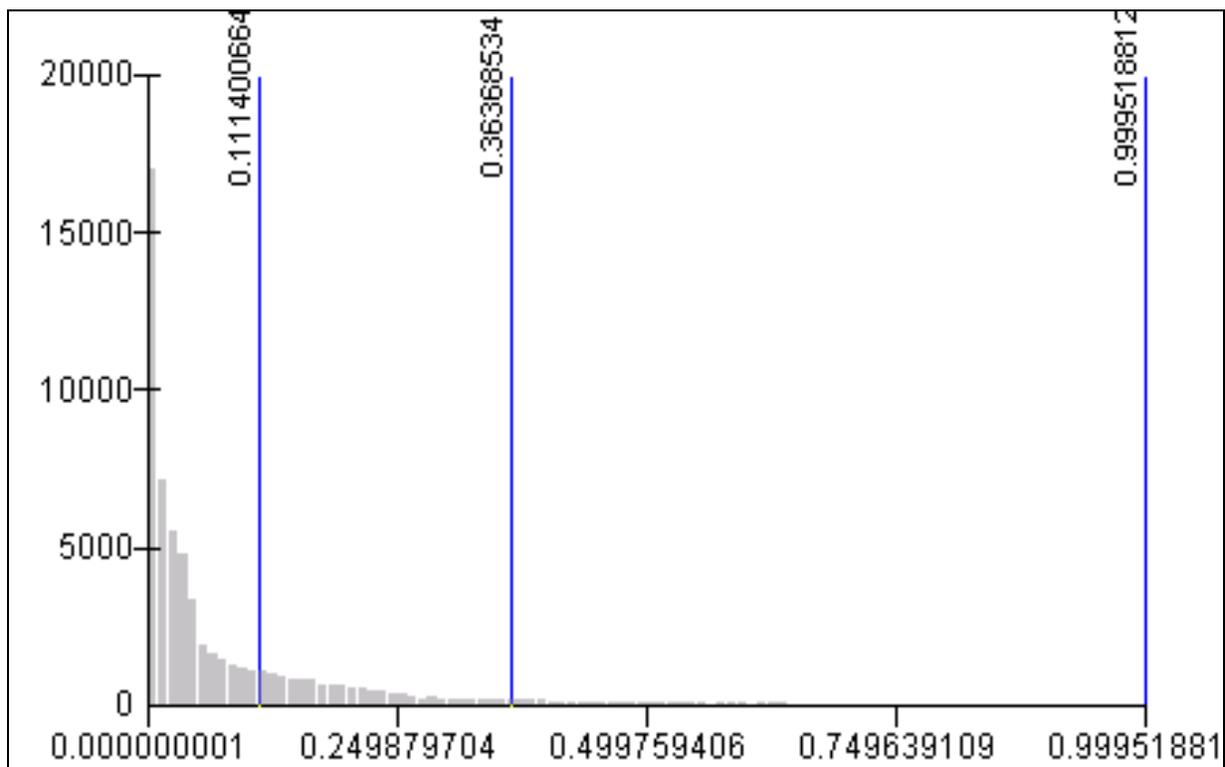
ArcGIS checks for mineral commodity points within a circular region (neighborhood) around each grid point. The radius of this circle was kept at the default value of 8,172 meters, which was selected by the ArcGIS software. Increasing the radius of this circle does not result in a significant increase in accuracy (ESRI, 2009b). Every mineral commodity point that falls within this circle is weighted by distance according to the Epanechnikov kernel function mentioned above. The point density values for each grid point have been normalized by dividing all point density values by the highest point density value anywhere in region of interest. This gives each cell in the map grid a value between 0 and 1. Thus, a cell with a value of 0 represents no point density, and a cell with a value near 1 represents high point density. Since there are different numbers of occurrence points for each commodity, the point density maps were normalized to allow for comparison of mineral potential between commodities.

Three cutoffs corresponding to low, moderate, and high mineral potential were assigned based on the population distribution of normalized densities using the Jenks natural breaks method (Jenks and Caspall,

1971). The Jenks natural breaks classification scheme determines the best arrangement of values into classes by iteratively comparing sums of the squared difference between observed values within each class and class means. The best classification identifies breaks in the ordered distribution of values that minimizes within-class sum of squared differences. The equation for identifying Jenks natural breaks, which is solved iteratively, is presented below.

$$SSD_{i,j} = \sum_{k=i}^j (A[k] - mean_{i,j})^2$$

Thus the Jenks natural breaks classification seeks to group similar values together, and place logical breaks between groups of values such that similar values are considered together (i.e. low, moderate, and high density). To illustrate, the plot below shows a histogram of point density values from this study for aggregate and the corresponding class breaks. This figure graphically illustrates how similar values have been grouped together to identify each of the three classes of potential (low, moderate, high).



Since this approach is based on a statistical calculation that groups population values together by minimizing differences within each population, it provides a reproducible, transparent and unbiased methodology for selecting the point-density classes that define low, medium, and high potential.

The classes defining low, medium, and high potential for each mineral commodity are presented in the table below.



Point Density Classes for Determining Mineral Potential

Commodity	Low Potential	Moderate Potential	High Potential
Leasable Minerals			
Oil and Gas	0.0 – 0.167	0.167 – 0.473	0.473 – 1.0
Coal and Humate	0.0 – 0.167	0.167 – 0.473	0.473 – 1.0
Geothermal Resources and Hot Springs	0.0 – 0.167	0.167 – 0.473	0.473 – 1.0
Locatable Minerals			
Gold, Silver and Copper	0.0 – 0.167	0.167 – 0.473	0.473 – 1.0
Gypsum	0.0 – 0.167	0.167 – 0.473	0.473 – 1.0
Limestone	0.0 – 0.167	0.167 – 0.473	0.473 – 1.0
Perlite and Pumice	0.0 – 0.167	0.167 – 0.473	0.473 – 1.0
Uranium	0.0 – 0.111	0.111 – 0.364	0.364 – 1.0
Salable Minerals			
Aggregate	0.0 – 0.111	0.111 – 0.364	0.364 – 1.0
Basalt and Cinders	0 – 0.167	0.167 – 0.473	0.473 – 1.0
Clay	0.0 – 0.167	0.167 – 0.473	0.473 – 1.0

The weighting function interpolates point density based on a limited data set. Thus, the point density maps strictly represent the relative number of occurrences, prospects, mines, etc within the vicinity of any given point on the mineral potential map (e.g. each grid cell). However, occurrences, anomalies, prospects, mines and so on are all a subset of *mineral occurrences*. Thus, the point density maps represent the relative measure of occurrences associated with a given commodity in the vicinity of each grid cell. Based on the assumption that a greater number of occurrences reflect a greater potential, a low density of mineral occurrence is equivalent to low mineral potential, a moderate density of mineral occurrence is equivalent to moderate mineral potential, and a high density of mineral occurrence is equivalent to a high mineral potential.