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Mineral and Energy Resources of the BLM Roswell Resource Area, East-central New Mexico

by

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SUMMARY

The sedimentary formations of the Roswell Resource Area have significant mineral and energy resources. Some of the pre-Pennsylvanian sequences in the Northwestern Shelf of the Permian Basin are oil and gas reservoirs, and Pennsylvanian rocks in Tucumcari basin are reservoirs of oil and gas as well as source rocks for oil and gas in Triassic rocks. Pre-Permian rocks also contain minor deposits of uranium and vanadium, limestone, and associated gases. Hydrocarbon reservoirs in Permian rocks include associated gases such as carbon dioxide, helium, and nitrogen. Permian rocks are mineralized adjacent to the Lincoln County porphyry belt, and include deposits of copper, uranium, manganese, iron, polymetallic veins, and Mississippi-Valley-type (MVT) lead-zinc. Industrial minerals in Permian rocks include fluorite, barite, potash, halite, polyhalite, gypsum, anhydrite, sulfur, limestone, dolomite, brine deposits (iodine and bromine), aggregate (sand), and dimension stone. Doubly terminated quartz crystals, called "Pecos diamonds" and collected as mineral specimens, occur in Permian rocks along the Pecos River. Mesozoic sedimentary rocks are hosts for copper, uranium, and small quantities of gold-silver-tellurium veins, as well as significant deposits of oil and gas, CO_2, asphalt, coal, and dimension stone. Mesozoic rocks contain limited amounts of limestone, gypsum, petrified wood, dinosaur remains, and clays. Tertiary rocks host ore deposits commonly associated with intrusive rocks, including platinum group elements, iron skarns, manganese, uranium and vanadium, molybdenum, polymetallic vein deposits, gold-silver-tellurium veins, and thorium-rare earth veins. Museum-quality quartz crystals in Lincoln County were formed in association with intrusive rocks in the Lincoln County porphyry belt. Industrial minerals in Tertiary rocks include fluorite, vein- and bedded-barite, caliche, limestone, and aggregate. Tertiary and Quaternary sediments host important placer deposits of gold and titanium, and minor silver, uranium occurrences, as well as important industrial commodities, including caliche, limestone and dolomite, and aggregate (sand). Quaternary basalt contains sub-ore-grade uranium, scoria, and clay deposits.

INTRODUCTION

LOCATION AND GEOGRAPHY OF STUDY AREA

The Roswell Resource Area (the "study area" of this report) is located in east-central New Mexico, approximately between latitudes 33°-35° N. and longitudes 103°-106° W. (fig. 1). The study area encompasses 14,014,720 acres [57,000 km^2 (about 21,890 mi^2)] and all of Guadalupe, Quay, De Baca, Curry, Roosevelt, Lincoln Counties, and most of Chaves County. Of this total acreage, the U.S. Bureau of Land Management (BLM) manages only about 1.5 million surface acres [6,010 sq km (about 2,320 sq mi)] and 3.9 million subsurface (mineral rights) acres [15,735 sq km (about 6,075 sq mi)].

Cities and towns within the Roswell Resource Area include Carrizozo (west), Santa Rosa (northwest), Fort Sumner (north-central), Tucumcari (north), Clovis and Portales (east), and Hagerman and Roswell (south). Federal and State lands included within the study area are Lincoln National Forest, the southern part of Cibola National Forest, White Mountain Wilderness Area, Salt Creek Wilderness Area, Sumner Lake State Park, Ute Lake State Park, Valley of Fires Recreation Area, Bottomless Lakes State Park, Bitter Lake National Wildlife Refuge, Grulla National Wildlife Refuge, Cannon Air Force Base, and the Melrose Bombing Range. Reserved lands adjacent to the study area are the Mescalero Apache Indian Reservation on the southwest and the White Sands Missile Range on the west. The Texas-New Mexico State line is the eastern boundary of the study area.

Prominent physiographic features of the Roswell Resource Area include the southern part of the Gallinas Mountains, the Jicarilla Mountains, the northern part of the Sacramento Mountains, the Capitan Mountains, the Pecos Slope, the Mescalero pediment, and the Llano Estacado (fig. 1). Major drainages include the Pecos River which drains into the Rio Grande, and the Canadian River that drains into the Red River. The Capitan and Gallinas Mountains rise to about 3,110 m (10,200 ft) and 2,620 m (8,600 ft), respectively; Sierra Blanca Peak in the northern Sacramento Mountains, reaches 3,661 m (12,003 ft) at the southwestern border of Lincoln County. The western escarpment of Sierra Blanca Peak has the highest relief in New Mexico [about 2,380 m (nearly 7,800 ft)]. The Sacramento Mountains, Jicarilla Mountains, and Gallinas Mountains form a north-south-trending mountain chain; the Capitan Mountains and smaller associated intrusives trend east-west. These mountain ranges slope to the Pecos River Valley, about 129 km (80 mi) to the east.

The arid, undulating, eastward-sloping area that extends east of the mountains to the Pecos River is referred to as the Pecos Slope; the slope ranges in altitude eastward from about 3,050 m (10,000 ft) to about 915 m (3,000 ft), and is locally interrupted by small mesas. In the Roswell Resource Area, the Pecos Slope is drained by several east-flowing ephemeral and perennial rivers, including the Rio Hondo, Arroyo del Macho, Arroyo de la Mora, Yeso Creek, Salado Creek, and Pintada Arroyo; each of these major streams has its own tributary system. Numerous large subsurface drainage systems extend eastward from the mountains into the Pecos drainage system, which is greatly modified and locally entrapped by karst activity. The Pecos River has been dammed to form two major reservoirs, the Sumner Lake and Los Esteros Reservoirs, both near Santa Rosa. The eastward-flowing Canadian River, located in the northeastern part of the study area, is also dammed along its course to form the Ute Reservoir. Two additional drainage basins are northwest of the study area: the Estancia Valley, an interior basin west of the Pintada Arroyo, and the Claunch Valley drainage into the Sierra Blanca basin near Carrizozo. Two interior drainage basins, the Encino and Vaughn, are located north of the Capitan Mountains, and south of Pintada Arroyo; these drain into the subsurface karst and eventually into the Pecos River system.

The Mescalero pediment extends southeast from Roswell to the Mexican border, and between the Pecos River and the Llano Estacado (the Staked Plains or Caprock). The Llano Estacado makes up the largest part of the study area to the east of the Pecos River, extending from the Canadian River to the southeast corner of New Mexico and from the Mescalero Pediment to beyond the Texas-New Mexico State boundary. It is crossed by large, mostly ephemeral stream systems with low gradients, which drain westward and southwestward into the Pecos River.

PURPOSE AND METHODOLOGY

This report assesses the potential for mineral and energy resources on the surface and in the subsurface within the BLM Roswell Resource Area, an area that contains many important commodities in a variety of geologic settings. Resource potential is the likelihood for the occurrence of undiscovered concentrations of metals and nonmetals, industrial rocks and minerals, and fuels resources. This report includes a description of stratigraphy and tectonic setting, the geochemical and geophysical evidence used in the mineral and energy resource assessment, a description of mineral occurrences and the hydrocarbon fields, an historical account of their exploration and production, and a description and analysis of the mineral resource tracts and hydrocarbon plays.

The MARK-3 computer program for mineral-resource simulation (Drew and others, 1986; Root and Scott, 1988; Root and others, in press) is a statistical method that is used herein to estimate potential gross in-place tonnages for unknown resource commodities. This mineral-resource assessment of the Roswell Resource Area relies upon previous work of the U.S. Geological Survey, the Canadian Geological Survey, and others who have developed mineral deposit models. Uranium and vanadium commodities for which no models are currently available are assessed by another similar statistical method, the deposit-size-frequency method (Finch and McCammon, 1987). The resource potential of industrial commodities other than gypsum are discussed, but no quantitative assessments were made. Two hydrocarbon plays are described, derived from the national assessment of 1988 (U.S. Geological Survey and Minerals Management Service, 1988; Mast and others, 1989).

Limited field investigations of the Roswell Resource Area were independently conducted in 1990 and 1991 by T. J. Armbrustmacher, Susan Bartsch-Winkler, J.A. Erdman, D. M. Kulik, S.L. Moore, C.S. Spirakis, and D.M. Sutphin. A summary of all available previously published geologic reports and maps on surface and subsurface geology and mineral occurrences was prepared by Bartsch-Winkler and Sutphin. Information from the Anaconda Collection (University of Wyoming, Laramie), the New Mexico Bureau of Mines and Mineral Resources (Socorro and Albuquerque, New Mexico), and Bureau of Land Management (Roswell, New Mexico) was obtained by M.M. Ball (oil and gas occurrences), Bartsch-Winkler (industrial mineral occurrences), Spirakis (sulfur occurrences), and Sutphin (metallic mineral occurrences). Information on the geology of the alkaline rocks was compiled by Armbrustmacher. Geologic map information was compiled and modified by Samuel L. Moore from the New Mexico Highway Map (1982). Edward J. LaRock transferred the geologic data onto a mylar base, and digitized, edited, and transferred the geology into ARC/INFO. Erdman and R.R. Tidball, and R.B. Tripp compiled and interpreted geochemical information from the National Uranium Resource Evaluation (NURE) surveys. Geophysical information was interpreted by Kulik. J.S. Duval studied and interpreted the NURE aerial gamma ray information for the study area. Data on various commodities were gathered by G.N. Breit (vanadium), W.I. Finch (uranium), J.K. Otton (uranium), Spirakis (sulfur), G. D. Stricker (coal), and Sherilyn Williams-Stroud (potash and brines). Various members of the study team identified models and evaluated the potential for deposits of certain commodities, and Sutphin, R.B. McCammon, and Finch conducted statistical analyses of pertinent data for the mineral resource assessment. Ball and others assessed the petroleum potential and outlined the oil and gas plays.

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GEOLOGY OF EAST-CENTRAL NEW MEXICO

By Susan Bartsch-Winkler

with a section on

Intrusive and extrusive alkaline rocks of the Lincoln County porphyry belt

by Theodore J. Armbrustmacher

GENERAL

Surface and subsurface geologic units within the Roswell Resource Area span Precambrian to Holocene time (maps A, B, C), yet the surface units are mostly Permian, Mesozoic, Tertiary, and Quaternary. The Roswell Resource Area contains three major terranes: the Lincoln County porphyry belt, the Pecos Slope, and the Northwestern Shelf of the Permian Basin.

The Roswell Resource Area is underlain by formations ranging in age from Precambrian to Holocene (maps A, B, and C). Uplifted sequences of sedimentary rock dip gently eastward along the Pecos Slope into the Northwestern Shelf of the Permian Basin. Exposed formations are composed mainly of clastic, carbonate, and evaporite successions above the warped and faulted Precambrian basement (maps B, C). Features of the Permian Basin, including the Tucumcari basin, Bravo dome, and the Roosevelt positive, were probably formed in Paleozoic time (Budnik, 1989). Laccoliths and stocks of Laramide (Tertiary) age known as the Lincoln County porphyry belt intrude the older sedimentary sequences of the Pecos Slope and are in the western part of the study area (map D). This belt generally includes the north-trending mountain chain composed of the Sacramento, Gallinas, and Jicarilla Mountains, and the east-trending Capitan Mountains and smaller Carrizo, Patos, Vera Cruz, and Lone Mountains intrusives and stocks. The rock units of the Pecos Slope have superimposed small-scale tectonic features that were reactivated at various times (Map E). Uplift and subsidence events resulted in evaporite dissolution and eventual development of karst terrane (especially in Permian rocks). The Pecos River and tributaries deposited Pleistocene and Holocene alluvium and terrace gravel and this fluvial system continues to dissolve evaporites and form karst.

STRUCTURE

Uplifts

Pecos Slope, Sacramento, and Capitan uplifts

Uplift was initiated by intrusive activity in Tertiary time in the Sacramento, Jicarilla, Gallinas, Capitan, and adjacent mountains (the highest points in the study area). High-angle, westward-dipping, normal faults and pre-Tertiary(?) thrust faults near the base of mainly Paleozoic and Mesozoic strata, manifest as scarps, fans, and step-faults, are exposed south and west of the study area in the Sacramento uplift, which marks the eastward extent of the Rio Grande rift (Pray, 1961) (map D). The steep west front of the Sacramento uplift is at least 2,135 m (7,000 ft) adjacent to Tularosa Basin (Kelley and Thompson, 1964)(map B). The back of the uplift is an eastwardly inclined surface called the Pecos Slope. The western boundary of the Pecos Slope in Lincoln County is defined by the distribution of intrusive and extrusive rocks in the mountain chain, referred to as the Lincoln County porphyry belt, and by the Dunken uplift (south of the study area) and the Tinnie fold belt (Kelley, 1971) (map D). On the Pecos Slope, anticlines, synclines, basins, monoclines, and circular domes occur; some of the folds are overturned.

The Capitan Mountains, probably a laccolith, is one of the largest Tertiary intrusions in New Mexico (McLemore and Phillips, 1991). The aplite roof and granite core of the pluton are exposed by erosion (Allen, 1988; Allen and McLemore, 1991). Sedimentary strata that crop out on the western and overlying parts (the roof) of the intrusive dip to the west; the eastern part (the core) of the intrusive is in contact with near-vertical strata (Kelley, 1971; McLemore and Phillips, 1991). The intrusion is probably a basement-related feature because it lies within the east-west Capitan Mountains lineament, which extends westward from the Matador trend in West Texas to Socorro in central New Mexico (Griswold, 1959; Kelley, 1971) (inset, map D). The junction of the north-northeast-trending structural zones and the east-west structural zone of the Capitan Mountains occurs in the vicinity of several other smaller intrusions, including the Carrizo, Patos, Vera Cruz, and Lone Mountains intrusions (maps A, D) (Griswold, 1959). According to Kelley (1971), the Capitan Mountains intrusion, which left-laterally offsets the north-south-trending Pedernal uplift (Mescalero arch), is offset in places by north- or northeast-trending faults.

Carrizozo anticline

The Carrizozo anticline is a broad elliptical-shaped, northeast-trending, doubly plunging, slightly asymmetric, fold that extends from the Sierra Blanca basin on the east to the southern end of Chupadera Mesa on the west (outside the study area) (map D). It crosses the north-south trend that extends from the Tularosa Basin to the Claunch sag (Kelley and Thompson, 1964).

Pedernal uplift

The buried Paleozoic Pedernal uplift (southern part of the Ancestral Rocky Mountains) extends from the northern edge of the study area at Vaughn to east of the southern Sacramento Mountains (map D). The Mescalero arch of Kelley and Thompson (1964), a broad structural divide that is offset by the Capitan Mountains, generally coincides with the Pedernal uplift (Kelley, 1971). The Pedernal uplift, which is composed of a Precambrian basement-rock core, probably was initiated in the Middle Pennsylvanian (early Atokan) time, with major uplift recurring in Permian time (Map B). No coarse clastic material from this Precambrian-age landmass is found in pre-Pennsylvanian rocks (Lloyd, 1949). However, Precambrian clastics are found in Lower Atokan and Lower Permian sedimentary rock sequences. In late Paleozoic time, the Pedernal uplift caused various overlying Paleozoic formations to be truncated along its flanks (Pray, 1949, 1954, 1961; Kottlowski, 1963; Perhac, 1964; Kottlowski and Stewart, 1970; Broadhead and King, 1988) (map B).

Matador uplift and Bravo dome

The pre-Permian Matador uplift is a prominent Precambrian basement feature that trends east-west in southern Roosevelt County and is marked by a series of en echelon fault-bounded blocks in the subsurface (Budnik, 1989) (map D). The blocks range in size from 13 km^2 to 130 km^2 (5 mi^2 to 50 mi^2), with as much as 1,220 m (4,000 ft) of basement relief (Budnik, 1989). Wells drilled in the area encountered Pennsylvanian and Permian sequences that overlie Precambrian basement rocks; each block along the trend contains oil reservoirs of Mississippian to middle Permian age (Budnik, 1989). Only small amounts of Precambrian detritus were eroded from the Matador uplift, indicating that the Matador uplift was a relatively low, positive feature during Pennsylvanian and Permian time (Lloyd, 1949). Pre-Mississippian strata are missing on the uplift. Multiple unconformities in strata overlying the fault blocks of the Matador uplift indicate a complex history (Budnik, 1989). The Roosevelt positive, an aligned series of small domes, lies at the western extremity of the Matador uplift. The positive was reactivated episodically in early to middle Paleozoic time and uplift took place until at least middle Permian time (Budnik, 1989).

The Bravo dome is parallel and similar to the Matador uplift in being a faulted (reactivated) Precambrian basement high that extends from eastern New Mexico to southwestern Oklahoma (Budnik, 1989) (inset, map D). The Bravo dome separates the Tucumcari basin on to the south from the Dalhart basin northeast of the study area. The Bravo dome apparently formed in Middle Pennsylvanian time and deformation continued into Miocene time (Budnik, 1989). The uplift influenced deposition of sedimentary rocks throughout Permian time; basement rocks of the dome are onlapped by Pennsylvanian strata and the Permian Glorieta Sandstone.

San Jon high

The San Jon high (also referred to as the Frio uplift) is a broad Precambrian basement positive which separates the Palo Duro and Tucumcari basins (Map D); Budnik (1989) describes the high as being composed of two small highs. It is bounded on the west by the Bonita fault and on the east by an unnamed and poorly known reverse fault. Subsurface data indicate that Pennsylvanian and Permian sedimentary strata thin over the San Jon high.

Basins

Sierra Blanca basin

The Sierra Blanca volcanic pile rests on a 1,940 km^2 (750 mi^2) structural basin defined by deposits of Cretaceous age [mainly Dakota(?) Sandstone] which crop out along its perimeter (Griswold, 1959; Kelley and Thompson, 1964)(Maps A, D). This basin is about 64 km (40 mi) long and 32 km (20 mi) wide, and has a north-northeast-trending axis (Thompson, 1966). The basin lies west of the Pedernal axis or Mescalero arch, east of the Carrizozo anticline, and northeast of Tularosa basin; the northern part of the Sierra Blanca basin has been modified by the White Oaks and Capitan faults and the Lone Mountain and other intrusives (Kelley and Thompson, 1964). The eastern edge of the basin slopes into a fault zone near Ruidoso, which has as much as 427 m (1,400 ft) of vertical offset (Kelley and Thompson, 1964). Folds and faults on the eastern edge of the basin near Sierra Blanca peak (including the Tinnie fold belt)(Kelley, 1971) trend east-northeast, nearly paralleling the buckle faults discussed below. The Sierra Blanca basin is Laramide in age, and is filled by Eocene and later volcanogenic and plutonic units (Thompson, 1972; Lucas and others, 1989; Cather, 1991; Moore and others, 1991).

Permian Basin

The Permian Basin extends in the subsurface from southeastern New Mexico and west Texas into southern Kansas and western Oklahoma (Budnik, 1989) (Map D; inset). The Northwestern Shelf is that part of the Permian Basin that lies north of the Permian Capitan Reef and extends into the study area; features of the Northwestern Shelf include Tucumcari basin, Bravo dome, Roosevelt positive, and the western part of the Palo Duro basin. Important features of the Permian Basin that occur in New Mexico but outside the study area boundary include the Delaware Basin (south of the Capitan Reef) and the northwestern part of the Central Basin Platform (east of the Delaware Basin). At the western extremity of the Permian Basin, especially in the central and northern parts of the study area, pre-Pennsylvanian rocks generally are shelf deposits that have been truncated and(or) eroded.

Tucumcari basin

The Tucumcari basin, in the northeastern part of the study area, is a Pennsylvanian-age, asymmetric, structural basin bounded by ancestral uplifts of the Rocky Mountains (Paleozoic Sierra Grande uplift on the north and Pedernal uplift on the south and west), on the northeast by the Bravo dome; and on the southeast by a subsurface horst block of Middle Pennsylvanian to Early Permian (Middle Pennsylvanian to Wolfcampian) age (Broadhead, 1989). The deepest part of Tucumcari basin is composed of down-faulted block structures (grabens) in basement rocks; it is as much as 2,745 m (9,000 ft) deep west of Newkirk (fig. 1; Broadhead and King, 1988; Broadhead, 1989). The basin is underlain by Precambrian basement and sedimentary units of Mississippian, Pennsylvanian, Permian, Triassic, Jurassic, Cretaceous, Tertiary, and Quaternary age (Dobrovolny and others, 1946); Mississippian rocks are pre-basinal (Broadhead, 1989). Pre-Mississippian strata are not present (Broadhead and King, 1988).

According to Broadhead and King (1988), gentle surface structures are not indicative of the large-scale subsurface structures in Tucumcari basin (map D). The northern, western, and eastern parts of the basin are complexly faulted, but major structural movement in the basin and surrounding uplifts was apparently limited to Middle Pennsylvanian through Early Permian time (Broadhead and King, 1988), because basin faults (rooted in Precambrian basement) cut these strata and control their thickness and facies distribution (Broadhead, 1989). Upper Permian units have few faults and are draped over deeper fault blocks (Broadhead, 1989). During the Laramide orogeny, some of the older structures in the Tucumcari basin were reactivated. The Bonita fault, an isolated structural feature in the southeastern Tucumcari basin, displaces beds as young as Cretaceous in age and may have offset strata as young as Quaternary in age; dissolution of Permian units complicate the analysis of fault movement (Budnik, 1989). The Bonita fault trends N.40°E. and dips 60°W; it has as much as 213 m (700 ft) of normal displacement (Stearns, 1972).

Faults and folds

Tinnie fold belt

The north-trending Tinnie fold belt near Tinnie is about 32 km (20 mi) long and about 5-8 km (3-5 mi) wide (Kelley, 1971) (map D). The belt consists of narrow anticlines and synclines with moderately steep limbs that overlie a narrow north-trending basement block (Bowsher, 1991). In the northern part of the belt where the basement block has structural relief of 1,800 m (about 6,000 ft) (Burt, 1991), as many as 12 folds occur in a width of 5 km (3 mi). In the vicinity of Hondo Canyon, as many as 9 folds occur in a width of 3 km (2 mi) (Kelley, 1971). Structural relief on the folds is as much as 300 m (1,000 ft) (Kelley, 1971). Folding and faulting in the Tinnie fold belt probably took place during Tertiary time. The Tinnie folds may be related to tectonic reactivation of Precambrian basement that underlies them (Craddock, 1964; Yuras, 1976; Burt, 1988).

Lincoln fold belt

In Rio Bonito Canyon east of Lincoln, the Yeso and overlying Glorieta and San Andres Formations are folded into a series of north-trending folds (the Lincoln fold belt of Craddock, 1960); overlying strata are not folded (Griswold, 1959) (map D). Folds occur in Yeso strata south and east of Corona (Fischer and Hackman, 1964), in the Claunch Sag, on Chupadera Mesa, and on the flanks of the Capitan Mountains (Kelley and Thompson, 1964). Because of their occurrence in (but not restriction to) the Yeso Formation, the folds are thought to be related to incompetency in bedrock, and were probably caused by collapse, intrusion, solution, slumping, and/or compressive or gravity tectonics, or combinations of these factors (Kelley and Thompson, 1964; Craddock, 1964; Foley, 1964). The Lincoln folds apparently formed in Tertiary time independently from, and unrelated to, basement activity.

Vaughn trend

The Vaughn trend is composed of a belt of minor deformation that extends through Vaughn on a north-south trend, aligning with the Tinnie folds (Kelley, 1972a,b) (map D). At its southern end, the trend is composed of staggered anticlines. Further north it is composed of a narrow fault zone that has, in part, right-lateral strike-slip movement (the Nalda shear zone) and which passes further north into a gentle flexure (the Derramadura monocline). Three miles east of the Nalda shear zone is the 40-km- (25-mi-)long Vaughn fault that, further to the north, becomes a 21-km-(13-mi-)long buckle or west-facing monocline (Leon monocline) that extends into Pintada Arroyo. According to Kelley (1972a,b), deep-seated extension in the Rocky Mountains may be manifest in the Vaughn sag, which is located between the Leon monocline-Vaughn fault on the east and the Derramadera monocline on the west.

Buckles and northeast-trending faults

A series of northeast-trending faults and folds, some termed buckles in the literature, occur on the southern Pecos Slope west of Roswell (Merritt, 1920) (map D). In general, the buckles are straight, exposed for 55-130 km (35-80 mi), and spaced at 13-32 km (8-20 mi) intervals. Many of the buckles may be right-lateral wrench faults, as evidenced by their great length and small amount of throw, associated drag folding, left-branching folds and short faults, and long left-diagonal folds in the blocks between the buckles (Kelley, 1971). Most plunge northeastward and diagonal to regional dip. These faults are named the Bonito fault, White Tail fault, Serrano buckle, Border buckle, Sixmile buckle, Y-O buckle, and the K-M buckle; many are related to gas accumulations. Additional, relatively minor, right-lateral offsets include the Ruidoso, Little Creek, Airstrip, and Champ faults and the Purcella buckle (Kelley, 1971). The Bonita fault is a normal fault.

The Bonito fault extends for about 58 km (36 mi) from Sierra Blanca to near Lincoln, and north of the Capitan Mountains intrusive (Kelley, 1971). It trends about N. 55° E. Offset faults, folds, and a sill indicate right-lateral movement.

The White Tail buckle extends southwestward for about 34 km (21 mi) from the vicinity of Hondo (Kelley, 1971). It trends N. 50°-60° E. The fault is downthrown on the southeast side, except at the southwest end where it is downthrown to the northwest; it probably has experienced some right-lateral movement, although no drag folds are apparent (Kelley, 1971).

The Serrano buckle is about 42 km (26 mi) long and trends about N. 35°E., extending northward from the Tinnie fold belt (Kelley, 1971). Relative movement varies along its length, and the buckle zone has a width of less than 91 m (300 ft) (Kelley, 1971). Drag folds and faults indicate right-lateral movement, with locally as much as 152 m (500 ft) of lateral offset (Kelley, 1971).

The Border buckle is about 97 km (60 mi) in length, and has northeast trends ranging from about N. 35°E.-55°E. (Kelley, 1971). This buckle is the most strongly deformed; the zone of deformation ranges from 488 m (1,600 ft) to less than 152 m (500 ft) in width (Kelley, 1971). The sense of offset changes repeatedly along the length of the buckle, and in places the strata contain brecciated intervals indicative of faulting (Kelley, 1971).

The Sixmile buckle is as much as 129 km (80 mi) long and trends about N.40°E. The upper beds in the Sixmile buckle are vertically offset, but the lower beds indicate possible strike-slip movement (Kelley, 1971).

The Y-O buckle is at least 116 km (72 mi) in length, as inferred from surface and subsurface evidence. The buckle apparently follows a pre-existing line of deformation. It trends about N.40°E.; the most deformed part of the fold is about 150-245 m (500-800 ft) wide (Kelley, 1971). Drag folds adjacent to the buckle indicate right-lateral movement estimated to be as much as 549 m (1,800 ft).

The K-M fault extends in the subsurface from Artesia to about Lake Arthur, near the southern border of the study area (Kelley, 1971). It is apparently about 48 km (30 mi) in length, with the southeast side downdropped as much as 61 m (200 ft) (Kelley, 1971).

Roosevelt County fault

The Roosevelt County fault is a normal fault which bounds the western margin of the Matador uplift (map D). Flawn (1956) suggested as much as 24 km (15 mi) of right-lateral offset has occurred on the fault based on offsets in Precambrian strata. The fault was reactivated as late as middle Permian time, as evidenced by the occurrence of as much as 76 m (250 ft) of relief in San Andres strata across the fault (Ramondetta, 1982; Budnik, 1989).

Alamosa Creek fault

The Alamosa Creek fault is a 10-km-(6-mi-) long, northeast-trending graben feature that contains rocks of Cretaceous to late Tertiary age (Budnik, 1989) (map D). The fault was active in middle Permian time and was reactivated twice in Cretaceous time. The history of fault movement is controversial because of the lack of subsurface information and because of known dissolution of Permian units. Strike-slip movement is suggested, however, by the lack of vertical offsets in underlying units of the surface graben.

Karst

Post-depositional jointing of lithified deposits reflecting release of stress caused by erosion of overburden occurred during regional uplift in the study area. Regionally, joint sets in bedrock allow percolation by surface- and ground-waters resulting in dissolution of water-soluble components in the rock, especially evaporites, limestones, and dolomites. Ultimately, caverns and vadose zones form and become holding areas for surface runoff. Subsurface drainage channels also form. Finally, the cavernous terrane is modified by collapse, forming breccia pipes filled with insoluble residue, destroying all evidence of previously formed features. Such features may be, in part, the result of upward flowing subsurface water under hydrostatic pressure (an artesian system) . This combination of features is typical of karst. Karst features, important aquifers in southeastern New Mexico, are described in detail by Bachman (1987). Karst has probably been forming in the Roswell Resource Area since Triassic time (Bachman, 1987).

Sinks

The Santa Rosa collapse basin (map D), perhaps the most notable karst feature in the study area, is a large circular sinkhole, about 10 km (6 mi) in diameter and as much as 122 m (400 ft) deep, that is infilled with sand, mud, and gravel to a depth of as much as 61 m (200 ft) (Kelley, 1972b). The collapse resulted from dissolution of underlying salt, gypsum, or limestone deposits of Permian age (Sweeting, 1972). The boundary of the sink is marked by faults and monoclinal flexures arranged in concave inward segments. Sink holes have formed along the flexures and adjacent uplands, but are especially prevalent along the west and north side of the Santa Rosa sink where the Pecos River and Pintada Arroyo enter the basin and have eroded into the basin fill. Near the town of Santa Rosa, many smaller sinkholes (not shown on the map) include the locally renowned Blue Hole. It is 18 m (60 ft) in diameter, more than 25 m (81 ft) deep, and has an artesian flow of 11,355 L (3,000 gal) per minute.

In southeastern Chaves County and western Lea County, sinks are aligned along joints that trend N.60°W. (Reeves, 1972) (Map D). East of Artesia, numerous small sinks and domes are present. The structures are noted by the presence of slumping, flexing, and apparent doming of bedrock caused by dissolution of evaporites and movement of salt; they are localized at the wedge edge of the Salado Formation in the shallow subsurface (Kelley, 1971; Bachman, 1987).

Contortion features

Contortion is notable in exposures of the evaporite-bearing Yeso Formation along the Rio Bonito Canyon, Lincoln County, and on the Pecos Slope. The incompetent folds associated with the Yeso have axes that are randomly oriented, highly curved in some places, and generally not continuous for more than 300 m (1,000 ft) (Kelley, 1971). Such features may result from faulting, but they are more likely caused by surficial collapse, evaporite intrusion, volume change accompanying hydration, and regional tilting (Kelley, 1971). In the subsurface, dissolution can be recognized as zones of abrupt thinning, especially in layers containing salt deposits. The layers abruptly change in thickness, and overlying strata may be warped or folded. In areas where groundwater movement is facilitated along faults, dissolved layers may be more common. Tectonic and nontectonic origins for folding in these layers may be difficult to distinguish.

Caves

East-central New Mexico contains numerous gypsum and limestone caves. Gypsum caves are developed in the Artesia Group in east and southeast New Mexico, especially in the vicinity of Lake McMillan east of Artesia, along the Pecos River, and in the vicinity of Roswell (Peerman and Belski, 1991). Tres Niños Cave, a privately owned gypsum cave west of Carrizozo, extends under a Quaternary basalt flow (National Speleological Society,1986). Millrace Cave, adjacent to the east entrance to Valley of Fires Recreation Area, is a gypsum cave that extends to 110 m (360 ft) depth beneath a Quaternary basalt flow (one of the deepest gypsum caves in the U.S.)(National Speleological Society, 1986). Fort Stanton Cave (near Fort Stanton), developed in limestone of the San Andres Formation, is the third longest [behind Lechuguilla (no. 1) and Carlsbad Caverns (no. 2)] and the earliest-discovered limestone cave in New Mexico; there are additional limestone caves in the vicinity of Fort Stanton Cave (National Speleological Society, 1986).

Outside the study area but in the same geologic setting, famous caves (Carlsbad and Lechuguilla) occur in the Permian Capitan Reef (or Capitan Limestone) in the Guadalupe Mountains (north and west of Carlsbad) (maps B; D, inset). Caves, including these exceptional examples, occur mainly along flanks or crests of anticlinal folds and other positive structures, and(or) at the intersections of joints and fractures in Permian carbonate rocks.

The genesis of caves in eastern New Mexico and Texas is poorly understood and numerous recent theories on their origin have been proposed (Bachman, 1987; Hill, 1987, 1989). One hypothesis is that in late Tertiary to early Quaternary time, uplift caused relative lowering of the water table, which may have allowed caverns to develop, especially in the limestone- and evaporite-bearing San Andres Formation and Artesia Group rocks in the southern and southeastern parts of New Mexico (Bachman, 1987). During this time, rainfall and runoff may have increased and drainages may have existed above the water table. Cavern and breccia-pipe development took place during dissolution of evaporites by downward-percolating water, especially at the joint intersections. Karst development probably was accelerated by climate change and uplift.

Davis (1980), using the replacement-solution hypothesis of Egemeier (1973), suggests that cavern development is the result of the (1) interaction of groundwater carrying hydrogen sulfide gas (from petroleum deposits) (2) reaction with air to form sulfuric acid, (3) sulfuric-acid dissolution of limestone and conversion of limestone in the cave to gypsum, and, finally, (4) build-up and collapse of gypsum in the cave and dissolution and removal by cave streams. Isotopic studies by Hill (1987, 1990) support the theory of sulfuric acid dissolution of certain limestone beds, and she proposes a possible connection between hydrocarbons and sulfuric acid generation (although the migration path and source of such hydrogen-sulfide-producing hydrocarbons is unknown), leading to formation of certain types of caves that contain gypsum blocks and rinds, native sulfur, and endellite clay deposits (Hill, 1990).

STRATIGRAPHY AND DESCRIPTION OF ROCK UNITS

Precambrian basement rocks

Precambrian rocks are best exposed in the Pedernal Hills in Torrance County, but also crop out in the Gallinas Mountains, Oscura Mountains, and other locations in the western part of the study area (Griswold, 1959) (map A). The rocks are dominantly pink granite gneiss, with minor occurrences of schist, quartzite, greenstone, and granite (Griswold, 1959). South of the study area near Whitetail, Precambrian rocks make up the core of the Pajarito Mountain dome (Kelley, 1971) (map D). The rocks are hornblende syenite, hornblende syenite gneiss, and diabase and are intruded by leucocratic syenite and hornblende syenite pegmatite; a well-developed paleosoil profile occurs locally at the top of the Precambrian (Kelley, 1971).

In the subsurface, similar lithologies are encountered. West of Lon, Precambrian pink biotite granite was encountered in a drillhole at 607 m (1,990 ft) depth (Griswold, 1959). Precambrian rocks form the pre-Permian Matador uplift (Lloyd, 1949). In Tucumcari basin, Precambrian-age igneous and metasedimentary basement rocks include granite, quartz diorite, monzonite, gabbro, and rhyolite (Broadhead and King, 1988). Precambrian basement rocks make up the ancient Pedernal uplift that lies buried under younger strata in the western part of the study area (maps B, D). The uplift was exposed during late Paleozoic time, shedding sediments into adjacent basins (Gonzalez and Woodward, 1972).

Pre-Permian rocks

Pre-Permian rocks of Lincoln County

Pre-Permian rocks are exposed in the western escarpment of the Sacramento Mountains south of study area boundary and in the Oscura Mountains (map B). In the Sacramento Mountains south of the study area, Precambrian quartzites and metasedimentary rocks are unconformably overlain by the Late Cambrian to Early Ordovician Bliss Sandstone and younger carbonate, sandstone, and shale formations ranging from Early Ordovician to Late Pennsylvanian in age (map C). In the northern Sacramento Mountains of Lincoln County, however, only possibly the Bliss(?) Sandstone, and possibly the Late Devonian Percha(?) Shale and Pennsylvanian-age rocks are exposed. Pre-Permian formations were truncated during Pennsylvanian and Permian uplift events, and most pre-Permian rocks are absent beneath the study area.

In western Lincoln County, Pennsylvanian rocks are as thick as 500 m (1,500 ft) (Grant and Foster, 1989). In the southern part of the study area, Pennsylvanian units unconformably overlie eroded Precambrian basement rocks, the source of detritus for Lower Pennsylvanian clastic sequences (map B). In Lincoln County, the pre-Permian sequences were erosionally truncated during and subsequent to the Pedernal uplift (Griswold, 1959). In southeastern New Mexico (see below), subsurface formations of pre-Permian age have not been correlated to the rocks which crop out in the Sacramento escarpment, although they may be partly equivalent (Grant and Foster, 1989). In the subsurface in the Tucumcari basin (see below), eroded remnants of the Mississippian Arroyo Peñasco Formation unconformably overlie Precambrian basement rocks and are overlain unconformably by Pennsylvanian rocks (Broadhead and King, 1988)(map C).

Pre-Permian rocks of the Northwestern Shelf

Sequences of pre-Permian Paleozoic rocks occur in the subsurface on the Northwestern Shelf; they are thickest in the southern and southeastern part of the study area nearest the Delaware Basin, but are successively bevelled from the rest of the study area nearer to the Pedernal Uplift and Central Basin Platform (maps B, C) (Grant and Foster, 1989).

Cambrian and Lower Ordovician rocks occur beneath the study area only in southeast Chaves County, where they are as much as 76 m (250 ft) thick. Middle to Upper Ordovician rocks occur beneath eastern Chaves and southwestern Roosevelt Counties where the Upper Ordovician Montoya Formation is as thick as 92 m (300 ft) (Grant and Foster, 1989). Silurian beds are 153 m (500 ft) thick beneath the southeastern tip of Chaves County (Grant and Foster, 1989). Devonian rocks are less than 30 m (100 ft) thick in the subsurface beneath southeastern Chaves County and southwestern Lincoln County (Grant and Foster, 1989). In some zones, Silurian and Devonian rocks (which may also change facies) are truncated up-dip and sealed by overlying Permian rocks. Mississippian rocks thin to the northwest and do not exist east of Roswell and north of Hagerman, beneath the western and southwestern parts of Roosevelt County, and southeastern De Baca County. Beneath southeastern Chaves County, Mississippian rocks are as thick as 305 m (1,000 ft).

Pennsylvanian strata are absent from beneath eastern Lincoln County, southeastern Torrance County, southwestern Guadalupe County, southwestern De Baca County, and most of western Chaves County (Grant and Foster, 1989). Exposed Pennsylvanian rocks in the southern Sacramento Mountains (south of the study area) are thicker than the total underlying Paleozoic sequence; they record continuous deposition throughout most of the Pennsylvanian (map B). Oil wells penetrate as much as 838 m (2,750 ft) of Pennsylvanian strata in the Northwestern Shelf and as much as 914 m (3,000 ft) of strata in the Delaware Basin in the vicinity of the Permian Reef (Grant and Foster, 1989).

Pre-Permian rocks of Tucumcari basin

In the subsurface of Tucumcari basin, Pennsylvanian rocks as much as 600 m (2,000 ft) thick unconformably overlie as much as 61 m (200 ft) of Mississippian strata (Arroyo Peñasco Group)(Grant and Foster, 1989). Pennsylvanian rocks include the Magdalena Group equivalents of the Strawn, and the Canyon Groups of the Delaware Basin (map C); the upper sequence (equivalent of the Cisco Group of the Delaware Basin) occurs in the adjacent Palo Duro basin in Texas, but is removed from Tucumcari basin (Broadhead and King, 1988).

In the northern part of Tucumcari basin, rocks equivalent to the basal Strawn rocks are truncated by younger units; in the central and southern part of the basin these rocks are conformably overlain by equivalent Canyon rocks. The source for equivalent Strawn sediment is the Precambrian Pedernal highland, which was emergent during Pennsylvanian time. Facies of Strawn-equivalent rocks change from coarse-grained proximal marine limestone and sandstone in the north to marine limestone with only local sandstone in the southern part of the basin (map C). In the northern part of the basin, the sandstones indicate a high-energy-, marginal-, or shallow-marine environment of deposition. The units intercalate with fossiliferous and silicic marine mudstone units. In the southern part of the basin, marine limestone facies rocks are interbedded limestone and mudstone and contain minor, generally nonporous, sandstone. The limestone is bioclastic wackestone and packstone, locally fossiliferous, with poor porosity. Locally these marine limestone facies contain oolites and areas that have undergone solution of limestone during probable subaerial exposure, creating improved porosity.

Canyon Group-equivalent rocks thin to the north onto uplifts, and may have been locally faulted and repeated by tight folding, possibly during deposition, resulting in increased apparent thickness. The facies distribution of these rocks is similar to the distribution of Strawn Group-equivalent rocks, with proximal, coarser, fluvial sandstone facies and marine limestone in the north grading southward into marine limestone facies (map C). Sandstone has poor primary and secondary porosity. Marine limestone is nonporous and impermeable because it is interbedded with mudstone.

The upper 25 m (800 ft) of strata equivalent to the Canyon Group thin eastward and southward, probably due to erosional truncation and syndepositional faulting near the San Jon high and the Northwestern Shelf. Sediments equivalent to Canyon Group sediments grade from coarse sandstone, limestone, and dolomite in the north to limestone in the south. The northern sandstones are porous and dolomites have minor porosity formed by dissolution and microfracturing. Limestones are interbedded with nonporous marine mudstones and carbonates.

Lower and Middle Permian rocks

Permian rocks are important reservoirs and potential hosts for hydrocarbons, potash, and sulfur in the study area. The Permian sequences include the Early Permian Bursum(?) Formation (in Lincoln County), Hueco Formation, Abo Formation, Yeso Formation, and the San Andres Formation.

Bursum(?) Formation

Exposures of the Bursum(?) Formation are limited to the southwestern part of Lincoln County. Rocks there are similar to surface exposures of the Bursum Formation from the northern Sacramento Mountains described by Pray (1961) as drab calcareous shales, thin argillaceous limestone, quartz sandstone, limestone conglomerate, minor red beds, and thin fusulinid-bearing limestone layers. In the subsurface west of Lon, about 70 m (230 ft) of Bursum(?) is composed of marine limestone interbedded with dark-red mudstone and arkosic conglomerate (Griswold, 1959). Some workers consider the Bursum(?)Formation to be a northern marine facies of the Hueco Formation (which occurs in the Tucumcari basin) (Broadhead, 1984b). The Bursum(?) is overlain by the Abo Formation; the contact is typically conformable (Kottlowski, 1963; Kottlowski and Stewart, 1970; Broadhead, 1984a).

Hueco Formation

The Hueco Formation, which occurs in the subsurface in the central and eastern part of the study area, is probably time-equivalent to the lower part of the Abo Formation. The lower Abo overlies the flanks of the Pedernal uplift, but the Hueco Formation conformably underlies the middle mudstone-rich unit of the middle part of the Abo Formation east of the flanks of the uplift (Broadhead, 1984a,b). The Hueco Formation is flat-lying, and is generally composed of interbedded limestone and mudstone with minor sandstone and conglomerate near the base (Broadhead, 1984a,b). In the subsurface, the Hueco Formation has been subdivided into upper and lower units (Broadhead and King, 1988).

The lower part of the Hueco Formation is 0-563 m (0-1,847 ft) thick, attaining maximum thickness in the northern part of the Tucumcari basin (Broadhead, 1989). To the north and west on the Pedernal uplift, it unconformably overlies Atokan Series and Precambrian rocks and Pennsylvanian Canyon Group; in the central and southern part of the basin, it unconformably overlies the Canyon rocks. Lower Hueco sediments are non-marine and contain coarser clastic units in the north and marginal-marine (with fewer coarse clastic units) in the south. A mixed marine facies occurs on the San Jon High and in the Palo Duro Basin in New Mexico. The lower part of the Hueco Formation is unconformably overlain by both upper Hueco and Abo deposits in the westernmost occurrences; elsewhere it is typically conformable with the overlying upper Hueco. Broadhead and King (1988) consider strata of the lower part of the Hueco Formation to be potential source rocks for oil and gas in Triassic rocks.

The upper part of the Hueco Formation is 95-160 m (310-520 ft) thick and includes a coarse sand in the northern part of the basin, muddy sediments in the northwestern part of the basin, limestone containing minor coarse-grained sandstone in the central and western part of the basin and on the San Jon high, and limestone in the southern part of the basin. Coarse sandstone and limestone units are porous, but locally the interstices are filled with red mud, lowering reservoir potential. The limestone units are composed of interbedded limestone, mudstone, and minor fine-grained sandstone, and are "tight" and nonporous. However, the sandstone in this limestone unit has poor oil-reservoir and limited "tight"-gas potential. Limestone of the Hueco Formation on the Northwestern Shelf and Delaware Basin contains abundant chert, minor red and gray shale, and some dolomite, and is a reservoir for oil and gas in stratigraphic and structural traps (Grant and Foster, 1989).

Abo Formation

In outcrop, the Abo Formation is described from the Oscura and Sacramento Mountains west and south of the study area (Lloyd, 1949; Pray, 1961) and on the Pecos Slope in Lincoln, Chaves, and De Baca Counties (Griswold, 1959; Kelley, 1972a,b). In much of the study area, the Abo Formation occurs in the subsurface (Broadhead, 1984b). In Lincoln County, the Abo

Formation increases in limestone content eastward (Kelley, 1972a); in the subsurface east of the Pedernal uplift, Abo clastics are correlated with interbedded limestone and clastic units of the Hueco Formation (Broadhead, 1984b).

The Abo Formation is composed mainly of dark, reddish-brown mudstone and very-fine- to very-coarse-grained arkosic sandstone and conglomerate that contains crossbeds, ripple-marks, fossils, and contains desiccation cracks and halite crystal casts. Arkosic sandstones, more common in the lower part of the formation, contain pink orthoclase and microcline clasts (Pray, 1961). Sandstones are well-sorted, and porosity is variable and dependent on the interstices (some sandstones have clay matrices or calcite or dolomite cements and others are porous). Abo Formation strata are generally darker red than those of the overlying Yeso Formation, but are difficult to discern from underlying Bursum(?) strata.

The Abo Formation is variable in thickness. It is as much as 427 m (1,400 ft) thick in the northwest (Pray, 1961). Outside of the western boundary of the study area in Torrance County, well information indicates about 305 m (1,000 ft) of Abo in a north-trending band; in Lincoln and De Baca counties, the Abo is 75-150 m (250-500 ft) thick (Kelley, 1972a,b). The Abo is as thick as 723 m (2,372 ft) in the northern part of Tucumcari basin (Broadhead and King, 1988).

The contact with the overlying Yeso Formation is gently folded and abruptly gradational where it is exposed in the western part of the study area (Pray, 1961), but sharp and disconformable in the subsurface in the eastern part of the study area (Broadhead, 1984a; Broadhead and King, 1988). It is locally unconformable with the underlying Bursum Formation (Kottlowski, 1963; Bachman, 1968; Kottlowski and Stewart, 1970). In the Gallinas Mountains, the Abo Formation overlies Precambrian rocks (Lloyd, 1949). Abo deposits are probably nonmarine in the northern part of the study area, but further south, the Abo is probably partly marine where it intertongues with the marine Hueco Formation (Broadhead, 1984a,b).

Yeso Formation

The evaporite-bearing Yeso crops out along the escarpment and crest of the Sacramento Mountains, west of the Pedernal Hills, outside the study area north of the Gallinas Mountains, in the Oscura Mountains, in the Jicarilla Mountains, and along the dip slopes of the Pecos Slope, predominantly between 105°W. to 107°W. longitude (Budding, 1964; Kelley, 1972c). It underlies most of the eastern part of the study area. There, the basal sandstone of the Yeso occurs on and west of Precambrian rocks of the Pedernal uplift, which affected the spatial distribution and thickness of the Yeso Formation. The formation grades eastward into bedded limestone, dolomite, anhydrite, sandstone, and mudstone (Broadhead, 1984a). According to Wasiolek (1991), the Yeso Formation is the principal aquifer of the western Pecos Slope.

The Yeso Formation is commonly contorted or collapsed; it consists of shale, siltstone, sandstone, limestone, dolomite, gypsum, interbedded anhydrite, and minor halite (Pray, 1961; Broadhead, 1984a). The Yeso is generally more gypsum- and clastic-rich in the north and more carbonate-rich in the south (Lloyd, 1949). The Yeso Formation is extremely variable in thickness, due, in part, to dissolution of evaporites and to discordant folding, and to thinning over the Precambrian basement uplift and thickening on the flanks (Kottlowski and others, 1956; Pray, 1961; Kelley, 1971).

In the vicinity of Ruidoso in Ruidoso Creek, nearly 300 m (1,000 ft) of Yeso crop out, but the base of the formation is concealed (Kelley, 1971). In the subsurface near Ruidoso, the lower 150 m (500 ft) of the formation contains numerous beds of anhydrite and gypsum, but the middle 150 m (500 ft) is composed of fine clastic sediment, and the upper part is sandstone-rich (Wasiolek, 1991). In the eastern part of the Mescalero Apache Indian Reservation (upper Rio Hondo drainage), the Yeso ranges from a few m (a few ft) to 520 m (1,700 ft) thick. In the Gallinas Mountains, as much as 300 m (1,000 ft) of Yeso occurs. As much as 560 m (1,830 ft) of Yeso was encountered in a drillhole south of Riverside and west of Roswell. It is 600 m (2,000 ft) thick in south-central Roosevelt County, southeast Chaves County, and west of Hagerman (Grant and Foster, 1989). In Tucumcari basin, the Yeso is 122-600 m (400-2,000 ft) thick (thickest in Curry County) (Foster and others, 1972) (Broadhead, 1989). The Yeso Formation apparently grades upward into the Rio Bonito Member of the San Andres Formation and into the Glorieta Sandstone (Pray, 1961; Kelley, 1971; Milner, 1978). Sharp contacts are locally present. Springs are common markers of the San Andres-Yeso contact (Pray, 1961).

San Andres Formation

Resistant beds (predominantly dolomite) of the San Andres Formation comprise the crest, much of the eastern slope, and the present erosion surface in much of the Sacramento and Jicarilla Mountains and the Pecos Slope (Pray, 1961). The San Andres is up to 365 m (1,200 ft) thick in the subsurface in Tucumcari basin and east of the Pecos River north of the Delaware Basin (Foster and others, 1972; Bachman, 1987; Broadhead, 1989). According to Bachman (1987), as much as 183 m (600 ft) of evaporites have been dissolved in the subsurface from the upper part of the San Andres Formation along the Pecos River near Roswell; dissolved beds are recognized as solution breccia (Welder, 1983). Marine fossils are present as well as oolite, indicating near-subaerial shelf affinities and a back-reef environment.

In the Tucumcari basin, the San Andres Formation consists primarily of anhydrite, dolomite, limestone, and salt (Broadhead and King, 1988). The San Andres Formation is the principal petroleum producer and is a primary objective for oil and gas on the Northwestern Shelf of the Permian Basin; it is also a source rock for later Triassic accumulations (Grant and Foster, 1989). The San Andres Formation is subdivided from base to top into the Rio Bonito and Glorieta Sandstone Members (undifferentiated), the Bonney Canyon Member, and the Fourmile Draw Member (Kelley, 1971).

Rio Bonito Member and the Glorieta Sandstone

The Rio Bonito Member of the San Andres Formation and the Glorieta Sandstone are intertonguing units. The Glorieta Sandstone (lower part) is thickest in the north-central part of the state (Milner, 1978; Pitt and Scott, 1981). In the study area, it is as much as 75 m (245 ft) thick in northern Lincoln County (Milner, 1978), 37 m (120 ft) thick northeast of Luna (Budding, 1964), 69 m (225 ft) thick near Corona (Kelley, 1971), and as much as 91 m (300 ft) thick in northwestern Tucumcari basin (Broadhead and King, 1988). In the Gallinas Mountains, where it is the youngest exposed rock unit, the Glorieta Sandstone is as much as 76 m (250 ft) thick (Kelley, 1949; Perhac, 1964). The Glorieta Sandstone is poorly exposed in the southeastern part of the Jicarilla Mountains and in the eastern and northern parts of the Capitan Mountains (Griswold, 1959). There, sandstone beds are as much as 20 m (60 ft) thick, typically about 1 m (2-3 ft) thick, parallel-bedded to crossbedded, and lenticular (Pray, 1961; Kelley, 1972c). The Glorieta Sandstone becomes thinner and finer grained to the south

(Kelley, 1971) and near Rio Hondo south of the Capitan Mountains, the sandstone occurs as much as 150 ft above the base of the San Andres Formation; typically 40-70 ft of dolomite occurs below the first sandstone (Kelley, 1971).

The distinctive Glorieta Sandstone is composed of rounded to subrounded, frosted, fine- to medium-grained, well-sorted orthoquartzite (Pray, 1961; Kelley, 1972c). Locally the sandstone is hematitic and contains iron concretions, ironstone, or brown chert (Kelley, 1972c). The Glorieta is permeable, locally oil-stained, and is potentially a good reservoir (Broadhead and King, 1988), but it does not produce oil or gas in New Mexico (Milner, 1978). It is an aquifer in Chaves County (Borton, 1972).

The Rio Bonito Member of the San Andres Formation is composed predominantly of carbonate rock in the study area (Kelley, 1971; 1972c; Milner, 1978). The Rio Bonito typically consists of beds that are 0.6-1.8 m (2-6 ft) thick, locally as much as 9 m (30 ft) thick. Rio Bonito rocks are typically lenticular, and locally crossbedded, oolitic, and fossiliferous, with rare occurrences of bioherms and algal stromatolites (Milner, 1978). They are mostly dolomite and limestone with rare chert lenses, and are typically banded in shades of dark and light gray with brown tinting (Kelley, 1971). Wackestone and mudstone are common (Milner, 1978). The Rio Bonito Member grades upward into the Bonney Canyon Member of the San Andres Formation (Kelley, 1971).

Bonney Canyon Member

The Bonney Canyon Member, the middle part of the San Andres Formation, is best exposed on the Pecos Slope west of Roswell and Artesia (Kelley, 1971), but it crops out from northeast of the Capitan Mountains to as far south as the Capitan Reef (Guadalupe Mountains) (Kelley, 1971). It is thin- to medium-bedded, locally laminated, porous, fine- to very-fine grained, indurated, dark grayish-brown, medium- and light-gray dolomite and limestone, containing marine fossils and numerous pale-yellow silty and sandy carbonate beds. In places, chert-bearing and oolitic beds are present. The beds typically are disturbed in the upper 15 m (50 ft), probably due to the localized removal of gypsum and anhydrite beds (Kelley, 1971).

The Bonney Canyon Member ranges from 18-91 m (60-300 ft) thick, thinning northward (Kelley, 1971). The Lleveland-Slaughter zone of porosity, widely recognized in the subsurface in the vicinity of Roswell and the zone of oil-producing dolomite in west Texas, is equivalent to the Bonney Canyon Member, although in places it may also include the lower part of the overlying Fourmile Draw Member (Kelley, 1971). The Bonney Canyon Member grades upward into the Fourmile Draw Member (Kelley, 1971).

Fourmile Draw Member

The Fourmile Draw Member is the upper evaporitic part of the San Andres Formation and is characterized by karst and surficial caliche. Measured surface thickness of the Fourmile Draw Member ranges from 104 m to 118 m (342 ft to 387 ft) (Kelley, 1971). In the subsurface in De Baca County about 9.7 km (6 mi) southwest of Fort Sumner, drillholes have encountered as much as 190 m (625 ft) of Fourmile Draw Member (Mourant and Shomaker, 1970; Kelley, 1972c). It is composed of thin beds, including predominantly dolomite, gypsum, and reddish mudstone. Thin-bedded sandstone, locally cherty, occurs at the top of the unit, as well as reddish, pinkish, or yellowish mudstone and red siltstone. White sandstone as much as 9 m (30 ft) thick is present west of Roswell.

Gypsum is abundant in the Fourmile Draw member within the study area, and intervals 15-30 m (50-100 ft) thick are not uncommon (Kelley, 1971). To the north and west, the member becomes more evaporitic, and in the vicinity of Ancho (northwest of the Jicarilla Mountains), an exceptional thickness of about 244 m (800 ft) of gypsum with minor dolomite and sandstone has been reported from the San Andres Formation (Kelley, 1971). In much of the area, sinkholes produced by dissolution of gypsum and other evaporites are common features.

Artesia Group

The Artesia Group crops out on the Delaware shelf (fore-reef or basin) of the Permian Basin, the massive Capitan Reef area, and the backreef (including the Roswell Resource study area). Each of these areas has different stratigraphic nomenclature for rocks of this stratigraphic position, reflecting the different lithofacies of time-synchronous parts of the deposit [maps B, C]. The Artesia Group changes character with backreef distance (northward) from the Permian reef complex of the Capitan Limestone, from structureless and massive close to the Capitan Reef to bedded in the backreef areas that crop out in the Roswell Resource Area (Kelley, 1971). Equivalents of the Artesia Group in the Roswell Resource Area include backreef units from the top of the San Andres Formation. The Artesia is divided into, in ascending order, the Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations.

Thickness of the Artesia Group is extremely variable due to dissolution of the evaporite beds. In Tucumcari basin, the Artesia Group in the subsurface is 41-280 m (134-918 ft) thick (Broadhead, 1984a) and is thickest in Quay, Curry, and northeastern De Baca Counties (Broadhead, 1989). The Artesia Group rocks thin to the north and west onto the Pedernal and Sierra Grande uplifts and the Bravo dome, partly due to erosional truncation (Broadhead and King, 1988; Broadhead, 1989). Karst features typify the Artesia Group rocks where they are exposed in the southern part of the study area. Evaporites of the Artesia Group are primarily gypsum on the surface; anhydrite and salt are the predominant evaporite deposits in the subsurface (Bachman, 1987).

Grayburg Formation

The Grayburg Formation is typically tan to brown, medium- to fine-grained sandstone and thin-bedded mudstone as much as 152 m (500 ft) thick, with minor cherty gray dolomite near the top. Bedding thickness, carbonate content, and sandstone content in the lower part of the formation increases southward with proximity to the Capitan Reef (Kelley, 1971). Gypsum is common and beds as thick as several tens of meters occur near Hope, about 12 km (20 mi) west of Artesia. Near Arroyo del Macho in the central part of the study area about 19 km (30 mi) north of Roswell, the Grayburg and Queen Formations are undivided and red mudstone and muddy gypsum predominate; thin dolomite beds are present in the lower part of the sequence (Kelley, 1971; 1972a,b). The Grayburg Formation is the most important reservoir rock in the Artesia Group.

In some of the western exposures (Capitan Mountains to Ruidoso), the Grayburg Formation is unconformable with the underlying San Andres Formation (Kelley, 1971), but north of the Capitan Mountains the unit is nearly conformable with underlying rocks. In most places, the lower contact of the Grayburg is irregular, in part due to solution of the evaporitic sequences and karst development within the Fourmile Draw Member (uppermost part of the underlying San Andres Formation); locally the Fourmile Draw Member is missing or is represented by collapse breccia (Kelley, 1971).

Queen Formation

The Queen Formation is a widely recognized unit in the subsurface. Surface exposures are more difficult to recognize due to dissolution of some units, and the formation is mapped with the Grayburg Formation north of Roswell (Kelley, 1971). The Queen Formation, which contains beds of anhydrite, dolomite, and salt, is lithologically similar to the Grayburg near Capitan Reef, but contains increasing amounts of clastic material. Progressively northward away from the reef in the back-reef area, the Queen Formation contains thin-bedded red sandstone and mudstone with dolomite and, in the vicinity of Roswell, gypsum and minor thin, magenta and gray dolomite predominates in the upper part of the Queen Formation (Kelley, 1971). Total thickness of the unit is unknown (Kelley, 1971), but it is as much as 91 m (300 ft) thick in southern De Baca and Roosevelt Counties.

The Queen Formation is the aquitard between the shallow and the artesian aquifers in the Roswell artesian basin (Havenor, 1968). The Grayburg and Queen strata are generally too fine-grained to be good reservoirs of oil and gas in the study area, except east of Roswell and east of Hagerman (Broadhead, 1989; Grant and Foster, 1989).

Seven Rivers Formation

The Seven Rivers Formation is recognized both on the surface (in the southern part of the study area) and in the subsurface as a distinct formation in the carbonate part of the shelf (back-reef) margin. Upper and lower contacts of the Seven Rivers Formation are well-defined due to the prevalence of intrastratal gypsum (Kelley, 1971; 1972c). Exposures of the Seven Rivers Formation are prominent east of Roswell in the Bottomless Lakes area. The unit is mostly anhydrite and thin-bedded (a few cm thick) dolomite in the north, but is more massively bedded [up to 3 m (10 ft) thick] and limestone- and dolomite-rich in the south near the reef (Kelley, 1971; Grant and Foster, 1989). Total thickness of the unit is unknown due to dissolution, but is as much as 140 m (460 ft) thick about 1.2 km (2 mi) north of the Capitan Reef in the vicinity of Carlsbad [about 19 km (30 mi) south of the study area] (Kelley, 1971) and about 110 m (360 ft) thick in De Baca and Roosevelt Counties (Grant and Foster, 1989).

Yates Formation

The Yates Formation crops out in the south-central part of the Roswell Resource Area. From Lake McMillan [about 7.5 km (12 mi) south of Artesia] to Roswell, it is predominantly gypsum with only minor 0.3-0.6-m- (1-2-ft-) thick beds of dolomite (Kelley, 1971). In the southern part of the study area, extending to about 6 km (10 mi) north of Roswell, greenish-gray to olive-drab siltstone and fine grained thin sandstone characterize the lower part of the Yates Formation and gypsum and red mudstone characterize in the upper part. Limonite ironstone concretions are abundant. In the north near Fort Sumner, the Yates and Tansill Formations are undifferentiated (Kelley, 1972a).

Near Lake McMillan, the unit is as much as 123 m (405 ft) thick, as measured in outcrop near the shelf margin adjacent to the Capitan Reef. Southwest of Portales near Elida, the formation in the subsurface is about 40 m (130 ft) thick (Kelley, 1971). Thickness variations in the Yates Formation, as measured in surface and subsurface exposures, indicate possible syndepositional tectonic activity along the Artesia-Vacuum trend (map D) (Kelley, 1971), but dissolution is a large factor in thickness variability.

"Pecos diamonds", in the upper part of the Seven Rivers Formation and the lower part of the Yates Formation (Kelley, 1971), may be used as stratigraphic indicators. They occur in 30-60 m-(100-200 ft-)thick beds in a belt that extends from about 3 km (5 mi) south of Artesia to 40 km (65 mi) north of Roswell (southwest of Yeso), and locally in Guadalupe County (Albright and Kruckow, 1958).

Tansill Formation

A thin [less than 30-m-(100-ft-) thick] north-south-trending belt of evaporitic rocks of the Tansill Formation crops out in the southern part of the resource area east of Hagerman (Kelley, 1971, fig. 7). North of Hagerman, the Tansill is covered by pediment gravel (Pleistocene Gatuna Formation) and truncated by Triassic rocks. South of the study area, the Tansill Formation is the uppermost shelf unit adjacent to the Capitan Reef and consists primarily of dolomite; there it is unconformably overlain by the Salado Formation (Deford and Riggs, 1941; Garber and others, 1989). In the subsurface, some salt is found with anhydrite south of the resource area.

Upper Permian rocks

Upper Permian rocks are composed of the Castile, Salado, Rustler, and Dewey Lake Formations in the Permian Basin. The Castile Formation does not occur north of the Capitan Reef on the Northwestern Shelf and, thus, does not occur in the study area [map B]. The Salado and Rustler Formations occur in the backreef area in southeastern New Mexico and pinch out to the north and west near the study area boundary. These formations are important sources of potassium salts as well as halite, polyhalite, and anhydrite; the Castile and Salado host world-class sulfur deposits south of the Capitan Reef in Culberson County, Texas.

Salado Formation

The Salado Formation of post-Capitan age is found shoreward as well as basinward of the Capitan Reef, and disconformably overlies the Tansill Formation from Carlsbad to Hagerman (Kelley, 1971). North of Hagerman in the shoreward area, the Salado Formation is covered by Cenozoic deposits. The Salado Formation is the oldest formation to have transgressed northward across the reef into the backreef area of the Northwestern Shelf, and represents deposition by a shallowing Permian sea.

In southeastern New Mexico, broad areas have subsided by solution collapse of the Salado Formation. In the study area, the formation ranges from 0-90 m (0-300 ft), pinching out northward onto higher parts of the shelf. In the subsurface in Eddy County south of the study area, the Salado Formation ranges from 365 m to 700 m (1,200 ft to 2,300 ft) thick, with extreme thickness variation due to salt dissolution (Kelley, 1971; Cheeseman, 1978; Bachman, 1984). The Salado Formation is composed mostly of beds of halite and commercial amounts of potash, with thin beds of anhydrite and sulfur (Jones, 1954, 1978; Bachman, 1987; Smith, 1980).

Rustler Formation

The Rustler Formation in the Roswell Resource Area, like the underlying Salado Formation, occurs shoreward as well as basinward of the Capitan Reef, and was deposited by a shallow Permian sea. Vine (1963) and Bachman (1987) described five members in the Rustler Formation in the shoreward area east of the Pecos River; a basal 37-m-(120-ft-) thick (unnamed) unit of siltstone, gypsum, anhydrite, and sandstone; a 9-m-(30-ft-) thick vuggy dolomite (Culebra Dolomite Member); a 55-m-(180-ft-) thick gypsum unit, including halite and anhydrite (Tamarisk Member); a 9-m-(30-ft-) thick dolomite with anhydrite (Magenta Dolomite Member); and an upper 8-m-(25-ft-) thick gypsum, anhydrite, siltstone, and halite layer (Forty-niner Member). Carbonate content increases, and evaporite content decreases, southward (Grant and Foster, 1989). Only the basal part of the Rustler Formation is exposed east of Artesia along the southern border of the Roswell Resource Area; at this locality the Rustler rests unconformably on the Tansill Formation (Kelley, 1971). The Rustler commonly shows evidence of dissolution and collapse into the underlying Salado Formation (Kelley, 1971) and according to Bachman (1984), complete sections are present only in some areas of the subsurface. The Rustler Formation is conformably overlain by the Dewey Lake Formation (Bachman, 1987).

South of the study area, the Rustler Formation is as much as 168 m (550 ft) thick (in southwestern Lea County) (Bachman, 1984), and as much as 152 m (500 ft) thick near the Pecos River (in Eddy County) (Grant and Foster, 1989). It thins to the north, and is only about 30 m (100 ft) thick on the Northwestern Shelf (Grant and Foster, 1989). It may only be tens of meters thick over limited parts of the study area.

Dewey Lake Formation

Red beds of the Dewey Lake Formation were deposited at the end of Permian time and represent retreat of the Permian sea and deposition in a shallow saline lake. The Dewey Lake Formation is composed of thin reddish siltstone and fine-grained, rippled, and small-scale crossbedded sandstone. The unit is cemented by anhydrite, selenite, clay, and carbonate, and is typically mottled to greenish-gray. The Dewey Lake Formation thins westward and is unconformably overlain by Triassic sediments.

In the subsurface in Eddy and Lea Counties south of the study area, the Dewey Lake is as much as 170 m (560 ft) thick (Bachman, 1984). However, only thin, discontinuous red beds of the Dewey Lake Formation occur along the southern border of the study area.

Bernal(?) Formation

In the vicinity of the Jicarilla Mountains, Budding (1964) identified a series of sandstone, limestone, and gypsum beds that he tentatively correlated with the Permian Bernal Formation of Bachman (1953). In the Jicarilla area, the Bernal(?) Formation overlies the San Andres Formation and underlies the Triassic Dockum Group; the beds are highly weathered and eroded. The Bernal(?) Formation underlies the Santa Rosa Sandstone in the northern part of the study area.

The lower 56 m (185 ft) is well exposed less than 0.5 km east of Ancho, but the unit varies from 82 to 98 m (270 to 320 ft) thick (Budding, 1964). In the vicinity of Santa Rosa, it is as much as 72 m (237 ft) thick and is composed of dolomite, red calcareous shale, greenish-gray shale, and siltstone. Locally, gypsum seams and fracture fillings are present.

Triassic rocks

Triassic continental rocks crop out over parts of Lincoln County, the eastern half of De Baca and Chaves Counties, and most of Guadalupe, Quay, Curry, and Roosevelt Counties (Grant and Foster, 1989, fig. 13). In the southeastern part of the study area, Triassic rocks are as much as 610 m (2,000 ft) thick; in the Tucumcari basin, they are 457 m (1,500 ft) thick. Typically, Triassic rocks unconformably overlie Upper Permian strata and were deposited as a result of Late Permian movement of the Pedernal uplift.

Dockum Group and the Redonda Formation

Triassic units in the study area are composed of two formations that make up the Dockum Group --the Santa Rosa Sandstone and the Chinle Formation (Grant and Foster, 1989)]. They are overlain by the Redonda Formation. In the Jicarilla Mountains, the Dockum and the Redonda are about 170 m (560 ft) thick (Budding, 1964). The Santa Rosa is unconformable on the Bernal(?) Formation; near Capitan, the Dockum and the Redonda are 146 m (480 ft) thick (Griswold, 1959). Dockum and Redonda, in the vicinity of the Pecos River near Roswell, are brecciated and occur in isolated collapses or sinks (indicating solution of underlying Permian rocks) (Bachman, 1987).

Santa Rosa Sandstone

The continental sandstone beds of the Santa Rosa Sandstone are typically thick, grayish and reddish brown, generally parallel bedded, with some lenticular and channel-crossbedded intervals; the unit is conglomeratic, especially near the base. Thin beds of red, brown, and variegated mudstone are intercalated with the sandstone. Vertebrate remains occur in the upper shaly part of the formation (Lucas and others, 1985a).

The Santa Rosa Sandstone occurs at depths of less than 600 m (2,000 ft) over most of northeast New Mexico (Broadhead, 1984a). The Santa Rosa Sandstone is best exposed along the Pecos River and western tributaries, especially in the north-central part of the study area near Santa Rosa. In the vicinity of Capitan, the Santa Rosa is 91 m (300 ft) thick (Griswold, 1959). In the Tucumcari basin, the Santa Rosa Sandstone is 20-107 m (67-350 ft) thick and is subdivided into a lower sandstone, middle mudstone, and upper sandstone. The thickest sequences occur in paleovalleys which were eroded into underlying Artesia Group units during Triassic time (Broadhead, 1989).

Chinle Formation

Continental rocks of the Chinle Formation crop out mostly east of the Pecos River in the northern part of the study area and to the east where they are generally covered by younger strata (Kelley, 1972 a,b). Thin outliers of the Chinle Formation occur west of the Pecos River. The Chinle Formation is typically reddish-brown mudstone with interbeds of clay-rich sandstone. The upper part of the Chinle Formation is variegated in shades of reddish purple and gray-green. The Cuervo Sandstone Member is a clastic middle member of the Chinle Formation in the Tucumcari basin.

The Chinle Formation is 55 m (180 ft) thick in the vicinity of Capitan (Griswold, 1959), as thick as 375 m (1,230 ft) in Quay County (Berkstresser and Mourant, 1966), and thought to have had a depositional thickness of 457 m (1,500 ft) in Tucumcari basin (Trauger and Bushman, 1964). The Cuervo Sandstone Member is 4-62 m (13-203 ft) thick in the Tucumcari basin (Broadhead, 1989).

The Santa Rosa Sandstone and Chinle Formation are intertonguing units with variable thicknesses, the Chinle Formation increasing in thickness northward in the study area (Kelley, 1971). Both units are unconformable with older rock units in the Roswell Resource Area, including the Permian sequences (Kelley, 1971; 1972a,b). The Santa Rosa Sandstone and Chinle Formation are unconformably overlain by the Redonda Formation and the Cretaceous Dakota(?) Sandstone (Kelley, 1971; 1972a,b).

Redonda Formation

The Redonda Formation occurs in the northern part of the study area near Tucumcari where it unconformably overlies the Chinle Formation and is overlain by the Exeter Sandstone of Jurassic age (Dobrovolny and others, 1946; Kelley, 1972a,b). The Redonda Formation is similar to, and has been tentatively correlated with, the dominantly eolian Wingate Formation of the Colorado Plateau (Griggs and Read, 1959; Kelley, 1972a,b). The Redonda Formation is an evenly bedded, reddish-orange, vertebrate-bearing sandstone that is as much as 137 m (450 ft) thick (Dobrovolny and others, 1946; Lucas and others, 1985b).

Jurassic rocks

Jurassic rocks were never deposited in southeastern New Mexico (Bachman, 1984, 1987). In the western and northwestern part of the study area (especially in Lincoln County), the Jurassic and Early Cretaceous were times of erosion (Budding, 1964). Thus, Jurassic rocks are present only in the northern part of the study area in the vicinity of Tucumcari, where they include the Exeter Sandstone and the Morrison Formation.

Deposition was apparently continuous throughout Jurassic time and there are no regional disconformities within Jurassic sequences, although Jurassic rocks are unconformable on underlying Triassic sedimentary rocks and are unconformably overlain by Cretaceous strata. Jurassic rocks in the region, including the Exeter Sandstone and the Morrison Formation, are deposits of continental eolian and stream affinity with origins in the Ancestral Rocky Mountains (Mankin, 1972). The lower formation, the Exeter Sandstone, is predominantly an eolian deposit which grades upward into a predominantly playa-lake deposit (possibly reflecting increased rainfall) (Mankin, 1972). The upper formation, the Morrison Formation, a fluvial or deltaic sequence, was deposited in a more humid (possibly subtropical) environment. Volcanic activity increased during deposition of the Morrison Formation, as evidenced by volcanic ash found within the unit in the study area.

Exeter Sandstone

The Exeter Sandstone (Entrada Sandstone of Lucas and others, 1985b) crops out along the Canadian escarpment, along the north-facing escarpment of the Llano Estacado south of the Canadian River, and in isolated buttes and mesas in northern Guadalupe and Quay Counties (Mankin, 1972). The Exeter Sandstone that rims Tucumcari basin is white to pale-brown, fine-grained, massive to crossbedded, and very-well to well sorted quartz sandstone that is slightly cemented. In the Tucumcari region, the beds are large-scale-crossbedded in the lower part of the formation and more massively bedded with smaller scaled crossbeds in the upper part.

The Exeter Sandstone is as much as 67 m (220 ft) thick in the Tucumcari basin. Typically, it is 18 m (60 ft) thick in northeastern New Mexico.

Morrison Formation

In the Tucumcari region, the Morrison Formation consists of lower variegated shale, middle mudstone and lenticular sandstone, and upper shale with intercalated silica-cemented sandstone (Mankin, 1972). These units are not continuous, however, and their relations vary within the study area. Typically, the Morrison Formation is a fine-grained, well- to poorly sorted sandstone with rare coarse to pebbly layers interspersed. In the lower part, there is a thin, continuous, and widespread red chert unit. The Morrison Formation also contains 0.3-1.0-m-(1- to 3-ft-)thick beds of gypsum, impure limestone, volcanic ash and bentonite, and nodular chert. It contains sparse fossils and is locally anomalously radioactive.

The Morrison Formation is 30-150 m (100-500 ft) thick, and is slumped in most locations. Thickness variations may be due to contemporaneous subsidence (F.D. Trauger, *in* Mankin, 1972). Rarely, bentonite beds as thick as 0.3 m (1 ft) are present.

Cretaceous rocks

Cretaceous units that crop out in the western part of the study area include the Dakota(?) Sandstone, Mancos Shale, and the Mesaverde Formation (Griswold, 1959). Subsurface relations suggest that the Cretaceous rocks rest unconformably on the Triassic Chinle Formation and are unconformably overlain by the Ogallala Formation.

Cretaceous rocks were probably eroded from the area to the south, where only remnants of Cretaceous strata are preserved in sinks and isolated outcrops near Carlsbad (Bachman, 1984, 1987). South of latitude 33° N., only sporadic occurrences of Cretaceous rocks are present in the subsurface. Cretaceous strata are thickest in the northeastern part of Lea County, thinning northwestward to about longitude 103° 30'W.

Rocks of Cretaceous age [Tucumcari(?) Shale] crop out and occur in the subsurface in Lea County adjacent to the southern border of the study area (Ash and Clebsch, 1961). Tucumcari Shale(?) in the subsurface is 0-60 m (0-200 ft) thick. On the surface, Tucumcari(?) Shale is typically 15-30 m (50-100 ft) thick.

Cretaceous rocks are exposed in the Tucumcari basin (Brand and Mattox, 1972). The rocks are probably marine south and east of Tucumcari, but interfinger north and west into continental sequences. Cretaceous rocks in the Tucumcari basin include the Tucumcari Shale, Mesa Rica Sandstone, and Pajarito Shale (Brand and Mattox, 1972).

Tucumcari Shale

The Tucumcari Shale in the Tucumcari basin is composed of fossiliferous, bedded, fissile, dark shale overlain by gray fossiliferous shale and yellow-brown clay (Brand and Mattox, 1972). Minor limestone occurs in the unit. In the Tucumcari basin, the Tucumcari Shale is as much as 24 m (80 ft) thick (Kelley, 1972 a,b). The uppermost beds contain thin sandstones that are similar to the overlying Mesa Rica Sandstone.

Mesa Rica Sandstone

The Mesa Rica Sandstone crops out in bluffs in the Tucumcari area and in the Canadian River escarpment north of Tucumcari (Brand and Mattox, 1972). The Mesa Rica may be correlative to the Dakota Sandstone, although the relation between the two units and the overlying Pajarito Shale are unclear (Kilmer, 1987). The Mesa Rica Sandstone is composed of crossbedded sandstone with intercalated shale and clay of deltaic origin. The basal part is a conglomerate that contains broken fossil pieces. The uppermost part contains thin shale beds similar to the overlying Pajarito Shale.

Pajarito Shale

The Pajarito Shale occurs only locally in the Tucumcari area; it occurs in the downthrown block of the Bonita Fault, on Mesa Rica in northwestern Quay County, and in the escarpment south of San Jon in eastern Quay County (Brand and Mattox, 1972). The Pajarito Shale is predominantly a delta-plain lacustrine shale with sandstone interbeds. The shale contains bentonitic and limonitic layers and iron concretions, and is locally fossiliferous. A thick sandstone occurs locally at the top of the unit and has been correlated with the Dakota Sandstone outside the study area in northeastern New Mexico and southeastern Colorado (Kilmer,1987).

Dakota(?) Sandstone

The Dakota(?) Sandstone, which is identified in the western part of the study area in the Sierra Blanca basin, is a transitional sequence that is a massive to locally crossbedded, coarse- to medium-grained, brownish to reddish sandstone. The upper part grades to thin- to medium-bedded shale and sandstone that is transitional into the overlying Mancos Shale (Kelley, 1971). The Dakota(?) Sandstone unconformably overlies older units, including the Chinle Formation, Santa Rosa Sandstone, Grayburg Formation of the Artesia Group, and Bonney Canyon Member of the San Andres Formation (Kelley, 1971).

The Dakota(?) Sandstone is typically from 30-45 m (100-150 ft) thick (Griswold, 1959; Kelley, 1971), but in the Jicarilla Mountains it varies from 36 m to 61 m (120 ft to 200 ft) thick.

Mancos Shale

The Mancos Shale, typically marine black shale interbedded with grayish siltstone and minor thin dark gray limestone beds and lenses, occurs in the western part of the study area in the Sierra Blanca basin (Griswold, 1959; Kelley, 1971) and underlies much of the Jicarilla Mountains region (Budding, 1964). The Mancos Shale is easily eroded and fills valley bottoms.

It is variable in thickness, but in the vicinity of Capitan, it is as thick as 119 m (389 ft) (Allen and Jones, 1951). It is estimated to be 125 m (410 ft) thick in the Jicarilla Mountains, where it conformably overlies the Dakota(?) Sandstone (Budding, 1964).

Mesaverde Formation

The Mesaverde Formation is well exposed in the Sierra Blanca Basin near White Oaks, Carrizozo, Capitan, and Ruidoso, where it contains coal (Kelley, 1971). In the Capitan coal field in the southwestern part of the study area, the Mesaverde Formation is composed of a lower 45-m-(150-ft-) thick sandstone, a middle shale and coal member about 61 m (200 ft) thick, and an upper sandstone 30-45 m (100-150 ft) thick (Kelley, 1971). The sandstone is typically fossiliferous, massive to medium bedded (thick-bedded in some areas), white, buff, or brownish in color, and is fine to medium grained (Kelley, 1971). The shale is light gray to black, and may contain some siltstone and coal (Kelley, 1971). The Mesaverde Formation is commonly faulted, intruded by dikes, and is poorly exposed (Kelley, 1971).

In the Jicarilla Mountains, the Mesaverde Formation is as much as 127 m (415 ft) thick (Budding, 1964). Coal beds in the Sierra Blanca Basin range from < 1 m to 1.4 m (<1 ft to 4.5 ft) in thickness.

In the Sacramento and Capitan Mountains, the Mesaverde is probably unconformably overlain by the Cub Mountain Formation, although Weber (1964) suggests a local conformable contact. In the Jicarilla Mountains, it is unconformably overlain locally by as much as 15 m (50 ft) of the Ogallala(?) Formation (Budding, 1964).

Cretaceous and Tertiary rocks

Cub Mountain Formation

The Upper Cretaceous and Tertiary Cub Mountain Formation occurs in the western part of the study area in the vicinity of the Lincoln County porphyry belt. Lower Tertiary rocks are not preserved in the southeastern part of the study area.

According to Weber (1964), the Cub Mountain Formation crops out southward from Cub Mountain (west of the White Mountain Wilderness Area) into the Three Rivers drainage area west of Sierra Blanca Peak. The unit is faulted and intruded by dikes and is as much as 183 m (600 ft) thick (Kelley, 1971). The Cub Mountain Formation is generally a poorly sorted, channel crossbedded, continental deposit. It is composed of purplish mudstone, arkosic, friable sandstone, lenticular conglomerate, and montmorillonitic claystone, mudstone, siltstone, and fine-grained sandstone that typically contain fine veinlets and seams of gypsum (Griswold, 1959; Weber, 1964; Kelley, 1971).

Late Tertiary and Quaternary deposits

Ogallala Formation

Late Tertiary rocks of the Ogallala Formation and Pleistocene rocks of the Gatuna Formation are exposed throughout the study area, extending as outliers as far west as the Lincoln County porphyry belt. The Miocene Ogallala Formation, named by Darton (1898), is extensively exposed in the Great Plains of the United States, extending from South Dakota to Texas, and is a major groundwater aquifer for this region. The High Plains of eastern New Mexico is covered by the most resistant upper part of the Ogallala Formation (Leonard and Frye, 1975).

The Ogallala Formation caps large portions of the Roswell Resource Area east of longitude

104°W. and the Pecos River. The Ogallala thins westward to its sources in the southern Rocky Mountains and the uplands between the Rio Grande and Pecos Rivers, from the eastern Llano Estacado escarpment in Texas to the west-facing escarpment of the Mescalero pediment on the east side of Pecos River valley (fig. 1) (Leonard and Frye, 1975). West of the Pecos River, it commonly forms discontinuous terraces below higher upland surfaces developed on older rocks. It crops out in high, northeast-trending, dendritic, pediment-covered, segmented mesas between Capitan and Ruidoso; these remnants may be fault-controlled valley fill (Kelley, 1971; Frye and others, 1982). Local thickness variability of the Ogallala can be attributed to evaporite dissolution and karst collapse at the surface.

The Ogallala Formation is composed of alluvial and minor eolian deposits, some containing Precambrian clasts, that are derived from the western uplands (Kelley, 1972a; Leonard and Frye, 1975). The composition of the Ogallala is variable throughout the study area depending on the source rock. In the north, channel deposits (gravels) are more common in the lower part of the formation. The more easterly exposures of the Ogallala Formation contain gravel deposits that occur further upsection. The more southerly exposures contain only rare coarse gravel deposits and in many of the southern locations, gravel is absent (Leonard and Frye, 1975). In uneroded areas, calcium carbonate caliche as much as 15 m (50 ft) thick is present at the top of the formation and minor silt- and clay-bearing sandstone is predominant (Leonard and Frye, 1975).

During deposition of the Ogallala, the climate of the region became increasingly arid. Alluvial deposition diminished, and thick, hard caliche (referred to as the "Ogallala climax soil") formed at the top of the Ogallala Formation. This soil covered earlier-formed Pleistocene stream valleys, causing streams to shift laterally on the relatively impermeable alluvial plain, without regard to earlier valley positions (Frye and Leonard, 1959; Leonard and Frye, 1975). North of Roswell, the Ogallala sediment was deposited by streams flowing generally east-southeast (Leonard and Frye, 1975); south of Roswell, however, the course of streamflow is not clear (Bachman, 1987). Thickness of the Ogallala is variable [ranging from nil to 61 m (200 ft)], reflecting the depth of the underlying erosional unconformity (Frye, 1971; Leonard and Frye, 1975).

Eastward tilting and warping of the High Plains continued after deposition of the Ogallala, lasting from latest Tertiary and early Pleistocene time into the middle Pleistocene (Frye and others, 1982). Downwarping apparently took place along the present Pecos Valley, and upwarping occurred on the eastern and western flanks of the valley. Ogallala distribution delineates stream capture caused by downwarping, collapse, or subsidence (Frye and others, 1982).

Quaternary rocks

Gatuna Formation

The Gatuna Formation is a relatively fine-grained valley-filling formation of uncertain age that is similar to, but younger, than the Ogallala, and is exposed mostly in the Pecos River Valley near Artesia, Hagerman, and Roswell, and possibly as far north as Santa Rosa. It is a predominantly orange-red (also gray, yellow, or purplish) friable sandstone, with minor amounts of conglomerate, clayey mudstone, siltstone, limestone, or gypsum, derived from the Dockum Group, Tertiary igneous rocks, and the Ogallala caprock (Kelley, 1971; Bachman, 1987). The Gatuna is fossiliferous, in places, containing fresh-water gastropod remains and contains at least one 620,000-yr-old Tertiary (Yellowstone) ash bed south of the study area in Nash Draw about 12 km (20 mi) east of Carlsbad (Kelley, 1971; Izett and Wilcox, 1982; Bachman, 1984).

The Gatuna Formation is consolidated in places, but is locally intermixed with underlying units due to slumping and collapse and it unconformably overlies older sequences (Kelley, 1971). The Gatuna Formation is as much as 91 m (300 ft) thick, although the thickness is highly variable (Kelley, 1971).

Basalt flows

Vesicular basalt flows located west of Carrizozo (the Little Black Peak and Carrizozo lava flows of the Valley of Fires Recreation Area) are termed malpais ("badlands"). These flows extend for 70 km (44 mi) and are up to 8 km (5 mi) in width; they encompass about 6.7 cu km (1 cu mi) of basalt (Allen and Jones, 1951; Weber, 1964). The flows represent probable recent (approximately 5,000-yr-old) outflow from nearby cinder cones that lie along the east-west Capitan Mountains lineament (Weber, 1964; 1979; Salyards, 1991).

Lava flowed southwestward over strata that include the Dakota(?) Sandstone (Weber, 1979). The lava field is typical of pahoehoe flows, containing ropy surfaces, pressure ridges, and collapse features. A basal flow located about 3 km (2 mi) south of U.S. Highway 380 consists of fine-grained massive subalkaline olivine basalt as much as 97 m (60 ft) thick (Weber, 1964). Much of the basalt in the flow is vesicular and contains phenocrysts of olivine in a fine matrix of andesine-labradorite, augite, olivine, and glass.

Unconsolidated deposits

Other Quaternary deposits are varied and widespread in the region; the deposits include rock glaciers, pediment deposits, terrace deposits, eolian loess and dune deposits, lake and playa sediment, and valley alluvium and gravel (map A). Quaternary sand dune fields occur along the Curry-Roosevelt County line and in Chaves County on the Llano Estacado east of Roswell (Reeves, 1972). They are thought to be remnants of post-glacial fluvial systems. In some areas, the Quaternary deposits are mixed due to slumping, landsliding, and collapse.

TERTIARY INTRUSIVE AND EXTRUSIVE ALKALINE ROCKS

by Theodore J. Armbrustmacher

Lincoln County porphyry belt

Alkaline igneous rocks in the Roswell Resource Area include all but the southernmost part of the Lincoln County porphyry belt (Kelley and Thompson, 1964). These rocks of Tertiary age comprise at least nine (Kelley and Thompson, 1964), twelve (Allen and Foord, 1991a), or fourteen (Kelley, 1971) intrusive and extrusive centers that lie between Corona on the north and Ruidoso on the south in the southwestern part of the study area (maps A, D). Allen and Foord (1991a) compiled age determinations of igneous rocks and concluded that there were three episodes of Cenozoic igneous activity: (1) 38.2-36.5 Ma including intrusive rocks from the Jicarilla Mountains, volcanic flows and intrusions from Sierra Blanca and Black Mountain, and perhaps compositionally similar rocks from the Gallinas Mountains and the Tecolote Hills; (2) 30-26 Ma for syenite and granite of Sierra Blanca, several dikes along the Capitan Mountains lineament, and perhaps compositionally similar plutons at Carrizo Mountain, Lone Mountain, and Patos Mountain; and (3) Quaternary basalt flows of the Malpais. Kelley and Thompson (1964) list igneous centers and their principal rock types: Gallinas Mountains (rhyolite laccolith in north, trachyte laccolith in the south), Tecolote Hills (syenite-diorite laccolith), Jicarilla Mountains [monzonite(?) laccolith and stock], Lone-Baxter Mountains [syenite(?) stock and laccolith], Carrizo Mountain [microgranite(?) laccolith], Patos Mountain [monzonite(?) laccolith], Capitan Mountain (microgranite stock and laccolith), Three Rivers area and Bonita Lake (monzonite to granite stocks). Allen and Foord (1991a) group the rocks into (1) "younger" Tertiary granitic plutons, including the intrusions at Capitan Mountain, Carrizo Mountain, Patos Mountain, and Lone Mountain; (2) "younger" Tertiary dikes, including the Railroad Mountain dike and the Jones Camp dike; (3) and "older" Tertiary alkalic complexes, including Black Mountain, Sierra Blanca, Baxter Mountain/White Oaks district, Tecolote Hills, Jicarilla Mountains, and Gallinas Mountains.

According to Allen and Foord (1991a), igneous activity in the study area was localized along two major structural features during two distinct episodes. Magmas of alkali gabbroic to syenitic composition, or volcanic equivalents at Sierra Blanca Peak, were emplaced during an earlier episode (38-30 Ma) along the north-south-trending Pedernal arch during the transition from Laramide compression to extension. Along this trend, alkaline magmas were intruded along subordinate northeast-trending faults during the transition of Laramide compression to extension. A later episode (28-26.5 Ma) of alkali gabbroic to granitic composition occurs along the east-west Capitan Mountains lineament and within the Sierra Blanca volcanic pile coincident with early rifting along the Rio Grande rift zone (Allen and Foord, 1991b). Rare-earth element data and Rb/Sr and Nd/Sm isotopic data presented by Allen and Foord (1991a) suggest that mafic alkaline magmas during the earlier episode were derived from metasomatized mantle, whereas granitic magmas during the later episode were derived from the lower crust. Just east of the Sierra Blanca basin is the north-south trending Mescalero arch which appears to be offset to the west in the vicinity of Capitan Mountain. Many of the igneous centers appear to be associated with these structures (Kelley and Thompson, 1964). The Sierra Blanca basin filled with at least 1,000 m (3,340 ft) of volcanic rocks during Oligocene time (Thompson, 1972). The volcanic rocks, which consist of andesitic to trachytic flow breccias, flows, and tuffs, were then intruded by magmas that crystallized into the leucocratic to mesocratic rocks of the Three Rivers and Bonita Lake stocks.

The alkaline rocks of the study area share a common igneous heritage with similar rocks of the Rocky Mountain front from West Texas to Montana, including those at Cripple Creek, Colorado, and north-central Montana (Judith Mountains, Moccasin Mountains, Bear Paw Mountains, etc). The tectonic setting appears to be subduction-related (Allen and Foord, 1991a), or back-arc extension related (Thompson, 1991c). Limited isotopic data suggest that the saturated to undersaturated alkaline magmas originated in the mantle and(or) lower crust.

Igneous centers

Gallinas Mountains

The Gallinas Mountains comprise at least two domal uplifts underlain by Precambrian granitic rocks that are in turn covered by almost 2,000 ft (600 m) of Lower Permian Abo Formation, Yeso Formation, and Glorieta Sandstone (Perhac, 1964, 1970). In fact, outcrops of foliated Precambrian granite exposed within the mountains represent one of only a few occurrences of basement in the Roswell Resource Area (map A). In Tertiary time, leucocratic magmas intruded the Permian sedimentary rocks as laccoliths and possibly as stocks. The intrusive contacts are mostly concordant with the bedding of the overlying sedimentary rocks when they are observed in outcrop. Flow banding is parallel to sedimentary rock bedding whenever it is observed.

Porphyritic latite occurs at Cougar Mountain, northeast of the main Gallinas Mountains (maps A, D). Nearby Yeso Formation is flat lying, suggesting that the porphyritic latite is a stock (Perhac, 1970). Major, rock-forming minerals are orthoclase, sodic plagioclase, and hornblende, with accessory amounts of quartz, magnetite, apatite, zircon, and titanite. Plagioclase and hornblende occur as phenocrysts and the other minerals constitute the groundmass.

The southern part of the Gallinas Mountains is underlain by a laccolith of porphyritic trachyte and associated syenite. The porphyritic trachyte contains orthoclase and sodic plagioclase phenocrysts, minor hornblende and (or) aegirine-augite, and groundmass consisting of altered feldspar with accessory amounts of quartz, magnetite, apatite, zircon, rutile, titanite, and ilmenite. The texture of the groundmass is trachytic. The syenite phase contains essentially the same minerals as the porphyritic trachyte but the texture is equigranular. Acmite and biotite are minor constituents of some specimens.

The north-northwest part of the mountains is underlain by a laccolith of porphyritic rhyolite that is more than 500 ft (150 m) thick at Gallinas Peak and thins away from this center. This rock contains feldspar phenocrysts set in a fine-grained groundmass of minerals nearly identical to the other rocks in the area. Small circular to elliptical bodies of trachyte breccia occur west of Rough Mountain. Fragments include porphyritic trachyte, shale, sandstone, limestone, and granite set in a trachyte matrix.

Nearly all the rocks have been hydrothermally altered, resulting in replacement of original feldspars and mafic minerals by clay minerals, ferric iron oxide, and other secondary minerals. Sedimentary rocks at the contacts with the igneous rocks show almost no evidence of contact metasomatic effects. Minor silicification of limestone and sandstone, and local development of skarn minerals is sometimes observed. The laccoliths are emplaced chiefly into the Yeso Formation and most of the mineral deposits occur in that formation.

Tecolote Hills

Subsilicic rocks including syenite, monzonite porphyry, and diorite occur in laccoliths with maximum thickness of 400 ft (120 m) in the Tecolote Hills (Rawson, 1957) (maps A, D). Allen and Foord (1991a) briefly describe compositions ranging from syenogabbro to syenite, and they suggest that the diorite of Rawson is biotite-augite-hornblende pyroxenite. Yeso Formation and Glorieta Sandstone are hosts for the laccoliths. The laccoliths appear to be an extension of the larger igneous bodies that occur in the Gallinas Mountains to the northwest (Griswold, 1959). A laccolith of monzonite porphyry underlies Tecolote Peak to a thickness of nearly 400 ft (120 m) and thins to about 200 ft (60 m) toward the east and south (Rawson, 1957). Reconnaissance revealed that 3 m (10 ft) of sandstone [Glorieta Sandstone(?)] overlies the laccolith at the top of Tecolote Peak. The monzonite porphyry laccolith overlies and is locally intrusive into a smaller diorite laccolith. Small syenite lenses occur within the diorite laccolith. Contact metasomatic alteration of limestone beds at the base of the diorite laccolith are observed locally.

Jicarilla Mountains

The main igneous centers in the Jicarilla Mountains are represented by two intrusions, one consisting of latite porphyry near the village of Jicarilla in the southern part of the mountains, and the other consisting of monzonite to diorite underlying Jacks Peak in the northeastern part of the mountains (Ryberg, 1968). Allen and Foord (1991a) found that the rocks consist of an alkaline sequence of biotite syenogabbro to syenite and a calc-alkalic monzonite and tonalite. The intrusions have caused the pre-Tertiary sedimentary rocks to be domed. The coarse-grained rocks have K-Ar ages on biotite of 38.2 and 37.3 Ma (Allen and Foord, 1991a; Thompson, 1991b). The intrusion at Jacks Peak is in contact with San Andres Formation; smaller sill- or laccolith-like bodies occur away from the main intrusions, chiefly within San Andres Formation. Small dikes of basaltic composition intersect the intrusion at Jicarilla and some of the surrounding sedimentary rocks.

Lone and Baxter Mountains

Lone and Baxter Mountains are the dominant physiographic features of the White Oaks area, southwest of the Jicarilla Mountains (Griswold, 1959) (maps A, D). Intrusive rocks of this area are of two major types--quartz rich and quartz poor; the Lone Mountain intrusive consists of quartz-poor rocks (Smith, 1964). Monzonite and syenite underlie Lone Mountain, where probable laccolithic intrusion has domed the surrounding San Andres Formation (Griswold, 1959; Smith and Budding, 1959). Lone Mountain rocks are uniform, containing sparse plagioclase and less than 10 percent quartz (Smith, 1964). Schnake (1977) indicated that the rocks in the Lone Mountain intrusion were zoned with a peripheral felsic zone surrounding a more mafic core. Allen and Foord (1991a) observed that the core consists of quartz syenite and the marginal zone consists of alkali-feldspar granite. Small intrusions extend southward from Lone Mountain through the White Oaks area to Baxter Mountain. Compositions of rocks underlying Baxter Mountain range from syenogabbro to syenite and lamprophyre. These rocks (and the sedimentary rocks in contact with them) are the hosts for ore deposits in the White Oaks district. Rocks from this area have a K-Ar age on biotite of 35.2-29.8 Ma (Thompson, 1991b).

Carrizo Mountain

Contacts between the igneous rocks underlying Carrizo Mountain and the surrounding Mesaverde Group (Cretaceous) rocks are obscured by alluvial fans and landslides. According to Elston and Snider (1964), the igneous rocks form a steep-sided laccolith or stock that have domed the Mesaverde Group rocks. Patton (1951) characterized the rocks as alaskites, but Weber (1964) described the presence of hornblende- and biotite-bearing quartz syenite locally showing trachytic texture. Elston and Snider (1964) concluded that Carrizo Mountain is underlain by a differentiated body, ranging from fine-grained spherulitic rhyolite with vertical flow banding at the contact to porphyritic granite with phenocrysts of intermediate plagioclase rimmed by orthoclase. Biotite and opaque minerals constitute over 10 percent of the rock. Pertl (1984) and Pertl and Cepeda (1991) described the Carrizo Mountain stock as a steeply-dipping rhyolite body with a central zone of quartz monzonite. Data from Allen and Foord (1991a) indicate that the rocks range in composition from quartz syenite to alkali-feldspar granite.

Patos Mountain

The close association of the Patos Mountain intrusive rocks with those of Carrizo Mountain and Lone Mountain suggest a similarity in origin. The Patos Mountain intrusion appears to be a laccolithic, but the lower part is concealed by alluvial and colluvial deposits. The Patos Mountain body is a texturally and compositionally zoned rhyolite, having a slightly more mafic, porphyritic center and a more silicious, fine-grained margin (Haines, 1968).

Capitan Mountain

The intrusive body underlying Capitan Mountain, emplaced at 26.5 $\pm$ 1.2 Ma (Allen, 1988), is the largest in the Lincoln County porphyry belt and one of the largest Tertiary intrusions exposed in New Mexico (Allen, 1988; Allen and McLemore, 1991). It is elongate in an east-west direction due to alignment along the western part of the 34° -parallel lineament (Moore and Foord, 1986), also referred to as the Capitan lineament (Allen, 1988), and herein as the Capitan Mountains lineament so as not to be confused with structures relating to the Capitan Reef. On the west, the intrusion is in contact with the San Andres Formation, and on the east, with the Yeso Formation; elsewhere, the contact is covered by surficial deposits. Carbonate rocks in contact with the intrusion are locally altered to calc-silicate skarns and replacement iron deposits. Although Kelley (1971) stated that the composition and texture of the rocks in the intrusion are remarkably uniform, Allen and McLemore (1991) indicate that the intrusion is zoned, with a high-silica, miarolitic, granophyric aplite in the roof zone at the west end, and a lower silica, fine-grained, alkali-feldspar granite porphyry core at the east end. Rocks from the west end tend to contain higher amounts of quartz and no mafic minerals other than iron oxides, whereas the rocks of the east end contain lesser amounts of quartz, feldspar phenocrysts, and biotite and amphibole as mafic minerals (Allen and McLemore, 1991). Allen and McLemore (1991) define three major textural types (granophyre, aplite, and porphyry) with geochemical differences. Granophyric types occur in the western part of the intrusion and grade into equigranular-textured aplite toward the east; rocks from the eastern half of the intrusion are porphyritic. Isotopic and rare-earth element data suggest that the rocks of the Capitan intrusion are derived from a lower crustal source.

Three Rivers area

The Three Rivers area lies at the southern end of the Lincoln County porphyry belt and constitutes part of the Sierra Blanca Igneous Complex (Thompson, 1966, 1972). The Complex consists of a thick pile of volcanic rocks that overlie with angular unconformity the Cub Mountain Formation (Cretaceous- Paleocene) and Mesaverde Group (Cretaceous)(map C). Rocks of the volcanic sequence comprise four formations, the Walker andesite breccia, Nogal Peak trachyte, Church Mountain latite, and Godfrey Hills trachyte, and consist chiefly of andesitic to trachytic flow breccia, flows, and tuffs (Thompson, 1972). The volcanic pile is in turn intruded by four stocks, Three Rivers, Rialto, Chaves Mountain, and Bonito Lake (map D), and these stocks appear to be comagmatic with their volcanic precursors.

According to Giles and Thompson (1972), the Three Rivers stock is a molybdenum-related, hypabyssal complex that consists of three major intrusive phases--(1) an early, passively emplaced shell of syenite porphyry, (2) quartz syenite intruded along the northeastern margin of the stock, and (3) late, equigranular quartz syenite to alkali granite forcibly injected along a northeastern trend into the syenite porphyry. Each phase has a different texture, but similar geochemistry and mineralogy (Thompson, 1972). The southern part of the stock that underlies Sierra Blanca Peak comprises five separate units ranging from syenite to alkali granite (Moore and Foord, 1986). The alkali granite has been dated at 26.8 ± 0.09 Ma (Moore and Foord, 1986).

The Rialto stock consists of hornblende-biotite monzonite cut by small bodies of comagmatic biotite monzonite (Thompson, 1968, 1972). Orthoclase and sodic plagioclase constitute nearly 90 percent of the hornblende-biotite monzonite. Biotite and magnetite partially replace hornblende, and quartz, apatite, rutile, and titanite occur as accessory minerals. The Rialto stock contains brecciated zones that have localized deposits of gold.

The syenite stock at Chavez Mountain intrudes rocks of the Cub Mountain Formation (Thompson, 1972). Rocks of the stock contain anorthoclase phenocrysts in a groundmass of sodic plagioclase, hornblende, and biotite. The texture is trachytic.

The dominant rock type in the Bonito Lake stock is hornblende-biotite syenite although the rocks become monzonitic toward the western margin (Thompson, 1972, 1973). Orthoclase and sodic plagioclase are more abundant than microperthite. Corroded remnants of clinopyroxene are partly replaced by hornblende and magnetite, which in turn are replaced by biotite. Hydrothermal alteration of the syenite occurs along the northern contact of the syenite and along fracture zones. Pyrite, molybdenite, and chalcopyrite have been added to the syenite that has been argillized and silicified.

Dikes

A generally northeast-trending composite dike swarm (map D) probably related to regional extension, occurs from the Sierra Blanca to the Jicarilla Mountains (Griswold, 1959; Kelley and Thompson, 1964). The dikes are composed of 7 different rock types, including (1) labradorite-olivine diabase porphyry, (2) olivine diabase porphyry, (3) diabase, (4) hornblende-biotite diabase, (5) rhyolite, (6) latite grading into trachyte, and (7) phonolite (Elston and Snider, 1964). The dikes in this belt generally form a radial pattern outward from the central part of the Sierra Blanca basin. [Some dikes are concentric with the basin in the Three Rivers area (Kelley and Thompson, 1964).] The dikes are younger than the Cub

Mountain Formation and cut all units including some intrusives, stocks, and sedimentary and volcanic rocks. Dikes in the Ruidoso area are postulated to have been related to considerable regional extension, totalling at least 1.5 km (1 mi) in the Mesaverde outcrop belt near Capitan (Jones, 1951; Kelley and Thompson, 1964).

A diabase-dike complex occurs in the subsurface in Tucumcari basin in Quay County; the dikes are probably of Tertiary age and may have been intruded along pre-existing faults on the northern edge of Tucumcari basin (Broadhead and King, 1988). Railroad Mountain dike, Camino del Diablo dike, and other small stocks, flexures, and numerous sills occur in the south-central parts of the study area (maps D). Railroad Mountain dike, about 50 km (31 mi) long and 31 m (100 ft) wide, has positive topographic expression and cuts the Triassic Santa Rosa Sandstone. It consists of medium-grained olivine gabbro (Kelley, 1971). Camino del Diablo dike, 40 km (25 mi) long and 15 m (50 ft) wide, has negative topographic expression. It is composed of surficially altered andesitic-basaltic diabase (Kelley, 1971).

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URANIUM IN GROUNDWATER AND GEOCHEMISTRY OF SEDIMENTS

by James A. Erdman, Ronald R. Tidball, and Richard B. Tripp

Two large databases were available for this mineral-resource assessment. These databases are from the National Uranium Resource Evaluation program (NURE) of 1° x 2° quadrangles and the database of 819 stream-sediment samples from National Forest lands in and near the White Mountain Wilderness Area (fig. 1). The NURE data source was selected because the NURE sample sites are fairly evenly distributed throughout the study area. The White Mountain Wilderness database covers too small an area for the present study; it was used to assess the mineral potential of the Wilderness Area (Segerstrom and others, 1979; Segerstrom and Stotelmeyer, 1984).

The NURE Hydrogeochemical and Stream Sediment Reconnaissance Program (HSSR) consisted of sampling surface water, groundwater, and stream, pond, and lake sediments throughout the United States to identify favorable areas for detailed uranium exploration. Los Alamos National Laboratory (LANL) was responsible for conducting the HSSR program in New Mexico, as well as several other Rocky Mountain states and Alaska, and for analyzing all the samples for uranium. Field-sampling techniques are detailed in Sharp and Aamodt (1978).

Supplemental analyses--that is, analysis of samples for elements other than uranium--were conducted for most of the samples from the Roswell Resource Area by the Oak Ridge National Laboratory (ORNL) in Tennessee (fig. 2). This contribution by two laboratories created difficulties in the data presentation, as described below.

NURE DATABASE

U.S. Geological Survey 1° x 2° quadrangles were used as base maps to plot results of the NURE hydrogeochemical and stream-sediment surveys. The Roswell Resource Area encompasses parts of nine such quadrangles, with the Roswell and Fort Sumner quadrangles most represented. The NURE data are available for each of these quadrangles in 12 separate reports (Broxton, 1978; LaDelfe, 1981; Los Alamos National Laboratory, 1980; 1982; Oak Ridge National Laboratory, 1981a-f; Warren and Nunes, 1978). All the NURE data bases for the quadrangles in New Mexico have recently been made available by the New Mexico Bureau of Mines and Mineral Resources (McLemore and Chamberlin, 1986).

Analyses for 5,872 samples were retrieved from the NURE digital tapes; about half were water samples and half sediment samples. The 3,059 water samples consisted of five types in two general categories: 165 surface-water samples (stream, natural pond, and artificial pond), and 2,894 groundwater samples (wells and springs). All water samples were filtered through a 0.45-micron membrane filter and acidified to the same pH. Because the number of surface-water samples is small and the areal coverage is not uniform, we have not used the surface-water data in this report. Extensive sinkhole (karst) topography in much of the study area limits clearly defined drainage systems. Only 84 of the groundwater samples were from springs; these were included with the 2,810 well-water samples.

The 2,813 sediment samples consisted of eight types: dry and wet stream sediments, dry and wet natural-pond sediments, dry and wet artificial-pond sediments, and dry and wet spring sediments. Most of these samples (1,938) were dry stream sediments. All sediment samples were dried at the same temperature and sieved to minus 100-mesh (0.15 mm); therefore, we combined all eight types into the same data base.

The numbers of analyses of the groundwater and sediment actually available were reduced from the above totals because of missing data, and (as in the case of zinc data on sediments analyzed by LANL) because of varying lower limits of determination. Also, groundwater samples are missing from large tracts within the Roswell and Fort Sumner quadrangles in the west-central part of the study area.

All uranium analyses were conducted at LANL. Water samples were initially analyzed for uranium by fluorometry (Hues and others, 1977). Those samples that contained more than 40 parts per billion (ppb)--the upper limit of determination without recalibration--were reanalyzed either by (1) a modification of the basic fluorometric method that not only increased the upper limit of determination but reduced the lower limit of determination in natural waters from 0.50 to 0.02 ppb, (2) delayed-neutron counting (DNC), or (3) mass spectrometry-isotope dilution. All sediment samples were analyzed by DNC.

The greatest difficulty in comparing the NURE sediment data arose from the use of different analytical methods for supplemental elements by the two laboratories. Los Alamos National Laboratory used neutron activation analysis, energy dispersive x-ray fluorescence (Hansel and Martell, 1977), and arc-source emission spectrography--all total analysis techniques. The laboratory at Oak Ridge, however, used plasma source emission spectrometry as part of a partial-extraction method described by Cagle (1977) and Arendt and others (1979). For this reason, the supplemental data bases from the two laboratories had to be statistically analyzed and interpreted separately.

ANOMALY DEFINITION AND DATA PRESENTATION

We used an empirical rather than statistical approach to define anomalous element concentrations. Except for the groundwater uranium data, lognormal probability plots were constructed for selected elements to show the general distribution and range of the data. Thresholds (Sinclair, 1991) for anomalous element concentrations and potentially different populations in the data were usually chosen from these plots where gaps or breaks-in-slope occurred. For uranium in groundwater, the 90th percentile of the frequency distribution was chosen as the anomalous threshold because no threshold was evident on the probability plot below a clear gap that segregated a few outlying samples from the rest of the population.

Elements whose distribution patterns appear to reflect mineralization or seem to relate to underlying tectonic structures were selected for display in single-element maps. Except for uranium, separate probability plots were generated for each laboratory because different analytical methods were used for sediments analyzed by LANL and by ORNL. As explained above, the methods used by LANL measured total element concentrations whereas the acid-leach method used by ORNL measured only partial concentrations. This difference in analytical methods resulted in consistently lower medians from the latter laboratory. In addition, the same suite of elements was not analyzed by both laboratories because they used different analytical procedures. For example, molybdenum data are only available for sediments analyzed by ORNL, and bismuth data are only available for sediments analyzed by LANL. All uranium analyses were performed at LANL, so the uranium map for sediment samples is based on a single probability plot.

Baseline averages given in the explanations that accompany each sediment map and text are either geometric means for samples of soils and other surficial materials from western United States (Shacklette and Boerngen, 1984) or soil averages cited by Levinson (1980).

Usable data sets consisted of 2,507 uranium analyses of groundwater samples; 2,391 uranium analyses of sediment samples; 2,004 sediment samples analyzed by ORNL for supplemental elements, and 387 sediment samples analyzed by LANL for supplemental elements. The data set for zinc in sediments analyzed by LANL was adjusted to 345 samples because lower limits of determination were highly variable (USGS unpublished computer program GXFIXX, A.T. Miesch, 1984). The supplemental data for the groundwater samples were not studied in detail for this report.

SPECIAL HANDLING OF SELECTED SEDIMENT SAMPLES

Twelve sediment samples were retrieved from the NURE-sample archives to help interpret several of the geochemical anomalies shown in the maps described below.

These unground, minus 100-mesh samples were split; one split was returned to storage and the other was panned to remove the clay fraction. Residual light minerals that remained in these cleaned sediments were removed by heavy liquid flotation (bromoform, specific gravity 2.8). The resultant heavy-mineral concentrate was separated into three fractions using a modified Frantz Isodynamic Separator. The most magnetic material, primarily magnetite, was not analyzed, nor was the slightly magnetic fraction which contains largely ferromagnesian silicates and iron oxides. The nonmagnetic fraction--the third fraction--which generally concentrates ore and ore-related minerals (zircon, sphene, barite, etc.) was saved for mineralogical analysis. All 12 samples were optically scanned for ore-related minerals, and four of the 12 were further studied using the scanning-electron microscope.

RESULTS

Uranium in Groundwater

Range: 0.02 (<0.50) - 3,078 ppb (μg/L)

Median: 4.4 ppb

Detection ratio: 2,452/2,507

Normal range in most natural water: 0.1 - 10 ppb (Hem, 1985)

Implications for Mineral Potential

Levels of uranium in groundwater greater than 98 ppb with one exception follow a broad north-south zone that lies just east of the Pecos River (fig. 3). These especially anomalous concentrations tend to occur in four clusters, as follows: (1) around San Jon in Quay County; (2) southeast of Cuervo in Guadalupe County; (3) around Urton Lake in De Baca County; and (4) east of Hagerman in Chaves County. The sample that contained the maximum ground-water concentration of 3,078 ppb was taken from a well near the town of Cuervo just south of extensive bluffs of the Chinle Formation. The remarkably tight Urton Lake cluster might represent groundwater dispersion of uranium from a nearby deposit in the Chinle Formation at Cebolo Creek (Finch, 1972) and subsequent concentration in the closed depression that drains into the lake. This uranium-laden groundwater most likely originates from outcrops of the Triassic Chinle Formation in the area. These redbeds are the main source rocks for uranium in the study area and elsewhere in the central Great Plains (Landis, 1960).

Nichols and others (1977) report that well water was the most reliable sample medium for outlining uranium deposits and, at wider spacing, potential uranium districts in northwest Texas. Their geochemical samples were collected from outcrop areas that included rocks equivalent to the Triassic Dockum Group. In the Roswell Resource Area, rocks equivalent to this unit are divisible into the Santa Rosa Sandstone and the Chinle Formation.

Miller and others (1984) agree that groundwater uranium is often used as a direct indicator for uranium exploration; but they caution: "The presence of groundwater with high concentrations of U is not necessarily an indication of the most favorable site for exploration drilling." Both Nichols and others (1977) and Miller and others (1984) describe the geochemical complexity of groundwaters associated with uranium mineralization and state that uranium enrichment in groundwater simply indicates oxidizing conditions where uranium has been mobilized, not deposited. Favorable sites for stable uranium deposits lie, instead, slightly down the hydrologic gradient from the zone where groundwater changes from oxidizing to reducing conditions. Roll-type deposits may form in a narrow zone where this change occurs.

Multiple ground-water flow systems exist in the Roswell Resource Area even within the same formation (D. McAda, U.S. Geological Survey, oral communication, 1991). Studies on the ground-water head distribution in the Pecos River basin show that ground water flows updip, downdip, and across lithologic or stratigraphic boundaries (Summers, 1981). The effects of these flow systems on the ground-water uranium distribution are beyond the scope of this basically descriptive report.

The important aquifers, however, differ spatially across the study area. According to Dinwiddie and Clebsch (1973), the main aquifers in Guadalupe County are in the consolidated sedimentary rocks of the Yeso Formation, Glorieta Sandstone, San Andres Formation, Bernal Formation, Santa Rosa Sandstone, and Chinle Formation, with the San Andres Formation most likely to yield water to wells in quantities sufficient for municipal supply or for irrigation use. Mourant and Shomaker (1970), on the other hand, report that in De Baca County to the south the Santa Rosa Sandstone, not the San Andres, yields large amounts of water to wells for municipal and irrigation purposes. In Quay County alluvial deposits of Quaternary age, the Ogallala Formation of Tertiary age, and the Exeter Sandstone of Jurassic age are the only formations that yield large amounts of water to wells (Berkstresser and Mourant, 1966). In southeastern New Mexico, the Ogallala aquifer is the sole source of potable ground water (Stephens and Spalding, 1984). Since the Ogallala Formation contains low-grade uranium deposits, all of these aquifers could serve as conduits for the mobilized uranium, especially east of the Pecos River where the ground water tends to become more alkaline and saline--conditions under which uranium is extremely mobile (Wanty and Schoen, 1991, p. 186-188).

Implications for Human Health

The maximum uranium concentration measured in the NURE ground water samples in the Roswell Resource Area is 3,078 ppb. Most natural waters contain uranium at concentrations between 0.1 and 10 ppb (µg/L). Levels of more than 1,000 ppb can occur in water associated with uranium-ore deposits (Hem, 1985, p. 148). The human health standard for dissolved uranium in groundwater adopted by the state of New Mexico is 5.0 mg/L or 5,000 ppb (New Mexico Water Quality Control Commission, 1988). However, recent recommendations by a U.S. Environmental Protection Agency (EPA) committee set a 100 ppb limit in groundwater; this limit was based on the heavy-metal toxicity of natural uranium to the kidneys (Wrenn, and others, 1985; Wrenn and others, 1987). This recommended limit approximates the 99th percentile of the groundwater uranium abundant in the Roswell Resource Area.

Interim guidelines released by the EPA in June 1991 (U.S. Environmental Protection Agency, 1991) are even more stringent. As a result of the proposed maximum contaminant level (MCL)[2] of 20 µg/L (ppb) uranium, about one in ten of the groundwater samples in the Roswell Resource Area, especially those from the Pecos River valley region, exceed the primary drinking water standard. Probably all of these anomalous samples reflect uranium that resides in the Chinle Formation.

Uranium in Sediments
Range: 0.10 - 37 ppm
Median: 2.4 ppm
Detection ratio: 2,391/2,391
Baseline average: 2.5 ppm (Shacklette and Boerngen, 1984)

Wrenn and others (1987) report that soils in the United States typically range from 1-4 ppm uranium. The upper limit of that range approximates the background threshold (90th percentile) of 3.3 ppm for uranium in sediments from the Roswell Resource Area.

Most sediments with anomalous uranium concentrations occur at sites that parallel outcrops of the Capitan Mountains intrusive or Precambrian crystalline rocks exposed in the Oscura Mountains (fig. 4). An array of uraniferous sediments around the Capitan Mountains intrusion may represent, in part, detritus shed from thorium/uranium/rare-earth veins and uranium/iron veins that cut Tertiary alaskite (McLemore and Chenoweth, 1989), although the distribution seems to indicate fairly uniform concentrations throughout the stock. Minor uranium anomalies occur in sediments at the headwaters of Rio Bonito, around White Oaks, and south of Gallinas Peak. Consistently high uranium concentrations are found in sediments along the northwest-trending, thin outcrop belt of Precambrian rocks along the west flank of the Oscura Mountains.

Many anomalous levels of uranium also occur in sediments that are probably derived from extensive outcrops of the Chinle Formation north of Santa Rosa. A widely spaced dispersion train of enriched sediments follows the floodplain of the Pecos River.

The most puzzling anomaly consists of a roughly linear suite of samples--five of which contain very high concentrations of uranium--in the southeastern corner of the Roswell Resource Area. This apparent feature extends from Long Arroyo northeastward to Little Salt Lake and Salt Lake on the New Mexico/Texas border (fig. 4). It lies on the north side of the projected strike of the K-M Fault, a structure that penetrates basement rocks. According to D.M. Kulik (oral communication, July 1991), relatively steep and linear gravity gradients indicate that this fault probably extends northeastward to a northwest-trending gradient that marks the Roosevelt County Fault.

The K-M Fault may serve as a conduit for the migration of uranium-enriched brines produced from underlying Pennsylvanian and Permian formations. The sedimentary section in and around the Delaware Basin to the south contains vast quantities of hydrocarbons. In a study on the relationship between uranium and the diagenesis of the Lower Pennsylvanian Morrowan rocks--a hydrocarbon reservoir in southeastern New Mexico--Denham and others (1989) state:

> In general, rocks rich in organic matter--potential hydrocarbon

[2]MCL is a level (concentration) of contaminant that might cause adverse human health effects if exceeded, and is enforceable for public drinking-water supplies

> source rocks--are enriched in uranium and thorium. During thermal maturation of hydrocarbon source rocks, uranium is released to migrate with pore fluids prior to and during hydrocarbon migration . . . Thorium remains essentially immobile.

Even though uranium should be extremely mobile in the alkaline and saline aqueous systems common to the area, it may adsorb to clays in surficial sediments after migrating in pore fluids along the K-M Fault.

Lithium in Sediments
Range: 2 - 183 ppm (ORNL); <5 - 83 ppm (LANL)
Median: 23 ppm (ORNL); 25 ppm (LANL)
Detection ratio: 2,004/2,004 (ORNL); 273/387 (LANL)
Baseline average: 22 ppm (Shacklette and Boerngen, 1984)

The most lithium-enriched sediments occur along a northeast trending zone similar to that reported for uranium in sediments (fig. 5). Their distribution supports the possibility that deep-seated brines associated with hydrocarbon reservoirs are leaking to the surface through the K-M fault. Supplemental data for groundwater samples are only available for most of the area covered by ORNL (see fig. 2); nevertheless, lithium concentrations in well-water samples in the southeastern part of the Roswell Resource Area and east of the Pecos River are almost consistently high. Thus, the surface lithium anomalies are supported by groundwater lithium anomalies for approximately the same area.

Oil-field brines are among several hydrologic environments cited by Mertz and others (1974) that concentrate lithium. Vine and Dooley (1980) suggest that the exploration for lithium brines may be warranted in Permian basins of the United States where the sequence of evaporites is known to include potash minerals. Potash is mined and processed in Eddy and Lea Counties in the Permian Delaware Basin just south of the Roswell Resource Area, and numerous oil and gas fields occur in the southeast corner of the resource area.

The source of the lithium and perhaps associated uranium anomalies in sediments from this area is equivocal pending more detailed studies of the underlying structures.

Silver in Sediments
Range: <2 - 9 ppm (ORNL); <5 - 6 ppm (LANL)
Median: <2 ppm (ORNL); <5 ppm (LANL)
Detection ratio: 27/2,004 (ORNL); 4/387 (LANL)
Baseline average: 0.1 ppm (Levinson,1980, p. 881)

Few of the sediment samples from the Roswell Resource Area contain detectable silver (fig. 6), because of the relatively poor sensitivity of the analytical methods used by LANL and ORNL. Therefore, any measurable silver is anomalous.

The silver anomalies can be attributed to the following sources: (1) lode or placer gold occurrences, (2) polymetallic veins, (3) porphyry molybdenum deposits--all three of these sources related to Tertiary stocks in the Nogal mining district, (4) veins in Precambrian rocks in the Oscura Mountains, or (5) sedimentary redbeds of Triassic age. A 4-ppm silver anomaly occurs in sediment from the Nogal district, which lies at the headwaters of Rio Bonito between the Capitan Mountains and the White Mountain Wilderness Area. Although primarily a lode gold district, four molybdenum anomalies centered along the South Fork of Rio Bonito were described by Segerstrom and others (1979). Molybdenum deposits can also carry silver, but small polymetallic deposits found in the district are characterized by lead-zinc-silver minerals in simple fissure veins (Griswold, 1959).

The sediment sample that contains the highest silver value--9 ppm--was collected from the south flank of the Capitan Mountains below Capitan Peak. A lead concentration of 442 ppm, well above a norm of 17 ppm for soils from the western U.S., was also reported in this sample. The source of this extreme silver-lead anomaly might be either polymetallic veins or contamination from lead shot. A scan by electron microscopy of the heavy-mineral concentrates prepared from this sample found no lead mineral, but barite was present.

East of the Pecos River, sedimentary rocks are the probable source of the silver anomalies shown in figure 6. Lindgren (1932) reports that copper ores, which often carry high assays of silver, are widely distributed in the redbeds of the Southwest.

The adjacent 4-ppm silver anomalies in sediment samples near Sumner Lake reservoir in the northcentral part of the Roswell Resource Area as well as the 3 ppm and associated non-posted anomalies east of Red Lake in Chaves County (fig. 6) probably reflect mineralized outcrops of the Chinle Formation. McLemore and North (1985) list silver as a commodity commonly associated with widespread uranium occurrences in the Chinle Formation of east-central New Mexico. An optical microscopic scan of the heavy-mineral concentrates prepared from the two sediments containing 4 ppm silver failed to identify any heavy minerals that might account for the silver anomaly.

Other element anomalies in sediments from the southeastern corner of Chaves County are described below.

Gold in Sediments
Range: <20 (<150) - 720 ppb (LANL)
Median: <150 ppb
Detection ratio: 3/387
Baseline average: 1 ppb (Levinson, 1980)

Gold was determined only in those sediments that were analyzed by LANL; coverage for this important element therefore is limited. The varying lower detection limits of 20 to 150 ppb by neutron activation analysis were well above the 1 ppb concentration normally found in soils. However, highly anomalous gold was found in three samples from Quay County (fig. 6). The highest value--720 ppb--came from a wet-spring sediment in a tributary to Ute Reservoir on the Canadian River, on the western edge of the Logan mining district as shown in North and McLemore (1986). Although no precious-metal production was reported for the district, gold occurs with pyrite in shales of stratabound sedimentary-copper deposits of the Triassic Chinle Formation (North and McLemore, 1986). A dry-stream sediment near the head of Barranca Draw northeast of Ragland yielded 270 ppb gold and anomalous barium (1,660 ppm), and a natural wet-pond sediment from a tributary of Barranca Draw east of Mesa Redonda contained 200 ppb gold. These latter two samples were collected about 8 and 19 km (5 and 12 mi) west and southwest, respectively, from the Red Peak mining district where argentiferous chalcocite nodules and stratabound sedimentary-copper deposits occur in middle and upper units of the Chinle Formation (North and McLemore, 1986). All three sites occur where the Chinle Formation crops out.

Molybdenum in Sediments
Range: <4 - 17 ppm (ORNL only)
Median: <4 ppm
Detection ratio: 47/2,004
Baseline average: 0.85 ppm (Shacklette and Boerngen, 1984)

Molybdenum was not determined in samples analyzed at LANL. However, because of its importance (particularly in the porphyry belt of Lincoln County) and its association with silver, we have included a map that locates samples with detectible (anomalous) molybdenum (fig. 7). Locations of anomalous molybdenum levels in sediments generally correspond with those shown on the silver map; however, no molybdenum anomalies were found in the Oscura Mountains.

The molybdenum-enriched sediments at the headwaters of Rio Bonito in the southwestern part of the Roswell Resource Area (5-9 ppm, fig. 7) probably were shed from the Three Rivers stock. This stock contains four of the five significant molybdenum anomalies described by Segerstrom and others (1979, p. 18-19, pl. 2) for the White Mountain Wilderness area. Although no molybdenum has been mined, its widespread occurrence in the syenitic rocks led these authors to conclude that molybdenum is by far the most likely mineral resource to be found in the wilderness area and vicinity.

The pair of unposted anomalous samples east of Sumner Lake reservoir also contained anomalous concentrations of silver, and most likely derive from mineralized redbeds of the Chinle Formation that form limited or extensive outcrops locally. No molybdenum minerals were identified in the heavy-mineral concentrates prepared from the sediments, however.

The largest molybdenum anomalies found in the NURE survey make up the cluster that lies along the east-central edge of Chaves County east of Red Lake where the concentrations range from 5 to 17 ppm. The molybdenum content of surface waters from this area also tends to be anomalous (maximum, 274 ppb) compared to surface waters sampled elsewhere. An additional cluster of anomalous sediments occurs in the southeastern corner of the county and east of Hagerman. Extensive exposures of the Chinle crop out at Red Lake and along the Mescalero Ridge to the south, and the NURE results suggest that these exposed rocks are mineralized.

Barium in Sediments
Range: 6 - 1,486 ppm (ORNL); 223 - 6,046 ppm (LANL)
Median: 454 ppm (ORNL); 474 ppm (LANL)
Detection ratio: 2,004/2,004 (ORNL); 387/387 (LANL)
Baseline average: 580 ppm (Shacklette and Boerngen, 1984)

Sediment samples that contain elevated levels of barium are numerous and extensive (fig. 8). Nevertheless, focus is drawn to several parts of the map, and especially to the porphyry belt and associated Tertiary stocks of Lincoln County. The source of the three-site cluster of posted values that lies east of White Oaks may be vein barite from the Fox Lode prospect or related barite occurrences (see discussion of vein barite, this report). Abundant barite was identified in a heavy-mineral concentrate prepared from a split of the sediment that contained 1,486 ppm barium. In the Nogal district to the south where high concentrations of barium in sediments are also found, barite occurs as an accessory mineral in polymetallic veins. Another cluster of barium-enriched sediments lies to the north in the Pajaro Canyon area near the Gallinas district. The barium source may be barite gangue found with fluorite and the rare-earth mineral, bastnaesite, in the nearby Gallinas Mountains.

Several clusters of anomalous barium lie east of the Pecos River. From south to north, these clusters center on (1) the Red Lake area, east of Palma Mesa, with silver, molybdenum, lithium, and uranium anomalies, (2) the Hernandez Draw and Six-Mile Draw area, and (3) the Taiban Mesa area east of Fort Sumner in De Baca County.

The Chinle Formation or, possibly, the underlying Santa Rosa Sandstone appears to be the source of these barium anomalies east of the Pecos River. Small amounts of barite frequently occur in mineralized Triassic redbeds (Lindgren, 1932). However, barite commonly forms a cement in sandstone beds of this age and may be unrelated to any significant mineral occurrences (W. Finch, personal communication, 1991).

Copper in Sediments

Range: <3 - 981 ppm (ORNL); <10 - 143 ppm (LANL)

Median: 16 ppm (ORNL); 21 ppm (LANL)

Detection ratio: 2,003/2,004 (ORNL); 380/387 (LANL)

Baseline average: 21 (Shacklette and Boerngen, (1984)

Anomalous concentrations of copper occur in sediments that are, for the most part, widely scattered. Some conspicuous multi-point anomalies appear only in the extensively mineralized Lincoln County (fig. 9). The weak cluster of anomalies located in the extreme southeastern corner of Roosevelt County remains unexplained. Although the source of these copper anomalies (and associated zinc anomalies shown in figure 10) is highly uncertain, it may relate to oil and, to a lesser extent, gas production.

Major producing fields in the region occur in the San Andres Formation (Grant and Foster, 1989). Copper sulfides are reported to have been found in drill core from related oil and gas wells; thus, the copper anomalies in surface sediments reported here could indicate leakage from hydrocarbon reservoirs. Very limited evidence of this possibility comes from a well-water sample a few miles northwest of the posted sediment anomaly of 129 ppm. The water sample had a highly anomalous copper concentration of 261 ppb, the sixteenth highest sample in a suite of 1,308 samples.

An alternative explanation for these copper and zinc anomalies may be leakage from possible underlying Mississippi-Valley-type (MVT) lead-zinc deposits. Two deposits in New Mexico that may be oxidized MVT deposits (North and McLemore, 1986) occur just south of the Roswell Resource Area near Artesia and Carlsbad adjacent to the Permian Basin. The deposits are restricted to collapse breccias in Permian dolomite and clastic sedimentary rocks. The Red Lake deposit east of Artesia consists of secondary copper, lead, and zinc in the Permian Rustler Formation. However, as North and McLemore (1986) explain, these two known deposits are small.

Copper is commonly found with uranium in clastic redbeds throughout New Mexico (McLemore and North, 1985). This appears to be the source of the two anomalous samples (47 and 66 ppm) between Tucumcari and San Jon in Quay County, an area mapped as Chinle Formation. Two other copper anomalies (134 and 143 ppm) were found in sediments collected from the Minneos Creek drainage in the northeastern part of Quay County. These occur downstream from small outcrops of the Jurassic Morrison Formation.

An outlier copper anomaly (981 ppm) comes from Salado Creek west of Sumner Lake reservoir. From 1915 to 1957, 13 million pounds of copper was mined from the lower member of the Santa Rosa Sandstone in the Pastura district about 25 mi to the northwest. Most of the production came from one deposit, the Stauber mine. Some copper, however, was also hosted in the Queen Formation (Artesia Group) at the Pintada Mine. The Santa Rosa Sandstone crops out in the Salado Creek drainage and thus may host local copper deposits. Barite was identified in the heavy-mineral concentrate prepared from the sediment, but no copper sulfides were found, suggesting that the copper resides as chalcocite, an oxide mineral commonly found in copper-bearing redbeds (Lindgren, 1932).

Zinc in Sediments
Range: <6 - 1,639 ppm (ORNL); <44 - 1,290 ppm (LANL)
Median: 48 ppm (ORNL); <44 ppm (LANL)
Detection ratio: 2,003/2,004 (ORNL); 167/345 (LANL)
Baseline average: 55 ppm (Shacklette and Boerngen, 1984)

Zinc anomalies in sediments are even more sparse than are those for copper (fig. 9). The following descriptions are limited to a few of the more interesting anomalies.

A cluster of three anomalous samples occurs in Quay County in the northeast corner of the study area (fig. 10). Two properties among the many deposits from the area listed by McLemore and North (1985) reported uranium and/or copper production. The Chinle Formation crops out where two of the sediments containing 1,290 and 178 ppm were sampled; Quaternary pediments that thinly cover the Chinle are mapped where the third sample was collected. Zinc occurs locally in some redbed sedimentary copper/uranium deposits (McLemore and North, 1985).

In De Baca County just south of Salado Creek, a highly organic-rich sediment contained 1,637 ppm Zn, the second highest zinc concentration. The zinc may have been complexed with the organic material. On the other hand, the proximity of this sample to the extreme copper anomaly in sediment from Salado Creek (fig. 9) may indicate a local mineralized source that could be an offshoot of the Pastura district.

Lastly, the strong multipoint, posted anomaly in the southeastern corner of Roosevelt County overprints the copper anomaly from the same area. High terrace gravels cover an almost featureless terrain. Numerous oil fields lie just to the south, and ephemeral ponds abound to the north. As with the associated copper anomalies, these zinc anomalies have no clear explanation, but suggest migration from a deep-seated source such as underlying Permian redbeds.

Thorium in Sediments
Range: <2 - 48 ppm (ORNL); 2.5 - 83 ppm (LANL)
Median: 6 ppm (ORNL); 8.5 ppm (LANL)
Detection ratio: 1,730/2,004 (ORNL); 387/387 (LANL)
Baseline average: 9.1 ppm (Shacklette and Boerngen, 1984)

Notably few anomalous concentrations of thorium were found in the sediments from the Roswell Resource Area (fig. 11). A single-point anomaly on the north side of the Capitan Mountains coincides with small thorium/rare-earth veins known to occur in this Tertiary pluton (Phillips and others, 1991). The anomalous site lies near the Bonito Fault, a major northeast-trending fault that bisects the intrusive. A heavy-mineral concentrate prepared from the sediment sample did contain an unidentified thorium-rich mineral, as well as barite, and the rare-earth minerals, allanite and monazite.

A major cluster of thorium-rich sediments follows the west flank of the Oscura Mountains along one of a few exposures of Precambrian rocks in the study area. Felsic igneous rocks characteristically contain thorium and rare-earth minerals.

We have no reasonable explanation for the source of the thorium anomalies associated with redbeds of the Chinle Formation near Taiban Mesa east of Fort Sumner. Heavy-mineral concentrates prepared from the anomalous sediments from the Taiban Mesa area were scanned by optical and electron microscopy. Barite was identified, but no thorium mineral. The multi-element anomalies in sediments around Taiban Mesa may be a surface expression of mineralized rocks at the juncture of deeply penetrating northeast- and northwest-trending faults. Taiban Mesa lies approximately on strike with projections of the Bonita fault, Roosevelt County fault, and the Border buckle. Interpretation of the gravity data for this report has extended the buckles northeastward across much of the Roswell Resource Area.

Cerium in Sediments
Range: <10 - 229 ppm (ORNL); 17 - 168 ppm (LANL)
Median: 48 ppm (ORNL); 54 ppm (LANL)
Detection ratio: 1,989/2,004 (ORNL); 387/387 (LANL)
Baseline average: 65 ppm (Shacklette and Boerngen, 1984)

The pattern of high concentrations of cerium in sediments coincides with the outcrop of both Precambrian and Tertiary igneous rocks (fig. 12). A plot of another light rare-earth element, lanthanum, produced an identical pattern.

Rare-earth rich sediments are derived from very pure felsic rocks, possibly granites or rhyolites. Precambrian rocks--predominantly pink granite gneiss--are best exposed outside of the study area in the Pedernal Hills west of Vaughn; but small exposures crop out on the west flank of the Oscura Mountains and north of Gallinas in Lincoln County. The closely spaced pair of unposted cerium anomalies located west of Gallinas may represent contamination from the mining of the rare-earth mineral, bastnaesite, in the Red Cloud copper and fluorite mines upstream.

The most obvious cluster of cerium anomalies derives from sediments in the eastern part of the Capitan Mountains intrusive (east of the Bonito fault shown in Map A), with a dispersion train trailing eastward from the intrusive to the Pecos Slope. Sources of this rare-earth element are probably the rare-earth minerals, allanite and monazite, identified in the concentrate prepared from the only thorium-rich sediment from the Capitan Mountains described above, with allanite mentioned as occurring in Th-U-REE quartz/fluorite veins of the pluton (Phillips and others, 1991).

These higher concentrations of cerium and lanthanum in sediments toward the eastern end of the Capitan Mountains are probably derived from Th-U-REE quartz/fluorite veins of the Capitan intrusive (Phillips and others, 1991). The distinct geochemical difference between sediments on either side of the Bonito fault may be related to the deeper level of exposure of the eastern part of the Capitan intrusive, and to erosion and concentration of elements from the rare-earth-bearing-veins that once occurred on the periphery of the eastern side of the pluton. These geochemical differences may be important in assessment of the rare-earth-element potential of the Capitan intrusive.

Vanadium in Sediments
Range: <8 - 250 ppm (ORNL); 12 - 296 ppm (LANL)
Median: 50 ppm (ORNL); 56 ppm (LANL)
Detection ratio: 2,003/2,004 (ORNL); 387/387 (LANL)
Baseline average: 70 ppm (Shacklette and Boerngen, 1984)

Vanadium is part of a suite of elements (vanadium, arsenic, selenium, and molybdenum) in groundwater that can serve as pathfinders for uranium occurrences (Nichols and others, 1977). Some vanadium was produced with uranium from the Little Rattler and Good Luck mines near San Jon, Quay County (McLemore and North, 1985, table 3; Breit, this report), but nowhere else in the Roswell Resource Area. Several clusters of vanadium-rich sediments from the study area, therefore, may represent vanadiferous uranium occurrences. These clusters are located where the Chinle Formation is exposed, and include the Taiban Mesa area, the area around Sixmile and Hernandez Draws, and the Red Lake-Long Arroyo area to the south (fig. 13). Vanadium-rich sediments are relatively insoluble in the clay fraction of sediments and therefore do not necessarily correlate with uranium-rich sediments.

Stronger vanadium anomalies are found in the southern part of the porphyry belt and in the vicinity of the Oscura Mountains in Lincoln County. Here the more likely source may be either magnetite from the numerous iron deposits in the county (Griswold, 1959) or vanadiferous ilmenite, a titanium-iron oxide mineral. The focal points of the vanadium enriched sediments tend to be near faults in the Oscura Mountain region and Tertiary volcanic flows just west of the White Mountain Wilderness Area. The pattern of anomalous titanium concentrations in sediments matches closely that of anomalous vanadium in Lincoln County and in the area around Sixmile and Hernandez Draws in Chaves County.

SUMMARY

The NURE geochemical data have identified patterns of ore-related elements on a fairly broad regional base. The data have also been useful in identifying locally anomalous areas that may relate to mineralization and possibly underlying structures that served as conduits for metal-rich fluids. At least some of these local anomalies identified herein, such as the Taiban Mesa and the Red Lake areas, should be studied in more detail and evaluated for possible new mineral occurrences.

A significant aspect of the groundwater uranium results is related to potential hazards to human health rather than mineral resource assessment. The maximum contaminant level (MCL) of 20 µg/L proposed by the U.S. Environmental Protection Agency in June 1991 could impact a number ofpublic drinking-water supplies that might exceed the standard.

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GEOPHYSICS OF THE ROSWELL RESOURCE AREA, NEW MEXICO

GRAVITY AND AEROMAGNETIC DATA

by Dolores M. Kulik

Gravity and aeromagnetic data were evaluated in conjunction with geological, geochemical, and aerial gamma-ray data in determining the mineral resource potential of the Roswell Resource Area. The gravity and magnetic data provide information on the subsurface distribution of rock masses and the structural framework. The data are of reconnaissance nature and are, in most cases, adequate only to define regional features.

Aeromagnetic data is from the Composite Residual Total Intensity Aeromagnetic Map of New Mexico (Cordell, 1983) and are shown on Map E. Most of the data in the Roswell Resource Area are from surveys flown by the U.S. Department of Energy National Uranium Resources Evaluation (NURE) program. These surveys are flown at 122 m (400 ft) above ground level and at flight line spacings of 5-10 km (3-6 mi). An index of data sources and methods of combining the surveys are included on the original map by Cordell.

Gravity data were provided by the University of Texas at El Paso. Bouguer values were computed for this study using the 1967 gravity formula (International Association of Geodesy, 1967) and a reduction density of 2.67 g/cm^3 (grams per cubic centimeter). Mathematical formulas are given in Cordell and others (1982). Terrain corrections were made by computer for a distance of 167 km from each station using the method of Plouff (1977). The complete Bouguer gravity data are shown on map F with a contour interval of 5 mGal (milligals). A colored digital topographic map of the Roswell Resource Area is shown on map G with a contour interval of 153 m (500 ft). The digital topographic data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Data Center. An isostatic residual gravity map of the study area and the surrounding region is shown on map H with a contour interval of 5 mGal. These data were taken from digital files produced for the isostatic residual gravity map of the conterminous U.S. by Simpson and others (1986). The geologic map (map A) and tectonic map (map D) include place names and identify structural features which will be referred to in the following discussion. These maps should be used together with the geophysical plates and overlays to provide those references.

Interpretation

Gravity anomalies reflect differences in density distribution of igneous, sedimentary, and metamorphic rocks, whereas magnetic anomalies usually reflect differences in magnetic susceptibility (relative magnetite content) only of igneous rocks. The anomalies may be caused by differences in magnetite content or by differences in depth to crystalline basement rocks. Sedimentary rocks may usually be considered non-magnetic.

Three broad magnetic highs (1, 2, and 3, on map E) occur along the eastern edge of the study area. Gravity anomalies A, B, and, to a lesser extent, C (map F) generally coincide with these magnetic anomalies, although the apex of the magnetic anomaly is offset to the south of the apex of the associated gravity anomaly because of the inclined polarization of the earth's magnetic field. The breadth and moderate gradient of both magnetic and gravity anomalies indicate that the sources of the anomalies lie within the basement. Keller and others (1980; 1989) determined that the gravity relief between the Delaware Basin gravity low and the

Central Basin Platform gravity high (which lie south of the area of map F) cannot be explained by differences in thickness of sedimentary rocks overlying the basement. Only density contrasts in the basement can explain the anomaly.

Broad, low-amplitude magnetic anomalies occur in the eastern half of the map and are caused by differences in lithology of the rocks of the Delaware Basin shelf and differences in depth to basement beneath these sedimentary rocks. Basalt flows of Quaternary age in the western part of the study area, which frequently have associated magnetic anomalies, have no characteristic associated anomalies in the study area, suggesting that these flows are thin.

The Lincoln County porphyry belt in the westernmost part of the study area where Tertiary intrusive rocks crop out is characterized by short-wavelength magnetic anomalies (4, map E) with magnitudes up to 1,000 nT. Similar anomalies extend to the northeast from the porphyry belt (area indicated by dotted line on map E), where only Permian sedimentary rocks are exposed. The magnetic anomalies suggest that intrusive rocks similar to those of the porphyry belt are present at shallow depth. Magnetic anomalies of 1,660-2,000 nt (5 and 6, map E) extend southeast of the porphyry belt. These are attributed to uplifted Precambrian crystalline rocks of the Pajarito Mountain area which crop out southeast of Ruidoso near the edge of magnetic anomaly 6.

A T-shaped gravity anomaly (D, maps H, I) indicates that relatively high density rocks underlie (1) the Lincoln County porphyry belt, (2) most of the northeast extension of the belt interpreted from magnetic data, (3) the area just northwest of the exposed intrusive rocks where similar rocks are probably also present in the subsurface, and (4) the area of Precambrian rocks southeast of the porphyry belt at Pajarito Mountain. The T-shaped gravity anomaly appears to be caused by a composite source including both Tertiary intrusive and Precambrian rocks. The shape of the anomaly suggests that the Tertiary rocks were emplaced in a northeast-trending zone, orthogonal to the north-northwest trend of the Precambrian Pedernal Uplift in this area. The northwest trend of the part of the anomaly attributed to Precambrian rocks is deflected to the northeast (E, map F) near Tertiary rocks that crop out west of Hondo.

Aeromagnetic data in the region of the Lincoln County porphyry belt indicates that there is no consistent correlation of intrusive rocks with either magnetic highs or lows, and some of the larger intrusions are spatially associated with both high and low anomalies. The lack of any consistent correlation indicates that the intrusive rock is widely variable in magnetite content.

Hand samples from outcrops in the porphyry belt were measured for magnetic susceptibility using a portable susceptibility meter. The results show high variability (table 1). Outcrop samples with measured susceptibility values greater than 1,000 x 10^5 SI units are associated with relatively high magnetic anomalies, whereas those with lower measured values are associated with magnetic lows or gradients between anomalies.

Magnetic lows in the Gallinas Peak and Rough Mountain areas are caused by hydrothermal alteration of the intrusive rocks, as reported by Armbrustmacher (this report). Magnetic lows in the Tecolote Hills area suggest that those rocks are altered as well. The two intrusive bodies of the Jicarilla Mountains are represented by separate magnetic highs. Values of samples 13, 14, and 15 range from 1,400 to 3,400 x 10^{-5} SI units, and are associated with one of the closed highs. The value of sample 16 (17,000 x 10^{-5} SI units) from near Jacks Peak is an order of magnitude higher (table 1). The sample site is on the west flank of another closed high with greater amplitude than that to the south. The location of the Jacks Peak anomaly suggests that the source body extends and is centered east and southeast of Jacks Peak in the subsurface. Monzonite and syenite of Lone Mountain have no associated magnetic anomaly. A magnetic high is associated with the syenite and syenogabbro of Baxter Mountain, which are hosts for the White Oaks ore deposits. The magnetic anomaly indicates that a large body of similar composition extends to the southeast and includes the west flank of Carrizo Mountain. A magnetic low is associated with the east half of Carrizo Mountain, extends north to Patos Mountain, and east for another 5-7 mi. Lower magnetic values continue around the northeast side of the Baxter Mountain high to Lone Mountain, supporting the suggestion of a similar origin for the Patos, Carrizo, and Lone Mountain rocks. A magnetic low is associated with the high silica rocks of the west end of the Capitan Mountains; magnetic values are variable to the east, are not clearly associated with the Capitan intrusive body, and may have a basement source. Magnetic values associated with the Sierra Blanca Igneous Complex are varied and more study is required to determine the relations of individual anomalies to mapped stocks and possible subsurface intrusive bodies.

While the general area of the porphyry belt is associated with a gravity high (map F), the intrusive rocks and associated volcanic flows at Sierra Blanca and the western end of the Capitan Mountains body are associated with gravity lows, further indicating the varied composition of igneous rocks within the belt. The complex relationship of lithology, age, mineralization, and geophysical character of the Lincoln County porphyry belt cannot be resolved with currently available data.

Gravity lows are associated with thick sequences of sedimentary rock in the Claunch sag (F,G, map F) and on the flanks of the Delaware Basin (H,I,J). Low anomalies which might be expected to occur over thick sedimentary rocks in the southeastern part of the map are overwhelmed by the high values from basement sources, including the uplifted Central Basin Platform and probable mafic bodies within it.

In the south-central part of the study area, strong northeast-trending gravity gradients parallel wrench faults, termed buckles (map D), with normal, reverse, and strike-slip components. The continuity of the gravity gradients suggest that the buckles extend to the northeast beyond mapped exposures for many km in the subsurface (to approximately 34° 30' latitude). The Bonita fault and the parallel unnamed fault to the southeast may be surface expressions of these features. Beyond these faults, northeast-trending gradients terminate against a northwest-trending gradient. Similar strong northeast-northwest trending gradients extend in a zigzag fashion across northeastern New Mexico and southeastern Colorado, and may represent a crustal transition and (or) change in basement character from the Rocky Mountains to the High Plains and interior craton.

An isostatic residual gravity map of the Roswell Resource Area and surrounding area (map H) was extracted from the data used to prepare the map of the conterminous U.S. (Simpson and others, 1986) in order to display regional features and to compare with the Bouguer gravity data (map F). Long-wavelength Bouguer gravity anomalies commonly show an inverse correlation with topography. Isostasy, as defined by Airy (1855) and Dutton (1889), uses the principle that the load of topographic features is compensated or supported at depth by mass deficiencies or "roots", as though the earth's crust were floating on a denser layer. The Bouguer correction commonly applied to gravity data (as in map F) removes the attraction of topographic features down to sea level. Supporting or compensating masses, if beneath those features, then produce broad gravity lows. The isostatic correction attempts to remove the attraction of the compensating masses and, thus, isolate the gravity anomalies that arise from sources within the shallow crust. An in-depth discussion of isostatic principles applied to gravity data and methods used in preparing the isostatic residual map of the U.S. is found in Simpson and others (1986).

If it is assumed that isostatic balance is everywhere effective, high anomalies remaining on the isostatic residual map (map H) imply relatively more mafic bodies within the crust, and low anomalies imply sedimentary basins or felsic bodies. The inverse correlation between Bouguer gravity and topography is not clearly expressed in the study area (compare maps F and G), suggesting that the anomalies on the Bouguer anomaly map are not caused by compensating masses, but arise from sources within the upper crust. Both the Bouguer and isostatic residual maps have similar anomaly patterns and clearly display crustal density anomalies related to these features identified by number on map H: (1) intrusive rocks of the Lincoln County porphyry belt (A, map F); (2) uplifted, relatively dense Precambrian rocks of the Pajarito Mountain area (B, map F), (3) other Laramide uplifts of the Rocky Mountains, (4) the Sierra Grande uplift, (5) the high-standing Central Basin Platform and intrabasement mafic intrusives (E, map F), (6) the Delaware Basin and its flanks (H,I,J, map F), and (7) the Midland Basin.

Conclusions

Gravity data define the presence and location of dense and(or) shallow basement rocks beneath sedimentary rocks of the study area, and indicate the greater subsurface extent of buckles mapped at the surface. Magnetic and, to a lesser degree, gravity data define the subsurface extent and location of intrusive rocks of the Lincoln County porphyry belt. The magnetic data suggest that similar intrusive rocks extend in the subsurface beyond the mapped exposures. Good correlation exists between measured susceptibility values of exposed rocks and their associated magnetic anomalies and varying lithologies may be correlated with individual magnetic anomalies in the northern part of the Lincoln County porphyry belt. Variability of susceptibility within intrusions in the Sierra Blanca Igneous Complex in the southern part of the belt prevents their correlation with individual magnetic anomalies. The lack of an inverse correlation between topography and Bouguer gravity values and the similarity of features on the Bouguer and isostatic gravity maps suggest that isostatic compensation has not been achieved in the study area.

AERIAL GAMMA-RAY DATA

by Joseph S. Duval

Aerial gamma-ray data used in this study were originally acquired as part of the NURE Program of the U.S. Department of Energy (DOE) (fig. 14). These surveys were flown at a nominal altitude of 122 m (400 ft) above the ground with flight line spacing of about 5 km. The data acquisition equipment included about 50 L of sodium-iodide detectors.

Because the gamma-ray data acquired as part of the NURE Program were found to be an inconsistent data base with regard to a constant datum among the various surveys, the data were reprocessed and appropriate corrections were applied to achieve a consistent data base. The procedures and corrections applied to the data are described by Duval and others (1989, 1990). The reprocessed NURE data were gridded using a minimum curvature algorithm (Briggs, 1974; Webring, 1981) and an initial grid interval of 2.5 km. For this particular study, the initial grid was regridded to an interval of 1.27 km using a 2-dimensional spline. The initial grid interval was chosen based upon the initial flight line spacing of 5 km and the data were regridded to facilitate comparison to the geology and to simplify computer processing associated with the preparation of maps at the desired scale of 1:500,000.

The NURE aerial gamma-ray surveys included measurements of the gamma-ray flux produced by the radioactive decay of K^{40}, and by members of the radioactive decay series of U^{238} and Th^{232}. The resulting measurements have been expressed as the apparent surface concentration of potassium, uranium, and thorium. The uranium and thorium concentrations are usually described as "equivalent" concentrations because of the possibility of radioactive disequilibrium in the uranium and thorium decay series. Maps I, J, and K show the data for the apparent surface concentrations of potassium (percent K), equivalent uranium [parts per million (ppm) eU], and equivalent thorium (ppm eTh), respectively.

The K, eU, and eTh data were imported into the Geographic Resource Analysis Support System (GRASS)(Lozar and Goran, 1987; Hastings, 1988; Lozar, 1989). Analysis algorithms within GRASS were used to analyze the data. In order to compare the gamma-ray data to the geology, a digitized version of the geologic map was also imported into the GRASS system and then converted to a grid with the same grid interval as the gamma-ray data (1.27 km). Because of the limited resolution defined by the grid cell size, some of the smaller geologic units (less than about 2 km^2) were not represented in the grid version of the geologic map. Table 2 and figures 15-17 show estimated average concentrations of K, eU, and eTh for the different geologic units within the study area. These average values were obtained by identifying the grid cells associated with each geologic unit and calculating the average values for those grid cells. Table 2 includes columns that contain calculated values for the standard deviation of the concentrations. Because of the processing used to obtain the data grids, the standard deviation values should not be interpreted as estimates of accuracy, but as indicators of the uniformity of the radioactivity of the mapped geologic units. Also the concentration estimates of those geologic units for which the grids contained fewer than 100 grid cells may not be reliable.

The most radioactive rocks in the study area are Tertiary volcanic flows (Tv) and alkalic intrusions (Tis), Tertiary and Cretaceous Cub Mountain Formation (TKcm), Quaternary and Tertiary intermountain gravels (QTg), undivided Cretaceous (Ku) rocks, and undivided Triassic (Tru) rocks (figs. 15a-17a). The most radioactive map units are also most variable, as shown by the calculated standard deviations shown as error bars (figs. 15b-17b). Table 2 lists the calculated standard deviation for mapped geologic units; asterisks mark the calculated standard deviations that are greater than the average values. Mapped geologic units QTg, Tv, and TKc have greater variability than the averages for K, eU, and eTh. Quaternary pediment and terrace gravels (Qal) have greater than average variabilities for eU and eTh. Mapped geologic units Tis, Ku, Tru, and Pya (Yeso, Abo, and Hueco Formations) have greater than average variabilities for K and eTh. Each of these mapped geologic units was examined to determine the nature of its gamma-ray characteristics. The Quaternary and Tertiary intermountain gravels (QTg) were found to have two areas with distinct characteristics. Part of these gravels has low radioactivity with concentrations of 0.6-1.4 percent K, 1.0-2.0 ppm eU, and 3.4-8.0 ppm eTh and part of it has higher radioactivity with concentrations of 1.4-3.0 percent K, 2.0-3.0 ppm eU, and 8.0-13.0 ppm eTh. The Tertiary volcanic flow unit contains localized areas with greater than 1.7 percent K, greater than 2.0 ppm eU, and greater than 8.0 ppm eTh. Quaternary pediments and terraces tend to reflect the source rocks from which the materials are derived and could easily be subdivided based upon the gamma-ray signatures. The Cretaceous and Tertiary Cub Mountain Formation crops out in three geographically separated clusters. Of these areas, the westernmost area is more radioactive and has concentrations of 2.0-3.0 percent K, 2.4-3.0 ppm eU, and 10.0-12.2 ppm eTh. The remaining areas have concentrations of 0.9-1.8 percent K, 1.6-2.4 ppm eU, and 6.9-9.3 ppm eTh. Undivided

Cretaceous units crop out in the northeastern and southwestern parts of the study area. The units in the northeastern area have lower radioactivity with values of 0.8-1.1 percent K, 1.6-3.0 ppm eU, and 4.7-6.8 ppm eTh. The units in the southwestern area have a similar range of values, but also include localized areas of higher radioactivity with concentrations of 1.6-2.8 percent K, 3.0-3.5 ppm eU, and 8.4-14.0 ppm eTh. Rocks of the undivided Triassic unit crop out in small isolated areas in the southwestern part of the study area and include areas of higher radioactivity with values of 1.4-2.0 percent K, 1.9-2.2 ppm eU, and 7.4-10.4 ppm eTh, and areas of lower radioactivity with 0.9-1.0 percent K, 1.4-1.6 ppm eU, and 5.8-7.0 ppm eTh. The Permian San Andres Formation has generally similar patterns for the distribution of K and eTh with large areas of low values which have 0.2-0.8 percent K and 2.1-4.0 ppm eTh and localized areas of higher radioactivity which have 1.7-2.9 percent K and 6.3-9.6 ppm eTh. Most of the area of the San Andres Formation has concentrations of 0.8-1.7 percent K and 4.0-6.3 ppm eTh. The distribution of eU within the San Andres Formation is distinct from the distributions of K and eTh, except for some low radioactivity areas in the northern part of the area which have 0.8-1.2 ppm eU. The eU pattern includes large areas of higher uranium concentration (2.4-2.7 ppm eU) which do not, in general, coincide with higher concentrations of K and eTh. This difference in the radioelement patterns suggests that the uranium has been moved by geochemical processes such as ground water circulation. The Permian Yeso Formation and related rocks have generally low radioactivity with concentration of 0.5-1.5 percent K, 1.3-2.5 ppm eU, and 2.8-7.0 ppm eTh with localized areas of higher concentrations (1.8-2.5 percent K, 1.9-2.4 ppm eU, and 8.2-11.5 ppm eTh). With the exception of the San Andres Formation, the variability of the radioelement concentrations noted above is probably a reflection of different lithologic materials within each mapped geologic unit or, in the case of the Quaternary units, of the different source rocks. The explanation for the difference between the distributions of K and eTh and that of eU within the San Andres Formation is unknown.

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INDUSTRIAL MINERAL RESOURCES OF THE ROSWELL RESOURCE AREA

by Susan Bartsch-Winkler,

with sections on
Potash, saline brines, and brine deposits
by Sherilyn Williams-Stroud, and
Sulfur by Charles S. Spirakis

Industrial minerals are an important mineral endowment of the Roswell Resource Area. Gypsum, caliche, clay, limestone, building stone, aggregate, sand and gravel, and gemstone (including "Pecos diamonds", smoky quartz, and petrified wood) are or have been produced in the study area. There are potentially important sulfur and potash reserves, but no production, within the Roswell Resource Area.

EVAPORITES

Evaporite deposits of southeastern New Mexico and western Texas occur in the Permian Basin backreef environment (fig. 18). Concentrations of halite, polyhalite, anhydrite, gypsum, and other salts probably were precipitated from seawater or were transported into the Permian Basin during periodic salt-brine influx from evaporite deposits surrounding the basin (Adams, 1969). Evaporites are deposited by trapping of sea-water brine and evaporation. Many evaporite deposits have been isolated by impermeable overlying and underlying units and, thus, are protected from groundwater dissolution (Bachman, 1987).

According to Pitt and Scott (1981) in their study of subsurface depositional cycles in the San Andres Formation in Guadalupe, De Baca, Chaves, Quay, Curry, and Roosevelt Counties, the evaporite deposits are transitional from halite to anhydrite, with halite occurring with greater frequency and anhydrite with lesser frequency northward. Also, anhydrite is more abundant and dolomite less abundant north of the Matador uplift (Gratton and LeMay, 1969). Evaporite beds are thick along the north-south border between Quay and Guadalupe Counties near Montoya, in Quay County south of Tucumcari, and in Curry County near Clovis. At the latter locality, subsurface evaporites consist mostly of halite. In the subsurface, evaporites are as much as 40 m (130 ft) thick in western Quay County, as much as 24 m (80 ft) thick in northern Roosevelt County, and as much as 18 m (60 ft) thick in southeast Roosevelt County (Pitt and Scott, 1981).

Potash

by Sherilyn Williams-Stroud

Since 1931, the Carlsbad District [about 80 km (50 mi) south of the southern boundary of the study area] has been the largest domestic producer and contains the largest reserves of potash in the U.S.; it is one of the world's major potassium deposits (Cheeseman, 1978). The total capacity of present New Mexico mining operations is estimated to be 1,500 thousand metric tons of K_2O equivalent per year (Searles, 1985). New Mexico contains about 55 million st of 100 percent K_2O equivalent total recoverable reserves, or about 57 percent of the nation's reserves (New Mexico Department of Energy, Minerals and Natural Resources, 1990), with most of the reserves located in Eddy and Lea Counties south of the study area. Potash is used primarily for fertilizer (Austin, 1980). The largest consumer of potash has been the U.S.S.R., with U.S. soybean and corn farmers in the Midwest having been the largest domestic users. However, due to transportation costs, only about 20 percent of New Mexico's potash is used domestically (New Mexico Department of Energy, Minerals and Natural Resources, 1990). The vast potash reserves in the Carlsbad potash district and in Utah and Canada are more likely to provide potash for domestic and world markets than any deposits beneath the Roswell Resource Area.

Carlsbad potash district

Twelve potash ore zones are identified in the Carlsbad potash district. They typically occur, but are not confined to, the middle and upper parts of the Salado Formation (Austin, 1980). A mixture of sylvite and halite (known as sylvinite) and langbeinite are mined (Cheeseman, 1978; Austin and Barker, 1990). Gangue minerals in the Salado Formation of the Carlsbad District include leonite ($MgSO_4 \cdot K_2SO_4 \cdot 4H_2O$), kainite ($MgSO_4 \cdot KCl \cdot 3H_2O$), carnallite ($MgCl_2 \cdot KCl \cdot 6H_2O$), polyhalite ($2CaSO_4 \cdot MgSO_4 \cdot K_2SO_4 \cdot 2H_2O$), kieserite ($MgSO_4 \cdot H_2O$), bloedite [$Na_2Mg\ (SO_4)_2 \cdot MgSO_4 \cdot 4H_2O$], halite, and anhydrite (Cheeseman, 1978). Major accessory evaporite minerals at Carlsbad are gypsum ($CaSO_4 \cdot H_2O$), anhydrite ($CaSO_4$), and halite (NaCl). Sylvite (KCl), carnallite, and langbeinite [$(Mg_2K_2SO_4)_3$] are interbedded with halite. According to Cheeseman (1978), a typical mixed-ore sample from the Salado Formation in the Carlsbad District contains 60 percent halite, 30 percent sylvite, 5 percent langbeinite, and 2 percent each of polyhalite and insolubles.

In the Carlsbad potash district, potash is mined by conventional underground techniques using drum miners to remove the sylvite ore in a room-and-pillar configuration. Because of the hardness of the ore, the mines that recover langbeinite ($2MgSO_4 \cdot K_2SO_4$) use jumbo drills and undercutters, blasting and mucking techniques, and shuttle cars. Sylvite ore is beneficiated into muriate of potash and langbeinite ore is beneficiated into sulfate of potash-magnesia (New Mexico Department of Energy, Minerals and Natural Resources, 1990).

Roswell Resource Area

The potash-bearing Salado Formation extends north and east from the Carlsbad potash district to the Northwestern Shelf, the Central Basin Platform, and the Midland Basin in Texas (Cheeseman, 1978) (map D, inset). The evaporite sequence is as much as 1,300 m (400 ft) thick and contains potassium minerals in the 12 soluble potash horizons that occur over a relatively confined area of approximately 5,000 sq km (1,870 sq mi) of the west-central Permian Basin (fig. 19) (Adams, 1970). The Salado Formation is as much as 700 m (2,300 ft) thick in these boundary areas of the Permian Basin and consists of generally flat-lying beds composed of halite, muddy halite, anhydrite, polyhalite, dolomite, and mudstone. Massive polyhalite beds in halite beds occur over the majority of the area of salt extent (Jones, 1972; Lowenstein, 1988) (fig. 19).

The northwestern part of the soluble potash zone of the Salado Formation falls within the Roswell Resource Area in the southeastern corner of Chaves County (fig. 19). Due to their southeast dip, potash-bearing beds probably are closer to the surface or probably have been dissolved to the north and west (the area of the Roswell Resource Area). The thickness of the Salado Formation in Chaves County thins northward from 200 m (about 660 ft) to zero m over an area of approximately 500 sq km (from the southern boundary of the Roswell Resource Area) (File and Northrop, 1966; Lowenstein, 1988; Austin and Barker, 1990) (fig. 18).

Thus, while economically important potash deposits are found in the Salado Formation near Carlsbad, the part of the potash facies of the Salado Formation which is located within Chaves County is not as thick as that found in the Carlsbad potash district (where the thickness ranges from 200 m to over 400 m). It is possible that the evaporite deposits in the Roswell Resource Area are of similar economic grade to those in the Carlsbad District, although the thicknesses of the potash beds in the study area may be the factor that determines whether the resource will become economic in the near future. A very rough estimate of the volume of K_2O which is currently economic in grade, based on the volume of halite in the Salado Formation in the Roswell Area (assuming the same ore grade as in the Carlsbad District) is approximately 1 billion sq m, or the equivalent of 1.9 billion metric tons.

The Rustler Formation, which overlies the Salado Formation within the Ochoan series, and the Tansill and Yates Formations, which occur below the Salado Formation, all contain evaporites (map C). Some occurrences of potash have been reported in these formations (Jones, 1972), but the potassium-bearing beds contain primarily polyhalite. Although polyhalite is not currently considered a potash ore mineral, recent studies suggest that finely ground polyhalite may be as effective as granular soluble potassium salts for the fertilization of acid soils (Barbarick, 1991). The total volume of polyhalite in the Salado Formation alone may approach 1.7 billion metric tons.

Gypsum

About 1900, near Ancho and in the Phillips Hills near Oscura, gypsum was quarried from beds in the San Andres Formation and Artesia Group that were from 3-6 m (10 to 20 ft) thick; the gypsum was processed locally for plaster (Talmage and Wooton, 1937; Griswold, 1959; Weber and Kottlowski, 1959). In 1902, a small testing plant was in operation at Ancho, and a large mill was under construction for processing gypsite. In 1903, 100 tons per day were being processed for cement, plaster-of-Paris, stucco, and other uses (Herrick, 1904; Jones, 1915). Near Acme northeast of Roswell, Permian gypsum beds of variable thickness have been quarried for plaster (Weber and Kottlowski, 1959). However, structural complications and the low purity of the gypsum (table 3) are inhibiting factors for commercial production (Weber and Kottlowski, 1959).

In order to be of economic value, gypsum deposits must be thick and laterally extensive, with only thin overburden. Typical ore dimensions of minable gypsum deposits range from 10 m to 50 m (33 ft to 164 ft) in thickness over an area of several square kilometers (Raup, 1991). Most gypsum is strip-mined, but beds having 50 m (164 ft) or more of overburden can be mined by conventional underground methods. Marine-bedded gypsum deposits account for the major part of the world's gypsum production. Often the gypsum in these deposits is the result of near-surface hydration of anhydrite, but the economic value depends on the completeness of this process.

Gypsum and anhydrite are important construction materials, agricultural additives, and important sources of chemicals. Gypsum is hydrous calcium sulfate, containing 20 percent water. This important property makes it an important additive (after calcining) of quick-setting plasters, such as plaster of Paris. Most gypsum is used for the manufacture of wallboard, Portland cement, and building plaster, and gypsum is used to break up alkaline-rich soils. Anhydrite (the anhydrous form of gypsum) is also used in many applications, but to a lesser extent due to differing chemical and physical properties. Alabaster, a crystalline form of gypsum, is used for carving. Economic gypsum deposits, however, must be relatively free of impurities. Table 4 lists the chemical compositions of various gypsum deposits in east-central New Mexico.

Stratigraphic occurrence

Large gypsum and anhydrite deposits in the Artesia Group and San Andres Formation occur from Carlsbad to Fort Sumner; they cover an estimated 3,630 sq km (1,400 sq mi) (Bachman, 1987). Gypsum beds in the Artesia Group are relatively thin and lenticular (Weber and Kottlowski, 1959). Gypsum deposits also occur on the western Pecos Slope and adjacent to the porphyry belt in the Yeso and San Andres Formations (fig. 20). Because they are at or near the surface, they can be mined easily. Gypsum deposits are estimated to cover 22,764 sq km (8,766 sq mi) (fig. 19; map L).

Gypsum in the Yeso Formation is the most important gypsum resource in the study area, although it is typically interbedded with clastic and carbonate units, is altered, and covered by thick overburden. The Yeso Formation crops out in the Rio Hondo, Rio Bonito, Rio Ruidoso, and the Rio Peñasco (in the southern part of the Mescalero Apache Indian Reservation), as well as in many smaller tributaries which drain the Pecos Slope east of the Sacramento Mountains. Gypsum beds in the Yeso Formation are generally 0.6-33 m (2-10 ft) thick and poorly exposed.

Gypsum occurs in the San Andres Formation near Ancho, Vaughn, and on Chupadera Mesa, and is a large component of the San Andres Formation on the Pecos Slope in Lincoln and Guadalupe Counties (Weber and Kottlowski, 1959; U.S. Geological Survey, 1965). The continuity of gypsum in the San Andres Formation is typically destroyed by dissolution and collapse; lenticularity of the gypsum beds may also be due to structural complications.

Large deposits of gypsum occur in the Castile and Rustler Formations south of the study area. Limited quantities of gypsum occur in the Rustler Formation in the southeastern part of New Mexico northeast of Carlsbad. Gypsum occurs only as small stringers in veins and as cement in the Dewey Lake Formation (Weber and Kottlowski, 1959).

Roswell Resource Area deposits

The study area contains vast gypsum resources (Weber and Kottlowski, 1959; Austin and others, 1982). The median estimated tonnage of undiscovered deposits of gypsum in the Roswell Resource Area is about 6 billion metric tons (Sutphin, table 11, this report).

Thick gypsum beds are exposed in a low hill at the northeast edge of the village of Ancho. Gypsum occurs at moderate depths beneath limestone in the region that extends southwestward from Vaughn to beyond Corona (Darton, 1920; Weber and Kottlowski, 1959) (fig. 20; map L). This gypsum contains thin limestone laminae and is coarsely crystalline, as much as 11 m (35 ft) thick, and locally contains selenite porphyroblasts (Weber and Kottlowski, 1959). The upper beds and associated gypsite cap are 9-11 m (30-35 ft) thick and consist of white, gray, and thin dark-gray gypsum beds with sparse limestone laminations. Chip samples taken from the top to the bottom of this sequence at 0.3-m (1-ft) intervals contained an average of 96.9 percent gypsum (Weber and Kottlowski, 1959). Other beds are 3.0-4.5 m (10-15 ft) thick.

Gypsum is exposed extensively throughout the Ancho area. However, as both Darton (1920) and Weber and Kottlowski (1959) acknowledge, structural complications, such as folding, fracturing, faulting, and igneous intrusions, seriously limit the economic potential of the area.

Darton (1920) and Weber and Kottlowski (1959) describe the occurrence of gypsum beds in the walls of sinkholes and in an abandoned rock quarry northwest of Vaughn in Guadalupe County. In the quarry, a gypsum bed at least 6 m (20 ft) thick was observed. The total thickness is not known, because the bottom of the bed could not be seen due to rubble cover. A random chip sample of the bed contained 94.8 percent gypsum. The gypsum is overlain by 3-9 m (10-30 ft) of limestone. Other pits in the area show approximately 3.4 m (11 ft) of gypsum and 0.6-4.0 m (2-13 ft) of limestone cover.

Additional exposures were seen in the wall of a sinkhole southeast of the quarry, and two gypsum beds are exposed in another sinkhole. In this sinkhole, according to Weber and Kottlowski (1959), the lower bed is a minimum of 5 m (17 ft) thick (the bottom of the bed was covered). Between the two gypsum beds is a 2.5-m-(8-9 ft-)thick bed of limestone, which was covered by an additional 4.6 m (15 ft) of gypsum in the upper bed. About 6 m (20 ft) of limestone separated the upper bed from the surface. A nearby drillhole had passed through gypsum with thin interbedded clay down to 52 m (170 ft). These observations led Weber and Kottlowski (1959) to conclude that gypsum beds lie beneath a thin cover of limestone and alluvium over a very large area near Vaughn; further exploration would be required to assess its extent and quality.

In the region from Vaughn to Santa Rosa, surface and near surface exposures of bedded gypsum in the San Andres Formation and Artesia Group are covered locally by a thin veneer of Tertiary and Quaternary deposits (Weber and Kottlowski, 1959). Deposits of massive gypsum are as much as 6 m (20 ft) thick. The gypsum is white, contains limestone seams, selenite porphyroblasts, and limestone nodules at the base, and grades upward into thin-bedded, gray to white gypsum with lesser amounts of limestone at the top (Weber and Kottlowski, 1959). Quarries expose good- to poor-quality gypsum as much as 5 m (17 ft) thick and the gypsum is overlain by blocky limestone (Weber and Kottlowski, 1959). A drillhole log from the area describes a thick sequence of gypsum interbedded with clay from the surface to a depth of 52 m (170 ft) (Darton, 1928; Weber and Kottlowski, 1959).

Gypsum deposits have been described from the Phillips Hills west of Sierra Blanca in Lincoln County (Schmalz, 1955). The deposits are in numerous beds of the San Andres and Yeso Formations, are poorly exposed, and occur as interbeds in limestone. Pure white gypsum beds up to 30 m (100 ft) thick are apparently covered by cellular gypsite and numerous interbeds of limestone and siltstone (Weber and Kottlowski, 1959). Weber and Kottlowski (1959) note that the beds are poorly exposed beneath dark-gray limestone and gypsite. A columnar section (Darton, 1920) shows beds up to about 30 m (100 ft) thick. The total thickness of the beds is approximately 122 m (400 ft), with the greater part described as being white and of good quality. At most places, the beds dip eastward at 5°-16°, but in some places they are almost horizontal. Weber and Kottlowski (1959) report that in some canyons, several acres of gypsum underlie a thin veneer of soil and limestone. In most places, however, extensive stripping or underground mining would be required to exploit large deposits. Chip samples of a 20-ft-thick interval indicated an average of 98.1 percent gypsum (Weber and Kottlowski, 1959) (table 4).

West of the Pecos River Valley on the Pecos Slope, gypsum beds are not as well exposed as they are further east in the Pecos River Valley, but they are near the surface and amenable to strip-mining (although the beds are of variable grade and thickness) (Weber and Kottlowski, 1959). The gypsum deposits are interbedded with dolomitic limestone and red beds, are lenticular, and relatively thin-bedded. Along the Rio Hondo and Rio Ruidoso and their upper tributaries, exposed thin beds of gypsum occur in the upper part of the Yeso Formation. The beds are generally 0.6-3.0 m (2-10 ft) thick and poorly exposed.

The southeastern New Mexico region (especially the Pecos River Valley from Santa Rosa to Carlsbad and to the east of Artesia and Hagerman) contains abundant gypsum in the Artesia Group, especially in the Grayburg, Seven Rivers, and Tansill Formations, that are at or near the surface (Weber and Kottlowski, 1959). In southeastern New Mexico and along Pecos River Valley, thin to thick Permian gypsum beds provide gypsum for local agricultural and industrial use, especially near Acme (Weber and Kottlowski, 1959). At Acme, the beds are light-gray crystalline gypsum 0.3-1.8 m (1-6 ft) thick that is interbedded with red beds and covered by gypsite. Gypsum beds are exposed near Roswell east of the Pecos River. They are 0.3-1.5 m (1-5 ft) thick, interbedded with red beds (shale, fine-grained sandstone, and siltstone), green shale, and limestone (Weber and Kottlowski, 1959), locally contorted, and contain lenses and small beds of high-purity gypsum. Intervals of gypsum-bearing limestone (with as much as 80 percent gypsum) are as thick as 6 m (20 ft). South of the study area and east of Artesia and Hagerman, extensive deposits of gypsum crop out.

Beds of pink to white alabaster as much as 66 cm (26 in.) thick are known to occur at one locality north of Roswell, but it is unknown whether alabaster deposits occur elsewhere in the study area (George Austin, New Mexico Bureau of Mines and Mineral Resources, oral communication, July 1991).

Halite

Halite-bearing strata occur throughout the Permian Basin in Kansas, Oklahoma, Texas, Colorado, and New Mexico (map D) (McKee and Oriel, 1967; Budnik, 1989) (fig. 19). Halite is most abundant in the Salado Formation near Carlsbad south of the study area. The Salado contains as much as 395 m (1,300 ft) of halite (Lowenstein, 1988), typically pink to pale red due to the presence of hematite, silt, or clay impurities. In the western Delaware Basin, salt layers in the Rustler Formation are represented by breccia, gypsum, siltstone, and sandstone due to solution and collapse; to the north, the Salado Formation halite beds wedge out (U.S. Geological Survey, 1965). Halite also occurs in other Permian formations including the Yeso, San Andres, Grayburg, Queen, Seven Rivers, Yates, and Tansill. Subsurface halite and anhydrite beds (but no potash) in the Yeso Formation are as thick as 590 km (1,935 ft) in sec. 33, T. 6 S., R. 9 E., Lincoln County (U.S. Geological Survey, 1965; Austin and others, 1982).

Halite deposits occur beneath all of Guadalupe, Quay, Curry, De Baca, Chaves, and Roosevelt Counties and beneath the eastern half of Lincoln County (Austin and others, 1982). Known halite beds of variable thickness occur on the surface and in the subsurface over approximately 34,000 sq km (13,000 sq mi) in the Roswell Resource Area. Despite these vast resources, there are no active salt mines in the study area (Austin and others, 1982).

Iodine and bromine in saline brines and brine deposits

by Sherilyn Williams-Stroud

Saline brine deposits form in a karstic setting where much groundwater is introduced into an evaporite sequence and the rocks are dissolved until the liquid is saturated. Brines also occur in beds associated with evaporite deposits, which may have been original deposition brines from which salts precipitated. The salts became trapped in higher-porosity associated rocks upon expulsion from the evaporites due to burial compaction. In many cases, these brines may be altered from their original composition by rock interactions. The permeability of the host rock is typically negligible, resulting in loss of circulation and stagnation of the brine (Bachman, 1987).

The presence of brine "aquifers" are important to the hydrologic regime of an area because they may contaminate ground water. Such aquifers may be perched above impermeable layers within evaporite sequences (Bachman, 1984). It is likely that brine deposits occur beneath the Roswell Resource Area in beds of Permian age, although their extent is unknown.

Iodine and bromine resources

Iodine and bromine occurs in brines south of the study area in the Rustler Formation, Dewey Lake Formation, and in the Bell Canyon Formation (an Artesia Group equivalent south of the Capitan Reef; map C) at concentrations of less than 1 ppm, and bromine occurs in brines at concentrations of 26-78 ppm (Steven J. Lambert, U.S. Geological Survey, written communication, 1991). In comparison to the low expected concentrations in the study area, concentrations of iodine in brines of commercial operations in Oklahoma range from 150 to 1,200 ppm, in Michigan at concentrations of 30 ppm, and in California at concentrations of 30 to 70 ppm (Lyday, 1985a). Bromine is produced commercially in Arkansas and Michigan from subsurface brines having concentrations of 5,000 ppm and 1,600 ppm, respectively (Lyday, 1985b). If brine aquifers containing iodine and bromine occur in the subsurface beneath the Roswell Resource Area, they would probably occur at subeconomic concentrations.

Sulfur

by Charles S. Spirakis

The United States is the chief world supplier of sulfur. Most sulfur is produced from salt dome caprock deposits beneath Texas and Louisiana (Bateman, 1950). Sulfur is extracted by the Frasch process, which uses hot water and high pressure to melt sulfur and force the molten liquid through pipes to the surface.

In the Roswell Resource Area, many occurrences of native sulfur associated with anhydrite have been reported (Talmage and Wooton, 1937; Hinds and Cunningham, 1970; Smith, 1978; Thomsen, 1990) and many other occurrences have been noted in drill cuttings and cores. Except for sulfur recovered as a by-product of oil and gas production, no sulfur has been produced in the Roswell Resource area, but exploration is continuing, especially near Artesia (south of the study area) and Santa Rosa. Near the study area boundary northwest of Artesia (sec. 8, T. 16 S., R. 22 E.), a 6-m- (20-ft-) thick sulfur bed of high purity was encountered at 940 ft depth (Talmage and Wooton, 1937). Sulfur occurrences in gypsum are also reported from near White Oaks (Jones, 1915; Talmage and Wooton, 1937). Although no native sulfur is being mined in the Roswell Resource Area, exploration is continuing, especially in an area stretching from just east of the city of Roswell to the southern boundary of the study area.

Texas deposits

Large deposits of bedded sulfur occur south of the Roswell Resource Area in the Rustler Springs district, Culberson County, Texas. The Rustler Springs sulfur district contains the world's largest sulfur deposits produced using the Frasch process. Production has totaled more than 36,100,000 long tons from 1969 to early 1990, with average daily production of 6,000-7,000 long tons (Hentz, 1990). The deposits are in the Salado and Castile Formations and in the Permian reef (Hentz, 1990; Crawford, 1990). The thick Castile Formation (which does not occur in the Roswell area) and the Salado Formation are targets in sulfur exploration in the Permian Basin, where there is evidence of both underlying petroliferous rock, intrastratal salt and clay units, and faults and/or joints (Hentz and Henry, 1989; Hentz, 1990). Sulfur is thought to have been entrapped and/or preserved by impermeable beds and structures (Hentz, 1990).

The Culberson sulfur mine, the largest in the Rustler Springs district, produces from an elliptical deposit in vuggy, secondary-limestone host rock. Sulfur occurs in the Castile and Salado Formations, lining both vugs and fractures in the central part of the body (Hentz, 1990). The deposit trends into a northeast-trending graben (Hentz, 1990). Shale deposits typically overlie the sulfur deposits and possibly are related to sulfur deposition. The Culberson deposit is not directly associated with oil, but minor oil and asphalt occur in surrounding strata, and oil fields to the south trend into the deposit. Barite deposits locally overlie the sulfur deposits. The Phillips Ranch deposit, west of the Culberson mine, also occurs in a northeast-trending graben, and the elongate orebody contains the thickest sulfur deposits in the central part of the graben (Hentz, 1990). The sulfur was apparently concentrated along fault zones that define the down-faulted block and that may have served as impermeable traps. Sulfur is restricted to the basal part of the Castile Formation in lenticular limestone beds as much as 140 m thick (Hentz, 1990). The Pokorny deposit, as yet unmined, is located northwest of the Culberson mine near a fracture zone (typically the fractures provide permeability); sulfur occurs in the basal part of the Castile Formation (Hentz, 1990). In other aspects, this deposit is similar to the Phillips Ranch deposit.

Origins and assessment of sulfur resources

In assessing the potential for native sulfur deposits, it is important to consider the volume of reductant (oil or gas) needed to make a large deposit. For example, it is estimated that the volume of oil needed to form the Culberson deposit was 200 million barrels (Smith, 1978). Deposits much smaller than the Culberson might become economic; nevertheless, substantial amounts of reductant are required. Two types of sulfur deposits that formed by similar processes might be of economic importance in the study area. In one of these deposit types, exemplified by the Culberson deposit discussed above, organic matter in the form of oil or gas migrated into anhydrite beds at the site now occupied by the sulfur deposit. Bacteria catalyzed the reduction of sulfate by organic matter to form hydrogen sulfide; hydrogen sulfide was then oxidized, either by excess sulfate or oxygen in meteoric water, to native sulfur (Feely and Kulp, 1957; Davis and Kirkland, 1970). Commonly, an impermeable cap of shale or salt overlies these deposits.

In the second type of sulfur deposit, exemplified by the native sulfur deposits in Lechuguilla cave, Eddy County, New Mexico (Spirakis and Cunningham, 1992), sulfate is reduced by organic matter to hydrogen sulfide; in this example, the reduction does not occur at the site now occupied by the sulfur deposit. It is possible that the reduction process occurs deep in the basin at sufficiently high temperatures for thermochemical sulfate reduction (that is, reduction not catalyzed by bacteria) to occur. In contrast to the first type of sulfur deposit, hydrogen sulfide in these deposits migrates away from its parent sulfate before being oxidized to native sulfur. As in the first type of sulfur deposit, the sluggish kinetics of hydrogen sulfide oxidation suggests that bacteria were involved in the oxidation.

In both of these deposit types, the critical factors in forming native sulfur are (1) sedimentary anhydrite as a source of sulfur, (2) organic matter to act as a reductant, (3) sufficient permeability to allow the organic matter to migrate to the anhydrite, (4) temperatures low enough for bacteria to survive and to catalyze the oxidation of hydrogen sulfide, and (5) presence of an oxidant. Temperatures low enough for bacteria to survive and the penetration of oxidizing groundwaters are ubiquitous in the upper few thousand feet within the Roswell area and, hence, are not useful for outlining most favorable areas within the study area.

In the study area, the region of high potential for native sulfur deposits may be outlined by superimposing the areas of high oil, gas, or tar sand potential upon the areas underlain by anhydrite deposits (fig. 21). Much of the Roswell Resource Area is underlain by anhydrite deposits, and individual beds are more than 30 m (98 ft) thick (Johnson and others, 1989). Migrated organic matter (oil, gas, and tar sand) occurs near Artesia and Santa Rosa. In this area, large deposits of both types described above might be found. An area of moderate potential, surrounds the region of high potential; it might contain sulfur deposits derived from migrated hydrogen sulfide. How far hydrogen sulfide can migrate before it encounters oxidizing conditions is not clear and, therefore, the outer limit of this region is not well defined.

Specific exploration targets within the favorable areas might be identified by applying other criteria, including the presence of cap rocks, the presence of secondary calcite that forms as sulfate is reduced by organic matter, and the identification of faults, dissolution zones, or other permeable zones that might have provided avenues for migration of organic matter, hydrogen sulfide, or oxidizing ground waters. Hentz and Henry (1989) suggested that grabens form migration paths and are prospecting guides for sulfur deposits in west Texas. In some cases, dissolution zones could be an indicator that sulfur-producing reactions had occurred. Although the oxidation of hydrogen sulfide to native sulfur does not produce acid,

$$H_2S + {}^1/_2\ O_2 \dashrightarrow S^\circ + H_2O$$

the continued (or concomitant) oxidation to sulfate does.

$$S^\circ + {}^3/_2\ O_2 + H_2O \dashrightarrow SO_4^{=} + 2H^+$$

So carbonate and sulfate mineral dissolution may be a prospecting guide for sulfur deposits. Because bacteria remove sulfate from groundwater as they reduce sulfate in forming native sulfur deposits, the solubility of gypsum and anhydrite is locally enhanced to the point of dissolution (Davis and Kirkland, 1970).

In addition to native sulfur deposits, sulfur might also be produced in the Roswell area as a byproduct in oil and gas processing (sulfur has been recovered from natural gas near Artesia, just south of the Roswell Resource Area) or from sulfide mineral refining.

Aggregate and construction material

Aggregate supply is plentiful in the eastern portion of the study area on the Llano Estacado, Mescalero Plain, Pecos and Canadian River terraces, and parts of the Pecos Slope (fig. 22). Road-building aggregates in all counties in the study area include sand and gravel river and creeks, caliche, gravel, and sand from the Ogallala Formation, basalt, igneous dikes, and sandstone and limestone (New Mexico State Highway Department, 1961; 1966; 1971-72).

Aggregate (exclusive of caliche) occurs in pediments, terraces, and valley alluvium throughout the Pecos Slope. The locations and descriptions of these numerous deposits are discussed by Kelley (1971). Caliche from the Ogallala Formation is commonly used as aggregate in the east-central part of the study area.

According to Lovelace (1972), the aggregate supply within the Roswell Resource Area is locally unlimited, but large areas are aggregate-poor (such as the populated region near Roswell). Concrete-quality aggregate, however, occurs only in terrace deposits of the Canadian and Pecos Rivers. Pecos River terrace gravel is most plentiful in De Baca County and Guadalupe County, but the highest quality, low-clay gravel is in De Baca County where the beds are as much as 18 m (60 ft) thick. Fair to good quality aggregate from pediment deposits occurs near Santa Rosa and Vaughn. The basal part of the Ogallala Formation contains coarse aggregate deposits, but is generally of poor quality and is buried by younger deposits. Extensive Quaternary sand dune deposits cover tracts from the vicinity of Clovis to the Mescalero pediment; they are used for aggregate.

Sand and gravel

Sand and gravel deposits have very low unit cost, but because they are required in modern construction of all types (especially in the paving and building industries), the total sand and gravel produced in the United States amounts to several hundred million tons (Bateman, 1950), easily the mineral commodity with the highest value, outstripping the production of all metallic commodities combined. The deposits occur in a variety of geologic settings, but most typically result from fluvial, eolian, and glacial deposition. The composition of the deposits determines use.

Deposits of sand and gravel occur and are utilized along the Pecos and Canadian River valleys and their tributary systems as well as in Tertiary and Quaternary deposits on the Llano Estacado (fig. 22). In addition to that extracted from Holocene deposits, sand is produced from the Glorieta Sandstone.

Caliche

Caliche is abundant in the Roswell Resource Area (fig. 23). Caliche is quarried locally for road metal and for pad construction in the oil industry; it may also be used as a substitute for high-calcium limestone, and as lime fertilizer (Talmage and Wooton, 1937). Deposits are as thick as 10-15 m (32-49 ft) on the Llano Estacado in the eastern part of the study area (Kottlowski, 1962). These deposits are the major caliche resource in the state. High-calcium caliche is used in various industrial processes. According to the New Mexico Department of Energy, Minerals and Natural Resources (1990), caliche production in the State increased by 431 percent between 1989 and 1990, and increased in value by 388 percent.

Caliche is a near-surface calcium carbonate deposit that forms by leaching (weathering) of calcium carbonate at the surface and redeposition beneath the surface (Lovelace, 1972). The surficial (source) sediments are continually reworked and redeposited by storms, providing for unlimited caliche formation, but rainfall totals must be within precise limits for optimal caliche precipitation (Bachman, 1987). Ground water helps to silicify caliche, and many caliche profiles have repeatedly been altered and recemented (New Mexico State Highway

Department, 1971-1972). Caliche is formed more easily on bedrock surfaces that have high calcium carbonate content, such as limestone, and it is not easily formed on sulfate-bearing surfaces and on surfaces protected by sand dune cover.

Multiple layers of caliche occur on much of the High Plains, principally in the Ogallala Formation (figs. 23, 24). In eastern New Mexico, aggregate caliche occurs on the Llano Estacado, the Buchanan Mesa surface (Kelley, 1972) and outliers near Buchanan, Taiban Mesa, the aggraded surface southeast of Vaughn, the aggraded surface west of Santa Rosa, the mesa south of Cuervo, the Mescalero pediment, and lower erosional surfaces near the Canadian River and other drainages (Lovelace, 1972; New Mexico State Highway Department; 1971-1972).

The best source of caliche aggregate is in the older caliche deposits, but quality is variable depending on amount of carbonate content, amount of sand cover, elevation of the caliche deposit, type of bedrock on which the caliche forms, the weather zone in which the caliche is formed, as well as other factors. The highest quality caliche is from the Llano Estacado where it is well-indurated and 1-2 m (3-6) ft thick. Typically the upper surface is laminated and is underlain by laminated to brecciated layers. Pisolitic structures are common. Locally, caliche on the Llano Estacado may be equivalent to high calcium limestone, but because they are localized and discontinuous, their use may be limited to road metal (Kottlowski, 1962; Siemers, 1982).

The most extensive deposits of caliche occur in Curry and Roosevelt Counties, and, except for areas covered by eolian deposits, both counties have unlimited supplies of caliche for use as aggregate (New Mexico State Highway Department, 1971-1972). From Clovis to Tucumcari, the Ogallala Formation contains as much as 4.5 m (15 ft) of caliche at the top. Near Taiban, caliche is developed on limy sand and silt, and the upper caprock is 1.5-3 m (5-10 ft) thick. Near the Roosevelt-Chaves county line, the caliche deposits are irregular, locally reaching thicknesses of 6 m (20 ft), but averaging 1.5 m (5 ft) thick. East of Roswell and to the south, caliche forms thicker caprock that is higher in lime content. Bretz and Horberg (1949) reported that caprock in this area is as thick as 9 m (30 ft) and includes an underlying chalky caliche that is up to 4.6 m (15 ft) thick (reported in Kottlowski, 1962).

Bretz and Horberg (1949) analyzed samples from the Llano Estacado, and reported an average of 3 percent insoluble residues from 12 samples of caprock caliche. However, samples from other zones in the caliche from widely separated localities had as much as 31 percent insoluble residues, indicating variability in the caliche and the necessity of testing to determine feasibility for use (Kottlowski, 1962).

Dike rock and scoria

The Railroad Mountain, Camino del Diablo, and other dikes in the study area have been quarried for road metal (Lovelace, 1972) (New Mexico State Highway Department, 1961; 1966; 1971-72) (fig. 22). Scoria, a lightweight aggregate, has coarser vesicles, greater strength, and more crystalline structure than pumice, and it is used locally for road surfacing and railroad ballast. In the Roswell Resource Area, abundant lava of the Little Black Peak and Carrizozo flows in western Lincoln County provide material for commercial and industrial uses, including decorative stone, road metal, landscaping, and building stone (File and Northrop, 1966; New Mexico State Highway Department, 1971-1972; Stoeser, and others, 1989).

Limestone and dolomite

Limestone and dolomite occurs on the western Pecos Slope and is quarried from Permian units on or near the surface (fig. 23). Depending on their composition, limestone and dolomite have been used in local road construction and as building stone, railroad ballast, sewage filter beds, and roofing granules. Typically, limestone composition varies laterally and vertically (Siemers, 1982). High-calcium limestone comprises some of the Ogallala caliche deposits on the Llano Estacado and is extracted from some quarries (Kottlowski, 1962).

High-calcium limestone

High-calcium limestone contains at least 95 percent calcium carbonate (about 53.22 percent CaO) and less than 3-5 percent magnesium carbonate (Bowen, 1957; Bates, 1960). It is used as a primary source of lime, and is important in the manufacturing and metallurgical industries (in the production of cement, paper, glass, alkalis, calcium carbide, and as a metallurgical flux). For industrial use, high calcium limestone must contain limited amounts of impurities (magnesium carbonate, alumina, silica, sulfur, iron oxide, and phosphorous). The correct combinations of raw materials, including limestone and gypsum, are combined to produce cement of the correct chemical composition.

Extensive outcrops of high-calcium limestones occur in Pennsylvanian and Permian deposits of the Sacramento and Oscura Mountains (Kottlowski, 1962). High-calcium limestone is present in the Bursum(?) Formation in the northern Sacramento Mountains (Otte, 1959). Some limestones of the Hueco Formation are high in calcium, and Permian units generally are high in calcium, except the San Andres, which has sporadic occurrences (Siemers, 1982). Due to the wide occurrence of the San Andres Formation, it is probable that there are numerous localized occurrences of high-calcium limestone in the San Andres on the Pecos Slope. In southwestern Chaves County along Rio Peñasco (outside the study area), the lower part of the San Andres contains high-calcium limestone with 97.4 percent calcium carbonate, 0.9 percent magnesium carbonate, and 1.3 percent silica (Kottlowski, 1962). Jurassic limestone, 0.6-3.0 m (2-10 ft) thick, was sampled near the Quay-Guadalupe county line east of Santa Rosa; analysis of this limestone showed 94.6 percent calcium carbonate, 3.5 percent magnesium carbonate, 1.0 percent silica, and 0.07 percent sulfur (Kottlowski, 1962).

Low-calcium limestone

Low-calcium limestone is used in aggregate and as dimension stone. With certain appropriate additives, the deposits in the vicinity of White Oaks may be used in the manufacture of Portland cement (Jones, 1915; Siemers, 1982).

The Upper Pennsylvanian sequences contain the best-quality massive limestones most amenable to quarry mining (Kottlowski, 1962). There are numerous limestone quarries near Vaughn and Tecolote (Lovelace, 1972) (fig. 22). Samples of limestone from the San Andres in the Gallinas Mountains average 20.02% magnesium oxide, 32.20% lime, and 3.26% silica (written communication from V.C. Kelley, 1957, *in* Kottlowski, 1962). Samples of limestone from the San Andres collected southwest of Vaughn, along the Rio Bonito canyon east of Capitan, and in the Phillips Hills contained 3.4-7.8% insoluble residues, chiefly quartz silt (Kottlowski, 1962). San Andres Formation about 6.4 km (4 mi) west of the Lincoln-Chaves County line on U.S. Highway 70, is medium-bedded to massive, dark-gray, fossiliferous, and contains gypsum stringers. Spectrographic analysis showed that it contains 22.3 percent magnesium carbonate and 1.7 percent silica. Limy beds of the Cretaceous Mancos Shale north of Capitan are as much as 18 m (60 ft) thick, lenticular, impure, and interbedded with black shale. Analyses showed that these beds contain 76.8 percent calcium carbonate, 2.6 percent magnesium carbonate, 13.1 percent silica, 3.1 percent alumina, 2.2 percent iron oxide, and 0.18 percent sulfur (Kottlowski, 1962).

Dolomite

Dolomite products include dead-burned dolomite, refractory magnesite, basic magnesium carbonate, and magnesium metal. These products are used in industrial applications, such as in furnace linings and in the manufacture of asbestos-fiber insulation.

Limestones in the Yeso Formation are apparently silty and dolomitic (Kottlowski, 1962). Limestones in the San Andres are dolomitic and contain more than 5 percent magnesium carbonate. While dolomitic rock is abundant in the San Andres and Yeso Formations and the Artesia Group in the study area, they are not high-purity dolomite deposits (Kottlowski, 1957). Of 49 randon chip limestone samples from the Roswell Resource Area, 36 were dolomitic limestone and only 8 were high-magnesium dolomite (Stanley Korzeb and Richard Kness, U.S. Bureau of Mines, written communication, 1992).

Building stone

The Guadalupe Courthouse and other buildings and homes in Santa Rosa are constructed of Santa Rosa Sandstone quarried within 4 km (2 mi) of the town (Talmage and Wooton, 1937). Red sandstone from the Morrison Formation or the Mesa Rica Sandstone in the Tucumcari area was used in construction in Tucumcari (Talmage and Wooton, 1937). Limestone and sandstone from surrounding areas is used in construction in Roswell (Jones, 1915; Talmage and Wooton, 1937). Jones (1915) mentioned the occurrence of bluish and light- and dark-gray marble near White Oaks and the Capitan Mountains that will take a high polish and may have potential for decorative stone.

Fluorspar and barite

Fluorspar

In Lincoln County, fluorspar occurs in two areas: these are 17 mined fluorspar deposits in the Gallinas district (Red Cloud, All American, Deadwood, Rio Tinto, Helen S, Conqueror No. 4, Hilltop, Eagle Nest, Bottleneck, Old Hickory, Congress, Hoosier Girl, Eureka, Summit, Last Chance, Buckhorn, and Sky High prospects) (fig. 25) and the Julia Ann prospect on Lone Mountain with no reported production (Rothrock and others, 1946; Williams, 1966). The fluorspar was probably produced from gangue in earlier mined lead and copper ores (Soulé, 1946).

At both localities, fluorspar occurs in brecciated zones, along contacts and faults, and as disseminations in rocks of the Yeso Formation that overlie Precambrian granite and have been intruded by Tertiary alkalic dikes and sills (Rothrock and others, 1946). Vein deposits are the most common type, filling fissures and interstices in Yeso quartz sandstone. Fluorite in fractures is typically localized and irregular. Disseminated deposits, in which the fluorite is most widespread, occur in replaced dikes, sills, and sandstones. Several periods of fluorite deposition and brecciation took place, wherein fluorite gradually replaced arkosic and calcareous sedimentary rock and intrusives. Bastnaesite and barite more commonly replace limestone.

Fluorspar grade and quality are irregular and variable. Higher grade ore bodies at the All American prospect assayed 77-80 percent CaF_2 and 11 percent SiO_2; composite values assayed 54.3 percent CaF_2, 23.2 percent SiO_2, 11.5 percent $BaSO_4$, and 1.5 percent CaO. The fluorite is mostly light blue to dark purple, with the richest fluorspar grade in deeply colored ore. The deposits are mainly fluorite, barite, and siliceous and argillaceous host rock fragments; minor constituents include calcite, dolomite, rare bastnaesite. Small amounts of galena, pyrite, chalcocite, celestite, barytocalcite, azurite, malachite, and limonite occur locally. Fluorspar production from Lincoln County totaled 1,190 tons in 1966 (Williams, 1966).

Vein barite

Vein barite deposits occur in the Gallinas Mountains in Lincoln County at the Fox Lode prospect between Jicarilla and White Oaks, and at the Helen Rae mine southwest of Nogal where barite is an accessory mineral to a lead-zinc-silver-bearing vein. In the Gallinas Mountains on the eastern edge of the Rio Grande rift, barite is found in several fluorite deposits that formed in association with alkalic intrusives; these include Red Cloud, Old Hickory, and Conqueror (Rio Tinto) mines and All American, Big Ben, Bottleneck, Eagles Nest, Eureka, and Hoosier Girl prospects (fig. 25) (Soulé, 1946; Williams, 1966; Rothrock, 1970; and Griswold, 1959). No barite has been produced commercially from these mines (Williams and others, 1964). At Red Cloud mine, the largest producing mine in the Gallinas Mountains, barite occurs in brecciated and altered sandstone in a 15 m x 15 m x 30 m (50 ft x 50 ft x 100 ft) ore body (Williams, 1966) from which fluorite and bastnaesite had been produced. Two samples by Soulé (cited in Williams and others, 1964) from Red Cloud mine contained 17.62 percent and 28.56 percent $BaSO_4$, respectively. Samples from other deposits in the Gallinas Mountains ranged as low as 11.72 percent, with none exceeding Red Cloud values.

According to Williams and others (1964), relatively pure barite is found at the Fox Lode prospect northeast of White Oaks. There, a 0.6-m-wide pocket of white, crystalline, fluorite- and quartz-free barite has been exposed. A composite sample yielded 89.7 percent barite with a specific gravity of 4.2.

West of the study area in the northern Oscura Mountains, the Hansonburg mining district has been the most important barite producer in the State. In 1982, it accounted for 90 percent of all recorded production (Smith, 1982). The Hansonburg deposits are veins in fault breccias and replacement bodies in fracture zones in limestone.

Bedded barite

Two types of deposit associations described by Clark and Poole (1989) as part of their classification of bedded barite deposits may apply to the geologic setting in the Roswell Resource Area: (1) Evaporite-associated, strata bound, syngenetic-diagenetic barite deposits are associated with anhydrite and celestite, forming in fresh to brackish water interfaces in nearshore marine or lacustrine settings. The minerals are concentrated during later diagenesis. (2) Carbonate-hosted stratabound epigenetic barite deposits are thought to form as a result of basinal brine or mineralized groundwater migration to sites where barite may precipitate, commonly in solution breccias or open spaces created in a karst environment (MVT deposits).

Bedded barite, several meters (a few tens of feet) thick, occurs in the subsurface in the Rustler Springs sulfur deposit (Salado Formation) south of the study area boundary (Smith, 1978). A barite deposit overlies the sulfur deposit, but the relationship of the barite to the sulfur is unclear. There are numerous and extensive barium anomalies in geochemical sediment samples in the Roswell Resource Area. Triassic beds are the inferred source; the barium is probably related to barite cement in sandstone and of no economic significance.

Although the geologic setting seems favorable for the formation of bedded barite, no barite has been produced from the Roswell Resource Area, and no occurrences are known (Smith, 1982).

Clay and adobe brick

Clays and clay products are used extensively in the building, ceramics, and oil and gas industries. The type of clay determines its use. The occurrence of clay as an impermeable layer in the stratigraphic section is of utmost importance in the exploration phase in the oil-and-gas industry and the use of clay as a constituent of drilling mud is important in the production phase.

Small deposits of fire clay occur 2.4 km (1.5 mi) southeast of Ancho in west-central Lincoln County (Darton, 1928; Talmage and Wooton, 1937; Griswold, 1959; Budding, 1964). A brick plant operated at Ancho from about 1912 to about 1922. According to Budding (1964), shale for making the bricks was mined about 3.2 km (2 mi) east of Ancho from the Dakota(?) Sandstone. Common clay deposits have also been mined near Acme (Talmage and Wooton, 1937).

Clay occurs as thin beds and in clay-rich zones in various formations that are at or near the surface in the study area. Rare beds of bentonite as thick as 0.3 m (1 ft) occur in the Morrison Formation. In Quay and Guadalupe County, thin beds of montmorillonite (smectite) occur in Triassic rocks (Northrup, 1959).

Although small deposits of clay were exploited in the past, none of the clays is commercial today in the Roswell Resource Area. Clays of the Mancos Shale and Mesaverde Formation that occur near Capitan in the Sierra Blanca basin could be used in making bricks (George S. Austin, New Mexico Bureau of Mines and Mineral Resources, oral communication, July 1991).

Adobe bricks are manufactured using sand, silt, and clay deposits from stream, alluvial fan, and terrace deposits as well as older deposits, such as the Ogallala Formation (Smith, 1982). Adobe has been used for several centuries for building construction in this region (e.g., notable in historic Lincoln). Adobe bricks, to which stabilizers have been added to conform to building codes for durability, are still being used today in building construction for use in both traditional and native architecture.

In the Roswell Resource area (as of the early 1980s), there are no adobe brick manufacturing facilities, although the region contains deposits that are suitable for adobe construction. According to Smith (1982) (fig. 26), abundant resources of adobe material occur throughout the study area in lower to upper Tertiary deposits, including the Ogallala Formation of the eastern Roswell Resource Area, and in Quaternary floodplain, arroyo, terrace, and dune deposits in areas adjacent to the Pecos River. While the deposits suitable for making adobe bricks are in large supply, they would have to be shipped to construction areas, generally near the larger towns.

GEMSTONES AND COLLECTIBLE SPECIMENS

Jasper occurs about 2 mi north of Ancho and is apparently suitable for ornamental use (Talmage and Wooton, 1937; Northrup, 1959). Petrified wood occurs in the Chinle and Santa Rosa Formations, but its use as a gemstone is limited due to variability in quality. "Pecos diamonds" are considered collectible by many and sold as local curios. Smoky quartz crystals described by Segerstrom and others (1979) have been mined from the Sierra Blanca Peak area. Quartz crystals are of specimen quality and as much as 20 cm (9 in) in length. They are unavailable for commercial mining due to their location within the White Mountain Wilderness Area (Hanson and Thompson, 1991). Mineral specimens of museum quality have been taken, as well, from the Mina Tiro Estrella claims in the Capitan Mountains (Hansen and Thompson, 1991; McLemore and Phillips, 1991). According to Jones (1904, p. 343; 1915, p. 75), jet occurs near Santa Rosa. A small quantity of turquoise has been reported from the Nogal District (Northrup, 1959, p. 525).

"Pecos diamonds"

In 1583, a Spanish miner named Don Antonio de Espejo discovered the occurrence of quartz crystals in gypsum known now as "Pecos diamonds" (also known locally as "Indian diamonds"). Although no industrial use has been developed for these unique crystals, they are sold locally as souvenirs of the area. They may occur only in North America, in the Pecos River Valley.

"Pecos diamonds" serve as stratigraphic markers in the lower part of the Yates Formation and the upper part of the Seven Rivers Formation (fig. 27, map C), especially in Chaves and De Baca Counties (Northrup, 1959). They are diagenetic quartz, dolomite, aragonite, and anhydrite crystals that are typically embedded at any angle with respect to bedding in weathered gypsum and dolomite. Prisms are doubly terminated (Tarr, 1929; Tarr and Lonsdale, 1929), and both positive and negative quartz rhombohedrons are present; locally common pseudocubic forms are also present. They range in size from microscopic to 9 cm (3.5 in) long and up to 4 cm (1.5 in) in diameter. Only a few have perfect crystal shape, and these are commonly less than 2.5 cm (1 in.) long (Albright and Bauer, 1955). They are clear or variously colored yellow, pink, brown, orange, green, white, or black. The color variation is probably due to trace amounts of iron and/or manganese oxides, organic matter, and other contaminants (Albright and Bauer, 1955). Quartz forms thin overgrowths on gypsum cores in some specimens. Relic bedding lamination occurs in some crystals.

Tarr (1929) suggested that the silica source for crystal formation is from associated sandstones and shales, with the bedded host gypsum causing coagulation and precipitation. Albright and Bauer (1955) note that there are no mineralized veins, fissures, or openings allowing circulation of solution-derived precipitation. Albright and Kruckow (1958) described the occurrence of crystals at 354 m (1,160 ft) depth in Lea County southeast of the study area, and suggested a probable diagenetic cause for their formation.

Smoky quartz

Occurrences of specimen-quality smoky quartz crystals and fluorite crystals are located within the Three Rivers stock of the Sierra Blanca Igneous Complex in the White Mountains

Wilderness Area (sec. 29, T. 10 S., R. 11 E.) (Segerstrom and others, 1979; Hanson and Thompson, 1991). Quartz crystals of museum quality have also been obtained from the Mina Tiro Estrella claims in the Capitan Mountains (Hanson and Thompson, 1991; McLemore and Phillips, 1991).

Quartz crystals from the Sierra Blanca range from 0.2 cm to 40.0 cm (0.08 in to 16 in.) in length, averaging about 7 cm (2.8 in) in length (Hanson and Thompson, 1991). They are found in miarolitic cavities and open fractures, and are adjacent to a breccia pipe (Hanson and Thompson, 1991). The quartz crystals contain phantoms, including rare amethyst phantoms, which record quartz crystal growth. Rare doubly-terminated specimens also were developed. The crystals have commercial value to mineral collectors and have been sold to tourists. However, because the locality is now within Wilderness Area boundaries, the crystals are no longer available for commercial extraction.

Petrified wood and bone

Petrified or silicified wood is found in the Triassic Chinle and Santa Rosa Formations in other parts of the state, and has been reported from the study area in association with sediment-hosted copper deposits. The quality varies according to silicification and alteration. According to Northrup (1959), a few small specimens of radioactive silicified bone, probably from the Ogallala Formation, have been found in Curry County (Barnes, 1955).

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METAL RESOURCES

MINING HISTORY AND PRODUCTION

by David M. Sutphin and Theodore J. Armbrustmacher

History of mining

The Roswell Resource Area has produced significant copper, gold, fluorite, iron, lead, silver, tar sand, and zinc as well as small quantities of manganese, rare-earth elements, tungsten, uranium, and vanadium (Appendix). Initially, the search for gold led prospectors into the area. Gold placers were discovered in Lincoln County, and their discovery led to exploration and discovery of other mineral deposits. World Wars I and II provided economic incentives to locate and produce much-needed mineral commodities, including copper, iron, rare-earth elements, and tungsten from previously marginal or subeconomic resources and poorly explored mineral occurrences.

The report on water and mineral resources of New Mexico (U.S. Geological Survey and others, 1965) provides information on mining districts and mineral deposits in the Roswell Resource Area. Information sources for specific mining districts include Griswold (1959) and Lasky and Wooton (1933) on the Oscura district, Perhac and Heinrich (1964) on the Gallinas district, Segerstrom and Ryberg (1974) and Segerstrom and others (1979) on the Jicarilla district, Thompson (1973) on the Nogal district, Anderson (1957) on the Tecolote district, and Bielack and Williams (1982) and Griswold (1959) on the White Oaks district. Locations of mining districts in Lincoln County referred to in this report are shown in figure 28. Table 5 summarizes the reported production of several commodities from the study area.

Gold

Gold was the first metallic commodity to be mined in the Roswell Resource Area, and has the most valued production. Mining was conducted in the days of Spanish rule by hauling water and panning gold and silver from stream gravels in ephemeral drainages. Gold placers in the Jicarilla and White Oaks districts were mined from Lincoln County in the 1850s (Griswold, 1959). By the 1860s, placer gold was also being mined along Dry Gulch in the Nogal district, which eventually led, in 1868, to discovery of the lode source of gold in the Helen Rae-American vein system. In 1879 and 1880, lode sources for placers were found in the White Oaks and Jicarilla districts, respectively.

White Oaks district

In terms of production value, the most important gold-mining district in the Roswell Resource Area is the White Oaks district. Gold at White Oaks occurs in veins in Tertiary monzonite and lamprophyre, Cretaceous shale, and in placer deposits (Lindgren and others, 1910; Jones, 1904). Production figures for placer operations prior to 1879 are lacking; from 1879 until 1957 the district produced at least 152,373 ounces of gold (Griswold, 1959). McLemore (1991) estimates 163,500 oz of gold were produced from 1850 through 1942. Total production in ounces for major mines in the district was as follows: Old Abe 45,745; South Homestake, 30,000; North Homestake, 20,039; Little Mack, 2,579; Smuggler, 279; and placer and other mines, including Rita, Lady Godiva, Little Nell, and Hannibal, 53,731, of which about 1,000 oz was from placers (McLemore, 1991). An additional 0.25 st Cu, 1,044 oz Ag, and 6.1 st Pb were produced as byproducts of gold mining between 1933 and 1951 (McLemore, 1991).

The first lode deposit in the district was discovered in 1879 at what would become the North Homestake mine, and soon after, other veins were discovered, including the vein that would be exploited in Old Abe mine. A 20-stamp amalgamation plant was built in 1893; in 1898, it was expanded to include cyanide extraction.

Old Abe mine, the largest producing mine in the district, was worked to a depth of 1,400 ft. Ore grade was highest in pockets and shoots near the surface. Despite the depth, significant amounts of water were not encountered, so that water for milling operations was brought to the site by truck. Ore at Old Abe contained free-milling gold in quartz-limonite veins which, through 1890, had an average grade of about 0.44 oz/st gold. Grade dropped somewhat thereafter. The most productive period was from its discovery until 1904. Pay zones formed pockets and shoots in the veins, which ranged in size from 1.2 to 6.1 m (4 ft to 20 ft) in width. Assays of individual samples ranged from 0.77 to 30.84 oz/st gold. Lindgren and others (1910) reported that the Fish Pond stope was 6.1 m x 15 m x 18 m (20 ft x 50 ft x 60 ft) and yielded $80,000 (about 3,870 oz) in gold at the 1910 price of $20.67/oz.

The history of other mines in the district is similar to that at Old Abe. At South Homestake mine, however, the Capitan and the Devil's Kitchen stopes were mined by glory-hole methods down to the 55-m (180-ft) level, where stoping began. The Smuggler and Little Mack mines were the last continuous mining operations in the district, operating until the 1930s. After WWII, North Homestake and Old Abe operated for a brief period. Since then, except for occasional exploration, the district has been a typical ghost mining camp.

Jicarilla district

As early as 1700, the Spanish may have mined the district's gold placers in gulches near the present-day village of Jicarilla (Smith and Dominian, 1904). But it was not until 1850, when prospectors began panning gold from gravels using meltwater or water they hauled in, that placer mining began in earnest. Such small-scale placer mining continued in the district until it was interrupted in WWI and remained shut down through the 1920s. During the depression in the 1930's, miners returned to the Jicarilla Mountains in search of gold. At that time, the district became home to about 300 miners, and in 1934 as many as 84 placer mines were operating. From 1933 to 1942, more than 1,800 ounces of gold and 143 ounces of silver were produced from placers (Segerstrom and Ryberg, 1974, p. 17). Entry of the United States into WWII ended gold mining in the district except for an occasional attempt to reinvigorate some of the placer locations. At one time or another, almost every arroyo in the district has been worked. However, the most productive were Ancho, Rico, Spring, and Warner Gulches.

Large-scale placering has also been tried in the district. In 1903, a large dredge-like placering machine was unsuccessfully tested west of the post office in Jicarilla. In the 1930's, power shovels and other power equipment for removing overburden were used, as were special sluices for gold recovery. Johnson (1972) notes that large-scale operations have not been successful because of lack of water and the thickness of the overburden. Within the alluvium, the gold is not well-concentrated in the channels, and large quantities of stream gravel must be processed to recover the gold, some of which consists of fine grains and thin foils that float by surface tension and are lost if special care is not taken. Small-scale operations in the past were successful for some miners, however.

About 1880, exploration began for lode sources of the placer gold, and small lodes have since been found. McLemore (1991) estimates that lodes produced 7,347 oz from 1912 to 1957. Segerstrom and Ryberg (1974) report that the only year for which lode-gold production records are available was 1933 when 83 ounces were produced from the Lucky Strike mine and another unnamed mine. There are many shafts and adits at the head of Ancho Gulch and near Ancho Peak. Most of these were dug early in this century and in the 1930s. In some mines, such as the Good Luck, Prince Albert, and Eureka, copper and silver accompanied gold. A "large" body at Hawkeye mine reportedly contained $13.50 gold/st ore at 1920 prices (Finlay, 1921-1922). The Gold Stain mine was less rich, having sulfide ore ranging from $4.00 to $5.20/st. The Honey Bee mine also contained copper ore.

An estimated 8,000 ounces of gold (Johnson, 1972) have been produced from the district's placers. This total may be erroneous, however, due to reporting problems associated with early small-scale operations. McLemore (1991) reports that byproducts of gold production from 1912 to 1957 were about 2,100 st Cu, 37,531 oz Ag, and 1.33 st Pb. From time to time, new exploration has been conducted and pilot plants have been built (see Segerstrom and Ryberg, 1974, p. 19), but little gold has been produced since 1942. Although platinum-group elements have been reported in the district, little information is available and no authoritative confirmation has been made.

Nogal district

Most of the Nogal district is located on the eastern side of Sierra Blanca Peak. For this report, the Nogal district includes the Bonito and Schelerville subdistricts, and other mineralized areas in the vicinity of Sierra Blanca Peak. According to Segerstrom and others (1979), the Bonito mining district is referred to in mining claim records as early as 1879. However, the official Nogal mining district was not established until July, 1880. Other unofficial mining district names, such as West Bonito, Tortolito, and White Mountain, have been used for part of the area.

Prospecting and mining in the Nogal district probably dates back to the time of Spanish rule. More recently, placer gold deposits were found in the district in 1865 at Dry Gulch and gold lodes were located in 1868. It was not until 1882, when the region was withdrawn from the Mescalero Indian Reservation, that prospecting was undertaken seriously (Anderson, 1957, p. 92). Most of the major veins in the area were discovered at that time.

Lode gold deposits were exploited sporadically in the Nogal district from the 1880s to the 1930s. Records of the earliest production in the district were not maintained. One source indicated that, until 1920, ten mines in the district had produced $212,000 worth of gold at the prices of the day (Thompson, 1973). From 1900 to the 1920s, the Parsons mine produced an estimated 15,000 ounces of gold from 85,000 short tons of ore. Since 1904, at least 25 lode mines and 19 placers have operated in the Nogal district. McLemore (1991) estimates that from 1858 to 1942, placers produced 200 oz of gold.

There was little mining activity during 1920-1933. About 1933, the Helen Rae and American mines produced from the same vein. In 1936, a 75-short-ton mill and an amalgam plant were installed, and development work began at the Silver Plume and Bonitá properties where gold was milled one year later. These mines produced 30 short tons of gold ore in 1938 and 84 short tons in 1939 (Anderson, 1957). From 1937 to 1953, a total of 914 short tons of ore (Segerstrom and others, 1979) was produced. Thompson (1973) suggests that the other mines in the district had only small-scale production. Total production was on the order of one million (1973) dollars. Segerstrom and others (1979) suggest that the small size of most of the workings and the lack of evident stopes indicates limited production. The ore probably was sold locally to merchants or to larger mining companies, such as those at White Oaks.

More recently, an attempt to recover gold from iron ore led to the Cimmarron mill site in Carrizozo being designated as a Superfund site by the Environmental Protection Agency. According to Brandvold (1991), potentially hazardous concentrations of cyanide, mercury, selenium, arsenic, lead, and copper were found in groundwater, soil, and tailings. The damage was caused by alleged operating violations while attempting to improve gold recovery. Cleanup was slated for 1991-1992. Exploration in the district continues. In 1989, an epithermal breccia system estimated to contain 190,000 oz of gold was reported at the Great Western deposit (Dayton, 1988).

Iron

The history of iron mining in New Mexico, from its prehistoric use as a pigment to post-WWII production, is discussed by Kelley (1949), and Smith (1991) summarizes more recent activities. Of the counties within the study area, only Lincoln County has iron deposits and historical iron ore production. The iron ore occurs as pyrometasomatic replacements in Permian carbonate rocks of the San Andres and Yeso Formations (U.S. Geological Survey and others, 1965).

Iron ore was probably discovered by prospectors looking for other mineral commodities such as gold, silver, and copper. Iron deposits were found in such gold-producing districts as the Gallinas, Jicarilla, and White Oaks districts, and iron deposits are found together with gold veins. White Oaks iron deposits were well known prior to 1900. Samples analyzed around the turn of the century from iron deposits at Lone Mountain and the Jicarilla district contained 62.2-65.52 percent Fe and 0.21-0.41 percent S (Kelley, 1949). At that time, the deposits were considered to be high-grade and to contain vast resources.

There are approximately 24 known iron deposits from the Gallinas to the Capitan Mountains (Griswold, 1959). Production of iron ore from these deposits probably began between 1900 and the beginning of WWI. The first recorded production was in 1913 when about 3,700 tons of ore were shipped from the Yellow Jacket mine in the White Oaks district to the Colorado Fuel and Iron Co., in Pueblo, Colorado (Griswold, 1959). From 1913 to 1921, mines in the Jicarilla, Tecolote, and White Oaks districts produced 40,457 short tons of iron ore that averaged 2.0 percent of New Mexico's production for that period, with a high in 1914 of 7.8 percent. No iron ore production was reported for Lincoln County from 1922 until 1942. About 1942, mines in the Gallinas, Jicarilla, Tecolote, and White Oaks districts were again activated, producing 13,759 short tons of iron ore or 7.3 percent of the state's iron-ore output. From 1913 to 1943, about 59,140 short tons of iron ore were produced from districts in Lincoln County, accounting for 1.2 percent of New Mexico's cumulative iron ore production for that period (table 6). In 1952 and 1953, the White Oaks district was again producing iron ore, this time from the Ferro mine, which had an output of 4,610 short tons. Total production for the Roswell Resource Area is about 270,000 to 320,000 short tons of iron ore.

Capitan iron deposit

The Capitan deposit, about 10 km (6 mi) north of Capitan, was explored extensively during and after WWII by the U.S. Geological Survey and the U.S. Bureau of Mines as part of the search for iron resources to meet the nation's strategic need for steel. Soulé (1947, 1949) led the exploration effort in which 179 holes totalling 1,064 m (3,490 ft) were drilled. Kelley (1949) mapped the deposit and described the geology using the drill hole data. Analyses of composite samples showed the deposit to contain about 3,000,000 short tons containing 48.1 percent Fe, 0.06 percent S, and 0.06 percent P (Kelley, 1949). Since 1975, when it was taken over by L.D. Larue and sons, 200,000 to 300,000 short tons of iron ore have been produced from the Smokey mine, whose pit has grown to about 450 m x 335 m (1,480 ft x 1,100 ft) (Smith, 1991). Presently, the Smokey mine, which exploits a portion of the Capitan deposit, intermittently produces 10,000 to 15,000 short tons per year iron ore having about 50 percent Fe (Hatton and Childs, 1990).

Other deposits in the Capitan Mountain area, such as the Major, the Red Wing, the Ajax, and the Oslo deposits, were prospected during WWII. Grades ranged from 59.3 percent to 63.7 percent Fe (Kelley, 1949; Sheridan, 1947), and resources were estimated to be about 22,000 short tons. No ore has been produced from these deposits.

Tecolote District

The Tecolote district has produced only iron ore from the Elda and the Iron Chief mines. The Elda mine produced 16,064 short tons of ore in 1915-19 and 1922. At the Elda mine, the ore was soft, porous, banded magnetite, averaging 1.5 m (5 ft) thick. Mining was done underground using room and pillar methods with only occasional timbering. No iron ore was produced from the Elda mine during WWII.

Kelley (1949) reports that the Iron Chief mine produced 9,034 short tons in 1917-18. This production is not accounted for in Griswold (1959) or in table 6. Other prospects in the district, such as the Betty Bond and the Iron City No. 2, are located within the same deposit as the Elda mine, but neither have produced.

Gallinas District

In the Gallinas district, the American mine (along the west side of Crashed Bomber Ridge) was mined in 1942-43 and then abandoned. The Rare Metals deposit, located about 460 m (1,500 ft) southwest of the American mine, has not been mined, but resources are estimated to be a few thousand short tons of material (Kelley, 1949). The Gallinas mine produced from an orebody exposed in a pit measuring 38 x 30 x 3 m (125 x 100 x 10 ft). Kelley (1949) doubted that more than a few hundred short tons of minable material remained. During those two years of production, the district produced 11,540 short tons of iron ore (Kelley, 1949).

Jicarilla District

In the Jicarilla district, iron ore mining was carried out during 1918-21 at the Jacks Peak deposits. Mining was renewed during WWII. In 1942-43, high-grade ore was mined in an effort to make the operations profitable. Total iron-ore production for these periods was 8,679 short tons (Kelley, 1949).

White Oaks District

The White Oaks district has three principal iron ore mines and prospects on Lone Mountain: (1) the Yellow Jacket mine, until exceeded by the Smokey Mine in the late 1970s, was the largest producer in the county, with nearly 38 percent of the total for the years 1913-1943, (2) the Black Knight prospect, and (3) the House prospect. The Yellow Jacket mine was developed shortly after 1900, with iron mining beginning in 1913 and ending in 1915. Further production occurred from July to December, 1942, for a total of 22,409 short tons of iron ore (Kelley, 1949). Both glory-hole and underground methods were employed. The House prospect has been assayed and explored, but as of 1959, no iron ore had been produced (Griswold, 1959). Uranium at this site has been discussed in Walker and Osterwald (1956, *in* Griswold, 1959), but the grade of the uranium in the deposit was uneconomical. In 1952-53, the Ferro mine produced a relatively substantial amount of iron ore from a steeply dipping magnetite vein.

Base-metals, silver, fluorspar, and rare earth

Copper, lead, zinc, and silver have been discovered and mined in several districts in the study area, including the Gallinas, the Nogal, the Pastura, and the Oscura districts.

Gallinas District

In the Gallinas district, numerous small veins in the iron deposits were being worked as early as 1885 for copper, lead, zinc, and silver. By 1904, several small mining operations in the district were shipping ore to Socorro for smelting. Records are incomplete, but from 1920 to 1922, the Red Cloud mine (on one of the earliest claims staked in the district) shipped 2,384 short tons of Pb-Cu-Ag ore to El Paso, Texas. From 1922 to the early 1940s, the Gallinas district was dormant. With the onset of WWII, the district was reactivated to provide iron and fluorite for the war effort. During 1942 and 1943, in order to obtain better information on the geology and resources of the district, the U.S. Geological Survey and the U.S. Bureau of Mines carried out extensive exploratory surveys defining and describing the district's resources and ores. Despite this new work, production from the district was small. From 1922 to 1949, an estimated 4,000 short tons of copper ore were shipped (Perhac and Heinrich, 1964).

From 1943 to 1955, fluorspar concentrates were shipped from three mines. In 1953-55, the Red Cloud and the Conqueror No. 9 mines shipped less than 2,000 short tons of fluorspar concentrates valued for their rare-earth content in the mineral bastnaesite. In 1954, 60 short tons of bastnaesite concentrates were derived from 1,000 short tons of fluorspar concentrates from the Red Cloud mine.

Other mines in the Gallinas district had small production. The All American mine produced 129 short tons of fluorspar ore in 1949-51. The Conqueror mine produced about 300 short tons of F-Pb-Cu ore in 1956. The Old Hickory mine was worked for Pb and Cu initially, and may have yielded fluorspar ore in WWII. McLemore (1991) reports that from 1909 to 1955, Gallinas district produced 23,723 oz Ag, about 193 st Cu, 863 st Pb, and about 8.7 st Zn.

Nogal District

The Nogal district has been considered chiefly a gold or molybdenum district, although Pb-Zn-Ag has been known in the district since the 1880s. The Helen Rae and the American mines, the most extensively worked Pb-Cu-Ag mines in the district, produced from the 1880s to the early 1930s. Other mines in the district include the Maud mine, where the upper workings were active in the 1890s and later worked in 1963-64. In this latter period, a composite sample at the Maud mine contained 7.10 percent Pb, 0.39 percent Zn, 0.017 percent Mo, 0.32 oz/st Au, and 1.28 oz/st Ag, with no detectable Cu. North and McLemore (1986) estimate that the district produced about 20,000 oz Ag between 1868 and 1942.

Pastura District

The only metal-mining district in Guadalupe County is the Pastura district where the Pintada and the Stauber mines have been exploited for copper, silver, and lead. Total production for the Pastura district was reported in McLemore and North (1985) as 265,954 short tons of ore valued at about $2.75 million, containing 6,879 short tons of copper, 23 short tons of lead, 8,466 ounces of silver, and 2 ounces of gold.

The Stauber deposit north of Pastura was discovered by a section worker on the Southern Pacific Railroad. Prior to 1915 when it was acquired by I.J. Stauber, it produced 2.7 short tons of copper and 48 ounces of silver from a single bed of Triassic Santa Rosa Sandstone. The mine was in operation from 1925 to 1930, from 1940 until the end of WWII, and from 1949 to 1957.

During WWI, a small amount of underground mining produced ore with typical assays of 1 percent copper, with rare nodules assaying at as much as 8 percent copper (Stauber, 1930). In 1942, the Stauber Mine was an important source of high-grade siliceous copper ore for smelter flux (Holmquist, 1947). From 1925-42, 2,876 short tons of copper were recovered from ore having a copper content of 3.86-5.24 percent (Holmquist, 1947).

The mine was operated later as an open-pit mine. Around 1954, the overburden became too great to remove economically and the mine returned to underground operations. In 1957, production amounted to 300 short tons of ore per day. Total production from 1915 to 1956 was over 264,000 short tons of ore containing 2.56 percent copper, 0.03 ounces per ton silver, and 0.0087 percent lead (Soulé, 1956). The original copper grade was slightly over 5 percent when mining began, but dropped to about one percent in later years.

The Pintada mine, located about 24 km (15 mi) southwest of Santa Rosa in Pintada Canyon on Rio Agua Negra, had small-scale open-pit production in 1916-17, 1951, 1956, and 1967-70. Shipments of 23 tons of 5.6 percent copper ore in 1916-17, 490 tons of 1.7 percent copper ore in 1951, and 980 tons of 2.4 percent ore in 1956, were shipped to the smelter (Burleson, 1966). The ore consisted of chalcocite, mostly finely disseminated and in streaks and patches, in fine-grained well-cemented sandstone.

About 1,597 short tons of ore containing 10.75 short tons of copper and 71 ounces of silver were produced at the Pintada mine from a 15 x 26 x 9 m (49 x 85 x 30 ft) pit (McLemore and North, 1985) from mineralized parts of the Artesia Group (Grayburg and Queen Formations) (Sandusky and Kaufman, 1972). Additional resources were located in the early 1970s, but poor economic conditions and low grade prevented their development. As of July 1990, the mine remained abandoned. Weakly mineralized host rock at Pintada mine that contained the greatest concentration of ore minerals was up to 3 m (10.5 ft) thick (Burleson, 1966). According to Read and others (1944), other weakly mineralized occurrences are present along Pintada Canyon (sec. 14, T. 8 N., R. 19 E.).

Oscura District

The Oscura district, in western Lincoln County, was not exploited until about 1900 when a few carloads of copper-silver ore were shipped. McLemore (1991b) estimates that about 21.1 st Cu and 124 oz Ag were produced from 234 st of ore. The district has remained idle since 1910. The ore is of refractory copper oxides, and its grade is variable. The district is now within the White Sands Missile Range, which would prevent further exploitation.

In Quay County, copper mineralization has been recognized along the base of the Canadian Escarpment for 8-9 km (5-6 mi) and to the south near the junction of Ute Creek and the Canadian River. In the latter area, there was some mining from 1910 to 1920, according to Soulé (1956). After 1920, there was no mining activity until the mid-1950s when claims were staked for uranium minerals.

West of Logan in Quay County, copper minerals, including malachite, azurite, and chalcocite, are reported to occur as replacements between grains and as nodular masses in a shaly sandstone of the Triassic Dockum Group sedimentary rocks approximately 13 km (8 mi) west of Logan in Quay County (Soulé, 1956). According to Soulé (1956), copper grades are low and scattered, and prospecting has been limited to shallow pits.

Tungsten

In addition to gold, tungsten was produced intermittently from 1915 to 1952 in the White Oaks district (Soulé, 1956). Griswold (1959) reports (from incomplete records) a production of almost 60 short tons of material containing 56.81 percent WO_3. The raw ore, which probably contained less than one percent WO_3, came from the South Homestake mine. In the early days of mining in the district, tungsten minerals were not recognized as being of economic importance and were discarded. Later, tungsten production came from old waste dumps.

Uranium

New Mexico's uranium industry has a rich history that has been well-documented. McLemore (1983) briefly summarizes that history and provides references for additional information. Much of the following is from that account.

In 1947, creation of the Atomic Energy Commission (AEC) fostered extensive exploration, development, and production of uranium in New Mexico and the nation. In the early 1950s, eastern New Mexico had a uranium boom of its own, since extensive exposures of the Morrison and Chinle Formations, the chief uranium-bearing rocks of the Colorado Plateau, were known to crop out (Finch, 1972a,b). To encourage exploration, the AEC conducted airborne radiometric surveys over eastern New Mexico from 1953 to 1955 and detected numerous anomalies. With this information, prospectors located uranium claims in the 1950s, and some of the more promising deposits were explored by pits and short adits, and a few were drilled.

Although extensive exploration led to the discovery of several prospects and occurrences in the Roswell Resource Area, little production resulted. AEC figures (McLemore, 1983) show that between 1948 and 1970, uranium production from the seven counties consisted of 1 pound of uranium oxide (U_3O_8) from three short tons of ore that contained 0.02% U_3O_8 mined from the Bear Canyon group of prospects in Lincoln County, and 91 pounds of U_3O_8 from 83 short tons of ore that contained 0.05% U_3O_8 from the Good Luck No. 1, the Little Rattler, and the Windy No. 9 mines in Quay County. Another 30 short tons of silicified uraniferous logs were shipped from the Bel Aro mine, Quay County, but were not recorded by the AEC (Finch, 1972b).

Manganese

Manganese was mined at the Arabella Manganese Inc. mine in the northeastern Capitan Mountains at some time between when Griswold (1959) described the deposit as a promising prospect and 1983 when Tuftin (1984) visited the site and found a mined-out or rubble-covered trench. Griswold (1959) reported that production began in 1959 when one short ton of concentrate containing 54 percent manganese was shipped. The government stockpile program was due to end that year, however, and there seemed little time to develop the property. When Tuftin visited, there were only abandoned workings. Sketches of the mine by Tuftin (1984, p. 14) show the dimensions of the trench to be approximately 52 x 21 x 11 m (170 x 70 x 35 ft), large enough to have yielded several thousand tons of manganese ore.

DESCRIPTION OF DEPOSITS

by David M. Sutphin and Susan Bartsch-Winkler

Metal-bearing deposits in the Roswell Resource Area are discussed by deposit type rather than by commodity, because grouping by deposit type allows appropriate deposit models to be used to describe the deposits. More than $600 million worth of resources of gold, copper, iron, molybdenum and other metallic commodities have been identified within the boundary of the Roswell Resource Area (tables 7,8, Appendix). Most of these metals have been produced in the past, and many are on U.S. Forest Service and private lands.

Most types of metal deposits found in the Roswell Resource Area are genetically linked to igneous rocks; they commonly occur as mineralized breccia and fractures, fissure veins, and disseminated and replacement deposits (Woodward, 1991). Mineral occurrences of manganese, uranium, and minor titanium may occur in sedimentary rocks distant from intrusions, as well as in or derived from igneous terrain.

Placer gold

Placer gold deposits have been an important source of gold in New Mexico. Outside of the study area, much of New Mexico's placer gold production has come from drainages below vein and skarn deposits in districts such as Elizabethtown-Baldy, Old Placers, New Placers, and Orogrande (North and McLemore, 1988; Johnson, 1972). In the Roswell Resource Area, gold placers with minor silver and possibly rare platinum-group elements (PGE) occur in Jicarilla, Nogal, Tecolote, and White Oaks districts in Lincoln County and in the bed of the Rio Hondo River in Chaves and Lincoln Counties which drains these districts. (While PGE occurrences have been mentioned in the literature, they have never been reliably documented for the Linocln County porphyry belt.)

The placer deposits of the Jicarilla district (fig. 29) have produced most of the placer gold in the study area and are the best known (Segerstrom and Ryberg, 1974). They occur on the north-facing mountain slopes in Ogallala(?) Formation, a fanglomerate of Miocene age. The fanglomerate consists of unsorted, unstratified, slightly lithified, coarse gravel (1-m size clasts), sand, silt, and minor clay derived from nearby Tertiary granodiorite and monzonite intrusives and older sedimentary rocks. Much of the gold was probably derived from small gold-pyrite veins and disseminations in intrusive monzonite porphyry (Segerstrom and Ryberg, 1974). At some sites, gold was found directly above decomposed gold-bearing rock. Quaternary placers contain reworked Ogallala(?) Formation and, thus, may contain second-cycle gold.

Gold in the placers of the Jicarilla district is very fine grained and difficult to extract. It is also erratically distributed vertically and laterally (Segerstrom and Ryberg, 1974). The gold grains are 2.0-0.061 mm in size, but some grains may be as small as 0.001-0.01 mm. Commonly, gold coats hematite grains and is floated off during washing. As a consequence, old tailings may be reprocessed with substantial recovery. Some of the principal placer mines and gold-bearing gravels of the Jicarilla district are in Ancho, Rico, Spring, and Warner Gulches (fig. 29).

Segerstrom and Ryberg (1974) estimate that the placer deposits in Jicarilla district cover a distance of at least 6 km (4 mi) of the gulches over an area of 13-16 sq km (5-6 sq mi), have an average thickness of about 5 m (15 ft), and contain 16 metric tons of gold. Using these estimates, the Jicarilla district reserves are about 46 million m^3 with a gold grade of about 0.35 grams/m^3. The volume is large when compared to other large-volume placers found elsewhere (Bliss and others (1987) (fig. 30), but the gold grade is typical. Jicarilla district placers may be the largest low-grade gold resource in the state. Segerstrom and Ryberg (1974) estimate the grades of individual deposits to range from 0.1 ppm (or 0.1 g/t) for low grade deposits to 1 ppm (or 1 g/t) for high-grade deposits. Placer deposits would offer an opportunity for placer gold production if a reliable source of water (or a process less reliant on water) is found.

Placer deposits in the remaining districts in the study area are less extensive than in the Jicarilla district. In Nogal district (primarily a lode gold district), placers have been worked along Dry Gulch. However, they are usually near the gold-sulfide veins of the Helen Rae and American mines. In the Tecolote district, as in the Jicarilla district, platinum-group elements have been reported along with gold in heavy mineral placers but, as of 1986, there was no positive identification (Northrup, 1959; North and McLemore, 1986). In the White Oaks district (primarily a lode-gold district), Baxter and White Oak Gulches and their small distributaries have been worked intermittently and were a source of income for miners when the lode mines were not producing. As with other districts, placer gold at White Oaks is derived from gold-bearing pyrite veins in the Tertiary intrusives. Most of the placer mining was conducted in the vicinity of the major lode deposits. Schrader and others (1916) report (*in* Johnson, 1972) that placer gold occurs along Rio Hondo, which drains eastward from deposits in western Lincoln County.

The Ancho placer deposit contains an estimated 1.5 million tons of material, which is more than about 53 percent of the 65 gold placers compared world-wide by Orris and Bliss (1986) (fig. 31). The Rico and Little Nugget Gulch placers (combined) may contain 8 million tons, about 63 percent larger than other placers in the world. The grades of the Jicarilla placers range widely. Segerstrom and Ryberg (1974) estimated the grades of individual placers at 0.1 ppm (0.1 g/t) to 1 ppm (1 g/t), which corresponds respectively to grades higher than 15 percent and 99 percent of world placers compared by Orris and Bliss (1986).

Manganese

Only one manganese mine and one prospect are known in the study area (Griswold, 1959). A small replacement deposit occurs north of Capitan Mountain at the Arabela mine 8 km (5 mi) west of Arabela. The deposit consisted of a 0.6-m-(2-ft-)thick vein in a northwest-striking shear zone near the contact of the alaskite intrusive in the Capitan Mountains and the San Andres Formation (Griswold, 1959). The vein contained a 15-cm-(6-in-)thick "soft-ore" zone of iron-manganese oxides having 15 percent manganese and a 46-cm-(18-in-)thick "hard-ore" zone of psilomelane fragments having 49 percent manganese. Psilomelane nodules also extended into the footwall. Only 1 ton of material having 54 percent manganese was shipped before 1959 (Griswold, 1959). Some time after 1959, the Arabella mine was expanded and the ore zone mined out or abandoned (Tuftin, 1984). Selected psilomelane nodules sampled by Tuftin (1984) contained 45 percent Mn and 0.02 oz/st Au. Chip samples yielded less than 1 oz/st Ag. The manganese-bearing zone may continue about 0.3 km (0.2 mi) northeast of the manganese mine (Tuftin, 1984).

Iron

The Lincoln County porphyry belt contains numerous iron deposits in skarn (Kelley, 1949); the Capitan, Gallinas, Jicarilla, Tecolote, and White Oaks districts all contain iron skarns. Iron skarns typically occur as replacements in San Andres and Yeso Formations rocks adjacent to Tertiary intrusions (Griswold, 1964). The grade of the deposits is generally high (nearly 50 percent iron), but individual deposits are small and reserves are low.

In Capitan district, the Capitan iron deposit is by far the largest and most economically important iron skarn yet identified in the Roswell Resource Area. The deposit is located west of the Capitan Mountains and has been described in detail by Kelley (1949), Griswold (1959), Anderson (1957), and Soulé (1947). The northwest quarter of the deposit presently contains the Smokey mine (Smith, 1991). The deposit is ring-shaped, about 397 m (1,300 ft) in diameter, with an average ring width of about 31 m (100 ft) (Kelley, 1949). Thickness of the deposit is limited, because drill holes from 60 to 120 m depth bottomed in the Capitan intrusive. The center of the deposit contains low-grade magnetite-bearing rock and brecciated limestone and marble. Magnetite is the predominant ore mineral, and hematite is subordinate. Gangue is calcite, epidote, phlogopite, muscovite, tremolite, quartz, and fluorite. The Capitan iron deposit may have formed in a pre-intrusive, pre-ore collapse structure or sinkhole in which the ore fluids collected and spread laterally into the adjacent limestone (Kelley, 1945; Smith, 1991).

In the Gallinas district, limestone of the Permian Yeso Formation was intruded by Tertiary porphyritic trachyte and syenite. Contact metamorphism of the limestone resulted in emplacement of silicate skarn minerals and magnetite and hematite. Ore is localized by the combination of igneous contacts, limestone, and local folds (Kelley, 1949, p. 172).

The iron skarns in Jicarilla, Tecolote, and White Oaks districts formed much like those in Gallinas district. In the Jicarilla district, Permian San Andres Formation limestone is intruded by Tertiary monzonite porphyry and in White Oaks district by syenite at Lone Mountain. The Tecolote district contains several small deposits where Yeso and San Andres Formations have been intruded by syenite.

An unusual uranium-bearing iron deposit occurs at the Prince mine on the north side of Lone Mountain (Walker and Osterwald, 1956). The uranium minerals coat fractures, fill pore spaces, and are dispersed as finely-divided grains within the magnetite-hematite ore. Uranium contents average about 0.020 percent; uranium contents of iron ore elsewhere in the area are typically one or two orders of magnitude less.

Of 168 skarn deposits reported world-wide that range in size from 30,000 to about 5 billion metric tons and have a grade of 15-70 percent iron, the median tonnage and grade is 7.2 million tons and about 50 percent iron (fig. 32) (Mosier and Menzie, 1986). Iron skarns in the study area are significantly smaller than the median. When available grades and tonnages for iron skarns in the study area are plotted on the grade and tonnage model, the Capitan deposit is shown to be larger than about 37 percent of the deposits in the model and the grade for the Capitan deposit is higher than only about one-third of the deposits in the model. Elda mine, for which only production figures were reported, ranks in the smallest 10 percent of deposits. The small size of skarn deposits in the study area may be because the intrusions with which they are associated are relatively small and scattered. The Capitan deposit is an exception, having over 3 million short tons that contain 45.6 percent iron (Kelley, 1949, p. 178-179).

Copper

Three copper deposits occur within the resource study area: the Estey, Pintada, and Stauber mines. All of these deposits are of the sediment-hosted Cu (red-bed) type (Cox, 1986b), occurring in oxidized sandstones with interbeds of green or gray (reduced) shale, siltstone, and sandstone. Like most red-bed deposits, those in the study area contain chalcocite and secondary copper carbonate-hydroxide minerals.

The Estey mine in Estey City (Oscura) district, which is within the White Sands Missile Range and closed to the general public, is located at the southeastern edge of the Oscura Mountains that lie along the western border of Lincoln County, extending southward from Socorro County. According to Lasky and Wooton (1933, p. 76, *in* Griswold, 1959), the copper deposit occurs in red beds of the Abo Formation, which is structurally repeated by faulting. Copper mineralization occurs in three horizons, the most important being an arkosic bed at the base of the red-bed sequence. Mineralized layers range in thickness from a few centimeters to one meter (3 ft). The main copper mineral is malachite, which is found in layers, fractures, and joints. Chalcocite is commonly associated with carbonaceous matter in the arkose, having replaced calcite cement in arkose and sandstone. The mineralized material contains a small amount of gold and silver, with coal and other carbonaceous matter noted in the gangue.

The Pintada mine is located about 24 km (15 mi) southwest of Santa Rosa in Pintada Canyon and has been described by Sandusky and Kaufman (1972). The deposit is in sandstone of the Permian Grayburg and Queen Formations of the Artesia Group; they are overlain regionally by the Triassic Santa Rosa Sandstone. The lower 60-75-ft of the undifferentiated Grayburg and Queen Formations unit is gypsiferous. This basal unit is overlain by a lower mineralized sandstone unit about 9 ft thick, containing both primary and secondary gypsum. The mineralized unit is composed of five sandstone units, locally crossbedded, that are interbedded with siltstone, mudstone, and shale. This unit grades upward into an upper sandstone unit that is 45-52 m (150-170 ft)thick, interbedded with siltstone, mudstone, and shale, and unconformably overlain by the Santa Rosa Sandstone. The deposit is generally flat-lying, dipping about 4 degrees north-northwest, and contains minor wavy bedding, folds, and minor gravity faults. The mineralized sandstone contains chalcocite and minor pyrite, carbonaceous material, and kaolin; it is locally stained by limonite. In addition to chalcocite, the main copper mineral, minor copper carbonate minerals are present. Copper minerals are associated with the carbonaceous material.

The Stauber mine contains disseminated copper minerals in sandstone overlain by a clay bed as much as 12 m (40 ft) thick and underlain by an iron-stained clay bed about 8-9 m (25-30 ft) thick (Stauber, 1930). The ore is mostly malachite, azurite, and chalcocite, with minor chrysocolla, bornite, and black copper oxide minerals (tenorite). Rarely, replaced mineralized logs are present that contain as much as 40 percent copper (Stauber, 1930). The ore was found to contain no detectable vanadium (Holmquist, 1947). Host for the copper minerals is the Santa Rosa Sandstone, a medium-grained gray sandstone with local iron staining and interstitial cement commonly composed of silica and calcite. The ore trend is parallel to the strike of the sandstone beds and occurs in small veinlets and fissures, and as interstitial cement, as well as disseminated grains. The ore content typically improves toward the base of the sandstone beds, but high-grade concentrations are found throughout the unit.

Local structures may control mineralization at both Pintada and Stauber mines. At Stauber, mineralization is related to a shallow depression that may be either the result of soft-sediment deformation of underlying clays, karst topography caused by dissolution of underlying Permian evaporites and carbonates, or gentle folding seen elsewhere in Guadalupe County (McLemore and North, 1985, p. 291-292). Pintada mine mineralization control is similar to that at Stauber mine.

Low-grade copper also occurs in association with uranium in the Triassic Chinle Formation near Logan and in the San Jon area of Quay County. There, in a shale bed in the upper member of the Chinle Formation, numerous nodules or concretions consist of cuprite, barite, malachite, fluorapatite, quartz, and minor chalcocite. Selected samples were reported to contain up to 22.6 percent Cu (McLemore and North, 1985, p. 296).

The grade and tonnage model of sediment-hosted copper deposits (Mosier and others, 1986) (fig. 33) characterizes these deposits as ranging in size from about 150,000 metric tons to about 1.6 billion metric tons, with a median of 22 million metric tons. Grades range from about 0.67 percent to about 10 percent Cu, with a median of 2.1 percent Cu. Production of 264,357 short tons from the Stauber mine (McLemore and North, 1985) (Appendix), when plotted on the grade curve for world sediment-hosted copper deposits (Cox, 1986b), is small. The copper grade of 2.56 percent for Stauber mine is higher than the grades of over 60 percent of the deposits, but the silver grade of 1.1 g/t for the Stauber mine is only at 20 percentile for deposits reporting recoverable silver. The reported production grade of 0.67 percent Cu for Pintada mine is at the very low end of the grade curve.

Porphyry molybdenum deposits

Porphyry molybdenum deposits are typically large-tonnage low-grade deposits that are closely associated with small- to medium-sized bodies of alkaline to calc-alkaline intrusive rocks. Most deposits that have been mined contained tens of millions to hundreds of millions of tons of ore, having grades of about 0.08-0.2 percent molybdenum. The deposits are characterized by stockworks or veinlets that contain mostly quartz and molybdenite, and pyrite is commonly abundant. Copper, tungsten, or tin are byproducts in some deposits. Many of the deposits are hosted in the genetically associated intrusive, but many others are partly or entirely in the adjacent country rock, especially above subsurface plutons.

The most significant property of the country rock that makes it favorable is brittleness --its ability to fracture so that a stockwork can form. Porphyry molybdenum deposits are believed to form when heat from a cooling and crystallizing body of magma causes circulation of large quantities of fluid that carry the dissolved components of the ore upward and outward to locations where the vein minerals are stable.

Porphyry molybdenum deposits of the low-fluorine type (Westra and Keith, 1981; Theodore, 1986) have been identified in the Rialto and Three Rivers stocks intruding the Sierra Blanca Igneous Complex in Lincoln County. Mineralized areas are in fine-grained, equigranular syenite possibly near an earlier vent.

Molybdenite mineralization occurred in areas of silicic alteration in the northeastern part of the Three Rivers stock where it comes in contact with the Sierra Blanca Igneous Complex in both the nordmarkite intrusive and the andesite volcanics. Molybdenum mineralization occurs in three forms: (1) molybdenite films along fractures and as fine-grained disseminations in quartz veinlets, (2) molybdenite and abundant breccia zones, and (3) anomalous molybdenum in aphanitic high-silica rocks that contain no visible molybdenite veinlets or smears. The third type of mineralization is believed by Giles and Thompson (1972) to represent hydrothermal fluid that was little fractionated --evidence for sparse molybdenum values in the mineralized zone. That is, hydrothermal differentiation and enrichment had little time to concentrate metal and form a large, economic ore deposit. Hydrothermal alteration, including silicification, argillization, and sericitization, and secondary development of K-feldspar, is most intense and prevalent on the northern and eastern periphery of the stock (Giles and Thompson, 1972). Sparse fluorite and 2-5 percent pyrite are found here also.

Geochemical sampling and analyses by Segerstrom and others (1979) has revealed four molybdenum anomalies associated with Three Rivers stock. These anomalies form an area with a radius of about 3.2 km (2.0 mi), centered along the South Fork of Rio Bonito about 4.2 km (2.6 mi) north-northeast of Sierra Blanca Peak. The southwesternmost of these anomalies is located on a ridge underlain by equigranular syenite of the Three Rivers stock, and extends from about Sierra Blanca Peak to about 2.9 km (1.8 mi) north-northwest. Typical geochemical samples contained 100 ppm Mo. One sample of float contained 1,500 ppm Mo; the molybdenum was found in limonite and in heavy mineral concentrates derived from limonite. The northwesternmost anomaly identified by Segerstrom and others (1979) is partially located in a breccia zone near the contact of nordmarkite and the Walker Andesite Breccia of the Sierra Blanca Igneous Complex at the head of Little Bear Canyon. A high value of 70 ppm Mo was found in a sample from this area. The northeasternmost anomaly, between Waltsmith Canyon and Eagle Creek had molybdenum values ranging as high as 150 ppm. The anomaly is located in equigranular syenite, nordmarkite, and Walker Andesite Breccia. The last of these four anomalies, the southeasternmost anomaly on a ridge at the head of Eagle Creek, had a maximum geochemical value of 150 ppm Mo, according to Segerstrom and others (1979). It was the object of an extensive drilling and geochemical exploration in the 1960s, but has yet to be exploited.

Four mineralized zones have been recognized in Rialto stock (fig. 34); (1) the inner molybdenite zone, (2) the magnetite zone that fringes the molybdenite zone of the west, north, and east, (3) the copper-rich zone that truncates the magnetite and molybdenite zones, and (4) the lead-zinc zone on the eastern and southern periphery of the deposit (Segerstrom and others, 1979). Pyrite is found in all four zones. Griswold and Missaghi (1964) report molybdenite mineralization in areas of the Rialto stock where the monzonite was silicified, sericitized, kaolinitized, and pyritized (map D; fig. 34). Several periods of hydrothermal alteration silicified, propylitized, and argillized the rocks.

Eight breccia pipes in the Rialto deposit are located at the intersections of joint and fracture systems near contacts of biotite-monzonite and hornblende-biotite-monzonite

(Thompson, 1973). The Parsons mine exploited a highly altered, gold-bearing breccia pipe in the central portion of the stock, and the Fulmer tunnel explored another. Locations of many of the mines and prospects of this deposit are shown in figure 34.

The Nogal Peak porphyry molybdenum deposit (Rialto and Three Rivers stocks) is estimated to contain 30 million short tons with a molybdenum grade of 0.05-0.18 percent and a copper grade of 0.22 percent (Hollister, 1978). Thus, the deposit is smaller than the median-tonnage low-fluorine porphyry molybdenum deposit (94 million metric tons; Menzie and Theodore, 1986), but may be higher in grade (fig. 35).

Base and precious metals in veins

Polymetallic veins

The Nogal district contains numerous mines and prospects in polymetallic veins adjacent to Rialto stock. The veins formed as fracture or fissure fillings within Sierra Blanca Igneous Complex after emplacement of the Rialto stock. The Helen Rae and American mines, typical of the many mines and prospects described by Griswold (1959) and Thompson (1973), produced gold from the same carbonate-quartz vein. Gold was probably contained in sulfides such as pyrite, galena, and sphalerite, which were minor constituents of the vein. The highest grade ore occurred at the intersection of the main vein with smaller crosscutting veins. Two barite veins, the easternmost of which contained a small amount of galena, are near the main vein. The Crow vein is host to the Renowned OK and Crow mines located south of the center of Rialto stock. This quartz vein contains galena, sphalerite, pyrite, and minor amounts of chalcopyrite in altered andesite. Griswold (1959) reported that the vein averaged 0.3 m (1 ft) in width and contained 11.3 percent Pb.

The Maud mine, in the southern portion of Rialto stock, is located on a vein composed primarily of quartz, sphalerite, and galena, with lesser amounts of pyrite, chalcopyrite, and barite. Vein width in the lower workings ranged from 40 cm to 208 cm (16 in. to 82 in.) (Thompson, 1973). A composite sample noted in Thompson (1973) from the face of the upper workings assayed at 7.10 percent Pb, 0.39 percent Mo, 0.32 oz/st Au, and 1.28 oz/st Ag.

Copper-fluorite-REE veins

The polymetallic veins and mineralized breccias in the Gallinas Mountains cut unaltered sandstone and siltstone of the Yeso Formation close to two alkalic laccoliths of porphyritic trachyte and porphyritic leuco-rhyolite (Perhac and Heinrich, 1964). The deposits have been exploited for base-metal sulfides, fluorite, the rare-earth mineral bastnaesite, silver, and gold. Typical hand specimens consist of a mass of fine-grained purple fluorite, barite, and bastnaesite in breccia. In addition, these minerals plus galena, chalcopyrite, sphalerite, chalcocite, malachite, azurite, and possibly wulfenite, have been identified (Griswold, 1959). Calcite and quartz are major gangue constituents of the veins. Copper minerals and fluorite commonly occur together (Perhac, 1970).

Numerous small fluorite-bastnaesite-copper deposits also occur in the eastern Gallinas Mountains in the Red Cloud mine (Soulé, 1946; Rothrock and others, 1946; Griswold, 1959; Perhac and Heinrich, 1964; Williams, 1966) . Nearly all of the deposits fill open spaces in faults and breccia pipes at fault intersections in the Yeso Sandstone. The Red Cloud copper deposits contain fluorite, bastnaesite, agardite, barite, mimetite, conichalcite, wulfenite, vanadinite, mottramite, cerussite, and chrysocolla.

The Red Cloud and Old Hickory mines on both sides of Red Cloud Canyon road were visited and sampled in 1990. At Old Hickory mine, fine-grained massive purple fluorite in breccia with calcite and quartz was observed; Griswold (1959) reports dolomite and barite, also. Secondary copper minerals were common in some specimens. Massive purple fluorite having a higher percentage of base-metal minerals (especially fine-grained to massive galena) than at the Old Hickory mine was observed in breccia at the Red Cloud mine. Sixteen analyses of samples collected from the deposits by Armbrustmacher for this study range from < 11 to 195 ppm Th and 2.5 to 142 ppm U.

The Conqueror No. 9 mine is located in a breccia zone composed of fragments of Yeso Formation (Griswold, 1959). The principal ore mineral was fluorite that occurs as breccia filling or matrix replacement. Fine-grained bastnaesite occurs in the ore. Soulé (1946) reported that hand-picked bastnaesite grains, with some contamination, contained 74.39 percent total rare-earth oxides, including 25.61 percent Ce_2O_3 and 48.78 percent $(La, Di)_2O_3$.

About 4,000 tons of copper ore and less than 2,000 tons of fluorite, from which about 60 tons of bastnaesite concentrate were extracted, were mined during 1920-1949 and 1942-1955, respectively (Perhac and Heinrich, 1964). Ore shipped during 1920-1922 contained 6 oz/st Ag, 22.1 percent Pb, 6.93 percent Cu, and 1.93 percent Zn. The Gallinas district is estimated to contain about 46,000 st fluorspar and 28,000 st material with 1.4 percent bastnaesite (Jackson and Christiansen, in press).

Gold and silver in telluride deposits

The study area contains numerous examples of gold-silver telluride-bearing veins (Thompson, 1991c) in the White Oaks, Vera Cruz, Bonito-Nogal, and Gallinas Mountains. These veins commonly occur where alkaline igneous rocks have intruded through a disrupted Precambrian basement and into younger sedimentary or volcanic rocks. Silica-undersaturated rock types, such as syenite, monzonite, and diorite, are some of the probable intrusive rocks that may host epithermal gold-silver-tellurium veins (Mutschler and others, 1985). The telluride veins may contain calaverite ($AuTe_2$), sylvanite ($AuAgTe_4$), hessite (Ag_2Te), and coloradoite (HgTe), as well as fine-grained pyrite, galena, and sphalerite (Cox and Bagby, 1986). Accessory minerals are quartz, calcite, purple fluorite, barite, celestite, roscoelite, and adularia. Kelly and Goddard (1969) describe in detail many of these minerals and their occurrence in the Boulder County telluride belt.

The breccia in the White Oaks district deposit surrounds a 1.6-2.5 km diameter breccia pipe that is cut by a variety of dikes and plugs. Most rocks show evidence of a least four episodes of alteration, and gold mineralization (dated at 34 Ma on adularia) is associated with the youngest episode, occurring in narrow, high-grade veins, sheeted fractures, and broad, low-grade zones of brecciation (Ronkos, 1991).

The Old Abe mine, the most important producer in the White Oaks District, exploited a narrow vein and a wide breccia zone along the contact between a monzonite dike and Cretaceous sedimentary rocks. The breccia contains fragments of both rock types. Mineralization consisted of veins of limonite and manganese oxide with minor quartz and gypsum. Griswold (1959) reports that gold occurred as thin plates, wire, and tiny blebs in the veins. Other minerals include albite, wolframite, heubnerite, tourmaline, fluorite, and auriferous pyrite (Anderson, 1957). Telluride minerals were not reported in the literature; however, they may not have been recognized. Pyrite is present in veins at lower levels in the mine. Higher in the mine, limonite is an alteration product of pyrite and is gold-bearing. Sericitic alteration and silicification were recognized. Other mines in the district, such as South Homestake, had similar mineralization. At the Old Abe mine, heubnerite was associated with the gold veins and was of such abundance that, once recognized, was mined for byproduct tungsten (Griswold, 1959).

The Vera Cruz mine in the northern part of the Jicarilla Mountains occurs in a hypabyssal breccia pipe that intrudes sandstone and shale in the upper Cretaceous Mesaverde Group (Ryberg, 1991). The breccia pipe containing the mine is about 200 m (660 ft) long and 60 m (200 ft) wide at the surface and is believed to widen with depth. The breccia consists of fragments that range to over a meter in size of highly altered sandstone, shale, and intrusive rock. Fine-grained gold occurs in the upper, oxidized portion of the pipe. Argillization and sericitization of the breccia has been intense. The central part of the breccia is highly silicified. Ryberg (1991) reports up to 5.43 oz/st Au in the silicified zone. The unsilicified part of the breccia yields 0.01 oz/st Au or less. Limonite and hematite are abundant and areas with more abundant iron oxides contain more gold. Beneath the old workings at the Vera Cruz mine, drilling has located a sulfide zone at least 90 m (295 ft) thick, having one percent Cu. Recent drilling identified 58 m (190 ft) of material grading 0.28 oz/st Au (Danielson, 1991).

In the Nogal district, the Bonito property (formerly the site of the Great Western mine) is presently being explored for gold and silver associated with alkaline intrusive rocks. The old workings consist of several adits located in a west-trending arm of Bonito Lake stock about 1.9 km (1.2 mi) south-southeast of the Maud mine (Thompson, 1973). Pyrite and quartz were noted in the adits where low-grade ore had been removed. An epithermal breccia system consisting of several breccia zones has been identified at the site. The 44-m-(143-ft-)thick Main zone is estimated to contain 1.3 million st having 0.045 oz/st Au and the 23-m-(75-ft-) thick Blue Front zone is estimated at 2,305,000 st having 0.057 oz/st Au (Dayton, 1988).

Mudpuppy-Waterdog prospect lies about 4.9 km (3 mi) northeast of the Great Western mine (Bonito property). Here, the stock is pervasively altered to propylitic, argillic, and phyllic zones concentrically around the prospect area (Fulp and Woodward, 1991). The prospect lies in a zoned epithermal breccia system like others in the district containing Au, Ag, Te, Cu, and Mo and may have the potential for a large-tonnage deposit. Geochemical analysis of rock samples has yielded values as high as 222 ppb Au, 0.69 percent Cu, and 3.2 ppm Te (Fulp and Woodward, 1991). Molybdite occurs as fracture coatings with values up to 0.28-0.90 percent Mo.

Perhac (1970) described several fairly small (70-m-diameter) breccia masses in the Gallinas Mountains, composed of angular rock fragments in a trachyte matrix. The poorly exposed breccia is a potential site for mineralization because of the nearby fluorite-bastnaesite-copper mineralization in breccia zones and because of the gold mineralization in breccias in other districts.

Dikes and sills of monzonite are abundant throughout the Jicarilla Mountains. Mineralization occurs in fractures and in disseminations in the monzonite porphyry in the form of pyrite, quartz, arsenopyrite, and minor amounts of copper and gold. Hydrothermal alteration is minor with bleaching occurring only in mineralized portions (Griswold, 1959). Weathering of these rocks and constituent veins and disseminations results in formation of the area's placer deposits.

The grade and tonnage model of Au-Ag-Te veins associated with alkaline rocks (Bliss and others, 1992) was developed for use in this study. The model includes grades and tonnages for 24 deposits consisting of gold-bearing epithermal veins and breccias associated with alkaline intrusive and extrusive rocks. Two deposits are likely mesothermal veins. White Oaks district is one of the deposits in the model. The tonnages of the deposits in the model range from 156,000 metric tons to 118 million metric tons, with a median of about 4.9 million metric tons. The gold grades range from 0.23 g/t to 46.7 g/t, with a median grade of 4.5 g/t gold. Silver grades are reported for 15 of the 24 deposits in the model and ranged from 0.75-84.0 g/t Ag. The median silver grade was 1.1 g/t.

Tonnage and gold grade (1.5 million metric tons at 10.7 g/t Au; Ag grade was not reported) of White Oaks district are compared to those in the grade and tonnage model (fig. 36) and indicate that White Oaks is a moderate-size, relatively high-grade deposit. White Oaks deposit is larger than about 31 percent of deposits of this type, containing more gold per ton than about 75 percent of these deposits.

Thorium-rare-earth veins

Thorium-rare-earth veins in the Capitan Mountains are associated with an alaskite to monzonite intrusive stock or laccolith that may represent the most siliceous major intrusive in this part of Lincoln County (McLemore, 1981). The veins were discovered in the 1950s during an extensive exploratory program for radioactive deposits, with radioactive anomalies having 3-5 times background scintillometer readings. Fluid-inclusion microthermometry and stable isotope data presented by Phillips and others (1991) indicate that the fluids responsible for the formation of the mineralized zones were of magmatic origin and were derived from the Capitan intrusion during cooling and injected into the brecciated zones. Small and irregular thorium mineral accumulations occur within joints and as fracture fillings in intrusive rocks at Capitan Mountain (Tuftin, 1984). Staatz (1974) reports the presence of 12 veins that are 3-46 m (10-150 ft) long and <1-2.4 m (0.02-8 ft) wide; 17 samples collected by him contain less than 0.01-1.12 percent thorium. The thorium-bearing vein minerals are thorite and allanite with gangue minerals, including quartz, tourmaline, purple fluorite, and iron oxides (McLemore, 1983). Willis (1988) found allanite, sphene, quartz, plagioclase, chlorite, and clay minerals. The allanite also contains cerium, a light rare earth. Fluid inclusions in sphene and quartz are very saline (the intrusive penetrates underlying Paleozoic evaporites) and indicate a homogenization temperature of 480°-580° C (Willis, 1988).

One of the prospects in the Capitan Mountains, the Barry prospect on the south slope, has a vertical, northwest-trending breccia vein about 0.3 m (1 ft) thick and possibly 100 m (several hundred ft) in length (Griswold, 1959). Several assays indicating as much as 1.7 percent thorium were reported, but the average grade was probably less. Other prospects nearby, such as Drunzer and King, are similar to Barry, and may contain uranium along with thorium and rare earths. Development of these veins in the Capitan Mountains has been limited to exploratory pits, shafts, and trenches (McLemore, 1981).

The size and grade of only one deposit in the Capitan Mountains is known; it is estimated to contain 21,800 metric tons of material having 0.56 percent ThO_2. No rare-earth grade was reported for that deposit. In comparison, thorium-rare-earth veins (Bliss, 1992a; Staatz, in press) range in size from less than about 2,000 metric tons to almost 500,000 metric tons (fig. 37), with a median tonnage of about 180,000 metric tons. ThO_2 grades range from less than 0.1 percent to about 4 percent, with a median of 0.39 percent. Less than half of the deposits are reported to contain rare-earth oxide grades.

Mississippi-Valley-Type (Southeast Missouri Pb-Zn) deposits

Mississippi-Valley-type (MVT) deposits, also referred to as Southeast Missouri Pb-Zn deposits, are stratabound, carbonate-hosted deposits of galena, sphalerite, chalcopyrite, pyrite, and marcasite. MVT deposits are characteristically located in ancient sedimentary reef facies on the flanks of paleotopographic highs (Briskey, 1986). No MVT deposits have been identified in the Roswell Resource Area; however, MVT deposits may be discovered in the study area because the geologic setting of the Permian basin may be favorable for their formation, and because MVT deposits are known nearby in the Hansonburg district in the northern Oscura Mountains in Socorro County. There, Pennsylvanian limestone of the Burrego Formation that hosts the Hansonburg deposits extends into the study area.

The Hansonburg district formed by mineralization of a Pennsylvanian reef-facies limestone built onto a topographic high created by differential uplift along the Capitan Mountains lineament (Putnam and others, 1983). Lead, fluorite, and barite deposits occur along westward-facing fault scarps in cliff-forming limestone, shale, and sandstone. Premineralization karstification of bedrock created open spaces into which low-temperature, upward-flowing ore fluids migrated through faults from the adjacent basin. Ore minerals, such as galena, fluorite, barite, and quartz with minor sphalerite, pyrite, and chalcopyrite, were deposited by simple cooling of the liquid.

Sulfur-isotope evidence suggests epigenetic ore formation for small lead-zinc-fluorite deposits south of the study area, which contain anomalous arsenic, barium, copper, iron, lead, molybdenum, and zinc; some deposits contain anomalous cadmium, gallium, antimony, silver, bismuth, scandium, uranium, vanadium and tungsten (Hill, 1989). Hydrogen sulfide gas generated by reactions between petroleum and anhydrite deposits at the lower contact of the Castile Formation may lead to sulfuric acid generation and dissolution of evaporites and calcareous deposits (cave generation). The small deposits in the Guadalupe Mountains area occur in the same structural and stratigraphic position as many of the caves (for example, along the flanks and crests of positive topographic features of the reef), and beneath impermeable (siltstone) layers in the Yates Formation. They may form veins and disseminated deposits in cements replacing the host rock, or occur in rocks with primary oolitic textures (Hill, 1989).

Mazzullo (1986) described MVT mineralization in the subsurface on the southern Central Basin Platform (southeast of the study area; inset map D). Host dolomites represent shelf marginal facies that grade laterally and landward into inner shelf carbonates and evaporites and seaward into basinal facies adjacent to a prominent basement fault. The minerals present include zoned sphalerite, accessory gypsum, and abundant pyrite. Mineralization probably took place in late Mesozoic to early Tertiary time, with mineralizing fluids from older basinal rocks migrating along the basement fault. The basinal brine and host fluids (locally sulfur-bearing) were mixed, causing complex sulfide mineral deposition after dissolution of the host rock.

Undiscovered resources of MVT deposits outside of known districts include possible deposits in the carbonate rocks of eastern New Mexico (Heyl and others, 1975). The regional occurrence of similar cement sequences (Mazzullo, 1986) suggests regional migration of fluids through rocks of the Permian basin; some of these fluids may have formed MVT deposits. Such deposits, if they exist, could represent a significant undiscovered resource in and near the Roswell Resource Area. Median tonnage for MVT and Appalachian zinc deposits is 35 million metric tons with the largest 10 percent being greater than 540 million metric tons and the smallest 10 percent being 2.2 million metric tons less (Mosier and Briskey, 1986). Median grades are about 4.0 percent zinc, 0.87 percent lead, and 0.48 g/t silver. A study of Canadian lead-zinc deposits (Sangster, 1986) found that 16 MVT deposits in that country had a median of about 3.2 million metric tons, with 95 percent greater than about 93,500 and 5 percent greater than almost 36 million metric tons. The median amount of contained lead and zinc was about 135,000 metric tons.

ESTIMATE OF UNDISCOVERED MINERAL RESOURCES USING THE MARK-3 SIMULATOR COMPUTER PROGRAM

by David M. Sutphin

In a previous section of this report, grades and tonnages of the same type of mineral deposits and occurrences in the Roswell Resource Area were described and compared to mineral deposit models of Cox and Singer (1986) and Orris and Bliss (1991). In this section, estimates were made of the numbers of 11 selected deposit types known or expected to occur in the Roswell Resource Area (table 8). Twelve deposit types having grade and tonnage models are estimated (table 9). When combined with estimates of the numbers of deposits that may be located in an area, statistical methods can be applied to grade and tonnage models to obtain estimates of the area's undiscovered mineral resources.

The technique used here in estimating the undiscovered mineral resources is based upon the three-step type of assessment described by Singer and Ovenshine (1979). These steps are: (1) using known geological, geochemical, and geophysical characteristics to delineate tracts that may contain specific deposit types; (2) estimating the probabilities that a certain number of undiscovered deposits exist in these tracts; and (3) estimating the amount of a given commodity contained in the undiscovered deposits by means of comparison with the grades and tonnages of known deposits of a similar type. Steps (1) and (2) are conducted by a team of specialists; step (3) is a computer simulation. The assessment team that delineated the mineral resource tracts and estimated the probabilities of undiscovered deposits in the tracts consisted of specialists in economic geology, geochemistry, geophysics, and mineral-resource assessment who had studied information on the study area and who had briefly visited and sampled many of the locations in that area. T.J. Armbrustmacher, S. Bartsch-Winkler, G.N. Breit, J.S. Duval, J.A. Erdman, W.I. Finch, D.M. Kulik, J.K. Otton, C.S. Spirakis, D.M. Sutphin, and R.R. Tidball, served on the team but not every member of the team participated in the assessment of each tract. R.B. McCammon assisted the team with the quantitative mineral-resource assessment of the tracts, and W.A. Scott executed the computer simulations.

Tracts favorable for the occurrence of undiscovered mineral resources in the Roswell Resource Area were delineated from interpretation of the geology, geochemistry, and geophysics of the area. Geology was used initially to select areas (or tracts) of favorable rock types and to interpret the structure of the surface and subsurface. Geochemical data revealed areas of anomalous values for both metals in deposits, such as silver or copper, or pathfinder elements, such as barium. Maps of geochemical data were used to reduce or expand the areas initially based on the geology, and for detecting targets in areas which might have been overlooked initially. Geophysical maps were used to outline the distribution of rock types in the subsurface. Remote sensing and aeroradioactivity surveys enabled detection of additional anomalies on the surface. The geology, geochemistry, and geophysics of the study area were compared to the geologic environments and characteristics of deposit types until a consensus on a tract borders was agreed upon by the assessment team. A consensus on the types of deposits permissible in the tract and the number of those deposits at the 90th, 50th, and 10th percent probability levels was agreed upon after further discussion.

The computer program used to transform estimates of the number of undiscovered deposits into estimates of contained commodities in those deposits is known in the U.S. Geological Survey as MARK-3, a computer program for mineral-resource simulation (Drew and others, 1986; Root and Scott, 1988; Root and others, in press). The program requires estimates of the number of undiscovered deposits of a given type within an area. The number of deposits is stated in terms of likelihood of occurrence, resulting in a probability distribution. Computer simulations are performed by selecting simulated deposits from this probability distribution, and for each simulated deposit, selecting a grade and tonnage according to probability distributions of the grades and tonnages of known deposits of the given type. Grade and tonnage models used in this report, with a few exceptions, were taken from Cox and Singer (1986), Bliss (1992b), and Orris and Bliss (1991) (table 9). The alkaline-associated gold-silver-tellurium (Au-Ag-Te) deposit model (Bliss and others, 1992) was developed for this study, while models for epigenetic vein barite and marine bedded gypsum are preliminary.

The grade and tonnage of the simulated deposits are accumulated as part of the simulation process. Once the simulations are performed, the program generates the probability distribution of the contained commodities in the simulated deposits that correspond to the initial estimates of the numbers and types of deposits. These results are presented in an attempt to bridge the gap between a qualitative assessment of the study area's favorability for mineral-deposit occurrences and a quantitative inventory of its mineral resources and do not explicitly consider the economic processes of exploration, development, production, processing, and marketing necessary to transform a mineral resource into a material product.

MINERAL DEPOSIT TRACTS

Six mineral resource tracts (I-VI; map L) were identified where undiscovered mineral deposits can be expected in the Roswell Resource Area. Tracts I-IV were identified as permissible for containing deposit types suitable for evaluation in the MARK-3 program (table 9). For tracts I-IV, estimates of one or more undiscovered deposits were made at 3 different levels of probability --the 90th, the 50th (median), and the 10th percent confidence levels. Tracts V and VI were identified as permissible for undiscovered uranium and vanadium resources and were evaluated using a different method (Finch and others, this report). Table 10 lists the types of undiscovered deposits permissible in tracts I-IV and the numbers of undiscovered deposits estimated at each level of confidence for those deposit types.

Tract I

Tract I was outlined from the composite geophysical gravity and geomagnetic outline of the subsurface boundary of the Lincoln County porphyry belt. Tract I extends from the village of Corona and the Gallinas Mountains in the northern part of western Lincoln County to the villages of Hondo and Ruidoso and Sierra Blanca Peak on the south. The western edge of tract I parallels the Phillips Hills in far western Lincoln County while the eastern edge includes the eastern end of the Capitan Mountains. Tract I has an approximate area of 8,058 km^2 (3,111 mi^2) and includes the Capitan, Gallinas, Jicarilla, Nogal, Tecolote, and White Oaks mining districts, which have been the most significant past producers of metals and have the largest identified metal resources in the study area. Included also in tract I are broad areas north and south of the Capitan Mountains where geophysical evidence suggests that several shallow intrusions have yet to be exposed.

Tract I was selected as having rock types and geology permissible for the occurrence of iron skarns, thorium-rare-earth veins, alkaline-associated Au-Ag-Te deposits, polymetallic veins, fluorite-bastnaesite veins, gold-PGE placers, porphyry molybdenum, low-fluorine deposits, epigenetic barite veins, and replacement manganese deposits.

The criteria used to determine that undiscovered iron skarns were permissible in tract I were (1) recognition that a large percentage of the exposed intrusions in the Lincoln County porphyry belt, such as those in Gallinas, Jicarilla, and White Oaks districts, had related iron skarns (Ia) and (2) presence of limestone host rocks in areas where shallow unexposed intrusions where detected by geophysics (Ib). Probability estimates of numbers of undiscovered iron skarn deposits to a depth of 1 km in tract I are: 2 or more at 90 percent probability, 4 or more at 50 percent probability, and 5 or more at 10 percent probability.

Tract I was considered permissible for undiscovered thorium rare-earth veins because of the identified occurrences of these veins in the Capitan Mountains, thorium geochemical anomalies in stream sediment samples, and the presence of faults and fractures where mineralization could have occurred. A 50 percent probability was estimated that 1 or more thorium rare-earth veins occur in tract I.

The exposed intrusions in tract I, such as those in the vicinity of White Oaks district, have been well-explored for gold deposits. The unexposed intrusions, however, are thought to have received little attention by modern exploration methods and are deemed permissible for alkaline-associated Au-Ag-Te deposits. It was assumed that many of the unexposed intrusions of the Lincoln County porphyry belt were of alkaline compositions like those exposed. A 90 percent probability was estimated for the occurrence of 2 or more alkaline-associated Au-Ag-Te deposits in tract I (table 10). There is a 50 percent probability that 4 or more undiscovered deposits and a 10 percent probability that 8 or more undiscovered deposits of this type occur in the upper km of tract I.

Insufficient information was available when the assessment team met to estimate the probability of occurrence of gold placers in the study area. Estimates are offered here after further study. Several factors were considered when estimating the numbers of undiscovered gold placers in tract I. The long mining history of placer deposits within the tract and the estimate of a large resource of placer gold in Jicarilla district are evidence that the tract has been well-explored for placer gold and that most deposits may have been discovered. Gold mineralization of the alkaline-associated Au-Ag-Te deposit type is very fine grained and occurs in foils and other shapes that do not lend themselves easily for placer enrichment at an appreciable distance from the source. There is a 90 percent probability that tract I contains one undiscovered gold-PGE placer deposit, a 50 percent probability that the tract contains two such deposits, and a 10 percent probability that the tract contains 4 such deposits (table 10). No estimate was made of placer gold deposits between tract I and the Pecos River in the center of the study area, which may have less than 10 percent probability for undiscovered placer gold deposits.

The estimate of undiscovered low-fluorine porphyry molybdenum deposits in tract I is based upon reported molybdenum anomalies (Segerstrom and others, 1979), geochemical anomalies in stream sediment samples, the presence of permissive volcanic host rocks in the southern portion of Lincoln County, unexposed intrusives in the tract, and magnetic lows that may be indicative of hydrothermal alteration of host rocks. Table 10 lists the estimates of undiscovered low-fluorine porphyry molybdenum deposits in the tract.

The presence of replacement manganese deposits at the Arabella Manganese Inc. mine and another small prospect nearby, the association with intrusive rocks, and the presence of faults and fractures suitable for vein mineralization suggest that there was a 50 percent probability that 1 or more deposits of this type are contained in tract I.

Based on the known occurrence of polymetallic veins in the Gallinas Mountains and in the Sierra Blanca, the presence of base-metal geochemical anomalies in the Sierra Blanca and elsewhere, and the occurrence of fractures and faults in areas they may be underlain by alkaline intrusives, a 90 percent probability was estimated that one undiscovered polymetallic vein deposit is contained in tract I. There is a 50 percent probability that two such undiscovered deposits occur there, and a 10 percent probability that four such deposits are contained in that tract (table 10). Another deposit type, fluorite-bastnaesite veins, was estimated to have a 10 percent probability of one deposit occurring in tract I. A deposit model for fluorite-bastnaesite veins has yet to be developed so the total probable tonnage cannot be estimated. A 50 percent probability was estimated for occurrence of one or more undiscovered thorium rare-earth veins.

Tract II

Tract II delineates areas permissible for sediment-hosted copper and southeast Missouri lead-zinc deposits in the western panhandle of Lincoln County. Tract II has an approximate area of 550 km^2 (346 mi^2). About three fourths of the tract is within the White Sands Missile Range and contains the southern portion of the Oscura Mountains. The remainder of the tract is immediately east of the missile range with a thumb-like extension lying between Walnut Canyon and Valley of Fires Recreation Area in the Malpais. Quail and Sixshooter Canyons in this area are part of tract. From west of the state park, the eastern boundary of tract II runs parallel to route 54 southward, passing west of Oscura and east of the Phillips Hills to the southern boundary of the study area. The eastern one third of this tract, including the thumb, overlaps with tract I.

Tract II includes outcrops and the inferred subsurface continuations of Permian and Pennsylvanian clastic and carbonate sedimentary rocks. The Permian sedimentary rocks of the Abo Formation are permissible for redbed-type sediment-hosted copper deposits because they are both permeable continental margin sandstones and host identified mineralization of this type in the Oscura district within the tract. Copper, silver, and base-metal geochemical anomalies within the tract suggest mineralization. Documentation of copper mineralization in faults in the Oscura Mountains (Bachman, 1968) both within and outside the tract is another positive indication. A 50 percent probability was estimated for that 1 deposit and a 10 percent probability that 2 undiscovered sediment-hosted copper deposits occur in tract II.

A 10 percent probability of one MVT deposit was estimated for tract II. This deposit type is permissible because of the extension into the tract of Pennsylvanian limestone and geologic structures associated with the Hansonburg district, which is outside of the study area on the northern end of the Oscura Mountains.

Tract III

Tract III encompasses a 30 mi diameter centered on the Stauber mine in Guadalupe County and has an area of 1,830 km^2 (707 mi^2). The boundary of the tract extends from east of Santa Rosa where route 84 and Interstate 40 (I-40) intersect, northward through the approximate center of the Perea Grant, and north of Colonias. Tract III includes about 10.5 mi of route 84 north of where it crosses I-40 west of Santa Rosa. The limit of the tract again crosses I-40 about 27 mi west of Santa Rosa, then crosses route 54 about 7 mi southwest of Pastura and route 219 about $6^1/_4$ mi south of Pastura. Besides the City of Santa Rosa, the tract includes the settlements of Pastura, Pintada, and San Ignacio. A very small amount of tract III overlaps with tract Va.

Tract III is permissible for the occurrence of sediment-hosted copper deposits. The criteria for outlining the tract are continuation of the Grayburg and Queen Formations and the Santa Rosa Sandstone, which host deposits of this type at Pintada and Stauber mines, and which contain copper and uranium minerals in measured sections of the Santa Rosa. Geochemical anomalies and karst topography in the tract favor formation of sediment-hosted copper deposits. The circular outline of tract III is the maximum radius from Stauber mine that the team would estimate the probability of a sediment-hosted copper deposit being discovered. The present subeconomic status of the Pintada deposit, and the relatively high amount of past exploration in the tract that apparently did not find additional deposits, suggests that there is only slight (10 percent) chance of another undiscovered sediment-hosted copper deposit in tract III.

Tract IV

Tract IV extends from the southern boundary of the study area in Chaves and Lincoln Counties and from the White Sands Missile Range in far western Lincoln County to the Mescalero Pediment east of the Pecos River in Chaves and De Baca Counties. The area of the tract is approximately 22,760 km^2 (8,766 mi^2) excluding the area of the Lincoln County porphyry belt (Tract Ia). The area surrounds 12 known deposits (Weber and Kottlowski, 1959), but does not take into consideration the vast deposits in the subsurface outside the tract in the eastern part of the study area due to insufficient information on gypsum grade and extent in these areas.

Tract IV is permissible for the occurrence of gypsum in Permian formations less than 60 m (200 ft) from the surface. The gypsum resources of the study area are compared to the marine-bedded gypsum deposit model (Kirkham, 1984; Raup, 1991) and to known gypsum occurrences. A quantitative estimate of marine-bedded gypsum resources here is based, in part, on a grade and tonnage model under development (Orris, 1991, personal commun.). The mineral resource assessment team did not estimate the probability of undiscovered marine-bedded gypsum deposits in the study area, since the deposit model was not available at the time of the assessment meeting and there are no recent, published figures of mined gypsum or resource estimates for gypsum from these deposits. Estimates herein are based mainly on descriptions and locations of deposits by Weber and Kottlowski (1959) and by Darton (1920).

Gypsum deposits of commercial grade are known at 12 locations within the study area (Weber and Kottlowski, 1959) (fig. 20). The largest of these deposits underlies and area of about 3,108 sq km (1,200 sq mi) in the Pecos River Valley. Successively large deposits within the study area underlie 389 sq km (150 sq mi) in the Vaughn area, the Rio Hondo and 267 sq km (103 sq mi) in Rio Ruidoso valleys, and 10 sq km (4 sq mi) in the Phillips Hills.

The combined area underlain by gypsum deposits is about 4,481 sq km (1,730 sq mi).

Tract IV contains all of the gypsum occurrences and the space between them. It was chosen as the part of the study area most likely to contain undiscovered gypsum resources. If it were underlain by one meter of material containing 90 percent gypsum, the total contained amount of that commodity would be about 52 billion metric tons. In comparison, the world's largest gypsum deposits, such as those in the Paris Basin, France, covers an approximate area of over 8,029 sq km (3,100 sq mi) with a thickness of up to 55 m (180 ft), and the Permian deposits of Oklahoma and Texas cover an area of about 2,590 sq km (1,000 sq mi) at a maximum thickness of 6 m (20 ft) (Pressler, 1985).

The grade and tonnage model for marine-bedded gypsum deposits (G.J. Orris, 1991, personal communication) consists of 12 deposits ranging in size from 1.1 million mt to 17 billion mt, with a median size of 158 million mt. Of the deposits in the model, four are in Canada, and there are three each in both Oklahoma and France. The Oklahoma deposits are the largest, ranging from 1.2 billion to 17 billion metric tons. Grades of world-model gypsum deposits range from 75 percent to 97.5 percent gypsum with a median grade of 94.1 percent. One of the deposits in the grade and tonnage model is located in New Mexico north of the study area at White Mesa (Sandoval County). At White Mesa, according to Weber and Kottlowski (1959), the gently dipping gypsum member of the Jurassic Todilto Formation is 15-30 m (50-100 ft) thick, and forms an arcuate band that is 0.3-1.2 km (0.2-0.75 mi) in width and 4.8 km (3 mi) in length. In 1959 an area of 1,180 acres was thought to contain 201 million metric tons of material containing 95 percent gypsum under relatively thin overburden.

Based on the fact that a large part of the study area is underlain by marine-bedded gypsum and that 12 potentially economic deposits are already known in the study area (Weber and Kottlowski, 1959), a 90 percent probability is estimated for two undiscovered gypsum deposits of the marine bedded type in tract IV. There is a 50 percent probability that 3 undiscovered deposits occur in the tract, and a 10 percent probability that 4 deposits of gypsum occur in the tract. The predicted median tonnage of gypsum in the tract is 6 billion metric tons. There is, however, an 10 percent probability that there is as little as 186 million metric tons in the tract of the grade and tonnage described by the model. There is also a 10 percent probability that the tract contains more than 29.9 billion metric tons of gypsum.

ESTIMATES OF TONNAGES OF METALLIC COMMODITIES AND GYPSUM IN UNDISCOVERED DEPOSITS

The estimates of the number of undiscovered deposits were used as input to the MARK-3 computer program which generated estimates of the undiscovered mineral resources (tables 11-13) in each tract and gives a total for tracts I-IV. The undiscovered resources are expressed as the median (50th percentile) of the distribution for each of the 20 commodities associated with the deposit types considered. The range of probability for the amount of each commodity is expressed by the 90th and the 10th percentiles of its distribution.

The median, rather than the mean, of the distribution was chosen as the primary measure of central tendency of each commodity distribution because the median is less sensitive to extreme values that arise during the simulation runs due to the highly positively skewed nature of most grade and tonnage distributions.

An example from table 12 serves to illustrate interpretation of the estimates. The median estimate of gold contained in undiscovered alkaline-associated Au-Ag-Te deposits is 262 metric tons. That is, if there were many regions of the same size and having the same geological, geochemical, and geophysical characteristics as the Roswell Resource Area, one would expect that 50 percent of the regions would contain more than 262 metric tons of gold in this deposit type and 50 percent would contain less. Ninety percent of the regions would contain more than 20.2 metric tons of gold in undiscovered alkaline-associated Au-Ag-Te deposits and ten percent would contain more than 1,500 metric tons of gold. It follows that for eighty percent of the regions, the gold contained in alkaline-associated Au-Ag-Te deposits would be between 20.2 and 1,500 metric tons. The wide range in the estimates for this example is due to the wide range (2-8) in the number of undiscovered deposits estimated and the large skewness of the distribution of gold grade for this type of deposit.

Predicted tonnages of commodities for each deposit type and the total predicted contained commodities in tracts I-IV are given in tables 12 and 13, respectively. For both tables, the parameters include the 50th (median), the 90th, and the 10th percentiles of each of the distributions. It should be noted that, in summing probability distributions, the median is not additive. Thus, the median estimates of total contained commodities in tables 12 and 13 are not simply the sum of medians of the commodities in the tracts. Moreover, the median estimates of the total contained commodities are larger than one's intuition might first suggest. The reason the estimates of the total contained commodities are larger than expected is because, for each of the tracts there is a probability that no deposits will occur. In summing the probability distributions, the probability that all of the tracts, for either a given deposit type or for a given commodity, will contain no deposits is naturally smaller, and this is in turn, gives rise to probability distributions having considerably greater medians.

Comparing the median tonnages estimated for each commodity in the study area with the median tonnages for tracts I, II, and III shows that tract I contains the majority of the metals in undiscovered deposits. That tract contains 100 percent of the gold, iron, manganese, molybdenum, and thorium, 57 percent of the silver, 44 percent of the lead, and 21 percent of the zinc. An almost negligible proportion of the copper is contained in tract I. Tract II is estimated to contain about 47 percent of the copper in undiscovered deposits. Estimated median values for the other metals--silver, cobalt, lead, and zinc--in tract II are zero as are the median estimates for copper, silver, and cobalt for tract III.

The E/C index, given for comparison, is defined as the median endowment to consumption index (Drew and others, 1986) where median endowment is divided by annual apparent consumption for each commodity. The E/C index is the number of years at the 1990 level of U.S. consumption that the commodities in undiscovered deposits represents. Gypsum, for example, represents about 73 years of consumption at the 1990 level, while the base metals, copper, lead, and zinc represent fractions of a percent. The E/C index should only be taken as a qualitative reference.

Resource estimates presented here for a particular commodity are point estimates (medians) which are subject to several variabilities, such as the contribution of a particular commodity from several deposit models, and the variances of the grade and tonnage distributions for the deposit models.

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URANIUM AND VANADIUM

URANIUM DEPOSITS AND OCCURRENCES

by Warren I. Finch, James K. Otton, and Charles T. Pierson

Sandstone

Sandstone uranium deposits have been discovered in the Roswell Resource Area in Chaves, De Baca, Guadalupe, Lincoln, and Quay Counties (Finch, 1972a,b) (see Appendix). Host rocks include the Santa Rosa Sandstone and Chinle Formation of the Triassic Dockum Group, the Triassic Redonda Formation, and the Upper Jurassic Morrison Formation. Although sandstone ore bodies may be either tabular or roll-front, most of those in the study area are tabular in form. Although their origin is controversial, tabular ore bodies were most likely formed during diagenesis under reducing conditions, whereas roll-front ores were formed by oxidation solution fronts advancing downdip in the host sandstone (Ruzicka and Bell, 1984; Turner-Peterson and Hodges, 1986). Vanadium minerals commonly occur with uranium minerals, and in some deposits vanadium is more abundant than uranium. Uranium minerals are commonly associated with pyrite and/or marcasite and with organic matter of plant origin. The vanadium occurs mainly in clay and oxide minerals that impregnate the sandstone.

In Guadalupe County, anomalous radioactivity related to uranium has been detected in the upper sandstone member of the Santa Rosa Sandstone at three sites. In Pintada district, at the American Uranium prospect, yellowish-gray limonitic calcareous sandstone about 15 cm (6 in.) thick contains 0.045 percent U_3O_8. Exploratory drilling has identified other thin uraniferous zones at depths of 3, 20, and 26 m (10, 65, and 85 ft). At the Porcupine prospect about 8 km (5 mi) northwest of the American Uranium prospect, anomalous radioactivity is identified by a light olive-gray sandy claystone near the base of the upper sandstone member. At a railroad cut northwest of Santa Rosa, anomalous radioactivity has been identified in an irregular claystone lens as thick as 1 m (3 ft) and as long as 122 m (400 ft) near the base of the upper sandstone member.

In northeastern Guadalupe County, the Branch Ranch and Neafus Ranch deposits occur in the middle sandstone member of the Chinle Formation. This member consists of interbedded fluvial sandstone, limestone-pebble conglomerate, and shale. Carbonized wood fragments occur in light-brown sandstone and in the limestone-pebble zone in the lower portion of the member. Uranium, although sparse, is associated with the carbonaceous zones in the minerals tyuyamunite and metatyuyamunite. At Branch Ranch, uranophane and unohoite have been identified. The primary uranium material in both deposits was probably uraninite associated with pyrite.

In Quay County, several uranium occurrences have been identified in the Chinle, Redonda, and Morrison Formations. From the middle sandstone member of the Chinle Formation, the Good Luck No. 3 mine yielded 8.43 short tons of ore averaging 0.22 percent U_3O_8. Another 80 short tons of trial material was shipped from Good Luck No. 1, Little Rattler, and Windy No. 9 mines. At Troutman Ranch in Quay County, a 0.3-m-(1-ft-) thick, 76-m-(250-ft-) long tabular body of disseminated uranium minerals in the middle sandstone is reported to contain 0.06 percent U_3O_8. At Wallace Ranch in Quay County, the upper shale member of the Chinle Formation contains uranium in thick, dominantly dark- to orange-red shale that overlies the middle sandstone member at the Red Peak prospect. Chert nodules containing malachite and azurite were found to contain 0.12 percent U_3O_8, over 10 percent Cu, 0.70 percent V, 0.003 percent Ag, 1.5 percent As, and 0.003 percent Se (Finch, 1972a,b). At the Fife prospects, uranium is found in a 20-cm-(8-in.-) thick pale yellowish-green calcareous, noncarbonaceous, laminated sandstone of the Redonda Formation. Finch (1972a,b) notes that in Quay County most of the uranium occurrences in the Morrison Formation occur in a small area west of Tucumcari. Deposits are associated with silicified wood, bone, and carbonaceous wood. Most of the silicified materials contain a few tenths of one percent U_3O_8, while sandstone and shale associated with this organic material contain a few thousandths of one percent U_3O_8. The Breen prospect in this area consists of a 30-cm-(1-ft-) thick roll with limonite and gray organic(?) material found to contain 0.004 percent U_3O_8. In western Quay County, small amounts of uranium occur also at the contact between the Dakota(?) Sandstone and Mancos Shale.

Veins in Tertiary igneous rocks

In Lincoln County, veins that contain thorium, REE, and U, and skarn deposits that contain uranium are known in three localities related to large faults that cut the Tertiary intrusives and adjacent units shown on the geologic map (map A). Uranium occurs in iron-rich veins cutting Tertiary alaskite at the Bear Canyon Mine, Capitan Mountains area. Uranium also occurs in veins filling fractures and breccia in the Yeso Formation and Tertiary trachyte porphyry (McLemore and Chenoweth, 1989). Uranium occurs in iron veins at the Prince mine on Lone Mountain. Tertiary intrusives are exposed in eight igneous centers in the southwestern part of the Roswell Resource area; three of the centers shown on the geologic map have faults associated with them and two of them have uranium-bearing veins (map A). The grade of these deposits is below the 0.03 percent U_3O_8 cutoff used as the lowest mining cutoff today. No data are available for tonnage, but the deposits are assumed to be very small. The undiscovered uranium endowment in Tertiary-age igneous rocks is insignificant. In western Lincoln County, a small occurrence in trachyte in the Little Black Peak Lava Flow Wilderness Study Area shows no evidence of production (Griswold, 1964; Stoeser and others, 1989; Berry and others, 1982).

UNDISCOVERED URANIUM RESOURCES

The Roswell Resource Area has a small potential for uranium resources in three types of uranium deposits: tabular sandstone, surficial, and vein. Small tabular sandstone-type deposits may be discovered in the Triassic Dockum Group and in Jurassic sedimentary rocks mainly in the northern part of the Roswell Resource Area (Appendix). Although several very small occurrences of uranium occur in the Morrison Formation just north of Tucumcari, the potential for uranium in the Morrison in the Roswell Resource Area is too small to consider further. Northwest of the study area, tabular sandstone deposits occur in the Permian part of the sequence of Permian and Upper Pennsylvanian rocks. Arid-land surficial uranium deposits occur in Tertiary sedimentary rocks in the adjacent area in Texas and such deposits may remain undiscovered in the Roswell Resource Area. In the southwest part of the study area, uranium is associated with iron skarn deposits and thorium veins in Tertiary intrusive rocks (see section on metals).

Sandstone uranium deposits

Sangre de Cristo Formation

Pennsylvanian rocks are present in the subsurface in the Tucumcari Basin but are absent in the area immediately to the south. In the National Uranium Resource Evaluation (NURE) program of the U.S. Department of Energy, a speculative uranium endowment[3] was calculated for the Permian and Pennsylvanian Sangre de Cristo Formation in the Tucumcari Basin area (U.S. Department of Energy, 1980). This endowment estimate resulted from the southeast projection of a favorable area that contains occurrences of small tabular uranium and copper deposits in the Coyote Creek district, Mora County (Tschanz and others, 1958) and from knowledge of the uranium in the Sangre de Cristo Formation in the isolated deep Conoco Leatherwood-Reed No. 1 well (Finch, 1972b). In the study area, the favorable part of the Sangre de Cristo Formation probably includes the Permian San Andres and Abo Formations (map A). Small tabular uranium deposits are known in the Abo Formation in the southeasternmost Colorado Plateau (Finch, 1991). In the NURE program, the use of a roll-front model for large and relatively high-grade deposits in Tertiary formations in the Shirley Basin district, Wyoming, to estimate uranium resources for the Sangre de Cristo causes one to question the validity of the estimate, particularly the grade and tonnage. The NURE estimate of 12,706 short tons of U_3O_8 for the Sangre de Cristo Formation (table 14) is here judged much too high. The San Andres and Abo Formations in the southern part of the study area are not favorable for uranium deposits.

Dockum Group

In order to evaluate the favorability of the Dockum Group for uranium, one needs to compare the Dockum Group to units of similar age and lithology on the Colorado Plateau. Major deposits of uranium occur in Triassic rocks in southeastern Utah and northeastern Arizona (Finch, 1991). Organic humic matter was a major factor in the formation of these deposits, but the source of uranium for these deposits was most likely volcanic ash in mudstone units overlying the host sandstone beds. This ash apparently came from volcanic centers adjacent to the western and southern edges of the Colorado Plateau (Granger and Finch, 1988; Stewart and others, 1986).

The amount of volcanic detritus in the Dockum is much less than in the Chinle of the Colorado Plateau, so that a volcanic ash source for uranium in the Dockum basin was probably insufficient to form extensive uranium districts and very large deposits. Ash from the volcanic centers west of the Colorado Plateau was probably not deposited in the Dockum basin because the basin is too distant. The Dockum basin is separated from the Colorado Plateau Triassic basin by

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[3]**Speculative resources:** undiscovered uranium resources that may occur either as known types of deposits in favorable areas in which no discoveries have been made or in new types of deposits not yet recognized for their economic potential.

Uranium endowment: the uranium that is estimated to occur in rock with a grade of at least 0.01 percent U_3O_8. Unconditional endowment is based on the assumption that one or more deposits exists in the favorable area.

the positive Ancestral Rocky Mountain highland and its southern extension, as evidenced by abundant thick coarse polymictic conglomerate at the base of Dockum in central New Mexico. Thus, surface transport of ash by streams from the Colorado Plateau would also have been unlikely. The source for Dockum basin deposits was most likely the southern Ancestral Rocky Mountain highland in central New Mexico and other highlands to the south and east (Stewart and others, 1986; McGowen and others, 1979).

Certain features of the stratigraphy and paleohydrology of the Dockum Group also may have played a role in limiting formation of uranium deposits there. Favorable host rocks for uranium in the Dockum, such as organic-rich fluvial sandstone and limestone-pebble conglomerates, lie above, rather than below, the only known ash-bearing strata. The underlying Permian non-organic marine sandstone beds would have been unfavorable for uranium deposition. Finally, paleohydrology of the Dockum basin was much different than the Colorado Plateau (Sanford, 1990) and probably did not yield saline-fresh water interfaces thought to be critical for the formation of tabular uranium deposits (Sanford, 1990; Granger and Finch, 1988). The Matador Uplift influenced sedimentation of the basal units of the Dockum Group. For example, the mudstone of the Dockum (a potential uranium source) in the basal Tecovas Formation thins over the Arch, and the Santa Rosa Sandstone (a potential uranium host) does not exist in Texas on the Arch. The Santa Rosa Sandstone probably did not extend south of the crest of the Arch in New Mexico. Therefore, the area south of the Arch in New Mexico is judged to be less favorable for the existence of uranium deposits than the area to the north.

Known deposits of Dockum sandstone in the Roswell Resource Area and adjacent areas to the north are small, particularly in the Sabinoso and San Jon areas where the productive deposits have yielded a total of about 100 tons of rock with an average grade less than 0.10 percent U_3O_8. The main host for the more productive deposits is a dense limestone-pellet conglomerate with a black carbonaceous coating. Uranium within the sandstone is limited primarily to the carbonized wood fragments; only small amounts of disseminated uranium occur in the sandstone. Host rock is lenticular, fluvial, channel-fill sandstone. Limestone-pebble conglomerate lenses are rarely greater than 1.5 m (5 ft) thick and 15 m (50 ft) long, and have little likelihood for hosting large uranium concentrations.

Estimates of speculative uranium endowment made for the NURE program (U.S. Department of Energy, 1980) for the San Jon favorable area herein termed the Dockum Group and Chinle Formation favorable area (map L) totals 1,340 tons U_3O_8 (table 14). The NURE estimate is based on the Cameron, Arizona control area, where the productive deposits are very large (Finch, 1991) and have higher average grade than those in the Roswell and adjacent areas. Thus, the NURE estimate for uranium endowment in the Roswell Resource Area is probably much too large.

For the Roswell Resource Area, new estimates of the undiscovered uranium endowment in Dockum Group rocks were made using the deposit-size-frequency (DSF) method (Finch and McCammon, 1987). This method was used because no grade and tonnage models are available for the use of MARK-3 method used in this report for metals and certain industrial minerals. The entire area underlain by the Dockum is considered to be favorable for the occurrence of uranium deposits and is divided into two parts: Tract VA and Tract VB (map L). The division between the two tracts is based on the character of the Dockum south of the Matador Arch (map D) where the rocks are essentially mostly dark red and contain very little carbonaceous matter. However, a few occurrences are known south of the Arch, and there are strong geochemical uranium anomalies in the area (figs. 3, 4; this report).

Size classes and grade ranges were established based on the sizes of known deposits in the

Sabinosa and San Jon areas. The numbers of deposits in the four size classes (ranging from 1 to 9,999 tons of mineralized rock) were estimated for both Tracts VA and VB (table 15). Using these data, the undiscovered uranium endowments in the Dockum Group for both tracts were calculated in probability distributions (table 16) using TENDOWG program (McCammon and others, 1988). The values of the undiscovered uranium endowment are less than one ton of U_3O_8. Thus, the potential for large uranium deposits in the Dockum is extremely small. The expected undiscovered deposits, buried by more than 305 m (1,000 ft), would not be economically recoverable by either conventional mining or in-situ leach methods. Mining ceased in the Sabinosa area in 1956 because the deposits were small and low-grade, inaccessible, and too costly to mine and explore (McLemore and Menzie, 1983). Exploration costs for small deposits would be even more prohibitive in the 1990s.

Surficial deposits in the Ogallala Formation

The area underlain by the Ogallala Formation in eastern New Mexico is shown to be favorable for surficial uranium deposits on the map by McLemore and Chenoweth (1989). Fairly large uranium deposits of this type are known in the area east of the study area in west Texas (Otton, 1984). These deposits were not known during the NURE program.

Although uranium has not been reported in the Ogallala Formation of eastern New Mexico, it has been found in outcrops and in the subsurface in scattered localities along the Ogallala outcrop at the southern and eastern edge of the Llano Estacado in the Texas Panhandle. The area of uranium occurrence extends from the Seminole Draw area northwest of Midland, Texas, northward to the Tule Draw area northeast of Lubbock. Deposits closest to the Roswell Resource Area lie 50 to 100 km to the east and southeast. Exploration drilling for uranium has been conducted by FRAMCO and Union Carbide in the Tule Draw area, by Kerr-McGee in the Sulphur Springs Draw area (north of Midland), and by Energy Reserves Group in the Seminole Draw area (Otton, 1984; Steve Schurman, private consultant, Denver, Colorado, written commun., 1990). Although information on grade and tonnage is very limited, deposits of uranium apparently range in size from a few hundred thousand to several million pounds of contained uranium. Grades are probably less than 0.1 percent U_3O_8.

Very little information is available on the nature of the uranium host rocks in the Ogallala Formation. Our examination of outcrop and available company data (Steve Schurman, written commun., 1990) suggests that three types of uranium hosts may be present: (1) silcrete; (2) lacustrine calcrete; and (3) sandstone; however, the available data are so limited that no specific deposit models may be developed.

Uraniferous silcrete occurs in scattered localities in the Amarillo 2-degree sheet (Seni and others, 1980), the Lubbock 2-degree sheet (McGowen and others, 1981, J.K. Otton, unpublished data, 1985), and the Plainview 2-degree sheet (Amaral, 1979). However, these occurrences are of very low grade (a few tens of ppm U), small size, and of limited uranium resource potential (Seni and others, 1980, p. 16). Lacustrine calcrete appears to be the host rock at the Sulphur Springs Draw deposit north of Midland, Texas. There, carnotite occurs in calcrete beds associated with fine-grained, greenish-gray mudstone beds of probable lacustrine origin. These beds may be similar to lacustrine (playa) beds that host the Lake Austin and Lake Maitland calcrete uranium deposits in western Australia (Heath and others, 1984; Caveney, 1984). In the Seminole Draw area, the host rocks are fine-grained sandstones that are probably in the middle of the Ogallala.

Away from the outcrop belt of the Ogallala in Texas and New Mexico, the distribution of uranium in the unit is little known. However, extensive sampling of Ogallala water wells was conducted during the NURE program both within the Roswell Resource Area (Erdman, this report) and in Texas. Scattered high values ranging from 100-200 ppb uranium occur in the study area and in the Lubbock, Texas area. Values as high as 40 ppb uranium occur in the Amarillo, Texas area. Such elevated uranium in waters was probably derived from leaching of uranium accumulations within the aquifer.

In the Roswell Resource area, the size, grade, and location of such accumulations cannot be estimated directly, but they may be comparable to known uranium occurrences and deposits to the east in Texas. Thus, the Ogallala Formation seems a likely host to uranium deposits in Tract VI in the Roswell Resource Area (Map P). Tonnage size classes and grade distributions were established for Tract VI based on the Texas area, and numbers of deposits in each size class were estimated (table 15). Endowment calculations for the Ogallala Formation using the deposit-size-frequency (DSF) method and the TENDOWG program show a mean uranium endowment of 1,287 tons of U_3O_8 for the Roswell Resource Area (table 17).

VANADIUM

by George N. Breit

Production

Eighty-four pounds of vanadium (V_2O_5) have been produced from deposits within the Roswell Resource Area as a by-product of uranium production (table 18), and of these, 82 pounds of V_2O_5 came from two small vanadium-uranium deposits hosted by the middle sandstone member of the Chinle Formation in Quay County (McLemore and North, 1985). Small amounts of vanadium also have been recovered from similar sandstone V-U deposits 48 km (30 mi) north of the study area. This production includes 174 pounds of V_2O_5 that was extracted from the Chinle Formation in the Sabinoso district (McLemore and Menzie, 1983) and less than a ton of silicified wood containing 0.31 V_2O_5 that was mined from the Morrison Formation in Harding County (Finch, 1972a,b).

Two pounds of V_2O_5 were produced from a uraniferous magnetite vein in Lincoln County (table 18). The vanadium content of this magnetite is only 0.04 weight percent (McLemore, 1983), which is consistent with the low grade of most hydrothermal magnetites. Based on the low grade compared to most vanadium deposits, the iron deposits of Lincoln County are not considered a vanadium resource.

Base-metal vanadate deposits have produced vanadium within New Mexico, but not within the Roswell Resource Area (Fischer, 1975). Vanadate minerals are reported to occur in metal deposits within and adjacent to the study area (DeMark, 1980; Jerome and others, 1965). The size of the deposits and the abundance of vanadates within the deposits are both small.

Undiscovered vanadium resources

V-U ore deposits are distinguished from other sandstone-hosted uranium deposits by their large vanadium concentrations (1.0-2.5 percent V_2O_5) and their V_2O_5:U_3O_8 ratios, which commonly range from 10:1 to 3:1. Samples analyzed for vanadium from exposed deposits in eastern New Mexico (Finch, 1972b; Leibold and others, 1987; McLemore, 1983; McLemore and Menzie, 1983; McLemore and North, 1985) were examined for high V values and V/U ratios. Of samples that contain greater than 0.005 weight percent uranium, only a few have vanadium contents greater than 1 weight percent; most contain 0.5-0.01 weight percent V_2O_5. The ratio of $V_2O_5 : U_3O_8$ in these samples range from 0.3 to 50, with a median of 5. The median value is within the range of other sandstone vanadium-uranium deposits, but the grade of both V_2O_5 and U_3O_8 are lower.

Host rocks for major V-U deposits located in Arizona, Colorado, and Utah include the Triassic Chinle Formation, Jurassic Entrada Sandstone, and the Salt Wash Member of the Jurassic Morrison Formation (Finch, 1991). All three formations or their equivalents are present in the study area; both the Chinle and Morrison Formations contain small deposits in the Roswell Resource Area. The greatest potential vanadium resource within the Roswell Resource Area are the V-U deposits hosted by the Chinle Formation of the Dockum Group.

Although deposits in the Chinle Formation are considered to have the greatest potential to produce vanadium within the study area, the potential for large deposits containing greater than 1 weight percent V_2O_5 is small. Vanadium-producing sandstone-hosted deposits typically contain ore layers that are suspended in the sandstone over relatively large areas. Deposits described within and near the Roswell area are small and hosted by carbonaceous organic matter, calcareous clay lenses, or limestone-pebble conglomerates; rarely is the ore disseminated within the host sandstone. Roswell sandstones are generally thinner and contain less carbonaceous matter than rock units that contain the large deposits in Utah, Colorado, and Arizona (Finch, 1972a,b; McLemore, 1983). Extensive exploration of the Chinle Formation in the study area during the uranium boom of the 1970s failed to yield any large discoveries. A numerical estimate of the vanadium resources within the Roswell Resource Area was calculated by multiplying the $V_2O_5 : U_3O_8$ ratio by the uranium resource estimate (table 16). The estimates of the uranium endowment for tracts VA and VB is less than 1 ton of U_3O_8, with ore grades of 0.03-0.08 weight percent U_3O_8. Considering the V_2O_5:U_3O_8 ratio of 5, this would suggest that only 5 tons of recoverable V_2O_5 is present in the resource area. The predicted tonnage is very small relative to areas elsewhere that contain producing sandstone-hosted vanadium-uranium deposits.

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HYDROCARBON AND ASSOCIATED RESOURCES

The Permian Basin, one of the largest oil- and gas-producing basins in the United States, extends from West Texas into southeastern New Mexico. Oil and gas discovered in this basin (in 4,400 oil pools and 900 gas pools) totals more than 90 billion bbl of oil-in-place and 106 trillion cu ft of gas-in-place (Dolton and others, 1979; Ward and others, 1986). Part of the Northwestern Shelf of the Permian Basin is included within Roswell Resource Area boundary.

Oil-bearing horizons in the southeastern part of New Mexico include rocks of the Ordovician, Silurian, Devonian, Pennsylvanian, and Permian Systems. Stratigraphic and structural traps form oil pools in Permian strata in much of the Northwestern Shelf including and bordering the southern part of the study area, and shelf or back reef facies are the dominant habitat for oil, especially in dolomitized limestones of Permian age. On the Shelf, hydrocarbons are recovered from Cambrian to Cretaceous rocks, but most production is from Permian units; that produce from structural traps, stratigraphic traps, and combinations of the two.

In this area, shelf or backreef deposits of the San Andres Formation and Artesia Group grade updip into siltstones, evaporites, and dolomites, which have higher average porosities than the nearby reef or forereef deposits. Backreef environments in these units provide the primary reservoirs for much of the Permian Basin, especially at the updip contact of lagoonal dolomite and clastics with coastal evaporites. Most of the explored producing areas are in New Mexico south and southeast of the study area. Exploration targets, however, include numerous structural and stratigraphic traps, and combinations of the two, in regions within the study area, including areas within Tucumcari Basin and on the landward parts of the Northwestern Shelf. Two principal oil-and-gas plays are described below for the study area.

In southern New Mexico, oil and gas activity is complicated by potash mining and reserves (Cheeseman, 1978). Oil and gas production in the Carlsbad Potash District of the Delaware Basin south of the study area is from Yates and Queen Formations of the Artesia Group and from Pennsylvanian Formations, which lie below the potash deposits (Cheeseman, 1978). Oil and gas exploration is restricted to potash-barren areas or areas that will not interfere with potash mining activities (Cheeseman, 1978).

In addition to oil and gas, other gases such as carbon dioxide are recovered during petroleum recovery or have been discovered during petroleum exploration. The potential for these associated gases in the Roswell Resource Area are assessed in this section of the report.

In the Sierra Blanca basin in the Lincoln County porphyry belt, coal has been mined from several horizons in the Mesaverde Formation. Most of the major coal mining ceased early in the century due, in part, to the lateral restriction of the coal beds and offsets by faulting.

PETROLEUM GEOLOGY OF THE ROSWELL RESOURCE AREA

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Introduction

This discussion presents an analysis of the petroleum geology of the Roswell Resource Area. The initial section describes structure, including regional tectonic setting and local structural styles, that determine configurations of hydrocarbon traps. The second section covers reservoirs and seals in the context of the area's stratigraphy. The third section treats source, maturation, and migration of petroleum. The fourth section deals with exploration and production history, that includes brief descriptions of typical, significant oil and gas fields and references to depositional environments, sediment body geometry, and composition, texture, diagenesis, porosity, and permeability of host rocks as they relate to hydrocarbon accumulation. Finally, we describe and analyze the region's oil and gas plays, and estimate the quantity of undiscovered recoverable hydrocarbons.

Structural controls of hydrocarbon traps

The residual Bouguer gravity anomaly map of eastern New Mexico (Keller and Hills, 1988) (fig. 38) shows a correlation of uplifts with positive residual anomalies, and a strong correlation of lows with negative residual anomalies for major structural elements of the Roswell Resource Area (map D). Positive anomalies running northward from central Lincoln County correlate with the Pedernal Uplift. This positive trend branches at the northwest corner of Guadalupe County. The northeastern branch follows the Sierra Grande uplift. At the juncture of the Sierra Grande uplift and the Bravo Dome, the positive anomaly turns to the southeast and marks the dome's axial trend toward the northern tip of Quay County. A well-defined chain of negative anomalies curves westward from the Palo Duro basin of Texas into the Tucumcari basin of New Mexico, and bends southward through De Baca County into Lincoln County. A large positive anomaly centered in Roosevelt County includes the Roosevelt positive that appears to be a westward continuation of the Matador Uplift from Texas. Another trend of lows curves westward through the Tatum basin and extends toward the southwest and south in Chaves County.

The magnitude of residual gravity anomalies is measured in tens of milligals. This exceeds, in most cases, the amount of anomaly that could reasonably be attributed to relief on basement rocks. It follows that the anomalies also reflect intrabasement density contrasts. High density, more mafic, basement rock areas are associated with uplifts and lower density basement materials underlie basins; thus, density contrasts which stem from lithology variations probably are attended by basement elevation differences due to a combination of differential erosion and faulting at the basement surface.

The main regional structural feature that essentially bounds the Roswell Resource Area on the west and north is the Pedernal Uplift and its northeastward and eastward continuations, the Sierra Grande Uplift and Bravo Dome. The history of this feature is complex. Thinning of lower Paleozoic strata toward its axis (map B) indicates that the Pedernal Uplift was a broad positive area or highland landmass of Precambrian rocks throughout early Paleozoic time. Major movement of the Pedernal Uplift occurred during the late Paleozoic Ouachita orogeny, when it was part of the southern end of the Ancestral Rocky Mountain range. Major unconformities, known from surface and subsurface studies, provide evidence for episodic uplift and erosion of the Pedernal from Pennsylvanian through Early Permian time (Maps B,C). Middle Permian strata continue across the uplift with only minor folding.

The history of the Pedernal uplift influenced the entire Roswell Resource Area. The region was part of a broad shelf area during pre-Pennsylvanian time, with pre-Mississippian strata limited by erosion and nondeposition to southern De Baca, Roosevelt, and Chaves Counties. During late Paleozoic tectonic activity, the various uplifts and basins in the area acquired their present shapes, and the region was exposed from late Permian to Cretaceous time. The Late Cenozoic was a time of renewed uplift, when the region bounded by the Pedernal-Sierra Grande-Bravo Dome system was tilted east (the present-day Pecos Slope). Regional tilting combines with stratigraphic configurations of depositional sequences in the Roswell Resource Area to produce abundant stratigraphic traps for oil and gas. Uplift and tilting were accompanied by igneous activity, which was concentrated in southwestern Lincoln County during Late Cenozoic time (the Lincoln County porphyry belt). Although regional southward and eastward dips are the primary trapping control for the Roswell Resource Area, some local structures also influence trapping. For instance, folding associated with the buckle zone of strike-slip faulting plays a role in formation of combination traps in Chaves County, and fault-bounded horst blocks may prove to be important in forming structural traps in the Tucumcari basin of Guadalupe and Quay Counties.

Reservoirs and seals

This section contains a description and discussion of important reservoirs and seals in the context of the regional stratigraphy of southeastern New Mexico. Paleozoic rocks in this region consist of three major stratigraphic intervals:

Pre-Pennsylvanian units

Relatively thin, 0-2,500-ft-thick, pre-Pennsylvanian units are composed primarily of dolomite (map B). Facies patterns within these rocks are indicative of deposition in a broad carbonate shelf environment. Rocks of the early Paleozoic onlap toward the north. In the subsurface of central Chaves County, the updip limits of the Cambrian and Ordovician Ellenberger Dolomite, the Middle Ordovician Simpson Group, and the Upper Ordovician Montoya Dolomite are found, while Silurian and Devonian formations pinch out farther north near the Chaves-De Baca County boundary. Lower Mississippian rocks continue into the Tucumcari Basin as the Arroyo Peñasco Group.

Dolomite units (Silurian Fusselman Dolomite and Wristen Formation) provide the only significant reservoirs (cumulative production exceeding one million barrels of oil equivalent (MMBOE) within the pre-Pennsylvanian section of the Roswell Resource Area (map C). Accumulations of oil and gas from these reservoirs typically occur on the flanks of Precambrian basement highs and are sealed by Pennsylvanian shale beds.

Pennsylvanian units

Pennsylvanian limestone units thin updip onto the Pedernal Uplift. In southern Chaves County, these beds have a combined thickness of approximately 610 m (2,000 ft) (map B). Pennsylvanian rocks show early indications of the existence of a platform edge near the Chaves-Eddy County line, where shelf limestones to the north, grade into the basinal shales to the south.

Within the Pennsylvanian section, three series are significant producers. Updip Morrowan and Atokan quartz sandstone units produce gas from stratigraphic traps sealed by shale beds. Virgilian (lower part, Cisco Group) limestone units are important oil producers with lesser amounts of gas. These fields owe their trapping configurations to combinations of updip stratigraphic pinchouts and drape-over-basement structures.

Permian units

The massive Permian section, changing in thickness from 3,050 m (10,000 ft) in the vicinity of the prograding platform edge in central Eddy County (map B) to 1,676 m (5,500 ft) in central De Baca County (the northern end of the regional section, map B), contains a great variety of depositional facies. In all Permian stratigraphic divisions, the predominantly limestone platform-edge facies separates downdip (southern) basinal quartz clastics, carbonates, and evaporites from updip (northern) shelf dolomites, which contain more terrigenous sand, shale, and evaporite deposits.

Three Permian series contain reservoirs with cumulative production exceeding one million barrels oil equivalent (1 MMBOE). Wolfcampian limestone units produce gas with minor liquids from stratigraphic traps sealed by interbedded shale units. Sandstone units in the Leonardian part of the Abo Formation are important gas producers within the Roswell region. Shales within this series provide adequate seals for both stratigraphic and combination structural and stratigraphic traps. Dolomites of Guadalupian age in the San Andres Formation constitute the most prolific oil producers of this region, and also produce significant quantities of gas. The extremely effective anhydrite seals within the San Andres Formation are major factors in the importance of this unit as a reservoir rock. Trap configuration in the San Andres is a combination of stratigraphic and drape-over-basement structures. Quartz sandstones in the Guadalupian Queen Formation are the youngest significant Permian reservoirs of the Roswell Resource Area. Both anhydrite and salt serve to seal the predominantly stratigraphic traps characteristic of Queen Formation hydrocarbon accumulations. Oil is much more important than gas in these reservoirs.

Post-Permian units

Triassic Santa Rosa Sandstone, a quartzose sandstone in the basal part of the Dockum Group is another potential reservoir rock of the Roswell region. This formation has a role in a speculative play in the Tucumcari Basin and has large resources of heavy oils and tar sands.

Hydrocarbon source and migration

Few published studies deal with hydrocarbon source and migration in the Permian Basin, but lack of exploration success in the distal limits of the Northwestern Shelf of the Permian Basin makes understanding source a necessity . An early and useful analysis of oils in Lower Ordovician Ellenburger reservoirs (Kvenvolden, 1966) identified five families of hydrocarbons whose sources were judged to range in age from Ordovician to Permian. Parke (1974) concluded that the distribution of condensate versus dry gas in the Ellenburger was consistent with the accepted roles of temperature and time in the maturation of hydrocarbons. Stahl and Carey (1975) concluded that the Devonian and Mississippian Woodford Shale was the source for Ellenburger hydrocarbons and that Permian shales were the source of hydrocarbons in Atokan sandstone reservoirs updip. In both cases, younger source rocks in downdip basinal settings were deemed to charge older reservoirs in updip settings with oil and gas. Although there are few published studies relating reservoir oil and gas to source beds in the Permian Basin, using geochemical typing, it seems likely that organic-carbon-rich formations in basinal settings, like the Woodford Shale and various shales of Pennsylvanian and Permian age, are the sources for the huge accumulations of oil and gas in the basins, platform edges, and shelves of the Permian Basin region.

Broadhead and King (1988) and Broadhead (1990a) document the occurrence of mature source rocks in Pennsylvanian shales in the Tucumcari Basin in the northern Roswell Resource Area. These studies suggest that the Pennsylvanian shales have supplied the Triassic Santa Rosa Sandstone in Guadalupe County with 90 million barrels of tar-in-place at Santa Rosa and 60 million barrels of heavy oil-in-place at Newkirk. Such conclusions provide positive evidence that the Tucumcari Basin is a viable exploration setting.

Migration paths require permeable beds extending updip or non-sealing faults connecting permeable strata at different structural levels. The time of migration or remigration of hydrocarbons clearly cannot predate the ages of the reservoirs and seals that hold and trap them. The youngest reservoir charged with petroleum is the Triassic quartz-rich Santa Rosa Sandstone. This reservoir is imperfectly sealed and hydrocarbons in it near Santa Rosa are exposed on the surface as tar sand.

The tilt responsible for the Pecos Slope that dips eastward on the eastern flank of the Pedernal Uplift (map B) occurred during Late Cenozoic tectonism, and, thus, hydrocarbons trapped in updip pinchouts on this slope necessarily migrated or remigrated to their present positions at that time.

Exploration and production history

Twenty oil and twelve gas fields (map M) in the Roswell Resource Area each have a cumulative production, through 1988, each exceeding one million barrels of oil equivalency [6 billion cubic feet (BCF) of gas equals one million barrels of oil] (tables 19, 20). Total liquids (oil plus natural gas liquids) recovered from these fields are 225 x 10^6 barrels. Total gas amounts to 830 BCF (Bureau of Land Management; 1989; Roswell Geological Society, 1985; New Mexico Department of Energy, Hill, 1988; NRG Associates, Inc., 1990).

Almost all of this oil and gas production has occurred in Chaves and Roosevelt Counties, the two southeasternmost counties of the Roswell Resource Area, with Chaves containing 57 percent of the liquids and 72 percent of the gas. A significant amount of the total gas (245.9 BCF, 30 percent) is associated with oil fields, while only 9.5 MMBOE of total liquids (4 percent) come from the gas fields. Caprock field, discovered in 1940, has produced 33 percent of the oil in the Roswell area. Fields discovered in the 1950s have produced 24 percent of the region's oil. The 1960s was the decade of discovery for most of the oil produced to date, with a total of 88.6 x 10^6 barrels, constituting 39 percent of the total for the area. Only 3 percent of the oil produced is from fields found in the 1970s, and only 1 percent is from fields discovered in the 1980s. This history of oil production indicates that oil exploration activity in the Roswell Resource Area is in a mature stage, which is characteristic of the entire Permian Basin Province (Robinson, 1988).

The Pecos Slope gas fields (Pecos Slope, Pecos Slope West, and Pecos Slope South), discovered from 1977 to 1980, have produced 317 BCF of gas (38 percent of the area's total) with most (261 BCF) occurring in Pecos Slope Field proper. Fields having produced 33 percent of the area's total were discovered in the 1950s. Sixteen percent of the area's gas was discovered during the 1960s, 39 percent during the 1970s, and 12 percent during the 1980s.

Production from major stratigraphic intervals has been 6.2 MMBO (3 percent) and 51.2 BCF (6 percent) from pre-Pennsylvanian (Silurian-Devonian) dolomite reservoirs; 55.9 MMBO (25 percent) and 296.3 BCF (36 percent) from Pennsylvanian quartz sandstone and limestone reservoirs; and 163 MMBO (72 percent) and 482.5 BCF (58 percent) from

Permian quartz sandstone and dolomite reservoirs. Permian oil production is more or less evenly divided among nine dolomite reservoir fields in the San Andres Formation and the single Queen-Formation quartz-sandstone reservoir at Caprock. Most Permian gas is associated with the nine San Andres fields. There are essentially no records of gas production from the Queen Formation sandstone at Caprock, although this field is reported to have solution gas drive. Production breakdown by reservoir lithology is 83.5 MMBO (37 percent) and 170.5 BCF (21 percent) in dolomite reservoirs, 86.8 MMBO (39 percent) and 490.2 BCF (59 percent) in quartz sandstone reservoirs, and 55.1 MMBO (24 percent) and 169.3 BCF (20 percent) in limestone reservoirs.

Perhaps the most meaningful statistic available from our study of Roswell Resource Area oil and gas fields involves initial reservoir pressures versus depth. A normal hydrostatic pressure gradient ranges from 0.43 to 0.47 psi/ft depth, depending on salinity. It is clear from Roswell area data that all of the area's oil and gas fields are underpressured. This observation is typical of shallow, uplifted, cooled hydrocarbon reservoirs (Spencer, 1988). As pointed out by Spencer (1988), low-pressured reservoirs can cause exploration and production problems. Deep mud and filtrate invasion can make log identification of hydrocarbons difficult. Underpressured gas reservoirs often yield poor or no shows, even when mud logging equipment is used, and drill-stem tests can be inconclusive.

The plan distribution of Pennsylvanian and Permian oil and gas fields reveals broad groupings that appear to be related to regional structure (fig. 39). The Virgilian (or lower Cisco) limestone oil production, trending east-west in southernmost Roosevelt County (labeled Penn V, fig. 39), bends to a north-south trend in Lea County. This bend marks a change in regional strike from east-west in the north along the southern flank of the Roosevelt positive (northern flank of Tatum Basin, map D) to the north-northeastern strike of the Pecos Slope. The Guadalupian dolomite in San Andres oil fields (labeled SA, fig. 39), north of the Virgilian limestone, have east-west alignments in the east, reflecting strike along the Roosevelt High, but gives way to north-south orientations in the west, reflecting strike of the Pecos Slope. The isolated cluster of oil fields in San Andres dolomite in central Chaves County extends east-west, but individual fields in this cluster trend north-south in response to the strike of the Pecos Slope. The Guadalupian Queen Formation quartz-sandstone oil fields of southeasternmost Chaves County (labeled Q, fig. 39), are aligned along the Pecos Slope strike. This trend is also apparent in the Pennsylvanian Morrowan and Atokan quartz-sandstone gas reservoirs (labeled Penn MA, fig. 39), including Buffalo Valley Field located just west of the Queen accumulations on the southern Chaves County line. The quartz-sandstone gas fields of northwestern Chaves County in the Leonardian part of the Abo Formation (labeled A, fig. 39) are also aligned north-south along the Pecos Slope strike. Gas accumulations generally occupy updip positions relative to oil.

A synopsis of typical fields

This section presents brief descriptions of four fields of the Roswell area. These fields typify stratigraphic units and production groupings within the Roswell Resource Area.

Peterson

Peterson and Peterson South fields (maps M,N) are typical of pre-Pennsylvanian oil and gas accumulations of the Roswell Resource Area in that they do not occur in any production grouping and instead appear to be randomly distributed. This may be a result of the low drilling density of pre-Pennsylvanian prospects (map N).

The Peterson and Peterson South fields were discovered in the 1970s with relatively minor gas and oil production in limestone beds of the Upper Pennsylvanian or Virgilian and Missourian Series (Cisco and Canyon Groups). The fields occurred above more important oil production in the Silurian Fusselman dolomite. Field extensions have merged these fields into a producing area, extending 8 km (5 mi) north-south and 3 km (2 mi) east-west.

Trap configuration is controlled by a local structure consisting of a faulted basement high (Green and Schlueter, 1989) that was uplifted and eroded during Early Pennsylvanian time. Upper Pennsylvanian Series (Cisco and Canyon Groups) sediments were draped over this Precambrian basement on the structure's crest and truncated pre-Pennsylvanian rocks are located on the structure's flanks. There is some indication that this structure existed as early as late Fusselman time, because upper Fusselman is only present on the downthrown side of the western boundary fault. Thickness variations in the Lower Pennsylvanian section on the structure confirm post-Mississippian and Early Pennsylvanian tectonic activity. Maximum structural closure on Upper Pennsylvanian beds is 52 m (170 ft) with throw on the western boundary fault of approximately 30 m (100 ft).

The Pennsylvanian reservoir consists of shelf limestone units that contain collapse breccias sealed by Wolfcampian shale beds. Gross reservoir thickness is about 30 m (100 ft), with an average pay thickness of 9 m (30 ft). Porosity averages 12 percent and permeabilities are measured in a few hundred millidarcies. The Virgilian carbonate reservoir with its combined structural and stratigraphic trap configuration is typical of other Pennsylvanian reservoirs in the Roswell Resource area, with the exception that at Peterson it is an isolated outlier, while most other Pennsylvanian limestone reservoirs are grouped in southern Roosevelt County (fig. 39).

The Fusselman Dolomite reservoir is a coarsely crystalline dolomitized shelf carbonate mudstone, with a gross thickness of 30 m (100 ft) and a pay thickness of 12 m (40 ft). The pay zone lies in the lower part of the Fusselman Dolomite (Green and Schlueter, 1989) (map C). The Devonian Woodford Shale overlies Wristen Formation on the flank of the structure. The Woodford Shale could provide the source for the hydrocarbons in both Peterson fields. The truncated updip end of the Fusselman Dolomite reservoir is sealed by Upper Pennsylvanian shale beds.

Pecos Slope

The complex of Pecos Slope fields (A, fig. 39) was discovered in 1977 as a result of reworking and relogging an exploration well originally abandoned in 1951 (Bentz, 1988). The field's dimensions are large. The combined Pecos Slope and Pecos Slope South fields extend 58 km (36 mi) north-south and 24 km (15 mi) east-west. Included are 557 sq km (215 sq mi) of productive acreage. Depth of production is 1,067 m (3,500 ft). The traps are of westerly-directed porosity pinchouts of very fine sandstone and siltstone beds encased in shale beds of the Leonardian part of the Abo Formation.

Regional east dip of the Pecos Slope in the field area varies from 9 to 18 m/km (50 to 100 ft/mi) (slope of 0.5°-1.0°). The right-lateral buckle zone (map D) passes through the field area, but does not appear to influence hydrocarbon accumulation. The net reservoir interval varies from 152 m (500 ft) in the east to a wedge edge on the Precambrian basement in the west.

Reservoir lithology consists of quartzose red-bed sandstone beds inferred to have been deposited in a distal-fluvial environment (Bentz, 1988), although this environmental interpretation is controversial. Anastomosing "channels" traverse almost the entire 56-km (35-mi) north-south dimension of the field. The "channels" are about 1.5 km (1 mi) wide and tens of m (ft) thick, have concave-downward cross-sections, and are composed of numerous branches inferred to have been deposited by north-flowing streams. The fine sandstone and siltstone beds are the pay zones in the field, but spaces between the grains may be plugged with anhydrite, dolomite, clay, and(or) calcite cement. Porosity averages 13 percent and permeability ranges from 0.3 to 0.03 millidarcies.

Both the pressure and compositional characteristics of the gas in the Pecos Slope field indicate connected migration of the gas throughout the field complex. However, the western part of the Pecos Slope field is separated from the main field complex by a non-producing zone.

Because of the very low permeabilities in the Pecos Slope fields, the hydrocarbons present qualify as "tight gas" under the Natural Gas Policy Act of 1978; under this legislation, production qualified for a subsidized price of $5.00/1,000CF. This preferential treatment of "tight gas" was responsible for the rapid expansion in development of the Pecos Slope region. In 1985, deregulation and an end to subsidization of tight gas resulted in considerable cutback in development.

The hydrocarbons have an API gravity of 51°, gas expansion drive, and are dry, with a gas/liquid ratio of 2.5×10^6 CF/barrel. The Leonardian Bone Spring Limestone in the Delaware Basin and Pennsylvanian shale in closer proximity to the Pecos Slope fields have been postulated as sources for these dry gas accumulations.

Chaveroo

The Chaveroo field, discovered in 1966, is representative of dolomite production in the Leonardian and Guadalupian San Andres Formation. The field trends east-west in southern Roosevelt County, extends into Chaves County (SA, fig. 39), and is about 19 km wide x 8 km long (12 mi wide x 5 mi long). Productive acreage exceeds 78 sq km (30 sq mi). The average depth of producing zones is about 1,280 m (4,200 ft).

Trap configuration is the result of the interplay of stratigraphic, structural, and hydrodynamic conditions (Gratton and LeMay, 1969). Depositional dip was toward the south and resulted in pinchouts to the north of porous, dolomitized, platform-interior carbonates between salt-bearing anhydrite beds. Subsequent eastward tilting superimposed an eastward dip of about 10 m/km (50 ft/mi) on the dolomite of the San Andres Formation; the tilted zone most critical to production extends from the Pecos River in central Chaves County to the Texas line. The eastward dip, in combination with northward pinchout of reservoir facies and north dip off the Roosevelt positive into the Tatum Basin, constitute two critical elements of trap formation at Chaveroo. The third element is hydrodynamic flushing through San Andres Formation reservoir intervals. This eastward water movement resulted in tilt to the east of oil-water contacts in excess of 6 m/km (30 ft/mi) (Gratton and LeMay, 1969). The net result is that the water contact is the basal seal on the westward updip margin of the hydrocarbon accumulations at Chaveroo. In light of the influence of hydrodynamic flushing in this trend, it is possible that San Andres oil first accumulated in northbound, updip porous pinchouts in post-Guadalupian time. The introduction of eastward tilt in the Cenozoic must have resulted in westward remigration into stratigraphic traps on the Pecos Slope adjacent to the Pedernal Uplift (map B). This is consistent with the plan configuration of east-west aligned fields to the east and north-south aligned fields to the west that is apparent in the San Andres trend of southern Roosevelt and Chaves Counties (fig. 40).

The reservoir consists of porous dolomites originally deposited in shallow-marine to transitional-evaporitic environments. Interfingering of lagoonal, tidal flat, and open marine limestone, dolomite, anhydrite, and salt occurs throughout the section. Pay sections are measured in tens of feet. Porosities average 6 percent and permeabilities average one millidarcy. Hydrocarbons of this field have API gravities in the low 20s and are soured by considerable H_2S (typical of all of the San Andres fields).

Caprock

The Caprock field, discovered in 1940, occurs in southeastern Chaves County and northwestern Lea County (Q, fig. 39). The reservoir is at a depth of about 875 m (2,870 ft), and the field occupies an area of approximately 122 km^2 (47 mi^2). It is about 32 km (20 mi) long. This reservoir is the most important oil accumulation in the Roswell Resource Area, having produced 74 million barrels of oil (MMBO).

Trap configuration is essentially stratigraphic and consists of westward porosity pinchouts in sandstone in the middle Guadalupian Queen Formation that occur on the eastern flank of the Pedernal Uplift. The reservoir consists of grey and red quartz sandstone averaging 6 m (20 ft) in thickness with a typical pay section of 3 m (10 ft). Porosity is around 20 percent, with permeabilities of a few hundred (100-200) millidarcies. The top and basal seals are anhydrite and salt beds. Anhydrite tends to plug porosity in west-northwestward-trending embayments along strike of the field (Dunn, 1956).

Hydrocarbons at Caprock have API gravities ranging from 36° to 40° (Dunn, 1956) and are high in sulfur (greater than 1.0 percent, typical of accumulations sealed by anhydrite) and nitrogen. Although gas production of only 10 MMCF is recorded at Caprock, solution gas is deemed to be the driving mechanism for the oil in this field.

Smaller fields in the sandstone beds of the Queen Formation, such as Double L and Sulimar, which were discovered in the late 1960s and 1970s, are located 3 km (10 mi) west and updip from Caprock at depths of around 610 m (2,000 ft). These small fields are very similar to Caprock in the nature of their traps and hydrocarbon character. According to Lampert (1977), these fields are potentially part of a regional oil-and-gas accumulation that is hydrocarbon-bearing, tight, and anhydrite- and salt-plugged, having non-producing sandstones that separate producing field areas.

PLAY ANALYSIS AND HYDROCARBON ASSESSMENT

The oil and gas assessments presented herein were derived from the national assessment of 1988 (U.S. Geological Survey and Mineral Management Service, 1988; Mast and others, 1989) and are based on hydrocarbon play analysis.

A hydrocarbon play is a group of actual or potential oil and gas accumulations that share certain geologic attributes. Some of the geologic attributes included in the hydrocarbon play analysis in this report are regional structural setting, reservoir type and configuration, sealing mechanisms, reservoir age, characteristics of the hydrocarbon source rocks, timing of hydrocarbon maturation and migration, and fluid types associated with the reservoir.

Two hydrocarbon plays that extend into the Roswell Resource Area have undiscovered, recoverable, conventional accumulations of oil and gas estimated to exceed 1 million barrels or equivalent in size; they are (1) the Northwestern Shelf-Pennsylvanian and Permian Play, and

(2) the Northwestern Shelf pre-Pennsylvanian Play (map M). Additionally, four other plays in two provinces (parts of the Permian and Palo Duro Basins that occur within the Roswell Resource Area) have expected oil and gas accumulations of less than 1 MMBOE. Estimates of undiscovered recoverable hydrocarbons for these 6 plays and for federal lands within these plays are presented here. The Tucumcari Basin Play, although not quantitatively assessed herein, could prove to be of future importance and is described and discussed at the conclusion of this section.

Northwestern Shelf Pennsylvanian and Permian play

The Northwestern Shelf oil and subordinate gas play is a combination of stratigraphic, stratigraphic and structural, and structural traps, in shelf margin and interior facies carbonate and (to a lesser extent) terrigenous clastic reservoirs of Pennsylvanian to Middle Permian age. The play area covers the whole of the Northwestern Shelf of West Texas and New Mexico south of the Tucumcari Basin and east of the Pedernal Uplift (maps D, M; fig. 40). Maximum thickness of Permian and Pennsylvanian sedimentary rocks in the area of this play is about 4,570 m (15,000 ft).

Reservoir rocks consist of porous limestone, dolomite, dolomitized mudstone and wackestone, and lesser amounts of fine-grained clastic rocks, frequently associated with evaporites, red beds, and sabkha facies. The reservoir rocks appear to have been deposited in strandline, intertidal to supratidal, and restricted shelf environments. The reservoirs are contained in the Pennsylvanian Morrow, Atoka, Strawn, and Cisco rocks, the Wolfcampian, and Leonardian Bone Spring Limestone and Clear Fork Group, the Leonardian and Guadalupian San Andres, and the Guadalupian Grayburg, Queen, Seven Rivers, and Yates Formations (map C). Gross reservoir thicknesses range up to 305 m (1,000 ft), porosities average 10 percent, and permeabilities average 6 millidarcies.

Source rocks are considered to be indigenous organic-rich calcareous shales and shaly limestones of Pennsylvanian and Permian age. It is inferred that Lower Permian sedimentary rocks are the primary source beds. Deposited under restricted shelf, intertidal, and lagoonal environments, the source beds are extremely rich in organic material. Hydrocarbon generation from adjacent organic-rich source rocks probably occurred during middle to late Permian time. Hydrocarbon fluids migrated laterally and upward into the reservoir rocks simultaneously with generation. Stratigraphic traps in the shelf sequence are formed by lateral facies changes into non-porous and impermeable strata. Structural traps are generally simple anticlinal closures which had topographic relief during the Permian. Buried-reef traps are also present. Seals consist of anhydrite, salt beds, nonporous dolomites, and red beds. Stratigraphically and structurally entrapped hydrocarbons occur at depths of 305-3,353 m (1,000-11,000 ft), with an average of 1,555 m (5,100 ft).

The first exploration discovery of this play was made in Texas in 1923, but most discoveries were made during the 1950s and 1960s. Approximately 55 fields (46 oil fields and 9 gas fields) larger than 1 million barrels of oil (MMBO) and 6 BCF gas have been discovered in the overall play since 1961. These post-1961 fields have combined known recoveries of only 225 MMBO, 627 BCF gas, and 11 MMBOE natural gas liquids. This oil play may contain more than 12 billion barrels of oil (BBO)-in-place. One of the largest oil fields discovered is Wasson, Texas, with approximately 2 BBO recoverable. The largest gas field discovered within the Roswell Resource Area is Pecos Slope, located in Chavez County, with 1.25 trillion cu ft (TCF) recoverable gas. Future resource potential is estimated as relatively good for the discovery of many additional small fields and possibly one or more medium-sized fields.

Northwestern Shelf Pre-Pennsylvanian play

The Northwestern Shelf Pre-Pennsylvanian oil and associated gas play is a combination of structural and stratigraphic, structural, and (to a lesser extent) stratigraphic traps in carbonate and subordinate clastic reservoirs of Early Mississippian through Cambrian age (map M; fig. 40). The play area encompasses the northern part of the Eastern Shelf, northern part of the Midland Basin, and a large part of the Northwestern Shelf (map D, inset). The thickness of lower Paleozoic sedimentary rocks is less than 1,524 m (5,000 ft).

Reservoir rocks consist of Ordovician to Mississippian limestone and dolomite, with a minor amount of Cambrian-age sandstone. The interbedded limestone and dolomite were deposited in the ancestral Tobosa basin, in environments that range from platform and strandline to deeper environments associated with evaporitic tidal flat and sabkha facies, and including mudstone, algal boundstone, wackestone, and oolitic grainstone. Significant reservoirs are in the Lower Ordovician Ellenburger Dolomite and Middle and Upper Ordovician Simpson Group, Upper Ordovician Montoya Dolomite, Silurian Fusselman Dolomite, the Middle and Upper Silurian Wristen Formation, and in Devonian and Mississippian carbonate rocks. Individual reservoir thicknesses are generally less than 30 m (100 ft); porosities average 8 percent, and permeabilities (extremely variable) average 60 millidarcies.

Source rocks in the lower Paleozoic rocks are considered to be indigenous and proximal organic-rich shale, argillaceous limestone, and mudstone. However, a substantial portion of the hydrocarbons in the play could have migrated long distances along extensive fault and fracture systems from overlying and underlying source beds. Source rocks for Cambrian reservoirs are thought to be in shales of the Simpson Group. For Ordovician and Mississippian reservoirs, source rocks are considered to be primarily Upper Devonian Woodford Shale and Middle and Upper Ordovician Simpson Group rocks. Hydrocarbon generation in these Paleozoic source rocks probably occurred during Permian time. Generated hydrocarbons readily migrated into adjacent reservoirs. Trapping mechanisms are a combination of structural and stratigraphic features. Simple and faulted anticlines exist, together with stratigraphic updip pinch-outs, reservoir rock truncations, porosity barriers, and lateral facies changes. Interbedded shales, source shales, impervious crystalline and argillaceous carbonate rocks, updip pinchouts, truncations, facies changes, and permeability barriers act as effective seals. Depths to entrapped hydrocarbons are extremely variable and range from 1,524 m (5,000 ft) to 3,962 m (13,000 ft), depending on the location within the play.

The first exploration discovery of this play was in Texas in 1927, but most discoveries were made during the 1950s and 1960s. Since 1961, 23 fields have been discovered, 20 of which are oil and 3 are gas. These contain more than 103 MMBO, 82 BCF of gas, and 3.5 million barrels of natural gas liquids. The average size of oil fields is 5.1 MMBO, and the average size of gas fields (discovered since 1961) is 9.7 BCF. The future resource potential of the play is probably fair to good, but limited to small-sized fields.

Small field plays

Although small fields (less than 1 MMBOE or 6 BCFG) are abundant, data for these fields tend to be incomplete and inaccurate. Full play analysis of these accumulations is impractical.

Instead, an alternative, statistically based approach is used by the U.S. Geological Survey to estimate remaining undiscovered recoverable oil and gas resources in smaller fields (Root and Attanasi, 1988).

The small fields are grouped for the whole province and separated according to fluid content into simplified oil and gas plays. Frequency and size of accumulations, discovered and undiscovered, that are larger than the MMBOE cutoff for full play analysis are used to construct log geometric curves that are then projected into the smaller field size classes. This method enables prediction of recoverable oil and gas still to be discovered in the smaller fields (Mast and others, 1989).

Small fields in two provinces, the Permian Basin and the Palo Duro Basin, were deemed relevant to oil and gas assessment of the Roswell Resource Area. Province-wide variation in geologic factors such as quality and quantity of structures, reservoirs, seals, hydrocarbons, areas, and drilling densities were used to arrive at percentages of oil and gas field resources for each province within the Roswell area for the area-wide resource assessment. A second iteration of this approach was used to estimate amount of small field oil and gas resources on Federal lands within the Roswell Resource Area.

RESOURCE ESTIMATES

Although the resource estimates reported herein were derived from the 1988 national assessment, some changes were made in the hydrocarbon play definitions to take into account new data unavailable at the time of that assessment. Play boundaries were extended farther to the north to expand play areas in which accumulations exceeding an MMBOE are deemed likely. Some lower Pennsylvanian production originally allocated to a Delaware basin play was reallocated to the Northwestern Shelf Pennsylvanian and Permian play, because this change facilitates description of oil and gas resources of the Roswell Assessment Area. In the national assessment, a single percentage of undiscovered oil and gas was used to allocate resources to Federal Lands within a given play (Dolton and others, 1990). This approach did not, in our opinion, adequately describe all of the undiscovered resources of Roswell Resource Area and Federal Lands within this area. Therefore, for this study, we used separate percentages for oil and gas to make these allocations. In general, this approach tended to increase the amount of gas resources inferred to be present in the Roswell Resource Area. The resources within the Roswell Resource Area and included federal lands were determined based on areas within the plays and variation of attributes affecting the probability of oil and gas accumulations, such as drilling density and quality of structures, reservoirs, seals, source, maturation, and migration paths.

Table 21 presents quantitative estimates of undiscovered, conventionally recoverable, oil and gas within the Roswell Resource Area. By conventionally recoverable, we mean that these estimates do not incorporate the less commonly exploited deposits, including intractable heavy oil deposits, tar sands, oil shales, gas from fractured shales or "tight" gas reservoirs with in-situ permeabilities of less than 0.1 millidarcy, coalbed methane or gas from geopressured shales or brines. Some of these unconventional hydrocarbon-occurrence types may be important future sources of oil and gas in this area, but they are not incorporated in table 21.

Roswell Resource Area

The assessments are presented in two categories: (1) the Roswell Resource Area as a whole (table 21a), and (2) federally-owned lands within the Roswell Resource Area (table 21b). Each category is subdivided into the same six plays. Estimates are presented as means in ranges between F95 (percentile representing a 19 out of 20 chance of occurrence) and F5 (percentile representing a 1 in 20 chance of occurrence). For the entire Roswell Area, our estimates indicate undiscovered recoverable oil and gas resources of about 55-140 million barrels of oil (with a mean of 87 million barrels), 260 to 555 billion cubic ft of gas (with a mean of 375 billion cubic ft), and 6 to 13 million barrels of natural gas liquids (with a mean of 8 million barrels). For Federal Lands within the Roswell Resource Area, we estimate undiscovered recoverable oil and gas resources of about 15-31 million barrels of oil (with a mean of 21 million barrels), 112 and 245 billion cu ft of gas (with a mean of 165 billion cu ft), and 2.5 to 5.5 million barrels of natural gas liquids (with a mean of 3.5 million barrels).

Tucumcari basin

Petroleum resources in the Tucumcari basin in the northern part of the Roswell Resource Area (map D) were considered too speculative to quantitatively assess. Broadhead (1989, 1990a) and Broadhead and King (1988) synthesized available subsurface information with gravity and magnetic data of Keller and Cordell (1983), Cordell (1983), and limited seismic reflection data. They arrive at a version of the nature of basement structure (map D) that differs significantly from that of Keller and Hills (1988). Their interpretation depicts a complicated system of basement horsts and grabens bounded by high-angle faults with throws exceeding 610 m (2,000 ft). This structural style offers possibilities of numerous stratigraphic as well as structural traps throughout the 112 km east-west x 81 km north-south (70-mi x 50-mi) area of the basin.

Residual gravity data suggests the possibility of a continuation of the Palo Duro-Tucumcari basin chain southward into two additional basins beneath eastern Lincoln County (Keller and Hills, 1988) (fig. 38). Thickness and facies variations indicate that faulting in the Tucumcari basin was active during Pennsylvanian and Wolfcampian time (Broadhead and King, 1988).

Potential reservoirs include Upper Pennsylvanian limestone, sandstone, and dolomite of the Permian Wolfcampian and Leonardian Series and sandstone of the Triassic Santa Rosa Sandstone (map C). Seals include Pennsylvanian shale and anhydrite and shale in the Permian section. Hydrocarbon shows occur in units ranging from Mississippian limestone to Upper Triassic sandstone of the Chinle Formation. The two most impressive deposits are the 90 million barrels of oil-in-place as tar sands in Santa Rosa Sandstone located 11 km (7 mi) north of Santa Rosa in Guadalupe County and the 60 million barrels of oil-in-place at Newkirk field in northeasternmost Guadalupe County (map A). Pennsylvanian shale is the probable source of these major shows (Broadhead and King, 1988). Lack of an effective seal for the Santa Rosa Sandstone appears to detract from the oil and gas potential of the Tucumcari Basin.

OTHER RESOURCES ASSOCIATED WITH CONVENTIONAL OIL AND GAS

Tar sand at Santa Rosa

The tar sand reservoir at Santa Rosa is a hydrocarbon accumulation that has migrated to the surface, through porous and permeable strata and along faults and fractures, some of which are results of collapse brecciation accompanying dissolution of evaporites. At the surface, these hydrocarbons lost their lighter components, due to biodegradation and dissolution, to become tars. These tars have, in essence, sealed themselves in the Santa Rosa Sandstone reservoir.

The reservoir is a stratigraphic trap, with an average thickness of 12 m (40 ft) over an area of 3,000 acres. Reservoir porosity is about 10 percent and permeabilities range from 100 to 200 millidarcies. API gravity of the hydrocarbons ranges between 5° and 13°. In addition to being biodegraded, the source may have been marginally mature, which means that they initially contained larger percentages of heavier and more complex hydrocarbon molecules. Broadhead (1990a) favors Pennsylvanian shale beds as the source for these deposits and rules out San Andres shale as a source based on its observed immaturity in proximity to the tar deposits. Time-and-temperature studies indicate that the source shales probably began delivering hydrocarbons to migration routes no earlier than Late Cretaceous.

Volume of the tar is estimated to be about 90 million barrels-in-place. The tars were mined in the 1930s for use as paving material. The exposures of the tar sand are currently flooded by the Los Esteros Reservoir (Broadhead and King, 1988). However, future economic conditions could revive commercial interest in these deposits.

Heavy oil at Newkirk

The heavy oil near Newkirk is trapped at shallow depths of 122-244 m (400-800 ft) in a drape of Triassic Santa Rosa Sandstone over a large basement structure in northeastern Guadalupe County. The trap has a stratigraphic component, as a facies change to mudstone in the Santa Rosa serves to limit the accumulation. The structure was formed in Pennsylvanian through Wolfcampian time (Broadhead and King, 1988), with completion of the trap by deposition of shale seals in the Upper Triassic Chinle Formation. The reservoir porosity is 20 percent, and permeabilities range around 200 millidarcies.

Volume of hydrocarbons is 60 million barrels-in-place. API gravity is 15°-17°. The Pennsylvanian shales are the most likely source of these hydrocarbons. Two attempts at steam flooding to recover oil at this location were made in the 1980s. Both failed, largely because injection pressures exceeded the low pressures in the shallow reservoir to the extent that excessive fracturing and steam loss precluded flooding.

In addition to the heavy oil deposits at Newkirk Field, Crysdale and Schenk (1990) list three small accumulations with API gravities of 19°-20° in stratigraphically trapped dolomite reservoirs (San Andres Formation) in Chaves County. Depths for these occurrences in Chisum, Leslie Springs, and Tower fields are 610 m, 457 m, and 1,249 m (2,000 ft, 1,500 ft, and 4,100 ft), respectively. Reservoir porosities are less than 10 percent, and permeabilities are measured in single digits. The largest volume produced is 56,000 bbls through 1984 at Chisum Field.

NON-HYDROCARBON GAS

by Susan Bartsch-Winkler and Mahlon Ball

Naturally occurring carbon dioxide (CO_2) gas is produced in northern New Mexico from the Bueyeros, Bravo Dome, and Des Moines fields, north of the study area principally in Union and Harding counties and Estancia Field west of the study area in northwestern Torrance County. Gas-field limits have not yet been defined by drilling (Broadhead, 1990b), but the major producing fields are located on the Bravo dome (projecting into the northeast part of the study area in Quay County) and the Sierra Grande uplift (map M). Nitrogen gas is produced from the Queen Formation (Artesia Group) east of Roswell and Hagerman (Grant and Foster, 1989). Small quantities of hydrogen and helium gas were detected in wells drilled in 1985 in east-central Guadalupe County (Latigo Ranch) (Setter and Adams, 1985). Hydrogen sulfide gas is encountered in San Andres dolomite reservoirs.

Carbon dioxide

Carbon dioxide may accumulate as a gas in petroleum reservoirs. The most important use of carbon-dioxide is in oil-recovery-enhancement techniques like those used in West Texas oil fields. Because carbon dioxide is miscible with oil, it acts as a solvent, displacing enough water to mobilize oil in water-invaded reservoirs that would otherwise be unrecoverable. Carbon dioxide dissolves in crude with facility, and it both lightens the oil and decreases its viscosity to make it more easily recoverable.

A major accumulation of carbon dioxide (CO_2) occurs on the crest of the Bravo Dome (map M) in Harding and Union Counties just north of the Roswell Resource Area. The Bueyeros field was discovered in 1916 at a depth of 61 m (200 ft), but was not produced until about 1930 due to the lack of demand for CO_2. The discovery well, an unsuccessful oil test, flowed at a rate of 25 million cu ft per day and blew out for one year before being capped and abandoned due to the lack of a market for CO_2 (Broadhead, 1987). The Des Moines field was discovered in 1935; the discovery well had a reported potential of 6 million cu ft (MMCF) per day (Anderson, 1959).

Bravo Dome field, an eastern extension of the Bueyeros Field that extends into the northeastern part of the study area in Quay County, was developed in the 1980s. In 1985, as many as 258 active CO_2 wells produced 101,227 MMCF (Broadhead, 1987). The gas is 98.6-99.8 mole percent CO_2, with minor amounts of nitrogen and trace amounts of noble gases (Johnson, 1983). According to New Mexico Department of Energy, Minerals and Natural Resources (1990), the Bueyeros Field has estimated reserves of 16 trillion cu ft of CO_2, and is projected to be the largest CO_2 field in U.S., encompassing 1.2 million acres. Estimated joint recoverable reserves for the Bravo Dome and Bueyeros fields range from 5.3 to 9.8 trillion cu ft gas (Johnson, 1983). A total of 279 producing wells in 1989 were located in Bravo Dome (New Mexico Department of Energy, Minerals and Natural Resources, 1990). The future looks promising for continued growth of the industry --prior to 1984, only $20,000 worth of CO_2 was produced, but this value jumped to $7 million in 1987 and $4.5 million in 1989 (New Mexico Department of Energy, Minerals and Natural Resources, 1990).

Carbon dioxide reservoirs in Permian and/or Pennsylvanian rocks have been exploited also in the western Estancia Basin (Beaumont, 1961). Gases in these wells are 67-99 percent

CO_2, but may also contain small amounts of nitrogen, oxygen, helium, and hydrocarbons. Wells produce from 1 to several million cubic feet of gas per day.

The main CO_2 reservoir in the Bravo Dome field is the quartz-rich Tubb Sandstone Member at the base of the Leonardian Yeso Formation (maps B,C) at depths of 610-762 m (2,000-2,500 ft). In the Tubb, the sandstone reservoirs are interbedded with beds of mudstone, dolomite, and anhydrite. According to Broadhead (1987), producing zones may be porous, sand-rich zones that have been acidified, perforated, and probably fractured. Productive sandstones range in thickness from 1.5 m (5 ft) to 6 m (20 ft), having a porosity range of 10-20 percent and permeabilities of a few tens of millidarcies. Other reservoirs include arkosic sandstone and conglomerate beds in the Abo Formation at depths of 762-914 m (2,500 to 3,000 ft) and the quartzose Triassic Santa Rosa Sandstone at depths of less than 305 m (1,000 ft) (Broadhead, 1987). Small shows of the gas have been encountered in the Yeso Formation, Glorieta Sandstone, and the Chinle Formation. These formations rest on Precambrian granite and metasedimentary basement rocks (Broadhead, 1990b), depending on the locality.

The source of the CO_2 is problematic. Some of the gas may be of magmatic origin. Chemical breakdown of carbonate rocks by igneous intrusions is an origin favored by many. Solution of carbonates by groundwater and thermal or bacterial decomposition of organic matter are also plausible ways of producing CO_2. Action of Tertiary intrusions in limestone beds in northwestern Harding and northern Union Counties north of Quay County, with subsequent migration of the CO_2 into the trap on Bravo Dome, seems the most likely explanation for this CO_2 occurrence.

Prospective areas for CO_2 in the Roswell Resource Area may include traps updip from Tertiary intrusions north and east of the porphyry belt of southwestern Lincoln County. Permian limestone and sandstone and Triassic Santa Rosa and Chinle Formation occur in the region northeast of the porphyry belt where they rest on Precambrian basement (Pedernal Uplift). In this area, the rocks may have formed stratigraphic or structural features that are amenable to CO_2 entrapment. However, thick sandstone units, like the Tubb Sandstone Member, do not occur in the region and the Triassic rocks are breached.

Nitrogen

Nitrogen (N_2) is the dominant element in the earth's atmosphere. When nitrogen occurs with hydrocarbon gases, it is often considered to be derived from surface-recharged groundwater that subsequently came in contact with oil and gas accumulations. Some N_2 is also produced as a byproduct of thermal maturation of hydrocarbon source materials. Nitrogen is used in production of fertilizers and explosives.

Anomalously high N_2 contents occur in associated gases of the Queen oil fields of southeastern Chaves County. The nitrogen content of gas at Double L field is 63 percent, at Sulimar it is 55 percent, and at Caprock it is 44 percent. Nitrogen is slow to react chemically (is inert) and therefore, has a tendency to be concentrated in gas-phase migration over long distances. The concentration of nitrogen in Queen Formation reservoirs may also reflect interaction with an eastward flux of groundwater on the Pecos Slope. Moderate amounts of nitrogen may occur in natural gases in the Roswell Resource Area.

Hydrogen sulfide

Hydrogen sulfide gas (H_2S) occurs where oil and gas accumulations are sealed by anhydrite, such as in the sour gas of San Andres dolomite reservoirs. Hydrogen sulfide gas is formed by bacteria-catalyzed sulfate reduction when oil or gas is in contact with anhydrite. Spirakis (this volume) discusses this process in detail. Moderate amounts of hydrogen sulfide gas occur with natural gases in the Roswell Resource Area.

Helium

Helium, a unique elemental gas, is chemically inert, has a simple chemical structure, a very low specific gravity, and a low density. Helium is thought to be formed during radioactive decay in igneous basement rocks. Being inert, this elemental gas is capable of long-range migration into traps. This capability may explain the lack of discernible correlation of helium occurrence and level of local basement rock radioactivity (Tiratsoo, 1979).

Helium is much more common in gases contained in rocks of Paleozoic age and near Precambrian basement. The highest helium content known in gases of the Roswell Resource Area (0.3 percent) occurs at Peterson field. Here, helium occurs in Cisco limestone rocks directly overlying a Precambrian basement high.

COAL PRODUCTION AND ESTIMATED RESOURCES

by Gary D. Stricker

About 1880, coal was mined in the Sierra Blanca or Capitan field in the vicinity of Capitan, Ft. Stanton, White Oaks, and Carrizozo to be used for local mining operations and to provide fuel for nearby Fort Stanton (Griswold, 1959). Additional coal was mined south of Carrizozo in the Willow Hill district (Griswold, 1959).

Until 1906, Lincoln County was the third-ranked producer of coal in the state (Griswold, 1959), but about that time competition from other coal fields with lesser faulting and greater coal-bed extent ended large-scale coal mining in the Capitan field (Bodine, 1956). Most mining was abandoned about 1910 (U.S. Geological Survey, 1965), but coal from the Capitan field was used to generate power for the town of Carrizozo until 1939 (Griswold, 1959). As of 1964, total cumulative production was at least 600,000 tons in Lincoln County (Bodine, 1956).

In the Capitan coal field, several coal horizons are present in the middle part of the Mesaverde Formation, which crops out around the Sierra Blanca basin in Lincoln County (Bodine, 1956), a north-plunging syncline covering approximately 1,125 sq km (435 sq mi) (Read and others, 1950). The Mesaverde is composed of intertonguing fossiliferous sandstone and shale of both marine and non-marine origins. Coal occurs in the middle shale unit and is variable in thickness with internal unconformities. Coal beds, which are commonly eroded beneath sandstone channels, are, in places, broadly folded into east-trending flexures. The middle coal-bearing shale is overlain by white sandstone that is as much as 18 m (60 ft) thick. Numerous dikes and sills intrude the coal-bearing rocks (Wegemann, 1914; Bodine, 1956). Near Capitan, White Oaks, and Willow Hill districts coal beds are disrupted by many faults with vertical displacements of as much as 91 m (300 ft). Faults with displacements of 1.5-3.0 m (5-10 ft) are common. Coal beds have well-developed cleating and variable thickness [generally less than 76 cm (30 in) thick, averaging 2.3 ft, and as thick as 2.1 m (7 ft)] (Bodine, 1956). Coals have an apparent rank of high-volatile C and B bituminous (Campbell and others, 1991), and coals near igneous intrusions are commonly of coking quality (table 22).

According to Read and others (1950), the estimated original resources of Lincoln County in the Sierra Blanca (Capitan) field are as follows (in millions of short tons): measured, 3.3; indicated, 8.0; and inferred, 1,400. Total original coal resources for Lincoln County are 1,410 million short tons.

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FIGURE 17.--Average concentrations of thorium versus uranium for the various mapped geologic units. (A) Concentrations plotted as open circles with the corresponding geologic unit symbols, and (B) concentrations plotted as open circles with horizontal and vertical lines representing the standard deviations (table 2) for uranium and thorium, respectively.

FIGURE 18.--Location of saline deposits in east-central New Mexico (after U.S. Geological Survey, 1965). Green=halite-bearing sediments; red=potassium-bearing sediments.

FIGURE 19.--Isopach of salt in the Salado Formation in New Mexico and Texas. Isopach contour in meters. Area enclosed by dotted line is extent of soluble potash salts, x-x line is extent of polyhalite (after Lowenstein, 1988).

FIGURE 20.--Location of gypsum deposits in the Roswell Resource Area, east-central New Mexico (modified from Weber and Kottlowski, 1959).

FIGURE 21.-- High potential for sulfur (stipple) in the subsurface, Roswell Resource Area.

FIGURE 22.--Aggregate quarries in the Roswell Resource Area (compiled from New Mexico State Highway Department, 1971-1972).

FIGURE 23.--Limestone, caliche, and dolomite in the Roswell Resource Area. Mesozoic limestone (dark stipple north of study area and within eastern Guadalupe County); caliche (light stipple east of Pecos River and in northern Quay County); Paleozoic limestone and dolomite (light stippl west of Pecos River) (after U.S. Geological Survey, 1965).

FIGURE 24.--Typical caliche section showing multiple caliche intervals on the plains near Fort Sumner (modified from New Mexico State Highway Department, 1971-1972, p. 61).

FIGURE 25.--Mines and prospects in the Gallinas Mountains, New Mexico (after Griswold, 1959).

FIGURE 26.--Adobe material sources in the Roswell Resource Area (modified from Smith, 1982, fig. 50). Light stipple = Quaternary deposits; medium stipple in eastern part of study area and in northern Santa Fe County = Middle and Upper Tertiary deposits; dark stipple in Lincoln County = Lower Tertiary deposits.

FIGURE 27.--Location (dark stipple) of surface deposits containing Pecos "diamonds" (from Albright and Bauer, 1955). Medium stipple enclosed by dashed line is area of uncertain Pecos-"diamond"-bearing surface deposits.

FIGURE 28.--Metals mining districts in Lincoln County, New Mexico (after Griswold, 1959).

FIGURE 29.--Mines, prospects, and placer deposits in the Jicarilla Mountains, New Mexico (after Segerstrom and Ryberg, 1974).

FIGURE 30.-- Estimated volume and gold grade for the Jicarilla district placers in comparison with the grade and volume model for gold placers (modified after Bliss and others, 1987).

FIGURE 31.--Grades and tonnages of Jicarilla Mountain gold-platinum-group-element placers plotted on the grade and tonnage model (modified from Orris and Bliss, 1986). Silver grades for the deposit model are not known because there are no reported silver grades for placers in the study area.

FIGURE 32.--Grades and tonnages of iron skarn deposits in the Roswell Resource Area, plotted on the grade and tonnage model (modified from Mosier and Menzie, 1986).

FIGURE 33.--Grades and tonnages of Pintada and Stauber mine production as compared to the grade and tonnage model (Mosier and others, 1986). Production grades and tonnages are calculated from McLemore and North (1985).

FIGURE 34.--Zonation of the Rialto stock porphyry molybdenum-low fluorine deposit, and mines and prospects within the deposit (after Thompson, 1973). Zone I, magnetite; Zone II, molybdenite; Zone III, copper; Zone IV, lead-zinc.

FIGURE 35.--Grade and tonnage of the Rialto stock porphyry-molybdenum low-fluorine deposit as compared to the grade and tonnage model (Mosier and Theodore, 1986).

FIGURE 36.--Grade and tonnage of alkaline-hosted gold deposit at White Oaks compared to world model.

FIGURE 37.--Grade and tonnage of Capitan Mountain deposit compared to the thorium rare-earth vein deposit model (Bliss, 1992).

FIGURE 38.--Residual gravity map of eastern New Mexico. Contour interval 2 milligals. A fifth-order polynomial surface was removed from the Bouguer anomaly values to produce this map. A total of 50,000 gravity readings were taken in southeastern New Mexico.

FIGURE 39.--Plan distribution of Pennsylvanian and Permian oil and gas fields of the Roswell Resource Area, New Mexico (modified from Roswell Geological Society, 1988). [Penn V, Virgilian (or lower Cisco) limestone oil fields; SA, Guadalupian San Andres dolomite oil fields; Q, Guadalupian Queen quartz sandstone oil field; Penn MA, Pennsylvanian Morrowan and Atokan quartz sandstone gas field; A, Abo Formation quartz sandstone gas field.]

FIGURE 40.--Regional oil and gas provinces of the Permian Basin and vicinity (Mast and others, 1989). Dark stipple indicates the Roswell Resource Area. Outlined areas are the Northwestern Shelf, Pennsylvanian and Permian (within dashed line) and Northwestern Shelf, pre-Pennsylvanian (within heavy dotted line).

MAP TITLES

MAP A--Geology of the BLM Roswell Resource Area (1:500,000-scale) modified from the New Mexico Highway Geologic Map (New Mexico Geological Society, 1982) by Edward J. LaRock and Samuel L. Moore.

MAP B--(A) North-south and (B) east-west geologic and lithologic cross sections, Roswell Resource Area and vicinity, New Mexico (modified from Roswell Geological Society, 1953; 1956). (C) North-south and (D) east-west geologic cross sections through parts of the southern Lincoln County porphyry belt (including Rialto, Three Rivers, and Bonito Lake stocks) near Nogal Peak (modified from Thompson, 1973).

MAP C--Correlation chart showing rock sequences in east-central and southeastern New Mexico (American Association of Petroleum Geologists, 1983; Broadhead, 1989; Dobrovolny and others, 1946; Kelley, 1942; Allen and Jones, 1951; Mourant, 1963; New Mexico Geological Society, 1982; Thompson, 1973).

MAP D--Tectonic features of the Roswell Resource Area. Parts of the Northwestern Shelf of the Permian Basin are delineated by the occurrence of halite-bearing units in Permian rocks (McKee and Oriel, 1967) (inset). Major structural features of the Roswell Resource Area include parts of the Northwestern Shelf of the Permian Basin (Bravo Dome, Tucumcari, Palo Duro, and Tatum Basins, and the Delaware Basin south of the Northwestern Shelf) encompassing approximately the eastern half of the study area. Elements of the Ancestral Rocky Mountains include the Sierra Grande uplift, the Pedernal Uplift, and the Bravo Dome (Budnik, 1989) (modified from New Mexico Geological Society, 1982; Grant and Foster, 1988). Structures and relative movement on the Precambrian basement surface of Tucumcari Basin are indicated (from Broadhead, 1989), and Precambrian basement penetrations (open circles) are approximately located. Lincoln County Porphyry Belt includes the zone of Tertiary intrusive rocks, indicated in red. The Tularosa and Estancia basins form the eastern border of the Rio Grande Rift. (Modified from New Mexico Geological Society, 1982; Grant and Foster, 1989).

MAP E--Composite residual total intensity aeromagnetic map of Roswell Resource Area (scale 1:500,000; C.I.=20 nt)

MAP F--Complete Bouguer gravity anomaly map of the Roswell Resource Area (scale 1:500,000; Contour Interval (CI) = 5mGal)

MAP G--Topographic (terrain) map of the Roswell Resource Area (CI= 153 m or 500 ft)

MAP H-- Isostatic gravity map of the Roswell Resource Area (scale 1:500,000).

MAP I--Apparent surface concentrations of potassium (percent K), Roswell Resource Area, New Mexico. scale 1:500,000

MAP J--Apparent surface concentrations of equivalent uranium [parts per million (ppm) eU], Roswell Resource Area, New Mexico (scale 1:500,000).

MAP K--Apparent surface concentrations of equivalent thorium [parts per million (ppm) eTh], Roswell Resource Area, New Mexico (scale 1:500,000).

MAP L--Mineral resource tracts of the Roswell Resource Area, east-central New Mexico.

MAP M--All wells (triangle, gas; square, oil; x, oil and gas; dot, non-producing), field names, and hydrocarbon play boundaries, Roswell Resource Area, east-central New Mexico. Scale 1:500,000; grid-cell spacing, 0.5 mile.

MAP N--Pre-Pennsylvanian well penetrations and production (triangle, gas; square, oil; x, gas and oil; dot, non-producing), Roswsell Resource Area, east-central New Mexico. Scale 1:500,000; grid-cell spacing, 0.5 mile.

Table 1. Susceptibility measurements of rock samples from the Lincoln County porphyry belt

[Locations shown on Map G. Values are multiplied by a correction factor of 2]

Sample Ros 91-	Lat/Long	Susceptibility in SI units x 10^{-5}	Rock type or location
1a	33°21'14"/105°24'25"	0	
b		0	Sedimentary rocks
c		0	(limestone, sandstone)
d		0	
2Ea	33°37'10"/105°27'40"	6	East Capitan Mountains
b		6	
c		10	
d		6	
e		8	
2Wa	33°37'16"/105°28'13"	65	West Capitan Mountains
b		25	
c		6	
d		60	
e		6	
f		10	
3	33°23'28"/105°45'31"	20	Sierra Blanca stock
4	33°24'20"/105°45'16"	20	Do.
5	33°23'23"/105°44'14"	25	Porphyry, Sierra Blanca
6		4000	Sierra Blanca Igneous Complex
7a	33°27'15"/105°43'30"	7000	Sierra Blanca stock at Bonita Lake
b		6600	
8a	33°29'11"/105°47'03"	6	Sierra Blanca stock, Parsons mine
b		0	Do.
9	33°30'05"/105°46'19"	7600	Sierra Blanca stock, Nogal Creek
10	33°30'02"/105°46'10"	16000	Andesite, Sierra Blanca
11	33°42'11"/105°41'00"	10	Carrizo Mountain stock
12a	33°42'04"/105°41'31"	500	Do.
b		500	Do.
13	33°50'17"/105°40'28"	2500	Southern Jicarilla Mountains
14	33°50'20"/105°40'32"	1400	Do.
15	33°51'02"/105°40'23"	3400	Do.
16	33°54'10"/105°38'00"	17000	Jacks Peak
17a	34°11'11"/105°44'12"	0	Rhyolite, Conquistador mine
b		0	Do.
18	34°13'00"/105°45'23"	0	Rhyolite
19	34°13'18"/105°45'16"	0	Do.
20	34°14'30"/105°47'10"	8	Rhyolite, Gallinas Peak
21	33°37'22"/105°33'25"	Exceeds instrument (>200,000)	Magnetite mine, Capitan Mountains

Table 2. Estimated average concentrations of K, eU, and eTh for different geologic units within the study area

[The table includes calculated standard deviations and the number of grid cell within each mapped geologic unit. Asterisks mark calculated standard deviations which are greater than the average value of the calculated standard deviations]

Map unit symbol (Map A)	K (%)	Std. dev.	eU (ppm)	Std. dev.	eTh (ppm)	Std. dev.	No. of cells
Qb	1.38	0.05	1.60	0.06	5.6	2.0	214
Qal	1.16	0.08	1.55	0.18	5.2	3.4*	23519
Qt	1.11	0.05	1.47	0.08	4.9	1.8	6393
QTg	1.82	0.28*	2.10	0.17*	8.3	4.7*	1233
To	1.18	0.04	1.61	0.08	5.1	2.1	2678
Tis	2.09	0.20*	2.35	0.11	10.2	3.6*	545
Tv	1.87	0.17*	2.16	0.21*	9.0	3.1*	408
TKc	1.83	0.32*	2.22	0.25*	9.2	3.3*	59
Mzu	1.16	0.01	1.76	0.03	5.0	0.9	13
Kmmd	1.50	0.29*	2.12	0.11	8.1	4.9*	789
K,u	1.25	0.02	2.00	0.04	6.2	0.8	61
Jme	1.23	0.03	2.07	0.06	6.0	0.3	37
Jm	1.13	0.02	2.15	0.08	6.1	0.5	230
Je	1.22	0.03	1.92	0.09	6.1	0.7	119
₮cs	1.59	0.19*	1.92	0.08	7.9	3.9*	59
₮c	1.13	0.04	1.81	0.09	6.3	1.5	3708
₮s	1.04	0.04	1.63	0.09	5.6	1.4	1888
Pds	1.01	0.01	1.37	0.01	4.3	0.1	14
Pa	1.22	0.04	1.52	0.05	5.2	0.6	3569
Psg	1.03	0.12*	1.77	0.11	5.1	2.1	10431
Ꞓu	1.11	0.15*	1.91	0.11	5.8	4.9*	464
pꞒu	0.86	0.02	1.97	0.09	4.7	0.7	89

Table 3. Mineral constituents of the Ancho gypsite deposits (Jones, 1915)

Mineral constituents	Ancho gypsite
Calcium sulphate (gypsum)	63.95%
Calcium carbonate	20.04
Magnesium sulphate	--
Magnesium carbonate	--
Magnesium oxide	.89
Potassium sulphate	--
Sodium carbonate	--
Sodium chloride	.09
Silica	3.57
Oxides, iron and aluminum	2.01
Moisture	9.45
Total	100.00%

Table 4. Chemical analyses of gypsum (in percent) from selected locations (from Weber and Kottlowski, 1959, table 1). Sample compositions are considered approximate for each deposit

Component:	Sample: 1	2	3
CaO	33.55	32.04	32.94
SO_3	45.16	46.10	45.65
H_2O (combined)	18.16	19.36	19.47
Fe_2O_3 and Al_2O_3	0.25	0.42	0.16
SiO_2 (insoluble)	0.57	1.10	0.16
MgO	0.36	0.20	0.55
CO_2	2.16	0.66	0.55
Total	100.21	100.88	99.02
$CaSO_4$ (calculated from the amount of SO_3 available):			
	76.9	78.4	77.6
Gypsum (Anhydrite from $CaSO_4$ plus combined water, adjusted to total 100 percent with impurities listed):			
	94.8	96.9	98.1

1: San Andres Formation gypsum, sec. 34, T. 5 N., R. 16 E., approximately 3/4 mi northwest of Vaughn. Twenty-foot chip sample from old quarry face.
2: San Andres Formation gypsum. Upper gypsum sequence in old plaster-mill quarry at Ancho, NE1/4 sec 25, T. 4 S., R. 11 E., chip sample at 1-ft intervals.
3: Gypsum in the upper part of the Yeso Formation and the lower part of the San Andres Formation, Phillips Hills. Sec. 21, T. 10 S., R. 8 E., chip-channel sample.

Table 5. Total reported past production, listed by commodity, for mines in the Roswell Resource Area, east-central New Mexico

[Coal, uranium, and vanadium production are discussed in other sections of this report (ounces=troy ounces; st=short tons). Figures modified from Griswold, 1959, p. 19-22]

Commodity	Production
Gold	214,000 oz
Silver	161,476 oz
Copper	7,092 st
Lead	909 st
Zinc	9 st
Iron	270,000-320,000 st
Tungsten (WO_3)	34.07 st
Manganese	small st
Rare earth concentrates	73 st
Fluorite concentrates	1,608 st

Table 6. Production of iron ore from Lincoln County deposits (modified from Griswold, 1959)

District	Mine	Years	Short tons	Percent iron
White Oaks	Yellow Jacket	1913-15, 1942	22,409	n.r.*
	Ferro	1952-53	4,610	n.r.
Jicarilla	Jack	1918-21, 1943	4,184	55-65
	Magnetite	1942-43	2,816	57.2
	Zuni	1943	928	n.r.
	Lane	1943	78	60.0
	Norma	1942	84	n.r.
	Hoecradle	1942	340	57.8
Tecolote	Elda	1915-19	16,064	54.5
	Consolidated	1942	56	n.r.
Gallinas	American	1942-43	4,417	55.7
	Gallinas	1942	7,179	48.7
Capitan	Smokey	1975-91	200,000-300,000	45.6
Undistributed		--	3,725	n.r.
Total		--	270,000-320,000	n.r.

*n.r., not reported.

Table 7. Reported identified mineral resources and estimated gross in-place value, listed by commodity, for mines and deposits in the Roswell Resource Area, east-central New Mexico

[Ounces are troy ounces; figures have been rounded]

Commodity	Value per metric ton* (dollars)	Identified resources (mt)	Gross in-place value** (million dollars)
Au	12,970,250	30.76	399
Cu	2,306	6,800	15.7
Fe	62.18	2,700,000	168
Fluorspar	119	46,000	5.47
Mo	7,434	19,000	142
Rare-earth oxides	2,334	255	.595
ThO_2	42	122	.0051
TOTAL	--	--	731

*Mostly calculated using average yearly prices for the years 1986-90 in U.S. Bureau of Mines *Mineral Commodity Summaries 1991.*

**Estimates of gross in-place value do not imply that these resources would be necessarily economic to produce. Such a determination would require economic analysis of mining and concentrating of ores and metal production.

Table 8. Mineral deposit types known to occur in the Roswell Resource Area

[Model numbers (Cox and Singer, 1986; Orris, G.J., 1991, pers. commun. for gypsum) are given in parentheses. *, notes availability of a grade and tonnage model]

	Deposit type	Roswell Resource Area example
*	Thorium-rare-earth veins (11c)	Capitan Mountain deposits
*	Iron skarn (18d)	Yellow Jacket mine
*	Replacement manganese (19b)	Arabella manganese mine
*	Porphyry molybdenum, low-fluorine (21b)	Rialto and Three Rivers stocks
*	Gold-silver-tellurium veins associated with alkalic rocks (22b)	White Oaks district
	Polymetallic veins (22c)	Maud mine
*	Epigenetic vein barite (27e)	Gallinas Mountains deposits
*	Marine bedded gypsum (35ae)	Ancho deposit
*	Sediment-hosted copper (30b)	Pintada and Stauber mines
	Sandstone uranium (30c)	Quay County occurrences
*	Gold-platinum-group-element placer (39a)	Jicarilla Mountains placers

Table 9. Grade and tonnage models used to estimate the undiscovered mineral resources of the Roswell Resource Area, east-central New Mexico (n.a., not available)

Model and number	Reference
Thorium, rare-earth element veins (11c)	Bliss (1992 -a)
Iron skarn (18d)	Mosier and Menzie (1986)
Replacement manganese (19b)	Mosier (1986)
Porphyry molybdenum, low-fluorine (21b)	Menzie and Theodore (1986)
Alkaline-associated Au-Ag-Te (22b)	Bliss and others (1992-b)
Polymetallic veins (22c)	Bliss and Cox (1986)
Fluorite-bastnaesite veins (n.a.)	---
Epigenetic barite veins (27e)	Orris, G.J. (1991, pers. commun.)
Sediment-hosted copper (30b)	Mosier, Singer, and Cox (1986)
Southeast Missouri, lead-zinc (32a) and Appalachian zinc (32b)	Mosier and Briskey (1986)
Marine bedded gypsum (35ae)	Orris, G.J. (1991, pers. commun.)
Gold, platinum-group element placers (39a)	Orris and Bliss (1986)

Table 10. Estimated numbers of undiscovered deposits in the Roswell Resource Area, east-central New Mexico, for 13 deposit types (n.a., not available)

Model (number)	Commodity modelled	Probability percentile .90	.50	.10
Tract I				
Th-REE veins (11c)	ThO_2, REO	0	1	1
Iron skarn (18b)	Fe	2	4	5
Replacement Mn (19b)	Mn, Cu, Fe, P_2O_5	0	1	1
Porphyry Mo, low-F (21b)	Mo	0	1	2
Alkaline-associated Au-Ag-Te (22b)	Au	2	4	8
Polymetallic veins (22c)	Au, Ag, Cu, Pb, Zn	1	2	4
Fluorite-bastnaesite veins (n.a.)		0	0	1
Epigenetic barite veins (27e)	Barite	1	1	2
Placer Au-PGE (39a)	Au, Ag	1	2	4
Tract II				
Sediment-hosted Cu (30b)	Cu, Ag, Co	0	1	2
Southeast Missouri Pb-Zn (32a)	Ag, Pb, Zn	0	0	1
Tract III				
Sediment-hosted copper (30b)	Cu, Ag, Co	0	0	1
Tract IV				
Marine bedded gypsum	Gypsum	2	3	4

Table 11. Estimated pre-mining tonnage and commodities contained in undiscovered deposits in each mineral-resource tract in the Roswell Resource Area, east-central New Mexico

[Figures are in metric tons]

Commodity	Median (.50)	Resource estimate probability range (.90	.10)
	Tract I		
Au	263	20.9	1,510
Ag	236	30.1	1,020
Fe	46,600,000	3,120,000	477,000,000
ThO_2	171	0	7,980
REO	0	0	780
Mo	49,900	0	502,000
Mn	773	0	147,000
Cu	7.55	0	302
Pb	4,030	52.7	48,100
Zn	1,230	0	36,000
Barite	127,000	473	1,720,000
	Tract II		
Ag	0	0	3,930
Cu	244,000	0	8,070,000
Pb	0	0	656,000
Zn	0	0	3,810,000
Co	0	0	82,000
	Tract III		
Ag	0	0	0
Cu	0	0	1,240,000
Co	0	0	0
	Tract IV		
Gypsum	1,770,000,000	114,000,000	23,500,000,000

Table 12. Estimated pre-mining tonnage of commodities contained in undiscovered deposits, listed by deposit type, in the Roswell Resource Area, east-central New Mexico

[Figures are in metric tons]

Deposit type		Median (.50)	Resource estimate probability range (.90	.10)
Th-REE veins (11c)				
	ThO_2	171	0	7,980
	REO	0	0	780
Iron skarn (18d)	Fe	46,600,000	3,120,000	477,000,000
Replacement manganese (19b)				
	Mn	773	0	147,000
	Cu	0	0	0
	Fe	0	0	322
	P	0	0	0
Porphyry Mo, low-F (21b)				
	Mo	49,900	0	502,000
Alkaline-associated Au-Ag-Te (22b)				
	Au	262	20.2	1,500
	Ag	137	1.35	637
Polymetallic veins (22c)				
	Cu	4.24	0	300
	Au	.017	0	1.09
	Zn	1,230	0	36,000
	Ag	26.9	.491	406
	Pb	4,030	52.7	48,100
Placer Au-PGE (39a)				
	Au	.141	.0059	.725
Sediment-hosted Cu (30b)				
	Cu	567,000	0	10,500,000
	Ag	0	0	2,390
	Co	0	0	128,000
Southeast Missouri Pb-Zn (32a)				
	Zn	0	0	3,810,000
	Ag	0	0	62.9
	Pb	0	0	656,000
Epigenetic vein barite (27e)				
	Barite	127,000	473	1,720,000

(continued)
Table 12. Estimated pre-mining tonnage of commodities contained in undiscovered deposits, listed by deposit type, in the Roswell Resource Area, east-central New Mexico--Continued

Deposit type	Median (.50)	Resource estimate probability range (.90	.10)
Bedded gypsum (35ae)			
Gypsum	1,770,000,000	114,000,000	23,500,000,000

Table 13. Estimated tonnages of commodities contained in undiscovered deposits in the Roswell area, east-central New Mexico

[Figures are in metric tons]

Commodity	Median (.50)	Resource estimate probability range (.90	-- .10)	E/C index[1]
Au	263	20.9	1,510	2.6
Ag	412	533	7,710	.1
Cu	516,000	4.56	11,000,000	.2
Pb	9,110	113	795,000	.01
Zn	5,950	3.98	4,450,000	.005
Fe	46,600,000	3,120,000	477,000,000	1.0
Co	0	0	129,000	0
Mn	773	0	147,000	.001
Mo	49,900	0	502,000	2.9
REO	0	0	780	0
ThO_2	171	0	7,980	3
Barite	127,000	473	1,720,000	.09
Gypsum	1,770,000,000	114,000,000	23,500,000,000	73

[1]Median endowment divided by the United States' 1990 apparent consumption (Drew and others, 1986). Consumption figures are from U.S. Bureau of Mines (1991). When apparent consumption figures were not available, reported consumption or apparent demand were used.

Table 14. NURE estimates of unconditional mean uranium endowment in the Roswell Resource Area (Modified from U.S. Department of Energy, 1980)

NTMS Quadrangle	Locality	Favorable area mi^2	Tons U_3O_8*
	Dockum Group and Chinle Formation*		
Tucumcari	San Jon-T	280	920
Clovis	San Jon-C	128	420
Total		408	1,340
	Sangre de Cristo Formation		
Tucumcari	Tucumcari	1,570	921
Clovis	Clovis-Sangre	470	275
Santa Fe	Undefined	750	11,077
Ft. Sumner	do.	1,520	433
Total		4,310	12,706

*Area within the Roswell Resource Area; tons for only Roswell Resource Area parts.

Table 15. Estimated grade distribution and size-frequency distribution for the Dockum Group and Ogallala Formation, Roswell Resource Area, New Mexico

Grade distribution (G)			Size-frequency distribution					
Percent U_3O_8 at 0.01% cutoff			Size class interval (tons of mineralized rock above cutoff of 0.01% U_3O_8)			Number of deposits*		
Lower (0.05)	Most likely value	Upper (0.95)	Lower (0.05)	Midpoint**	Upper (0.95)	Lower (0.05)	Most likely value	Upper (0.95)
				Dockum Group				
Tract VA		A = 4,276 mi^2						
.03	.05	.08	1	3.2	9.9	10	20	30
			10	32	99	5	10	20
			100	320	999	1	1	1
			1,000	3,200	9,999	0	0	1
					Total	16	31	52
Tract VB		A = 5,687 mi^2						
.02	.04	.06	1	3.2	9.9	5	10	15
			10	32	99	2	5	10
			100	320	999	0	1	1
			1,000	3,200	9,999	0	0	0
					Total	7	16	26
				Ogallala Formation				
Tract VI		A = 4,938 mi^2						
.03	.05	.08	$1x10^5$	$3.2x10^5$	$9.9x10^5$	1	2	4
			$1x10^6$	$1.7x10^6$	$2.9x10^6$	1	1	2
			$3x10^6$	$5.5x10^6$	$1.0x10^7$	0	0	1
					Total	2	3	7

*Odds are 9 to 1 that the stated interval contains the true mean value.

**Midpoints of size-class intervals for size class intervals are represented by the geometric mean of the upper and lower limits.

Table 16. Probability distribution of estimated uranium endowment in the Dockum Group, Tracts VA and VB, Roswell Resource Area, New Mexico

U_3O_8 (tons)	Probability unconditional (in percent)	U_3O_8 (tons)	Probability unconditional (in percent)
Tract VA			
0.19	0.05	0.35	0.55
.22	.10	.36	.60
.24	.15	.37	.65
.26	.20	.39	.70
.27	.25	.40	.75
.28	.30	.42	.80
.30	.35	.44	.85
.31	.40	.47	.90
.32	.45	.51	.95
.33	.50		
Mean = 0.34			
Tract VB			
0.12	0.05	.28	.55
.15	.10	.30	.60
.16	.15	.31	.65
.18	.20	.32	.70
.20	.25	.35	.70
.21	.30	.37	.80
.23	.35	.40	.85
.24	.40	.43	.90
.25	.45	.49	.95
.26	.50		
Mean = 0.28			

Table 17. Probability distribution of estimated uranium endowment in the Ogallala Formation in Tract VI, Roswell Resource Area, New Mexico

U_3O_8 (tons)	Probability unconditional (in percent)	U_3O_8 (tons)	Probability unconditional (in percent)
726	0.05	1,315	.55
832	.10	1,363	.63
908	.15	1,414	.65
971	.20	1,468	.70
1,027	.25	1,527	.75
1,079	.30	1,593	.80
1,128	.35	1,670	.85
1,175	.40	1,768	.90
1,222	.45	1,914	.95
1,268	.50		
	Mean = 1,287		

Table 18. Vanadium production from deposits within the Roswell Resource Area

[All production was during 1954-1957 (from McLemore, 1983)]

Mine name	Location	V_2O_5 (lbs)	Ore (tons)	Host rock	Deposit type
Good Luck	Sec. 6, T. 7 N., R. 32 E.	38	24	Chinle Fm.	Sandstone V-U
Little Rattler	Sec. 11, T. 11 N., R. 33 E.	44	59	Chinle Fm.	Sandstone V-U
Bear Canyon Group	Sec. 9, T. 8 S., R. 17 E.	2	3	Magnetite vein	Uraniferous vein intruding alaskite

Table 19.--Geological, Engineering and Production Parameters of Oil Fields Exceeding Cumulative Production of 1MMBOE through 1988 in the Roswell Resource Area

[Strat, stratigraphic; comb, structural/stratigraphic; struct, structural; s gas, solution gas; sour, high sulfur content; sweet, low sulfur content; kmd, permeability in millidarcies; API grav., American Petroleum Institute, gravity; init press, initial pressure; GOR, gas to oil ratio; NGL, natural gas liquids; MMBOE, million barrels oil equivalency; BCF, billion cubic feet; T_o, bottom hole temperature; GOR, Gas-Oil ratio in cubic ft/barrel; SA, San Andres; N, North; Pn, Pennsylvanian. In order of decreasing size]

(1) Field Name	(2) County	(3) Reservoir	(4) Disc. Date	(5) Depth Top Ft.	(6) Trap Type	(7) Net Pay Thick Ft.	(8) Porosity %	(9) kmd	(10) API Grav.	(11) Drive	(12) Init. Press. psi	(13) Oil & NGL 1 MMB Cum. Prod.	(14) Gas BCF	(15) Misc.
Caprock	Chaves	Queen Formation sandstone	1940	2971	Strat	10	21	250H 150V	38	S gas	900	74	--	S 1.07% $>N_2$, T_o154F
Allison	Roosevelt	Virgilian limestone Cisco Group	1954	9490	Comb	11	7	200	48	Water	--	26	51	Sweet
Chaveroo	Roosevelt	San Andres Formation dolomite	1965	4184	Comb	40	6	0.7	26	S gas	1340	26.2	31.4	Sour GOR 810 T_o110F
Cato	Chaves	San Andres Formation dolomite	1966	3496	Comb	33	8	1.0	26	S gas Water	1116	17.4	30	Sour T_o100F
Milnesand (SA)	Roosevelt	San Andres Formation dolomite	1958	4534	Strat	40	8	1.0	29	S gas Water	1100	14.5	14.7	Sour T_o90F
Tobac	Chaves	Virgilian limestone Cisco Group	1964	9058	Comb	10	7	100	44	S gas Water	3083	10.1	12.4	Sweet
Vada	Roosevelt	Virgilian limestone Cisco Group	1966	9792	Strat	10	8	150	47	S gas Water	2800	9.4	26.6	Sweet T_o145F
Todd	Roosevelt	San Andres Formation dolomite	1963	4202	Comb	40	4	--	24	S gas	1339	4.0	19.2	Sour T_o102F
Twin Lakes	Chaves	San Andres Formation dolomite	1950	4266	Comb	--	7	--	24	S gas	700	4.8	5.4	Sour T_o100F
Peterson S.	Roosevelt	Silurian dolomite Virgilian limestone	1978	7808	Comb	10	8	20	46	S gas	2634	4.3	15.3	Sweet T_o152F
Prairie S.	Roosevelt	Virgilian limestone	1960	9651	Comb	24	6	90	49	Water	3159	4.0	6.9	Sweet T_o186F
Bluitt (SA)	Roosevelt	San Andres Formation dolomite	1951	4500	Comb	30	8	5	27	S gas	1515	4.0	14.7	Sour T_o105F
Double L.	Chaves	Queen Formation sandstone	1969	1920	Strat	6	22	40	35	Gas Cap S gas	743	3.9	5.8	$>N_2$ (55%) T_o84F

Table 19 (continued)

Tom Tom	Chaves	San Andres Formation dolomite	1967	3914	Comb	20	7	2	25	S gas	1192	3.2	2.0	Sour T°100F
Peterson	Roosevelt	Virgilian limestone	1971	7542	Comb	--	--	--	35	--	--	1.6	5.7	--
Tomahawk	Chaves	San Andres Formation dolomite	1967	3914	Comb	22	7	--	26	S gas	1302	2.2	1.9	Sour T°102F
Sulimar	Chaves	Queen Formation sandstone	1968	2028	Strat	6	20	150	35	S gas	--	2.3	0.8	>N_2(55%)
Milnesand Pn	Roosevelt	Virgilian limestone	1956	9125	Comb	--	3.6	1.4	44	S gas	--	1.0	1.7	Sweet
Diablo	Chaves	San Andres Formation dolomite	1962	2060	--	--	--	--	30	--	--	1.0	--	--
Bluitt (N)	Roosevelt	Silurian-Devonian	1987	8845	--	--	--	--	--	--	--	1.0	--	--

Table 20.--Geologic, Engineering and Production Parameters of Gas Fields Exceeding Cumulative Production of MMBOE (6BCF = 1 MMBOE) through 1988 in the Roswell Resource Assessment Area

[Strat, stratigraphic; comb, structural/stratigraphic; struct, structural; s gas, solution gas; sour, high sulfur content; sweet, low sulfur content; kmd, permeability in millidarcies; API grav., American Petroleum Institute, gravity; init. press., initial pressure; NGL, natural gas liquids; MMBOE, million barrels oil equivalency; BCF, billion cubic feet; T_o, bottom hole temperature; W, west; S, south]

(1) Field Name	(2) County	(3) Reservoir	(4) Disc. Date	(5) Depth Top Ft.	(6) Trap Type	(7) Net Pay Thick Ft.	(8) Porosity %	(9) kmd	(10) API Grav.	(11) Drive	(12) Init. Press. psi	(13) Oil & NGL 1 MMB Cum. Prod.	(14) Gas BCF	(15) Misc.
Pecos Slope	Chaves	Abo, sandstone	1977	4406	Strat	30	13	.03-.05	54	S gas	1125	4.0	261	Tight gas
Buffalo Valley	Chaves	Atoka sandstone	1959	8181	Strat	22	12	High	61.5	S gas	3282	0.9	132	T_o135F
Bluitt (Wolfcamp)	Roosevelt	Wolfcampian limestone	1959	8022	Strat	36	13	80	50	S gas	--	0.5	36	--
Foor Ranch	Chaves	Silurian Fusselman dolomite	1981	6154	Struct Drive	10	13	--	--	Water	2377	0.1	36	T_o120F
Pecos Slope (W)	Chaves	Abo sandstone	1980	2923	Strat	20	14	0.3	--	S gas	--	0.5	30	--
Pecos Slope (S)	Chaves	Abo sandstone	1979		Strat		14	0.3	--	S gas	--	0.5	25.5	--
Little Lucky Lake	Chaves	Silurian & Devonian dolomite	1958	11050	Comb	84	6	55	--	--	--	2.1	13.2	--
Diamond Mound	Chaves	Atokan-Morrowan sandstone	--	--	--	--	--	--	--	--	--	0.4	23.3	--
Tule	Roosevelt	Pennsylvanian limestone	1986	6759	Comb	10	--	--	62	--	--	0.1	9.0	--
Springer Basin	Chaves	Atokan-Morrowan sandstone	1979	8050	Strat	8	13	--	62.5	S gas	3000	0	7.8	T_o145F
Haystack	Chaves	Virgilian limestone (Cisco)	1970	5832	Comb	11	7	13	56.5	S gas and Water	2421	0.1	6.3	T_o112F
Vest Ranch	Chaves	Queen Formation sandstone	1971	5999	--	2	--	--	--	--	--	0.3	4.1	--

Table 21A.--Quantitative Undiscovered Oil and Gas Assessments for Roswell Resource Area, New Mexico

		Oil (Millions of Barrels)			Total Gas (Billions of Cubic Feet)			Total NGL (Millions of Barrels)		
Province name	Play name	F95	F5	Mean	F95	F5	Mean	F95	F5	Mean
Permian Basin	NW Shelf Penn-Perm	19.82	86.88	45.87	108.76	329.87	198.72	2.43	7.73	4.55
	NW Shelf Pre-Penn	1.86	7.39	4.04	1.38	5.48	2.97	0.07	0.28	0.16
	Oil <1 MMBO	27.34	37.81	31.21	54.67	75.61	62.42	0.0	0.0	0.0
	Gas <6 BCF	0.0	0.0	0.0	92.86	138.71	109.40	3.07	4.58	3.61
Palo Duro Basin	Oil <1 MMBO	4.76	8.75	6.22	0.67	1.23	0.87	0.0	0.0	0.0
	Gas <6 BCF	0.0	0.0	0.0	2.38	4.47	3.15	0.0	0.0	0.0
TOTAL ROSWELL AREA		53.78	140.83	87.34	260.72	555.37	377.53	5.57	12.59	8.32

Table 21B.--Quantitative Undiscovered Oil and Gas Assessments for Federal Lands within the Roswell Resource Area

		Oil (Millions of Barrels)			Total Gas (Billions of Cubic Feet)			Total NGL (Millions of Barrels)		
Province name	Play name	F95	F5	Mean	F95	F5	Mean	F95	F5	Mean
Permian Basin	NW Shelf Penn-Perm	3.00	13.32	6.99	52.47	157.74	95.38	1.16	3.67	2.17
	NW Shelf Pre-Penn	0.74	2.96	1.62	0.55	2.19	1.19	0.03	0.11	0.06
	Oil <1 MMBO	10.93	15.12	12.48	21.87	30.25	24.97	0.0	0.0	0.0
	Gas <6 BCF	0.0	0.0	0.0	37.15	55.48	43.76	1.23	1.83	1.44
Palo Duro Basin	Oil <1 MMBO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Gas <6 BCF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL ROSWELL AREA		14.67	31.40	21.09	112.04	245.66	165.30	2.42	5.61	3.67

Table 22. Analyses of Sierra Blanca coals (Campbell and others, 1991)

Proximate analyses (14 samples; data in percent, except Btu/lb)	
Moisture	5.53±4.51
Ash	13.51±5.32
Volatile matter	31.46±7.91
Fixed carbon	47.24±5.93
Btu/lb:	
As received	11,175±1,787
Mineral matter free	12,983±2,047

Ultimate analyses (12 samples; data in percent)	
Carbon	61.33±7.74
Hydrogen	4.58±0.49
Nitrogen	1.17±0.16
Oxygen	13.37±5.78
Sulfur	0.75±0.16

Major oxides (4 samples; data in percent on an ash basis)	
SiO_2	60.19±6.42
Al_2O_3	15.78±1.26
Fe_2O_3	2.60±0.29
TiO_2	1.25±0.10
CaO	4.41±0.48
MgO	0.88±0.11
K_2O	0.32±0.03
Na_2O	0.65±0.14

Trace elements (4 samples; data in parts per million on an ash basis)	
As	8.13±0.25
Cu	14.04±6.33
Hg	0.10±0.05
Li	8.52±1.10
Mn	32.73±30.17
Ni	4.38±2.13
Pb	7.97±3.26
Sb	1.60±0.77
Se	2.81±0.78
Th	5.10±2.21
U	2.85±0.96
Zn	8.49±7.42

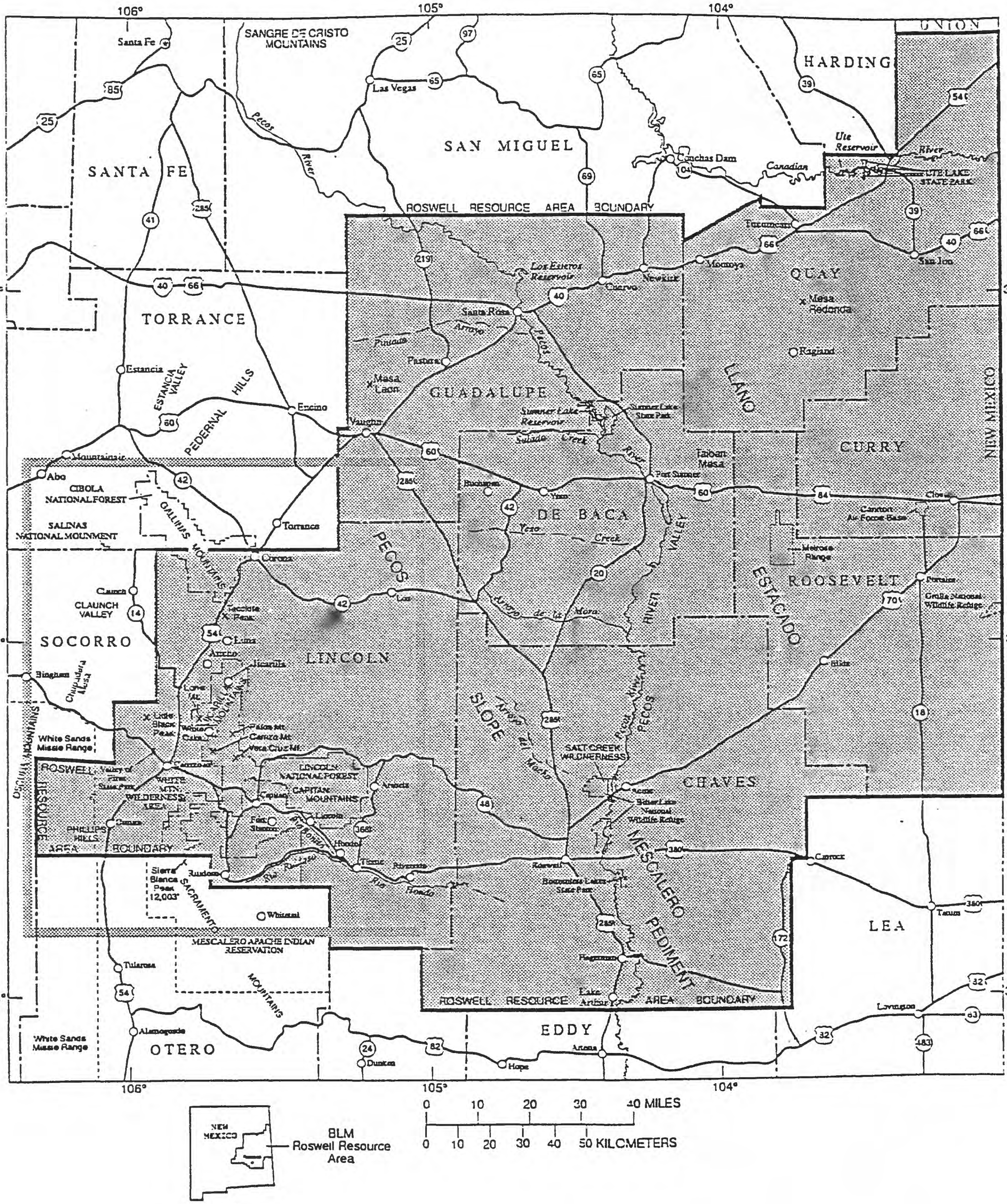


FIGURE 1 --Map of the Roswell Resource Area, New Mexico, showing locations and physiographic features mentioned in text. Area within broad stippled outline includes the Lincoln County Porphyry Belt shown in fig. 28.

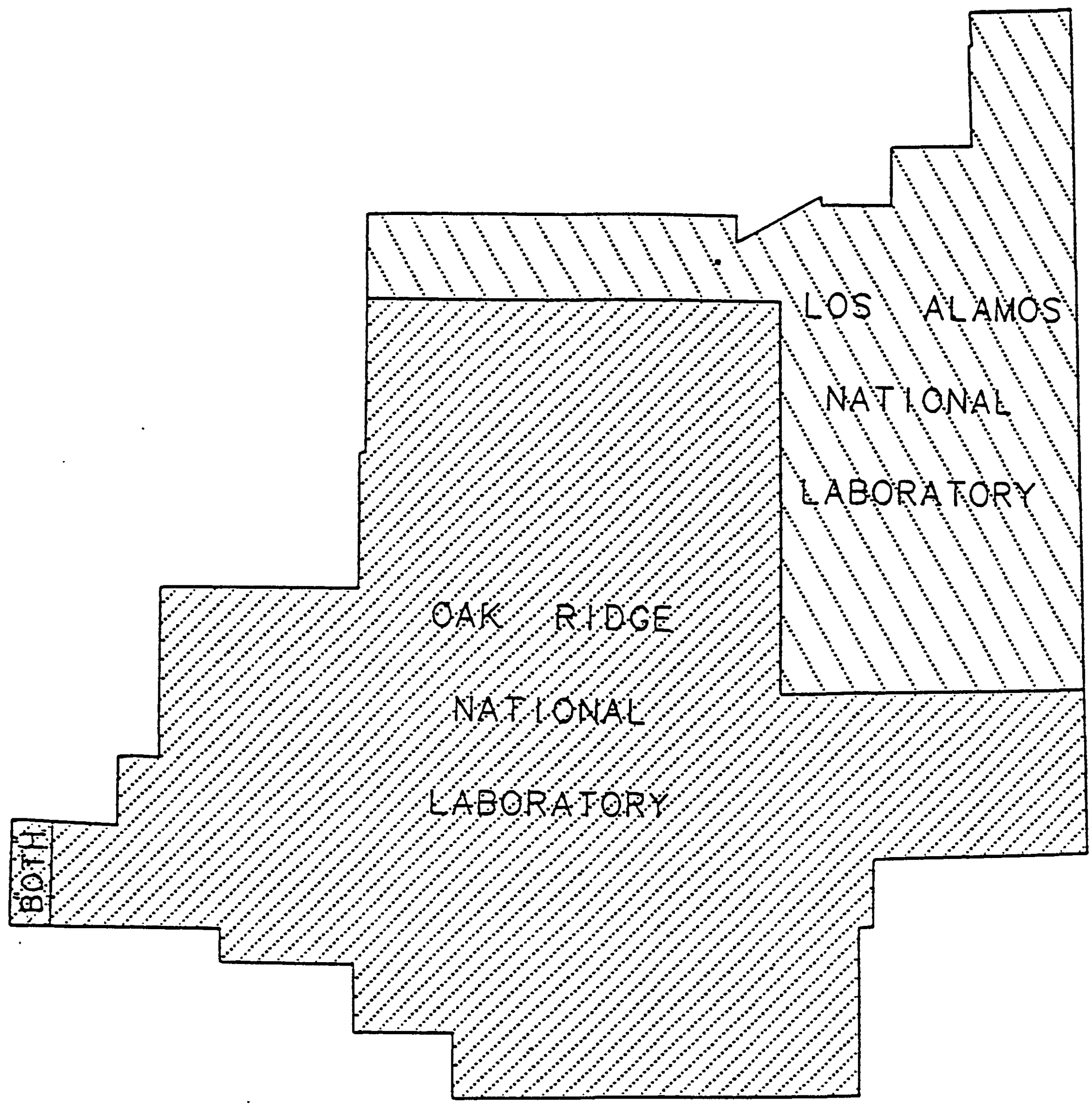


FIGURE 2. NURE sediment sample coverage of the Roswell Resource Area by Los Alamos and Oak Ridge National Laboratories

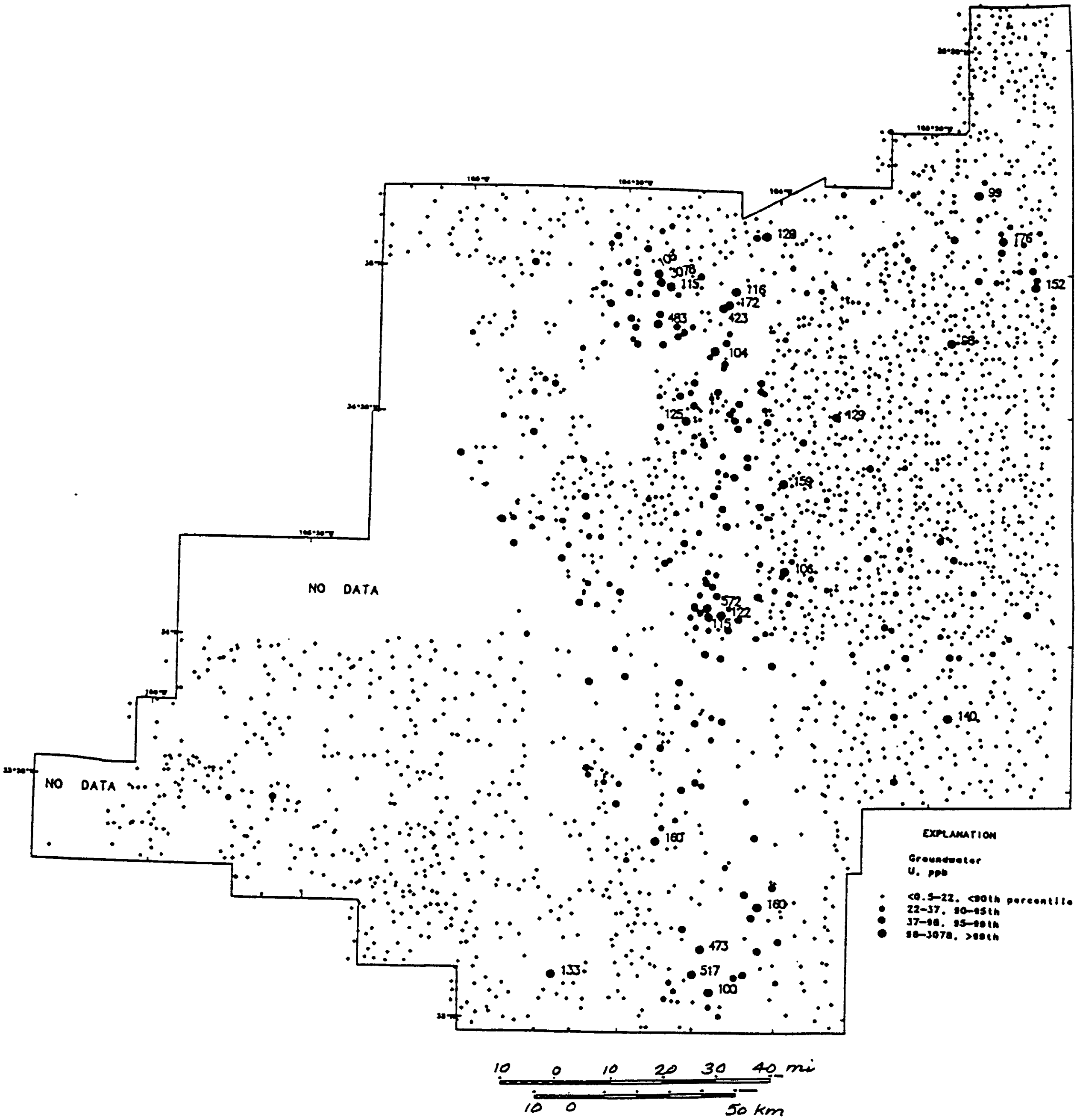


FIGURE 3. Uranium in groundwater

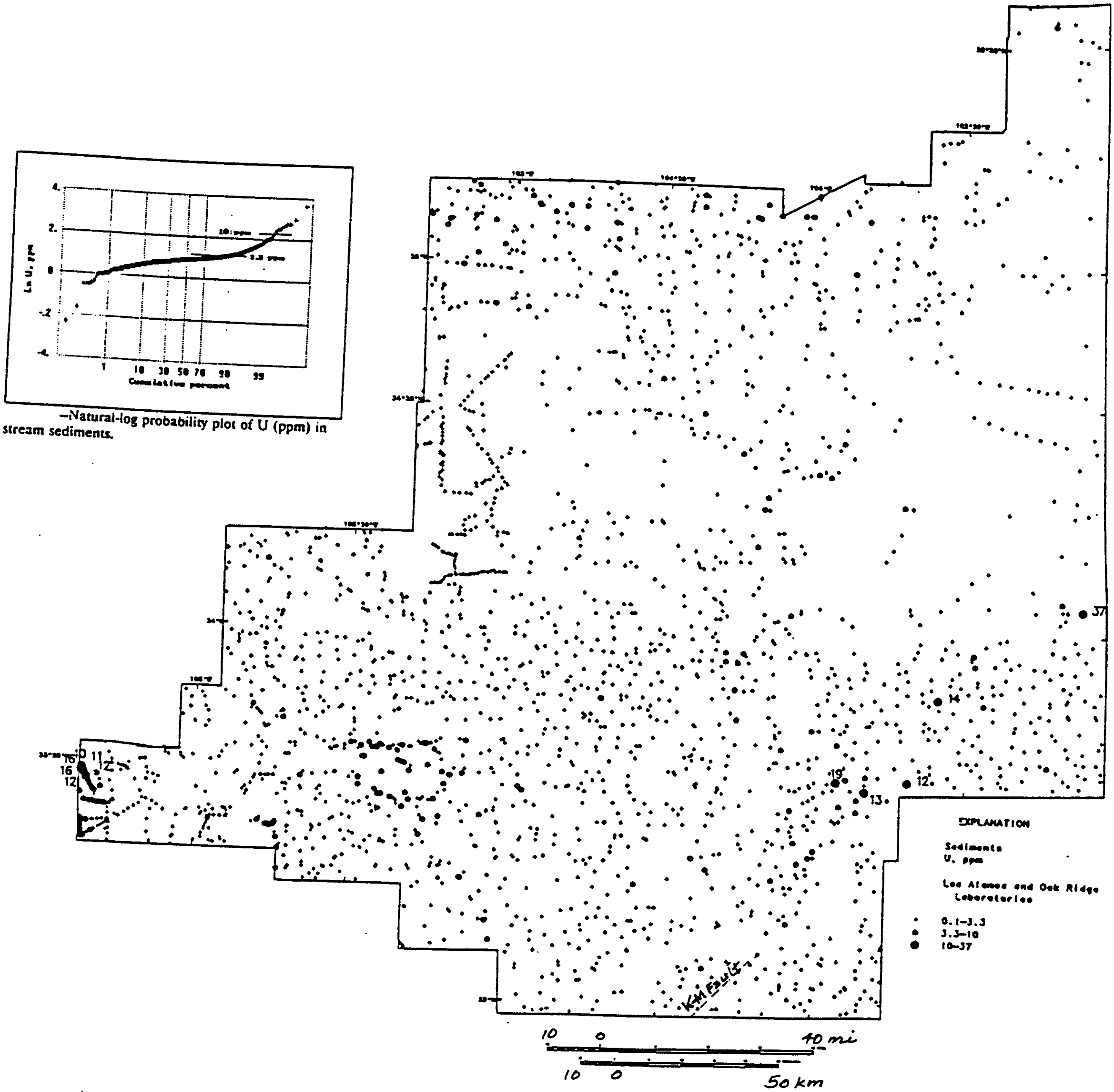
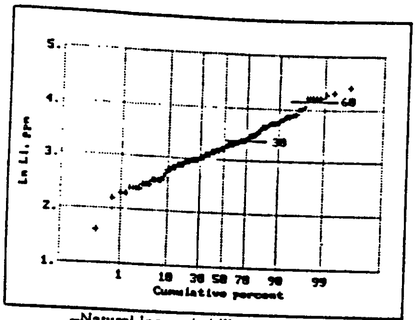
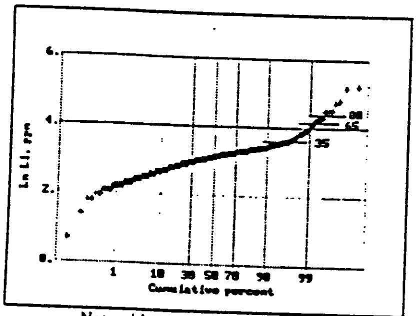


FIGURE 4. -Map of uranium in sediments, Roswell Resource Area



–Natural-log probability plot of Li (ppm) in sediments. Los Alamos laboratory.



–Natural-log probability plot of Li (ppm) in stream sediments. Oak Ridge laboratory.

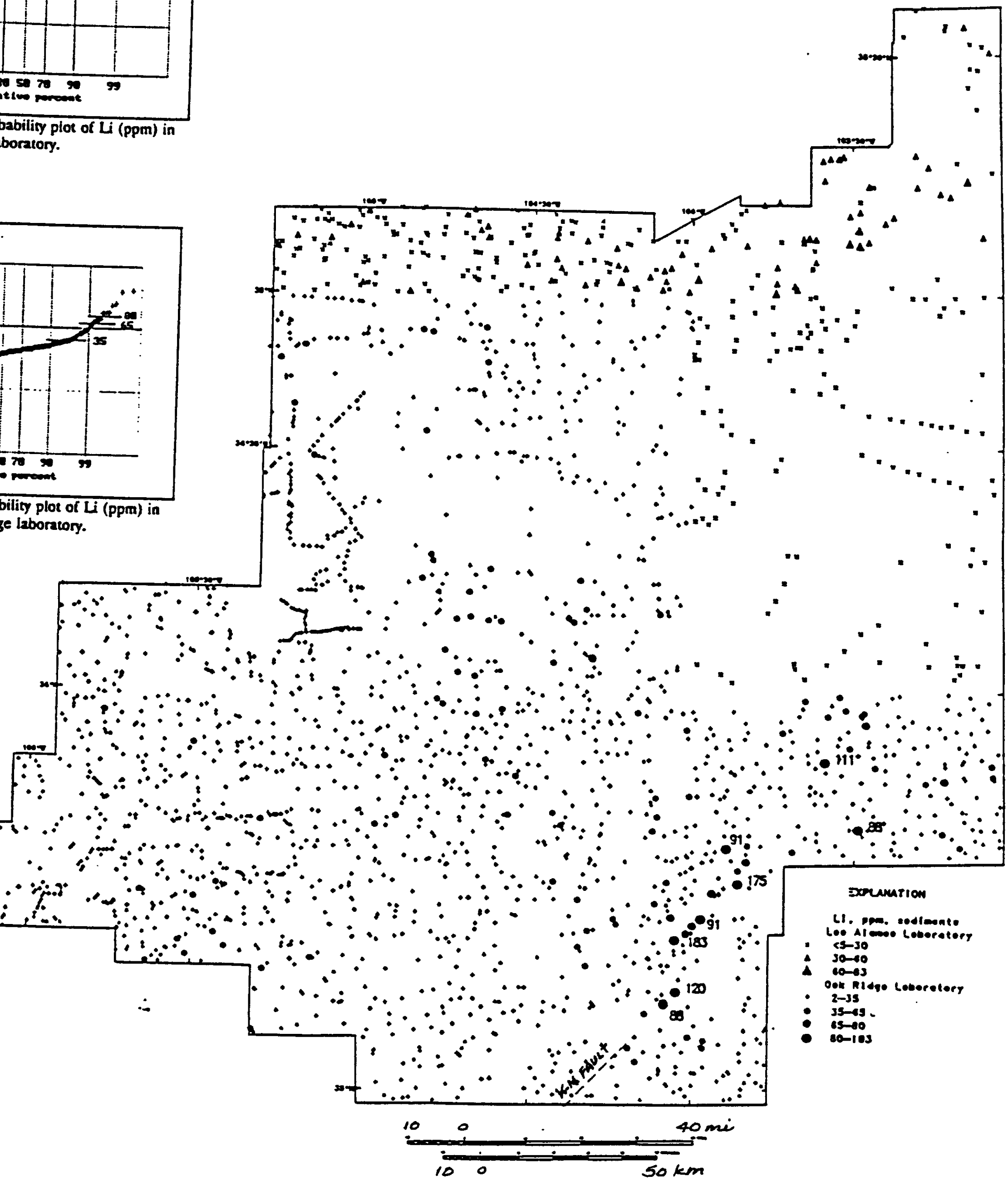


FIGURE 5.--Map of lithium in sediments, Roswell Resource Area.

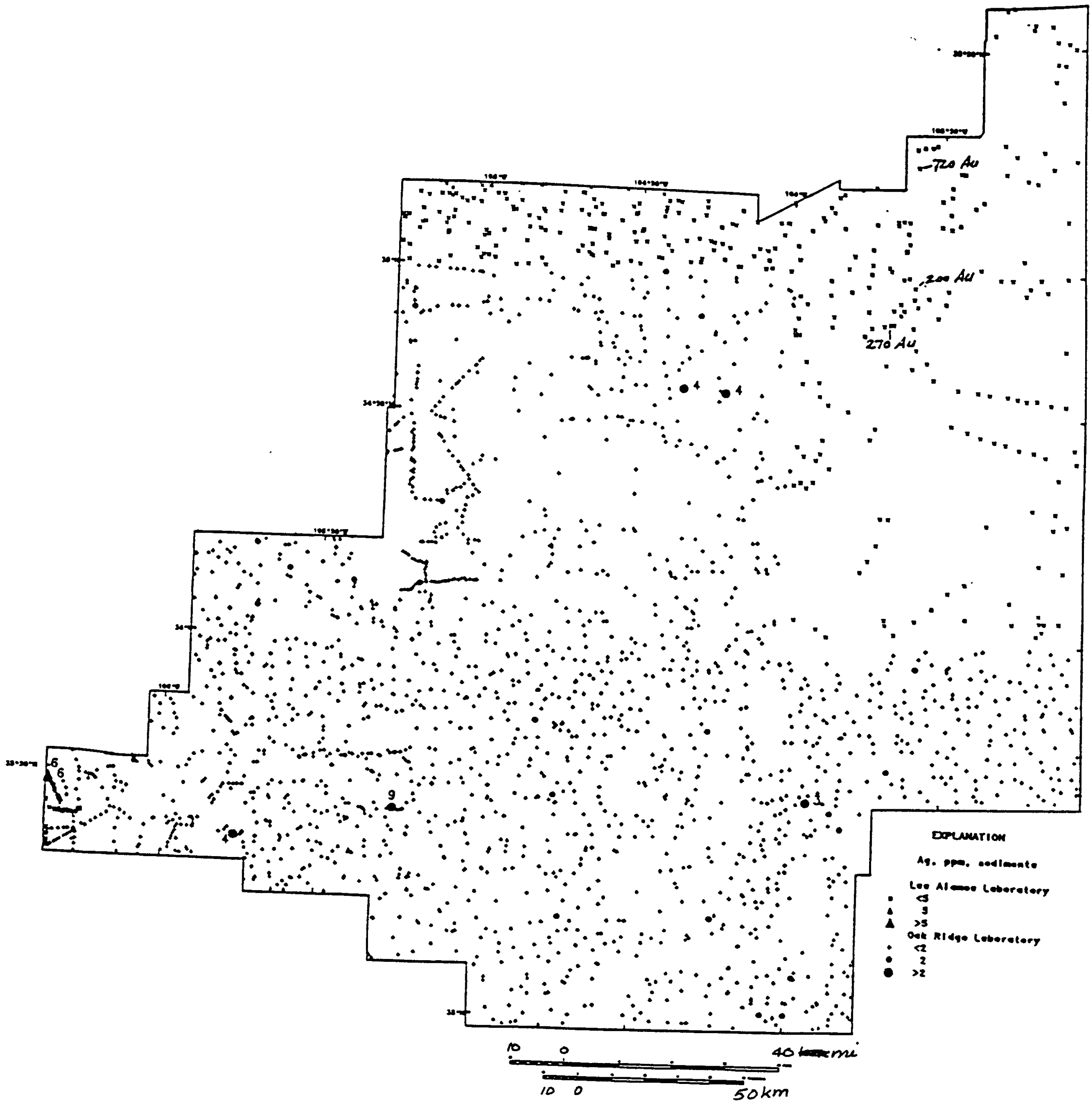


FIGURE 6. --Map of silver (ppm) and gold (ppb) in sediments, Roswell Resource Area.

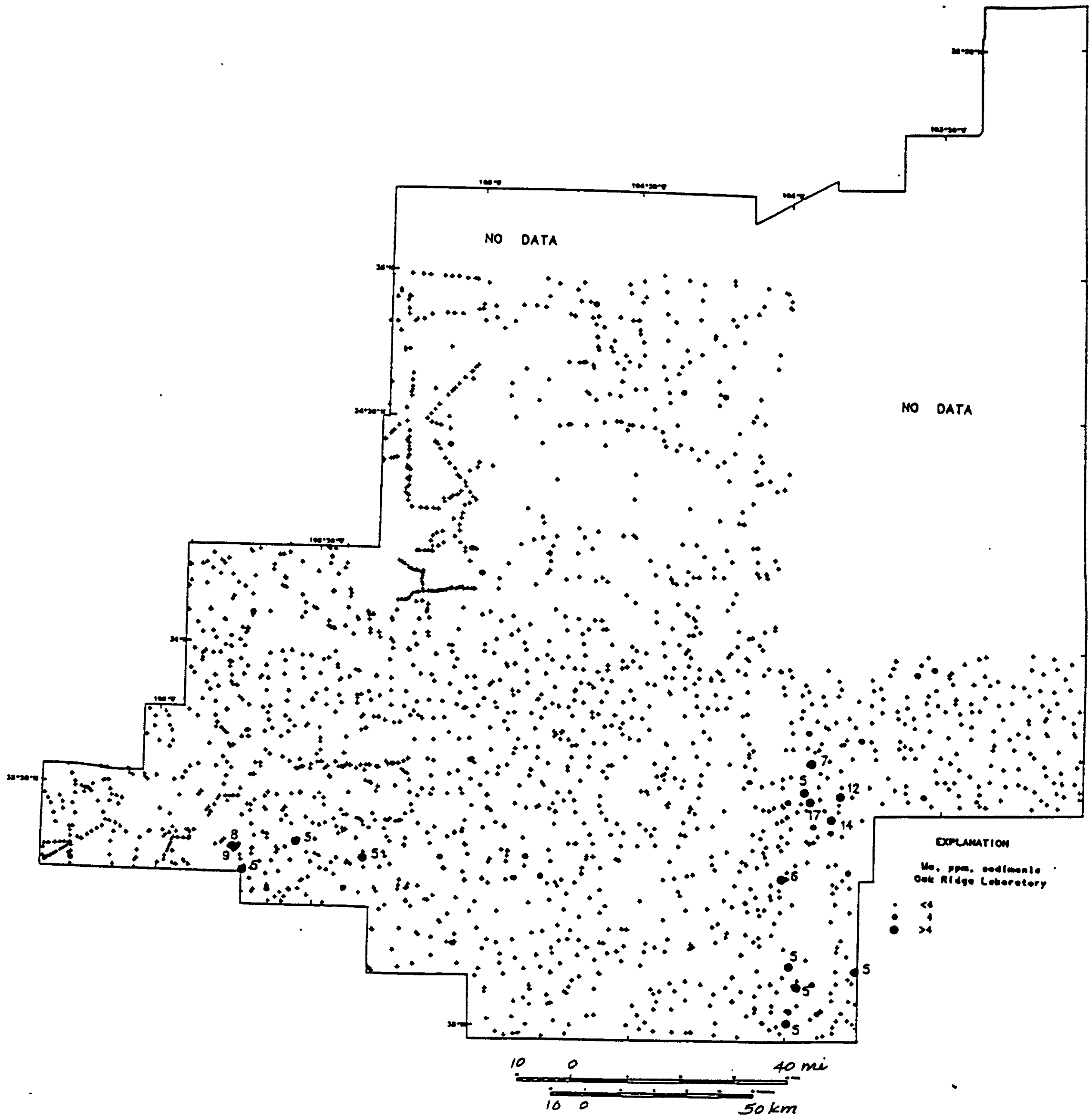
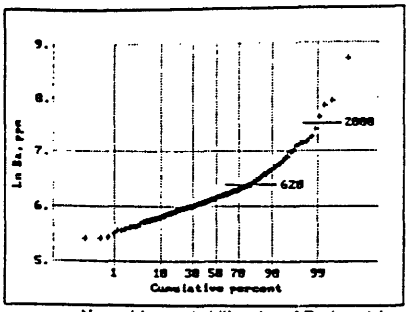
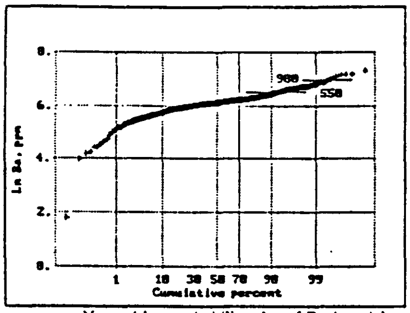


FIGURE 7.--Map of molybdenum in sediments analyzed by Oak Ridge National Laboratory, Roswell Resource Area



–Natural-log probability plot of Ba (ppm) in sediments. Los Alamos laboratory.



–Natural-log probability plot of Ba (ppm) in stream sediments. Oak Ridge laboratory.

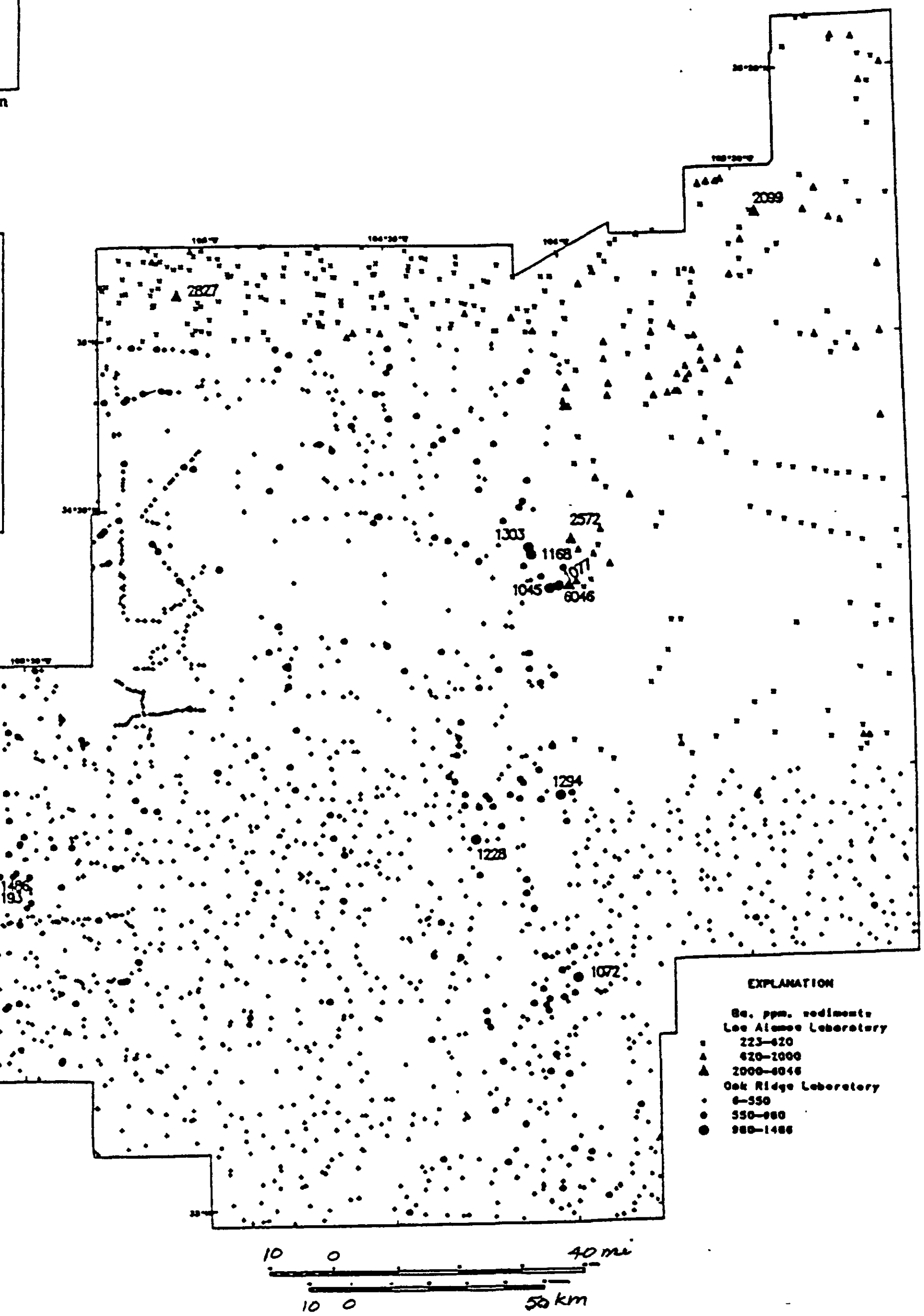
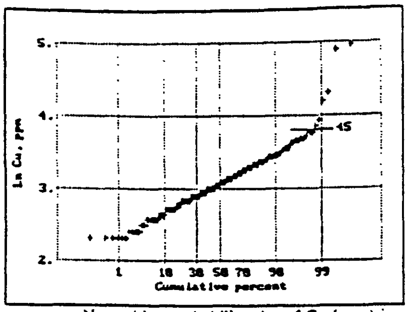
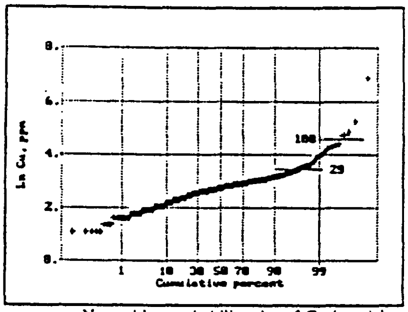


FIGURE 8. --Map of barium in sediments, Roswell Resource Area.



–Natural-log probability plot of Cu (ppm) in sediments. Los Alamos laboratory.



–Natural-log probability plot of Cu (ppm) in stream sediments. Oak Ridge laboratory.

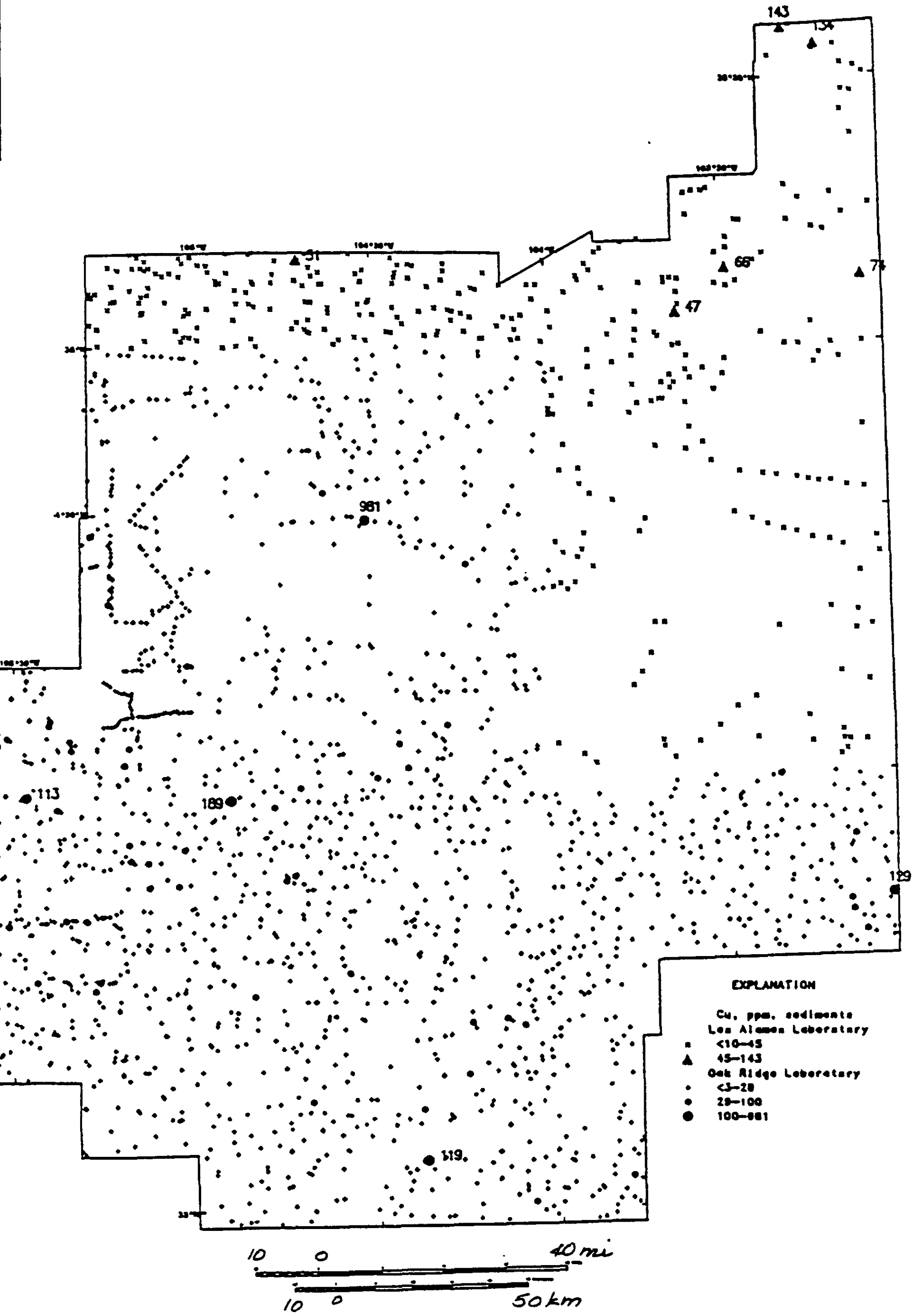
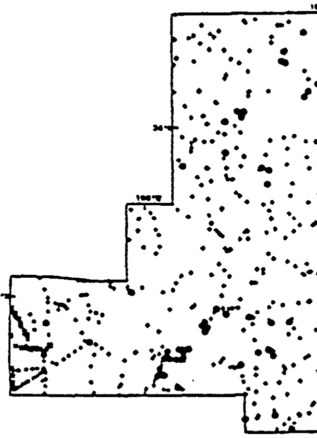
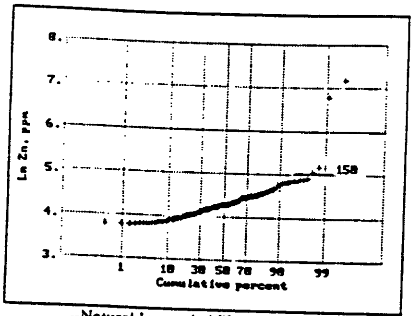
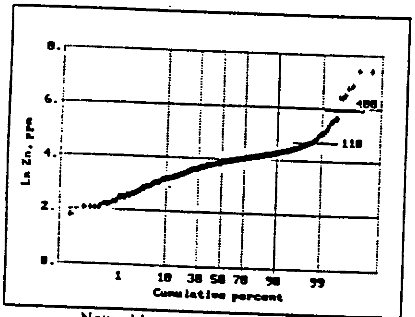



FIGURE 9. --Map of copper in sediments, Roswell Resource Area



–Natural-log probability plot of Zn (ppm) in sediments. Los Alamos laboratory.



–Natural-log probability plot of Zn (ppm) in stream sediments. Oak Ridge Laboratory

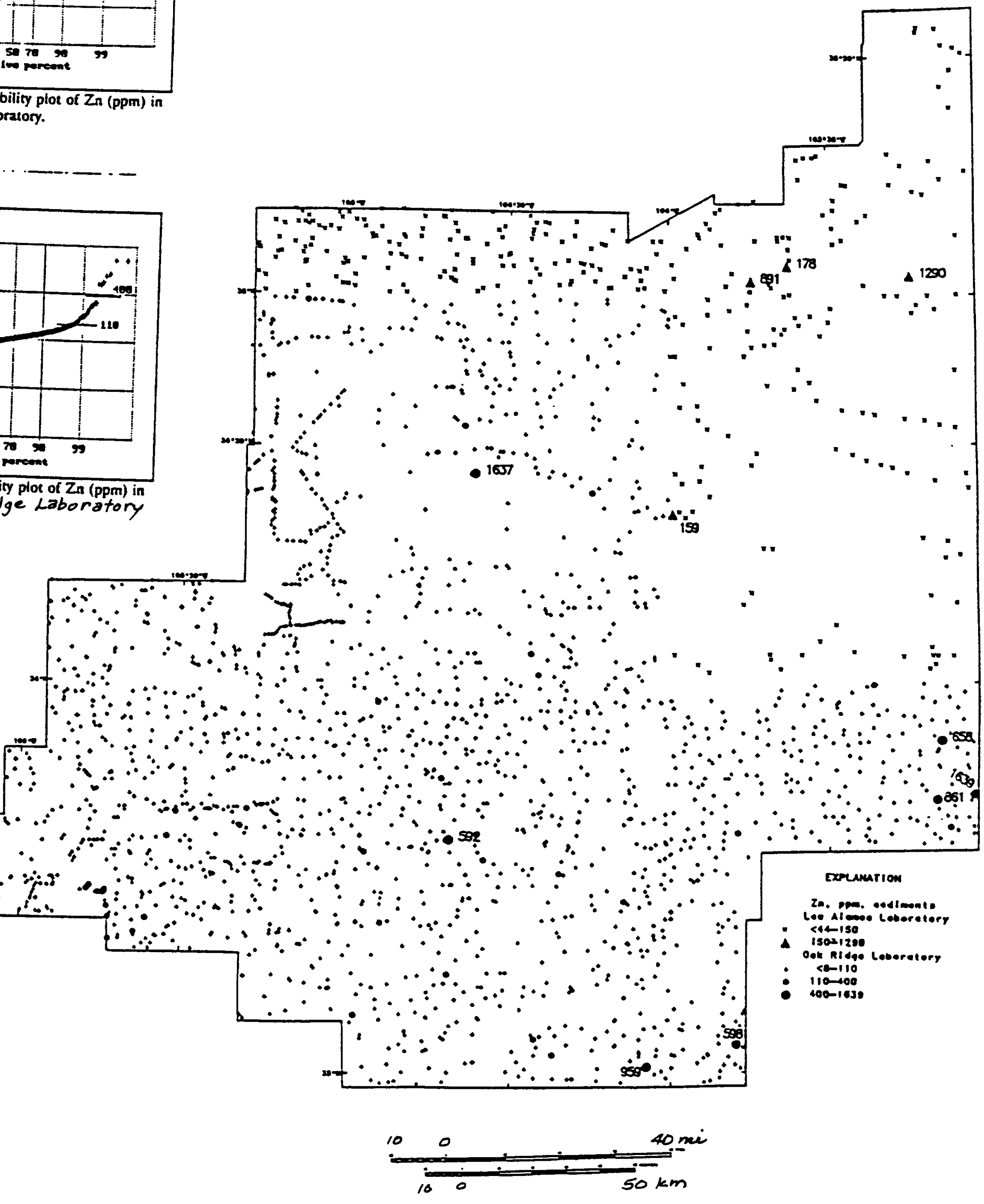
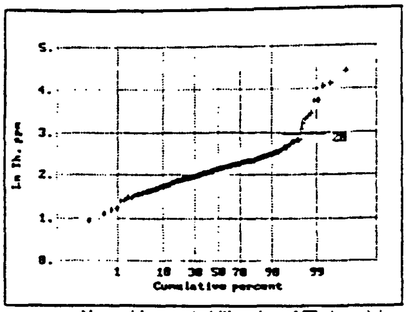
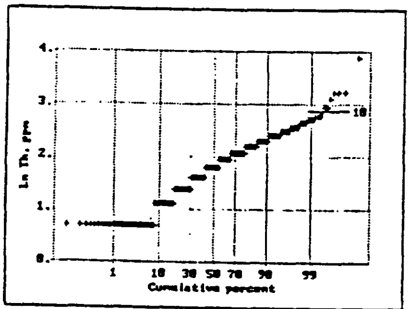


FIGURE 10. --Map of zinc in sediments, Roswell Resource Area



–Natural-log probability plot of Th (ppm) in sediments. Los Alamos laboratory.



–Natural-log probability plot of Th (ppm) in stream sediments. Oak Ridge Laboratory.

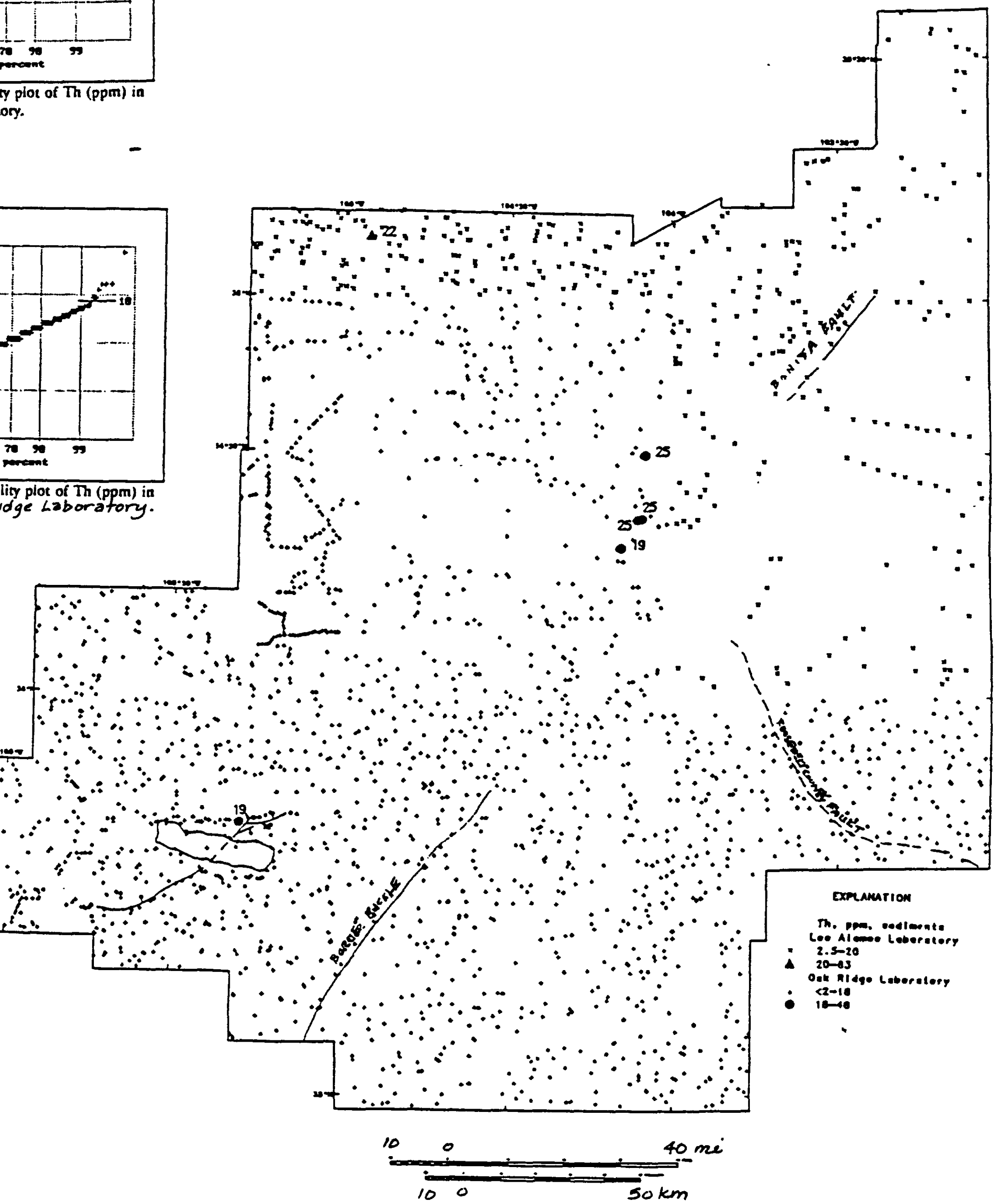
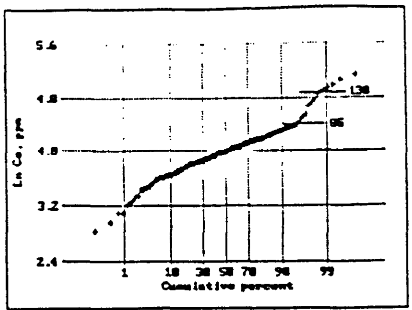
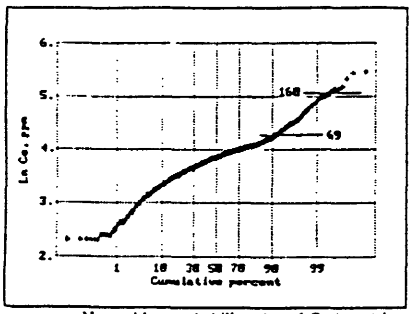


FIGURE 11. --Map of thorium in sediments, Roswell Resource Area



-Natural-log probability plot of Ce (ppm) in sediments. Los Alamos laboratory.



-Natural-log probability plot of Ce (ppm) in stream sediments. Oak Ridge laboratory.

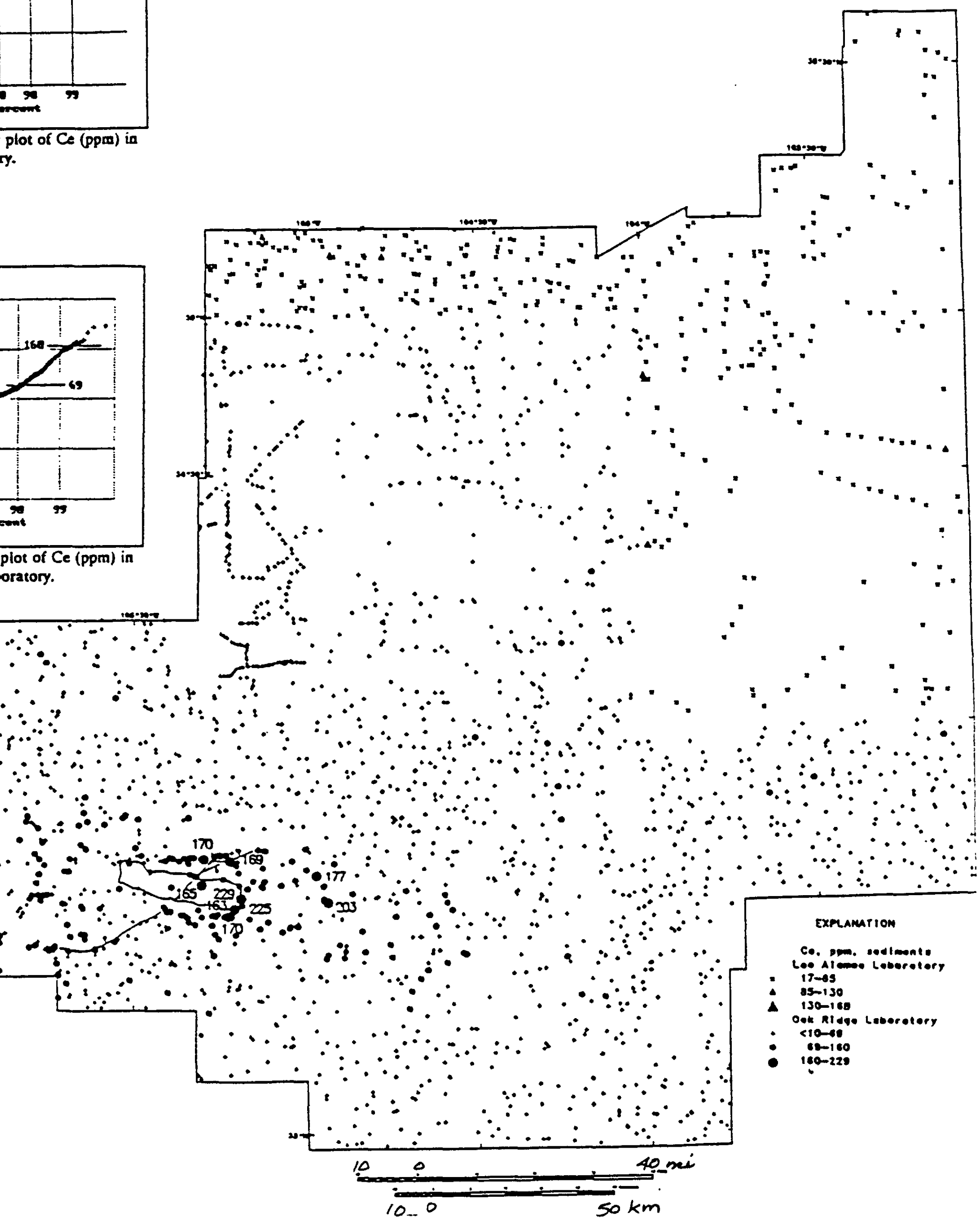
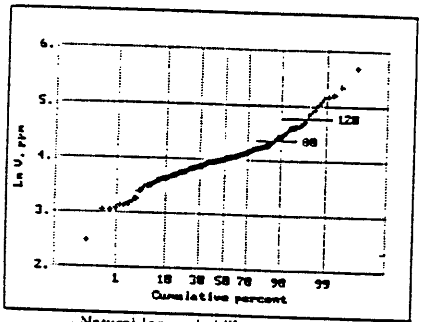
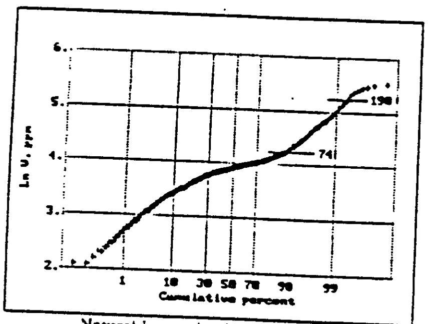


FIGURE 12. --Map of cerium in sediments, Roswell Resource Area.



–Natural-log probability plot of V (ppm) in sediments. Los Alamos laboratory.



–Natural-log probability plot of V (ppm) in sediments. Oak Ridge laboratory.

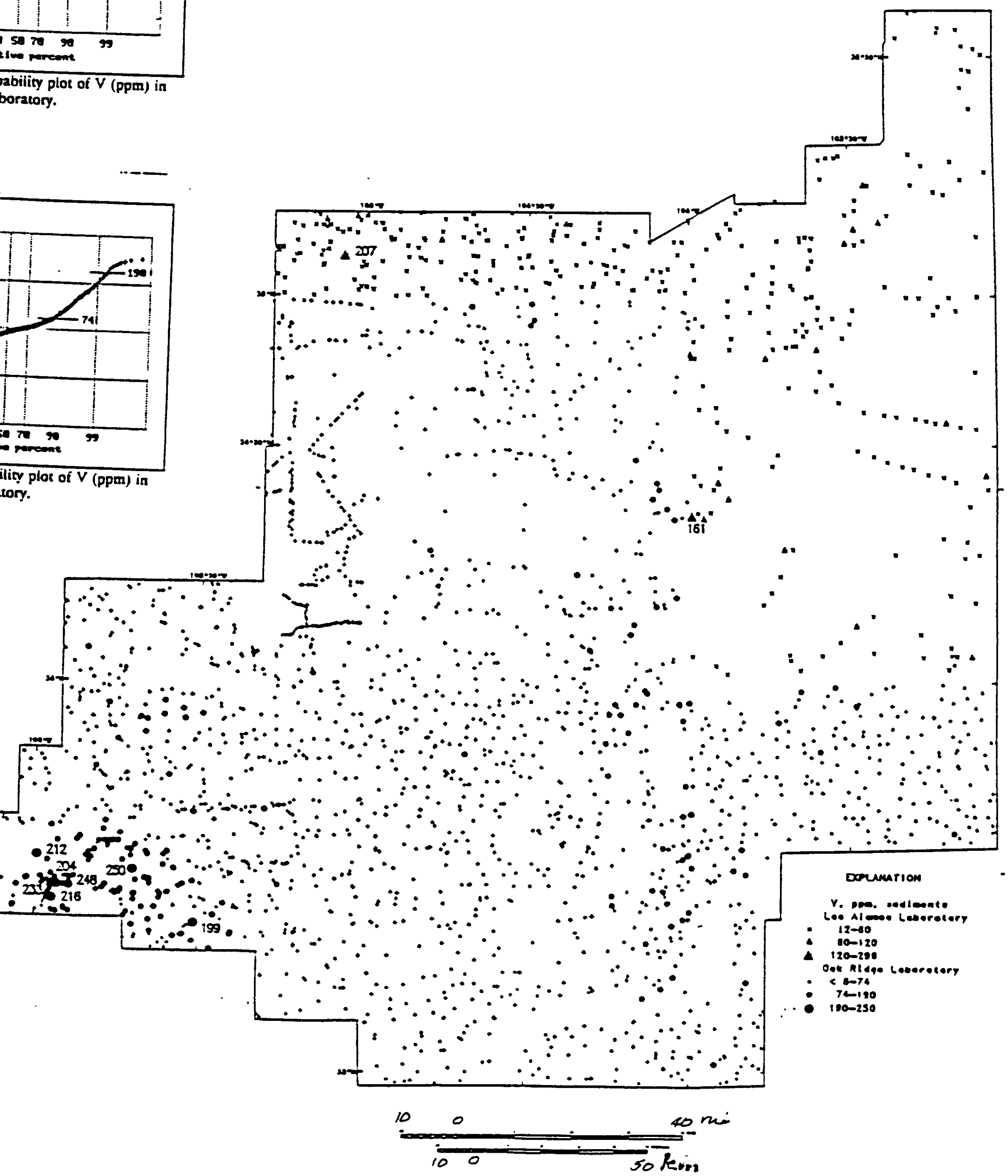


FIGURE 13. --Map of vanadium in sediments

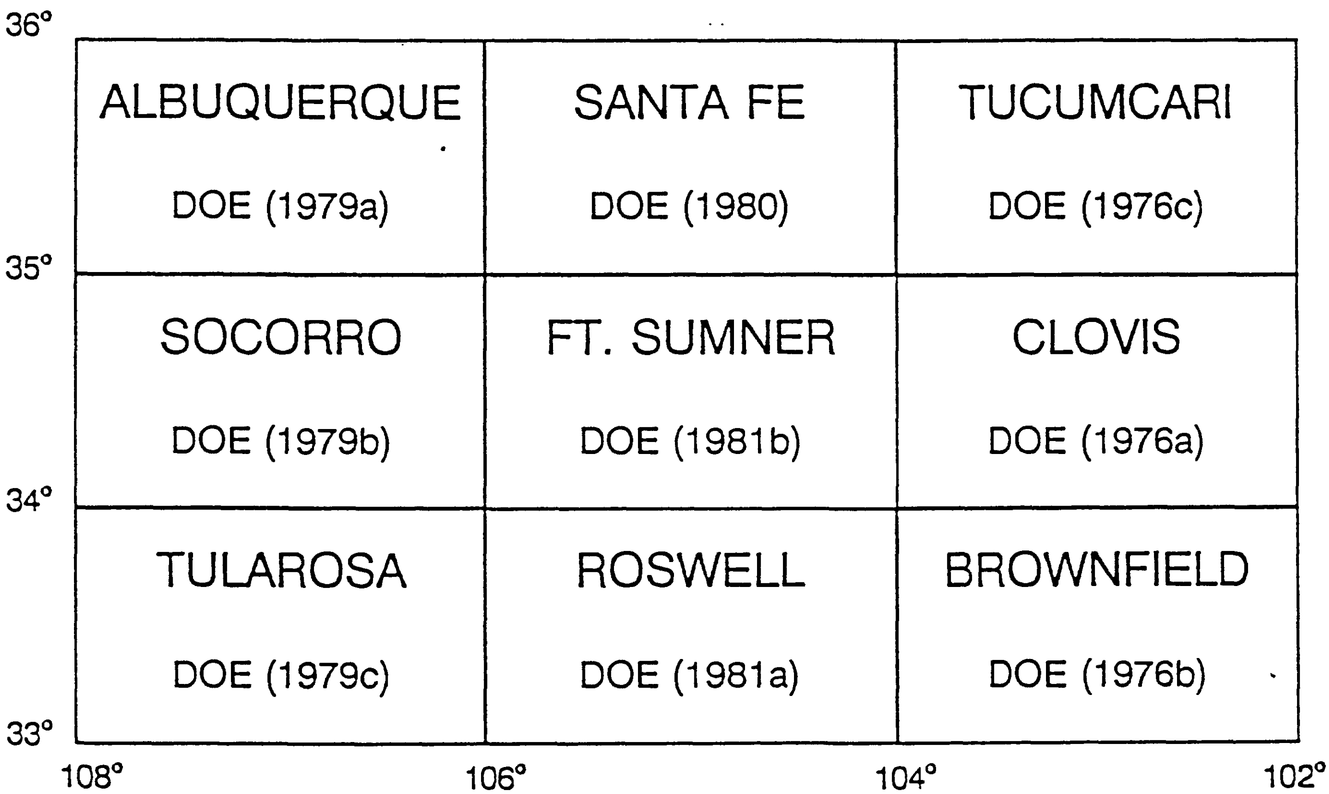


FIGURE 14. Locations of aerial gamma-ray surveys.

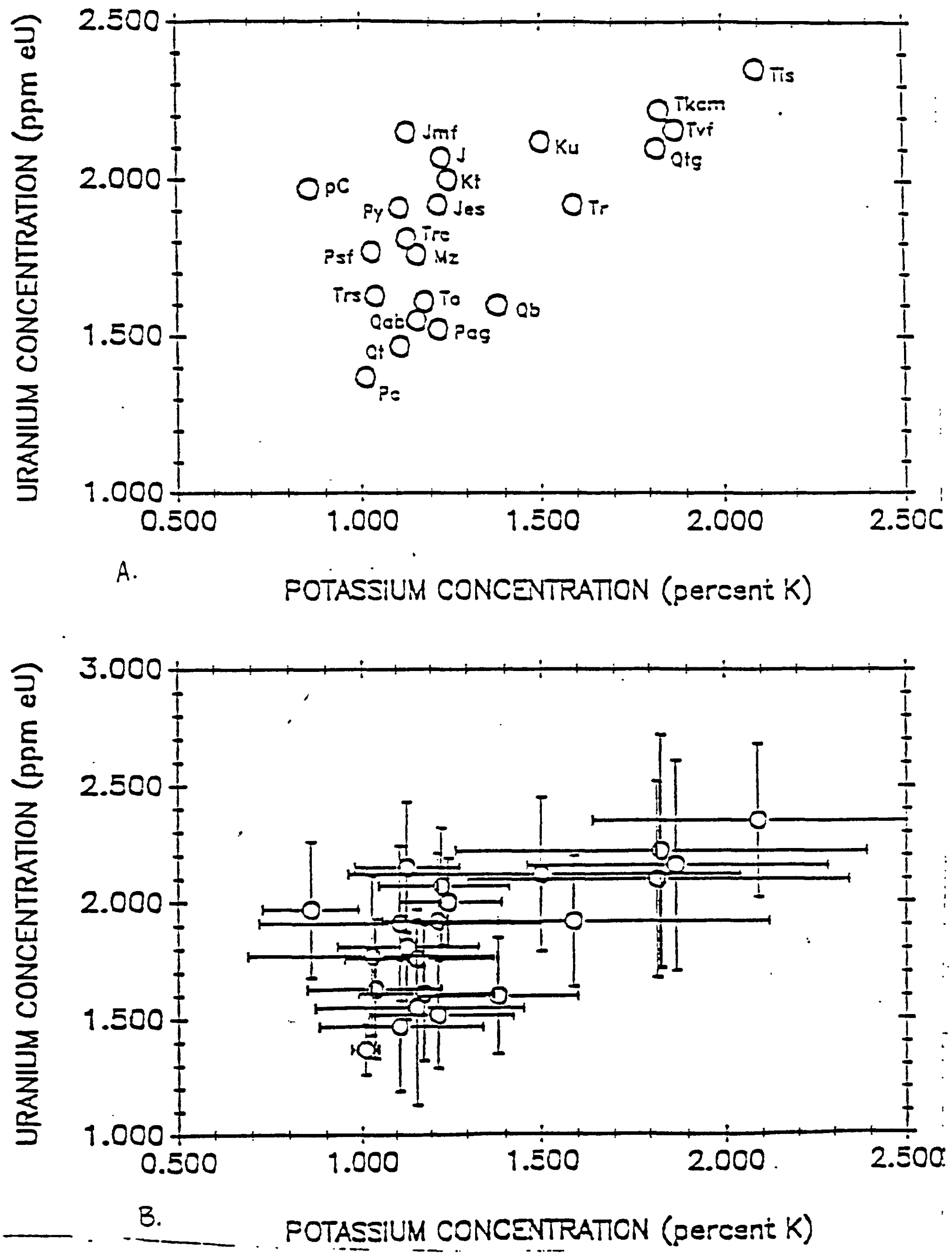
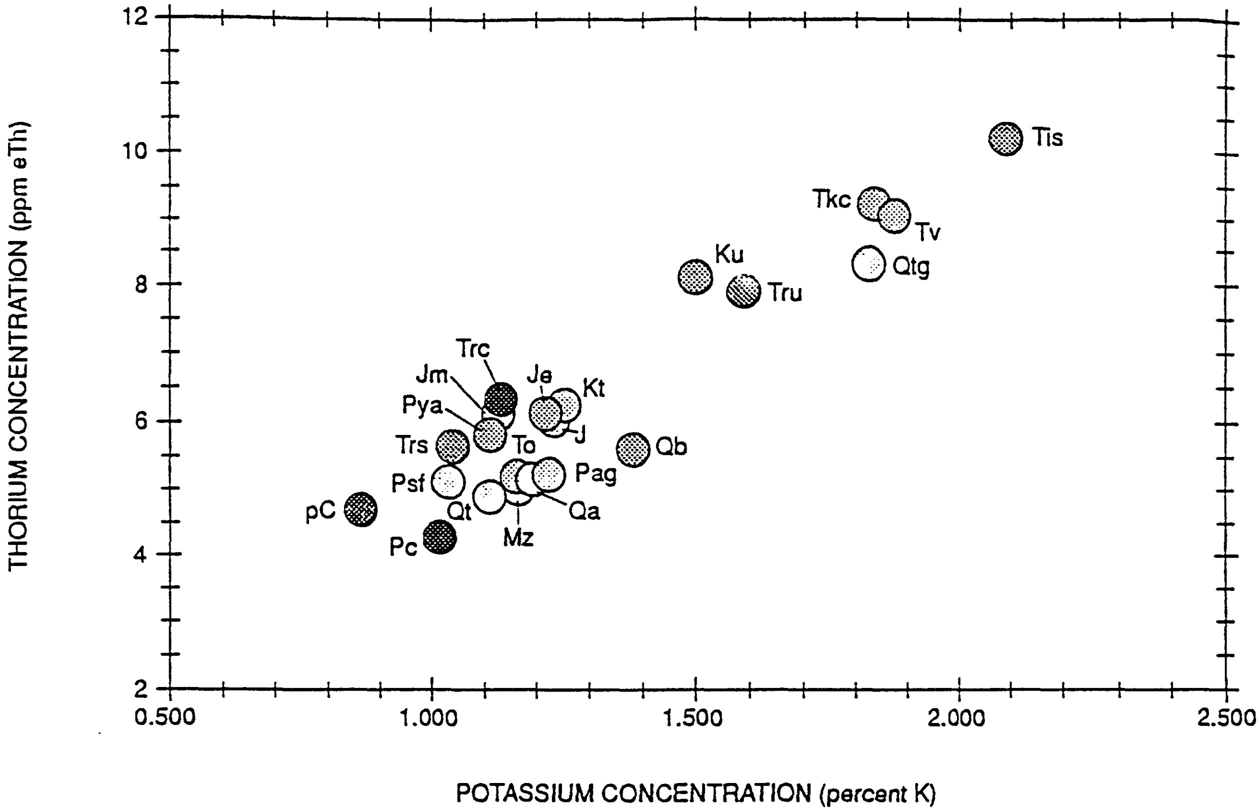


FIGURE 15-- Average concentrations of uranium versus potassium for the various mapped geologic units. (A) Concentrations plotted as open circles, with the corresponding geologic unit symbols, and (B), concentrations plotted as open circles, with horizontal and vertical lines representing the standard deviations (table 2) for potassium and uranium, respectively.



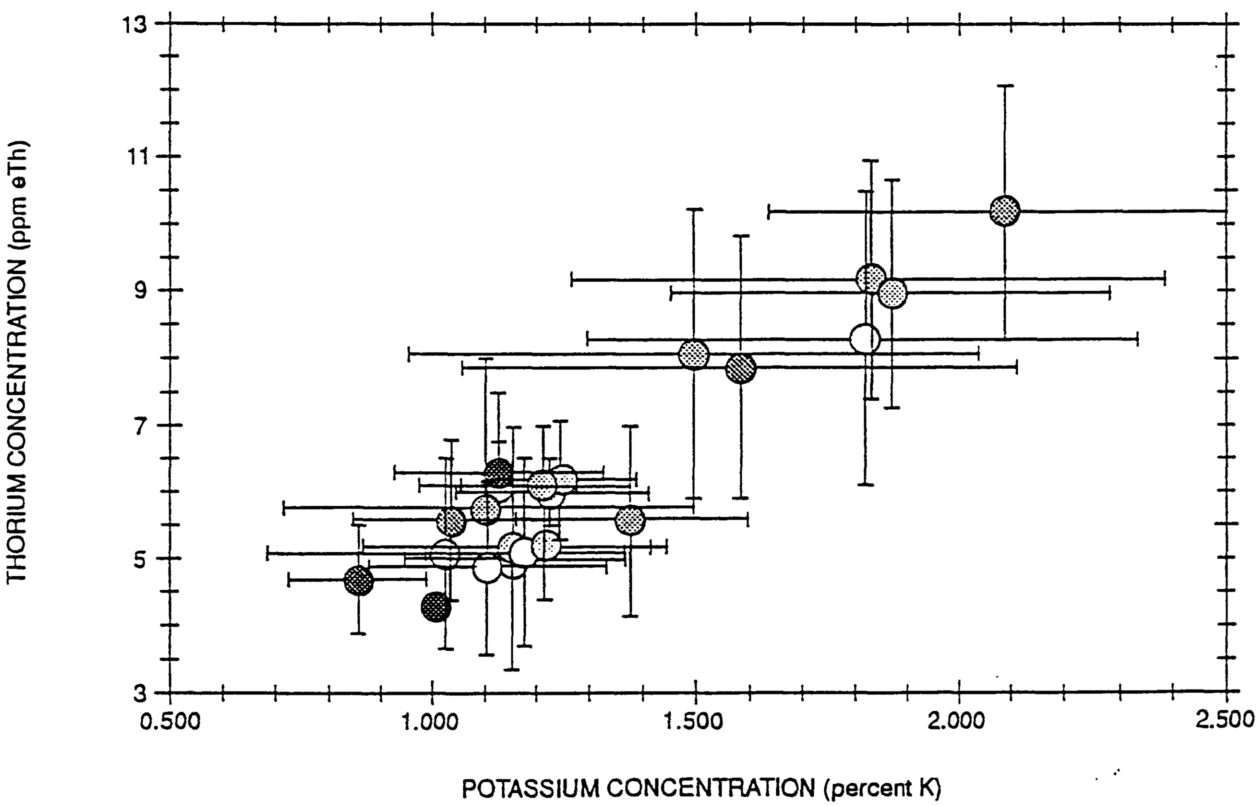
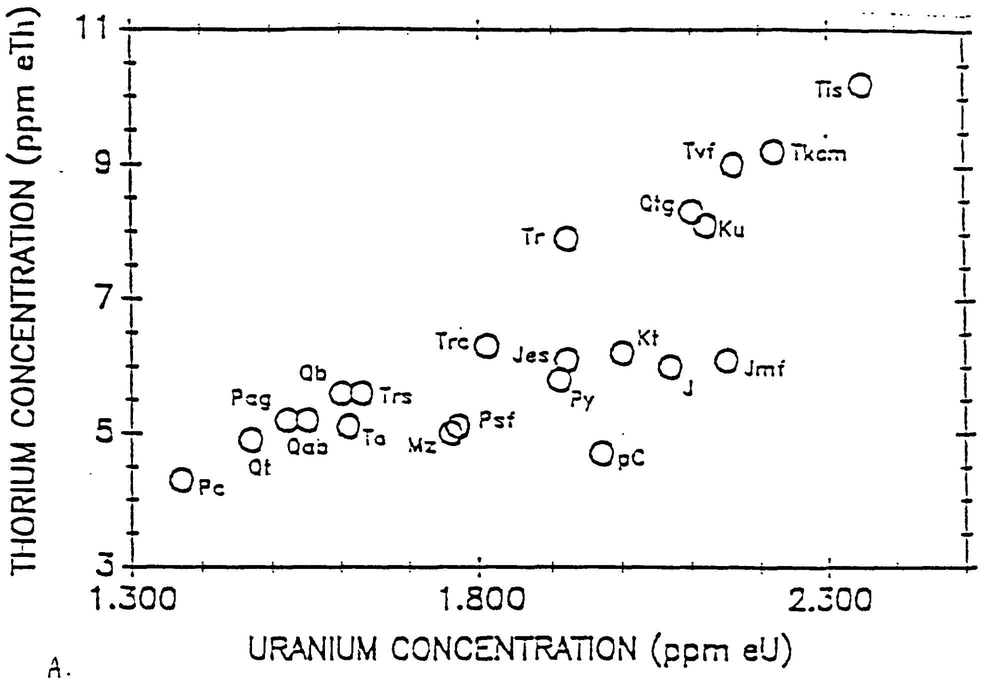
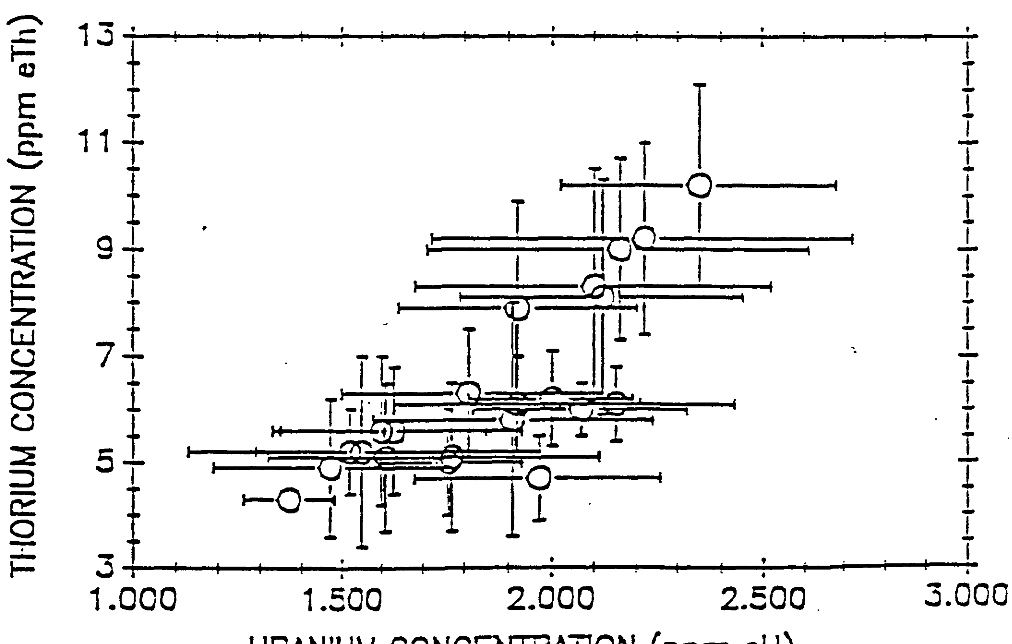


FIGURE 16 --Average concentrations of thorium versus potassium for the various mapped geologic units. (A) Concentrations plotted as open circles with the corresponding geologic unit symbols, and (B) concentrations plotted as open circles with horizontal and vertical lines representing the standard deviations (table 2) for potassium and thorium, respectively.



A.



B.

FIGURE 17 --Average concentrations of thorium versus uranium for the various mapped geologic units. (A) Concentrations plotted as open circles with the corresponding geologic unit symbols, and (B) concentrations plotted as open circles with horizontal and vertical lines representing the standard deviations (table 2) for uranium and thorium, respectively.

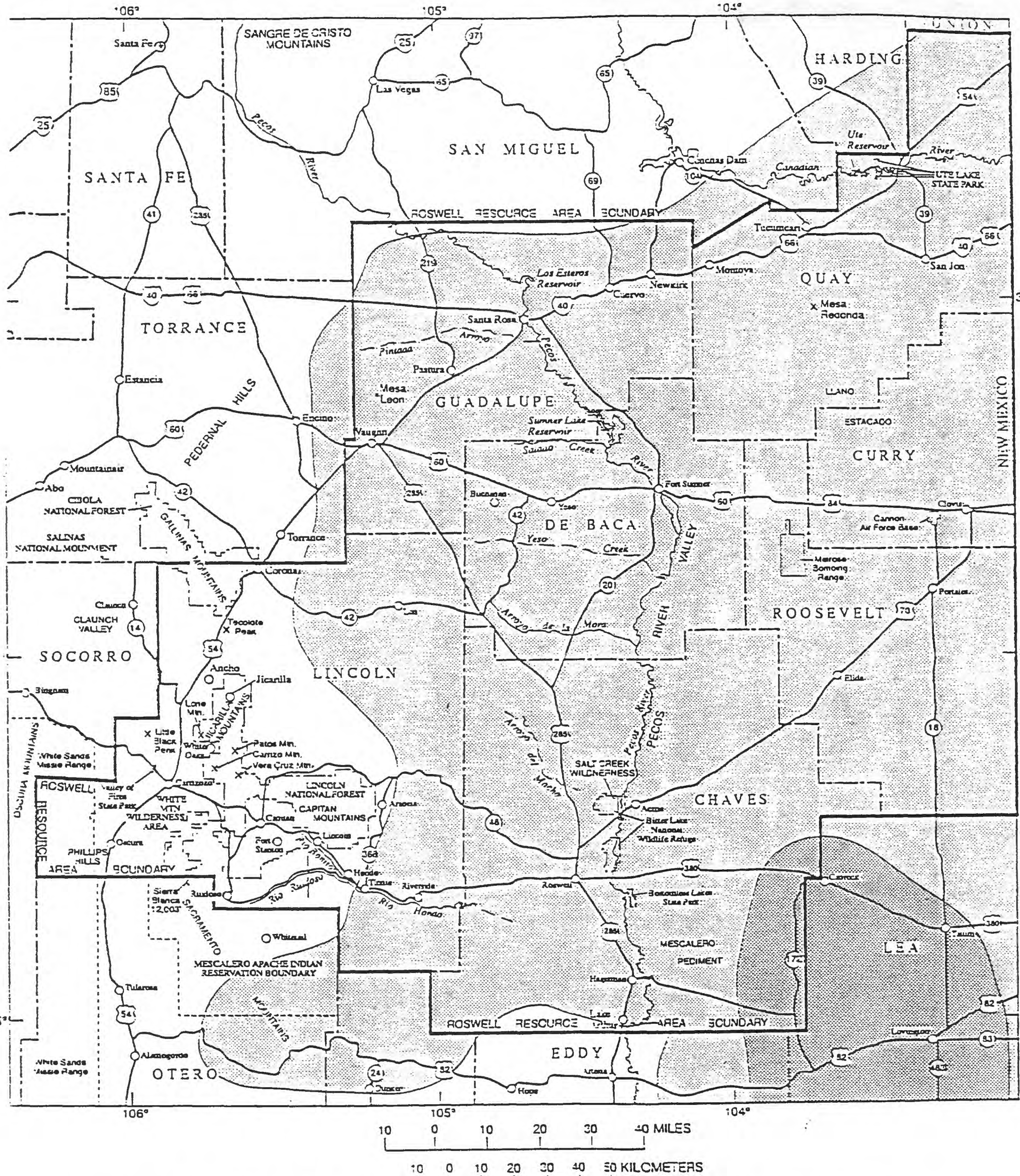


FIGURE 18. Location of saline deposits in east-central New Mexico (after U.S. Geological Survey, 1965). Light stipple=halite-bearing sediments; dark stipple=potassium-bearing sediments.

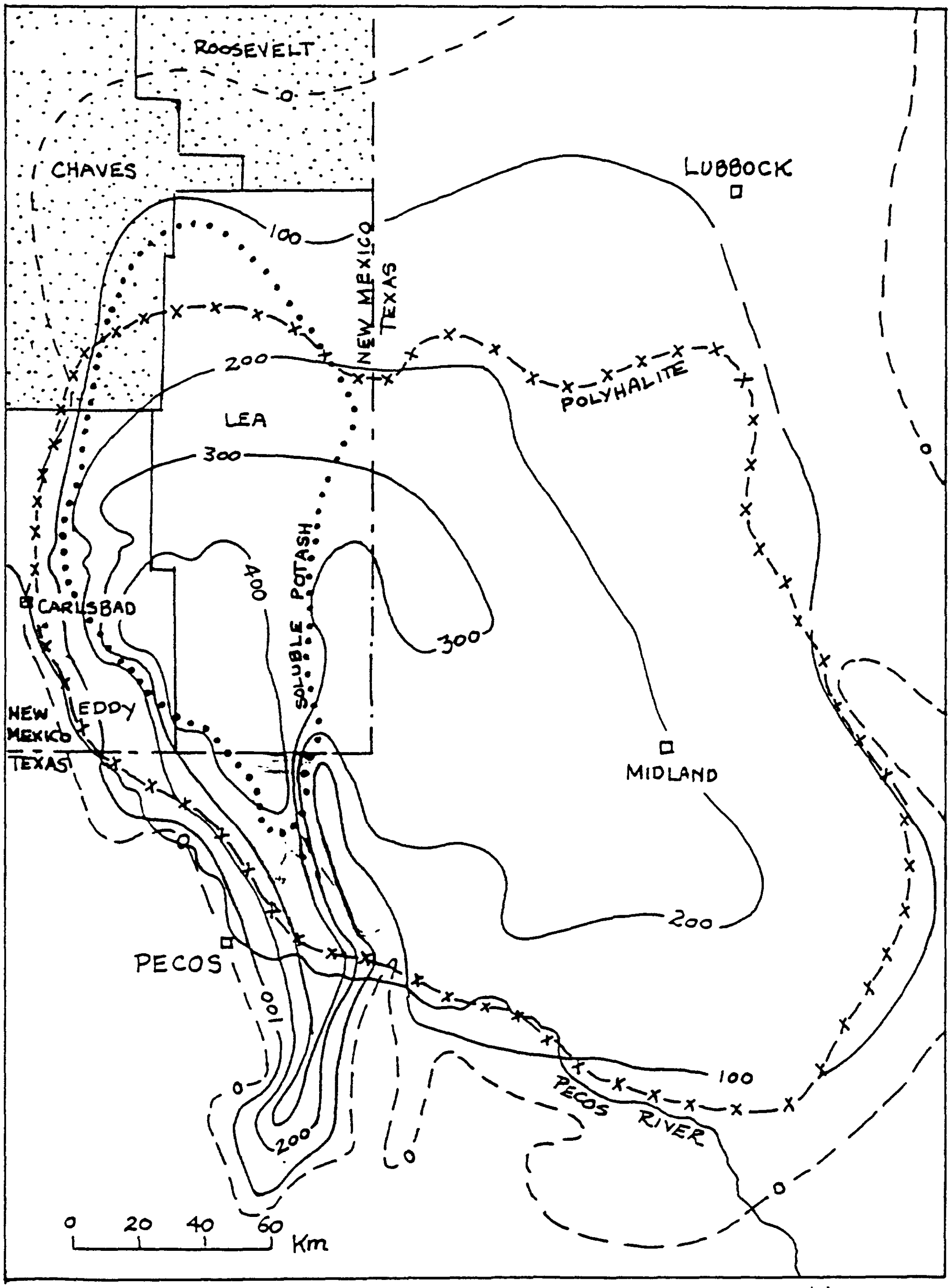


FIGURE 19.--Isopach of salt in the Salado Formation in New Mexico and Texas. Isopach contour in meters. Area enclosed by dotted line is extent of soluble potash salts, x-x line is extent of polyhalite (after Lowenstein, 1988).

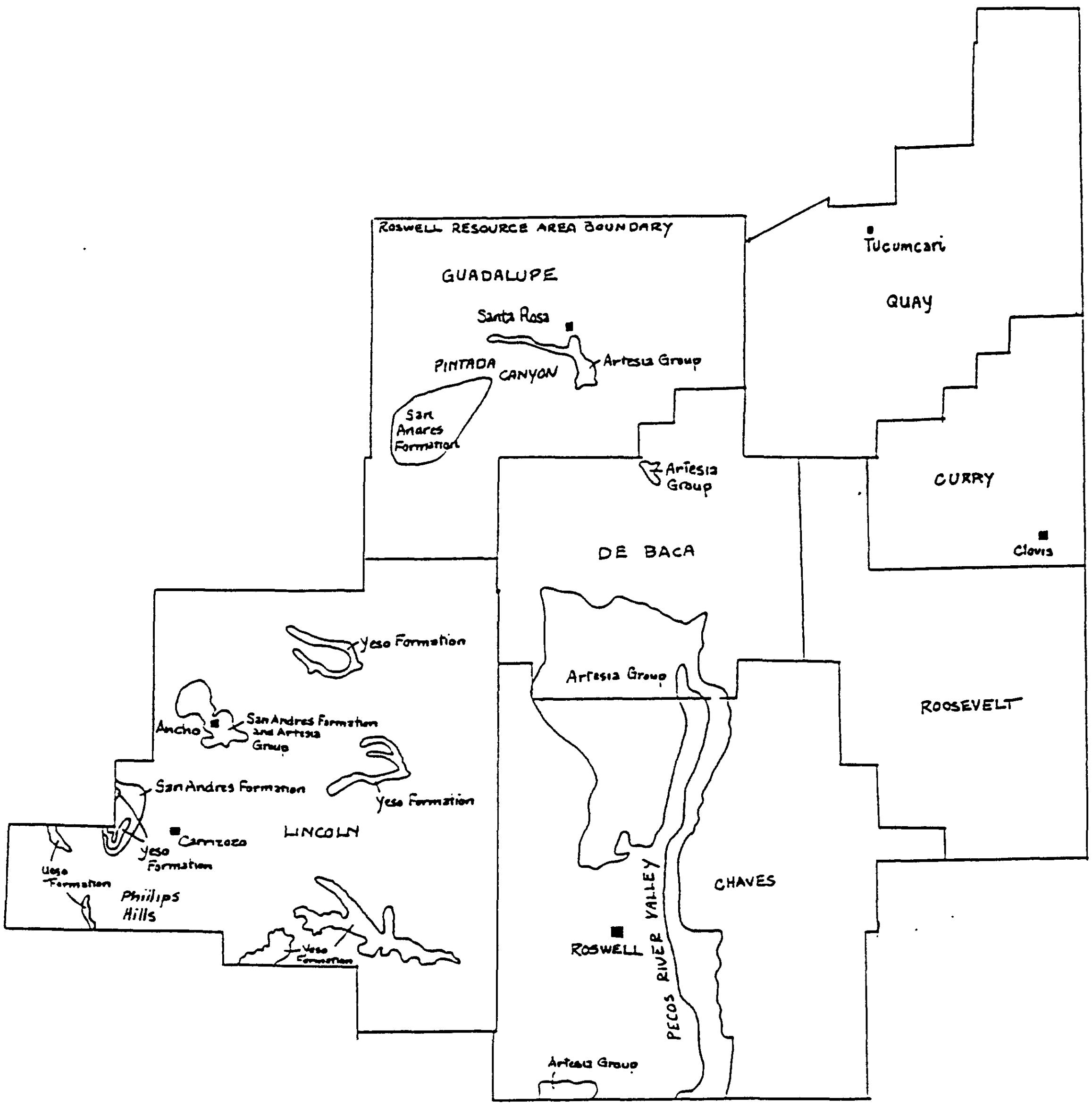


FIGURE 20. --Location of and geologic unit containing gypsum deposits in the Roswell Resource Area, east-central New Mexico (modified from Weber and Kottlowski, 1959).

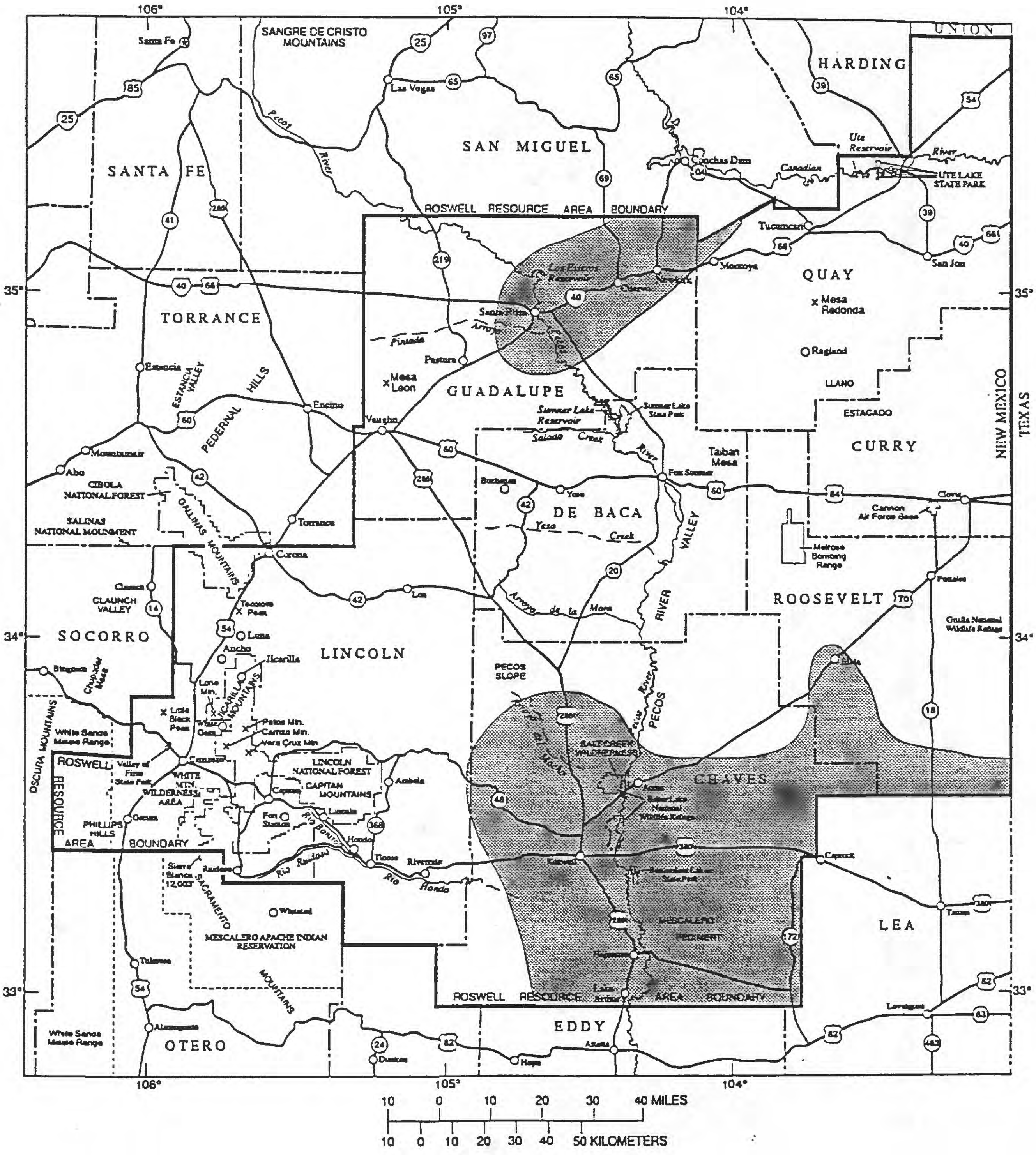


FIGURE 21. -- High potential for sulfur (stipple) in the subsurface, Roswell Resource Area.

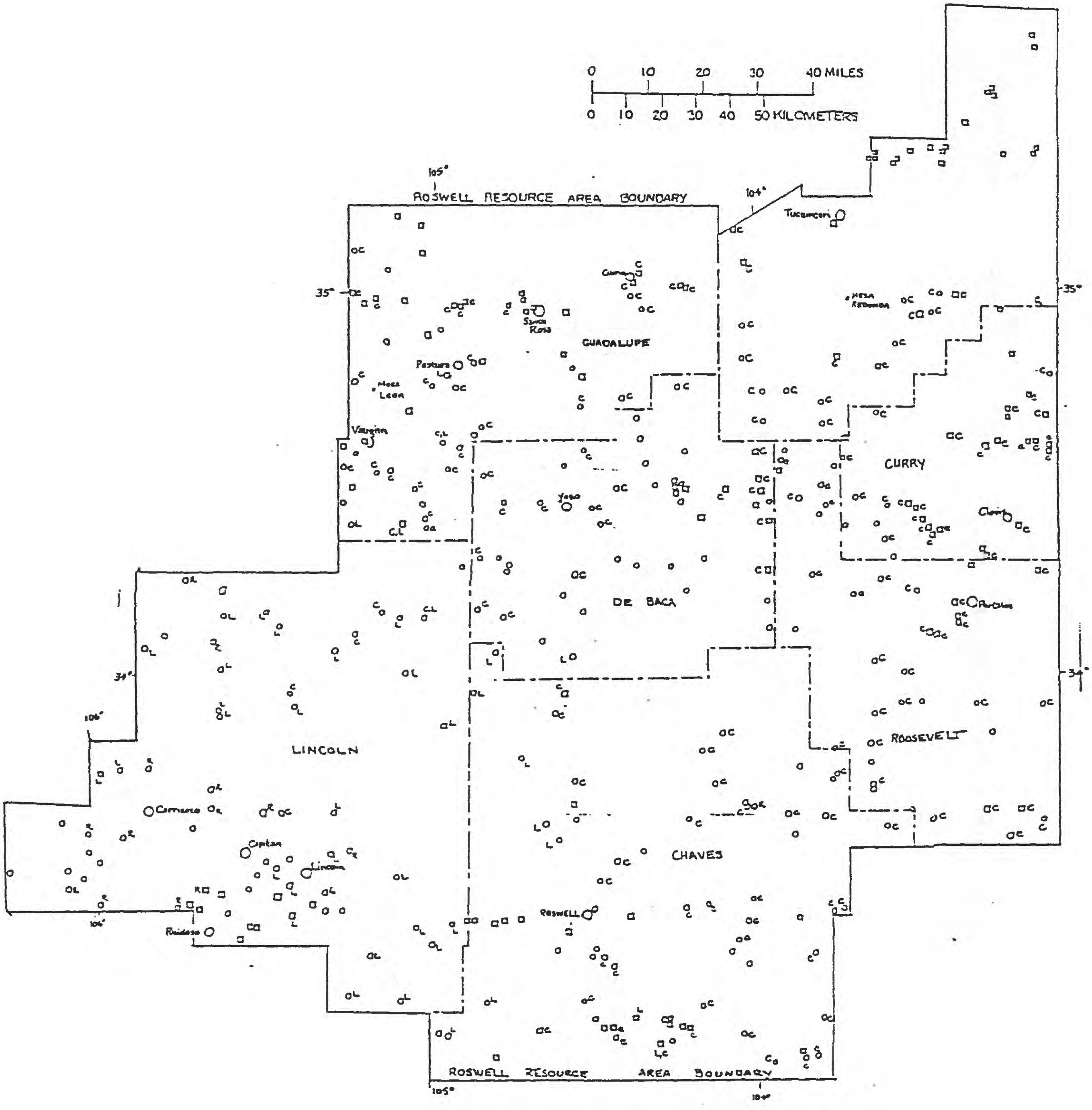


FIGURE 22. –Aggregate quarries in the Roswell Resource Area (compiled from New Mexico State Highway Department, 1971-1972). Square, developed pit; circle, prospect pit; C, caliche (all or in part); L, limestone and dolomite (all or in part); R, intrusive, metamorphic rock (all or in part). All other quarries are sand, gravel, or both.

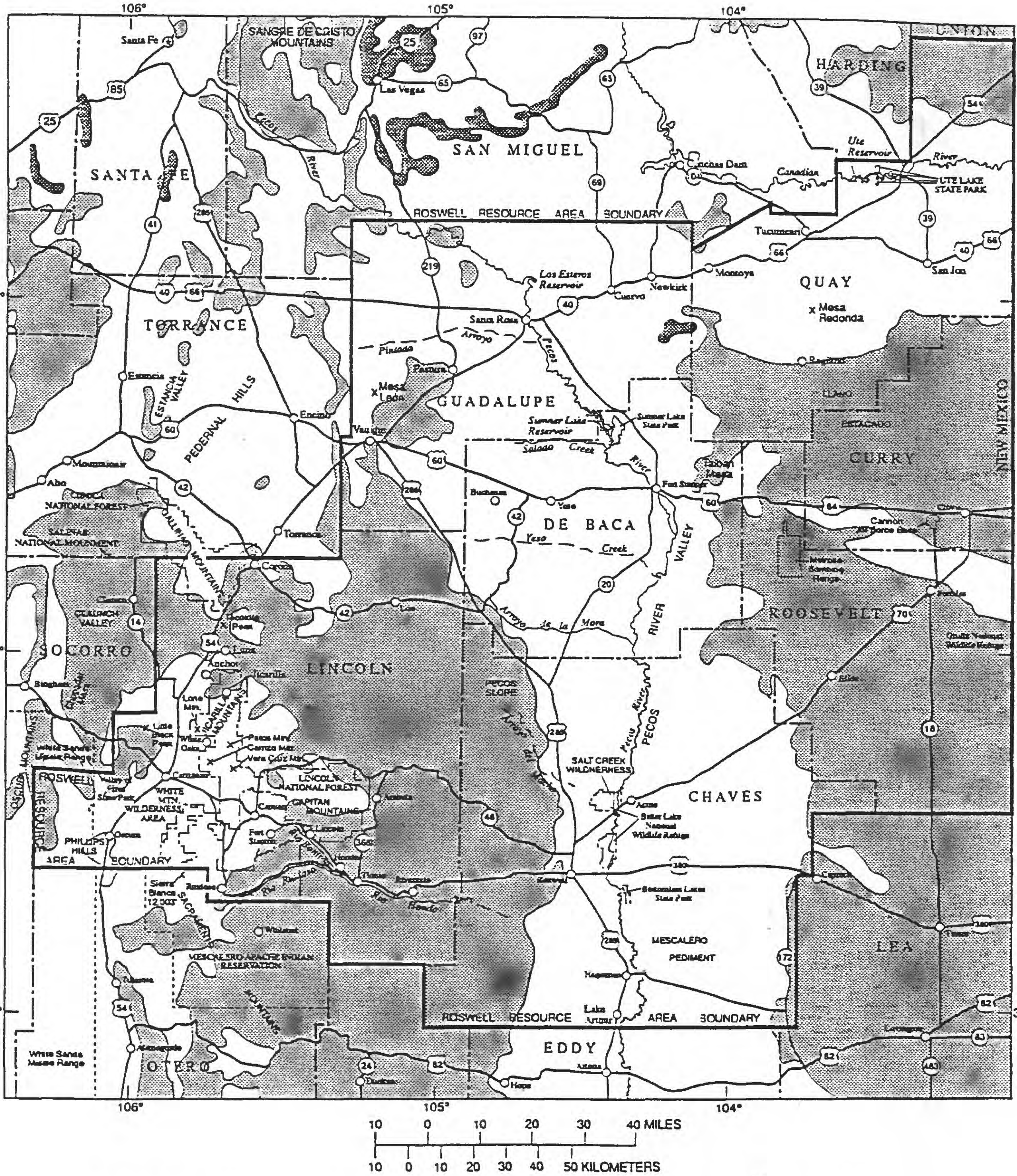


FIGURE 23. –Limestone, caliche, and dolomite in the Roswell Resource Area. Mesozoic limestone (dark stipple north of study area and within eastern Guadalupe County); caliche (light stipple east of Pecos River and in northern Quay County); Paleozoic limestone and dolomite (light stipplewest of Pecos River) (after U.S. Geological Survey, 1965).

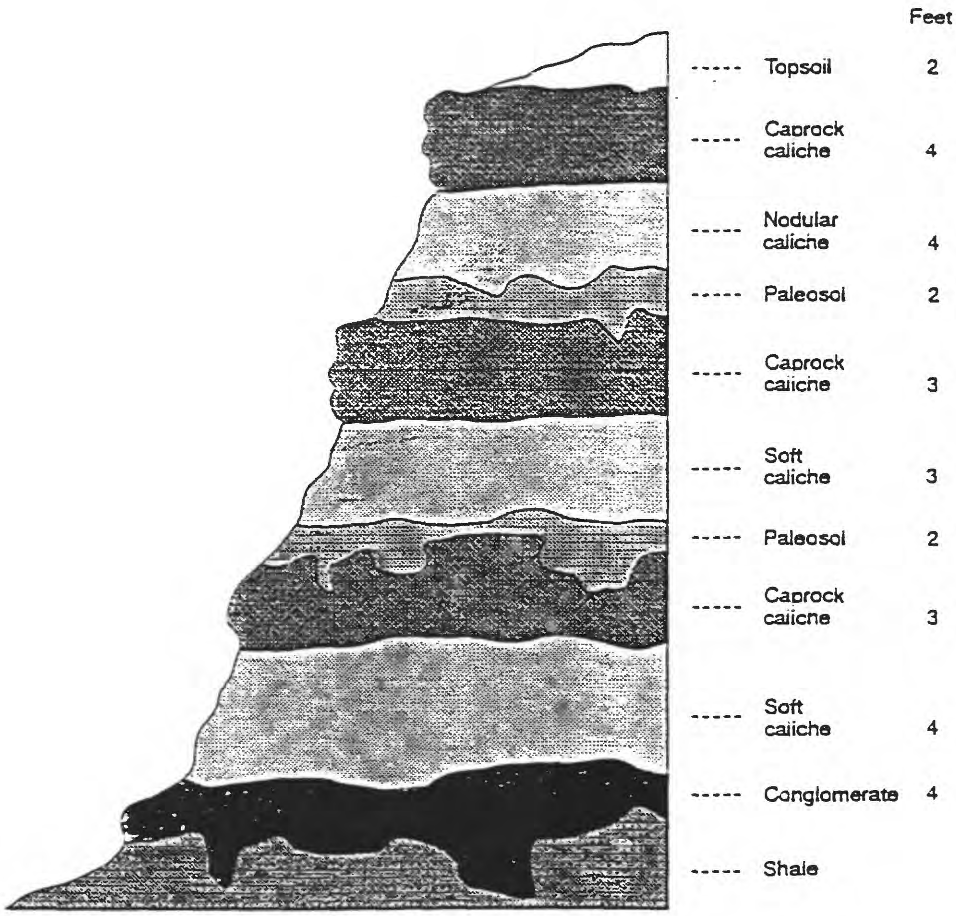
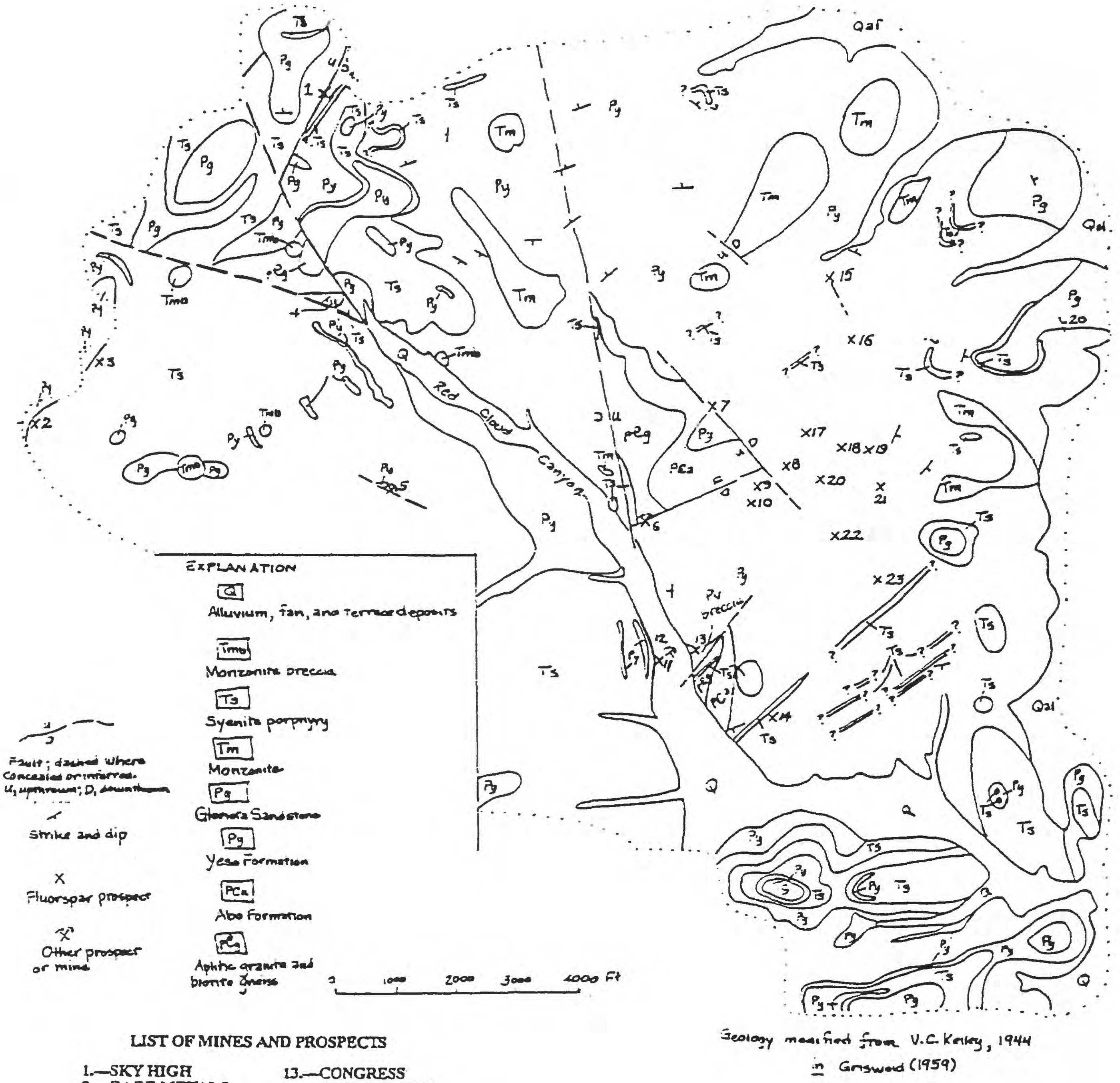


FIGURE 24. --Typical caliche section showing multiple caliche intervals on the plains near Fort Sumner (modified from New Mexico State Highway Department, 1971-1972, p. 61)



LIST OF MINES AND PROSPECTS

1.—SKY HIGH
2.—RARE METALS
3.—AMERICAN
4.—ALL AMERICAN
5.—IRON LAMP
6.—HELEN S
7.—EAGLE NEST
8.—CONQUEROR NO.4
9.—HILLTOP
10.—BOTTLENECK
11.—LAST CHANCE
12.—BUCKHORN
13.—CONGRESS
14.—HOOSIER GIRL
15.—OLD HICKORY
16.—HOOSIER GIRL
17.—EUREKA
18.—SUMMIT
19.—DEADWOOD
20.—RED CLOUD
21.—RED CLOUD
22.—RIO TINTO
23.—HOOSIER BOY

FIGURE 25.--Mines and prospects in the Gallinas Mountains, New Mexico (after Griswold, 1959).

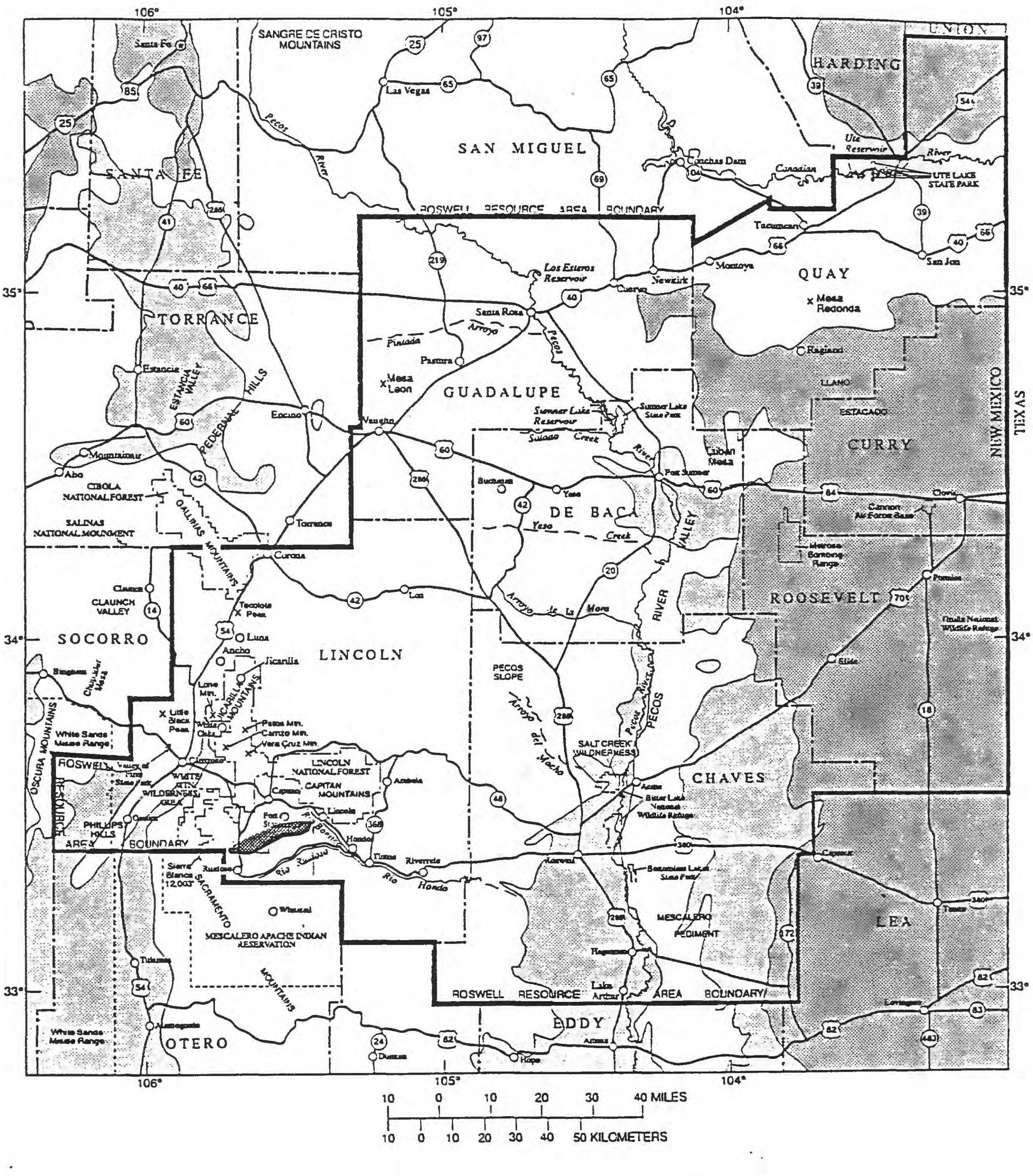


FIGURE 26. --Adobe material sources in the Roswell Resource Area (modified from Smith, 1982, fig. 50). Light stipple = Quaternary deposits; medium stipple in eastern part of study area and in Harding, Union, and northern Santa Fe Counties = Middle and Upper Tertiary deposits; dark stipple in Lincoln County = Lower Tertiary deposits.

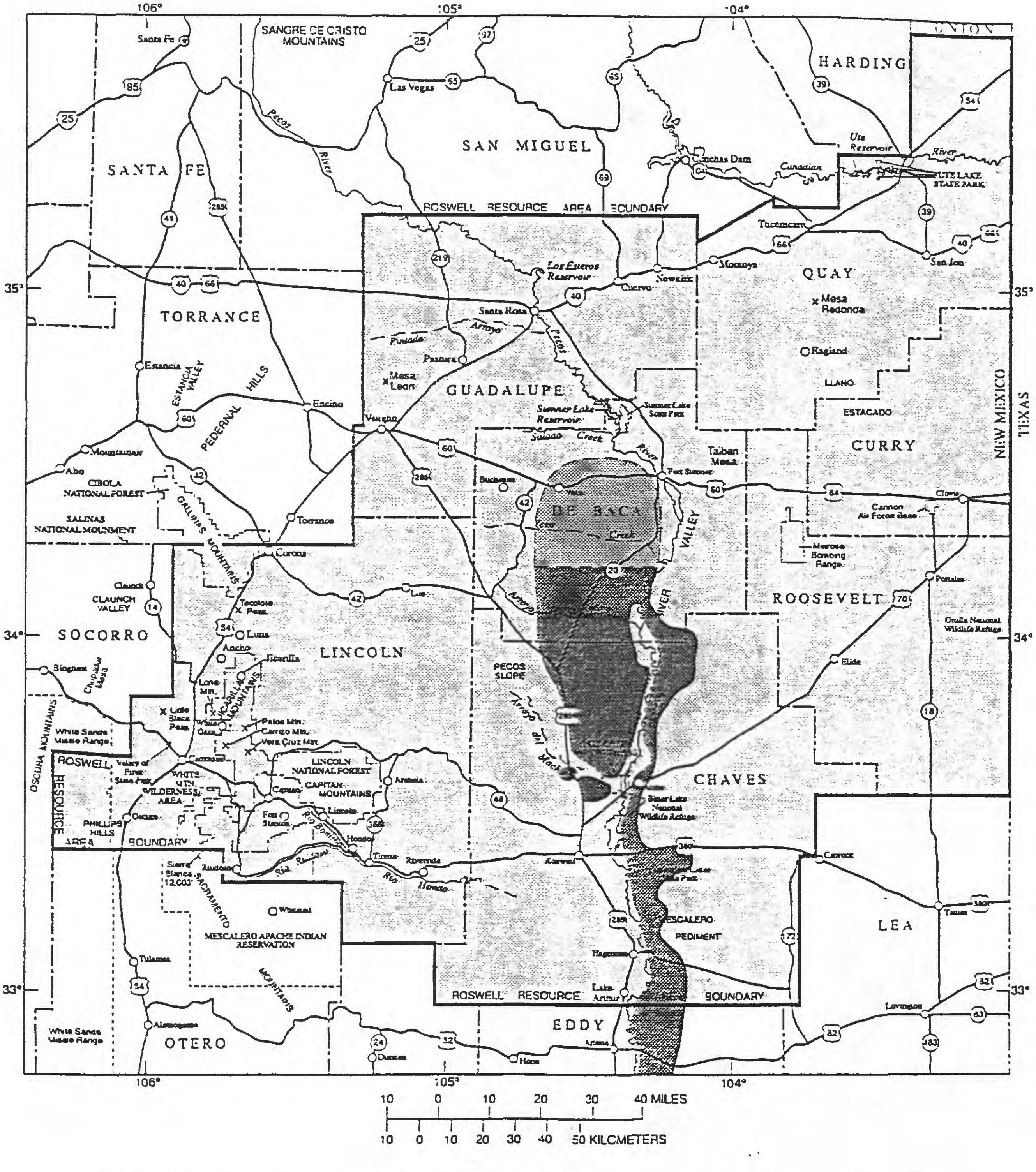
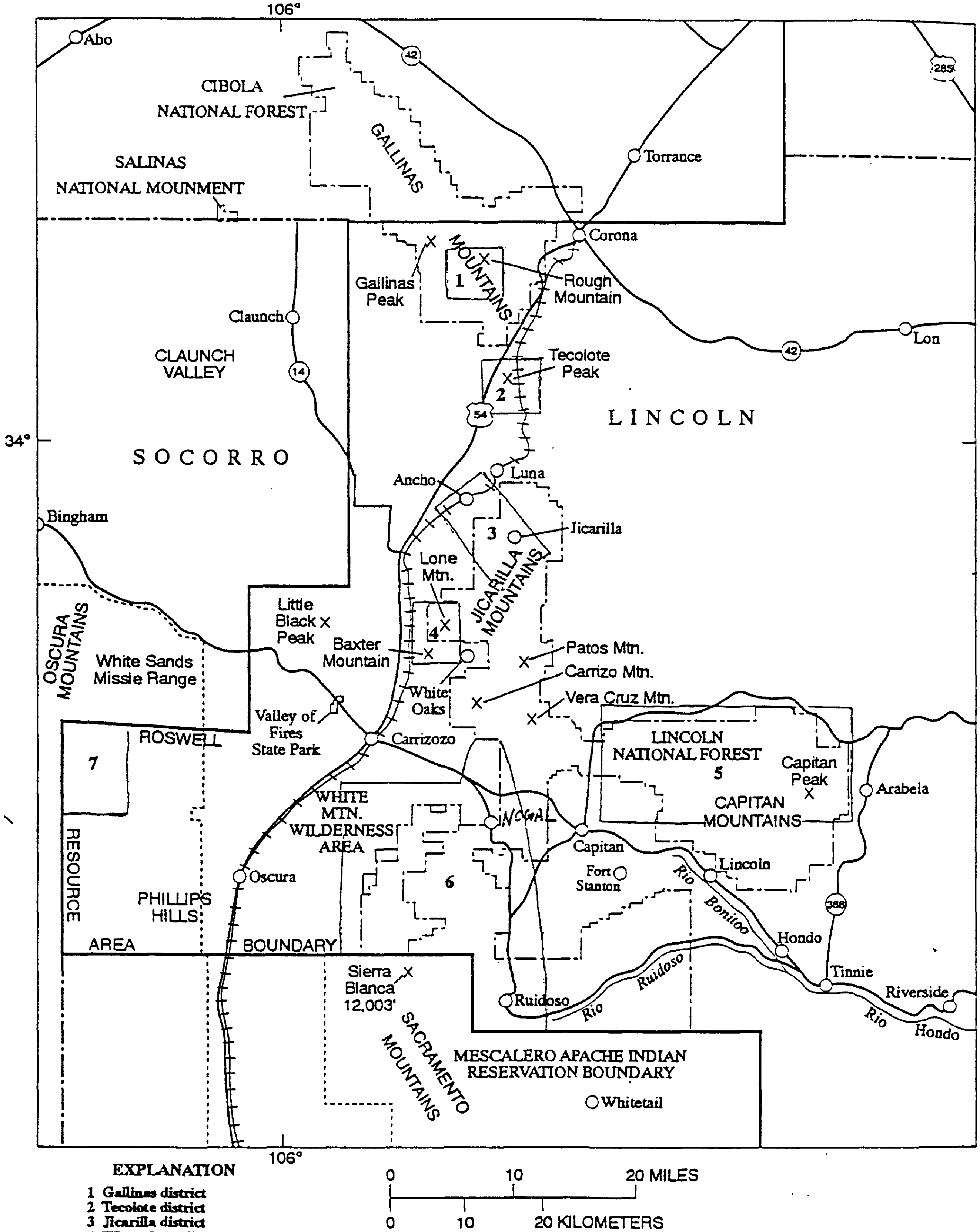


FIGURE 27. --Location (dark stipple) of surface deposits containing Pecos "diamonds" (from Albright and Bauer, 1955). Medium stipple enclosed by dashed line is area of uncertain Pecos-"diamond"-bearing surface deposits.



EXPLANATION

1 Gallinas district
2 Tecolote district
3 Jicarilla district
4 White Oaks district
5 Capitan Mountains district
6 Nogal district
7 Oscura district

FIGURE 28. --Metals mining districts in Lincoln County, New Mexico (after Griswold, 1959).

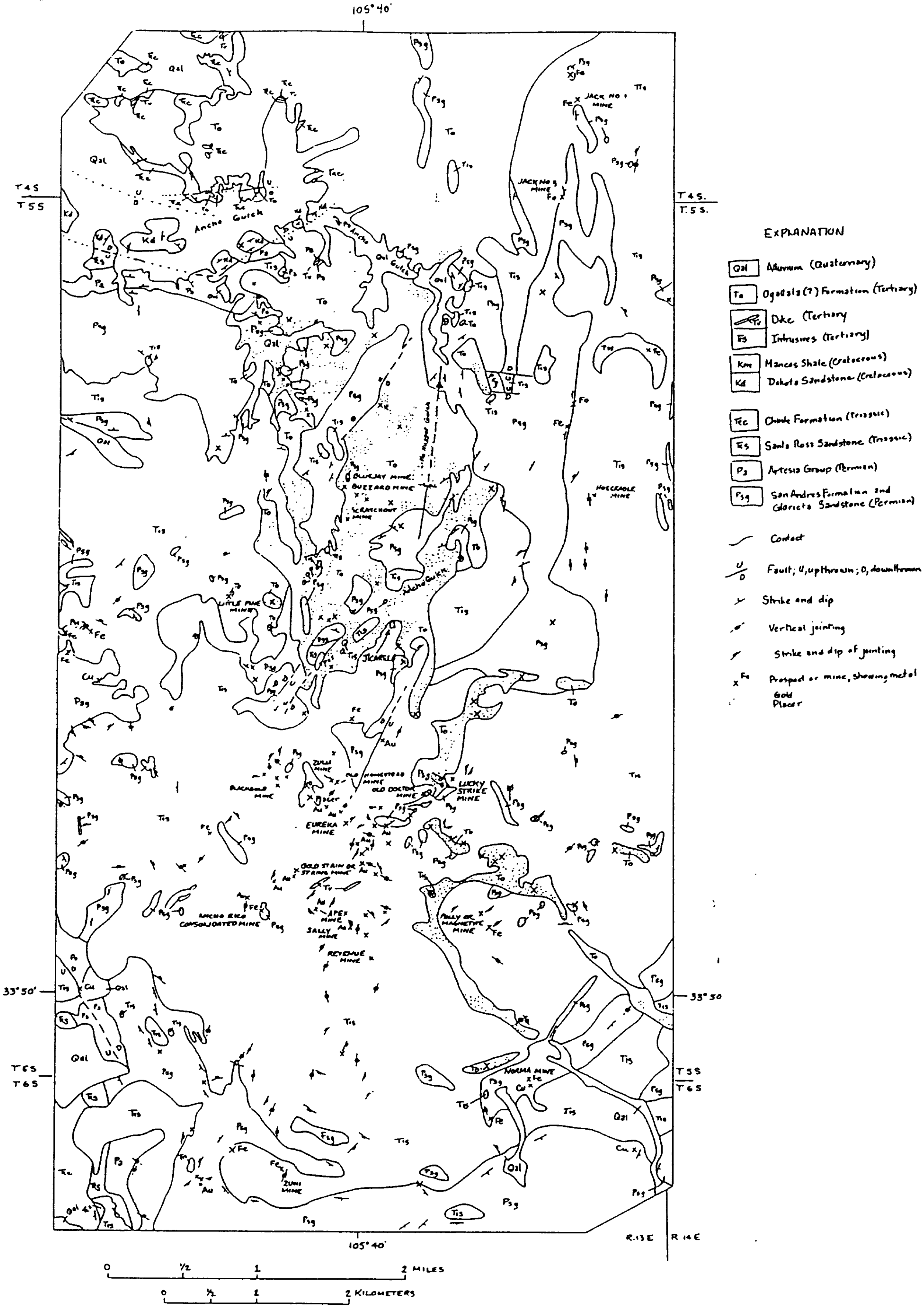


FIGURE 29. --Mines, prospects, and placer deposits in the Jicarilla Mountains, New Mexico (after Segerstrom and Ryberg, 1974).

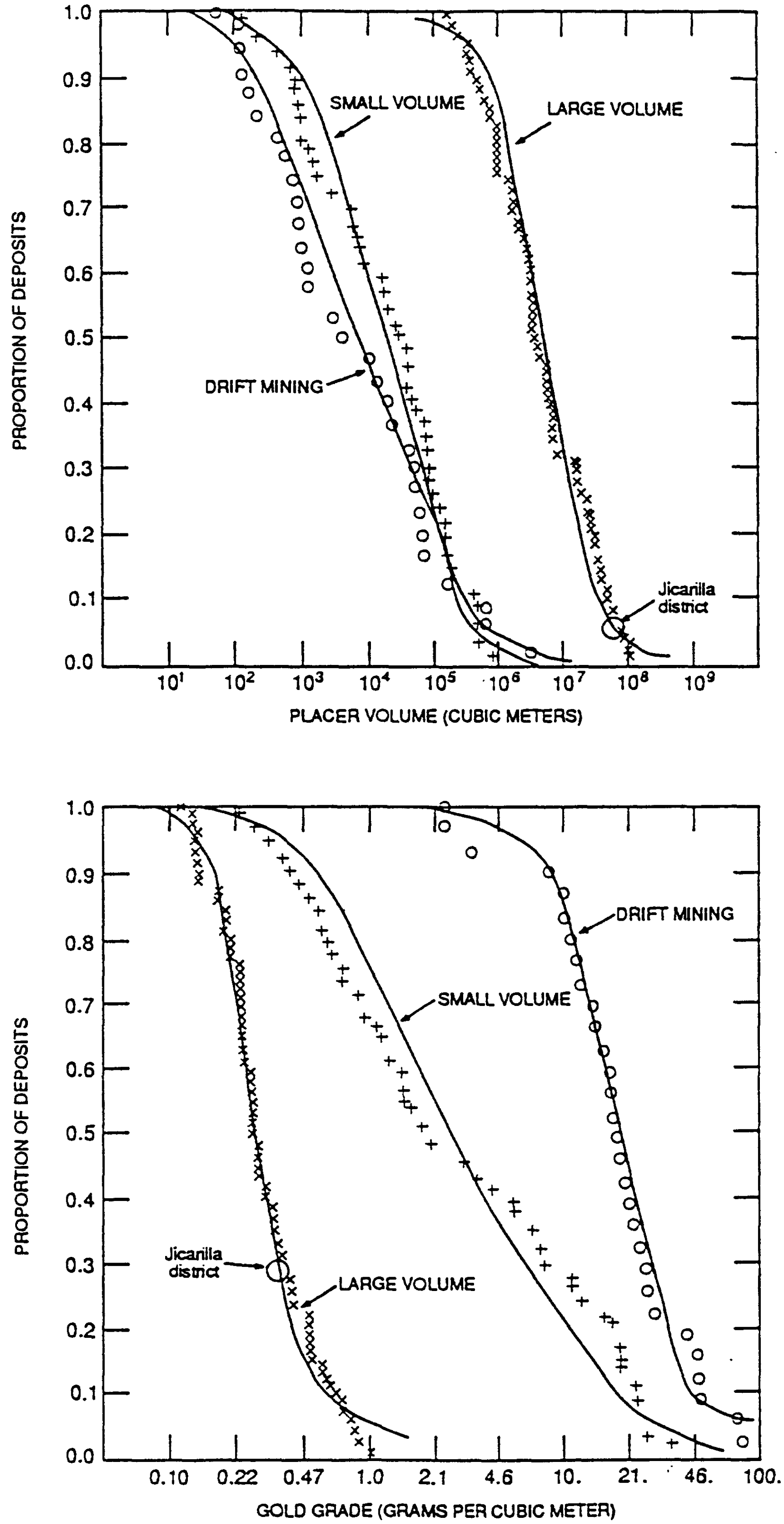


FIGURE 30. -- Estimated volume and gold grade for the Jicarilla district placers in comparison with the grade and volume model for gold placers (modified after Bliss and others, 1987).

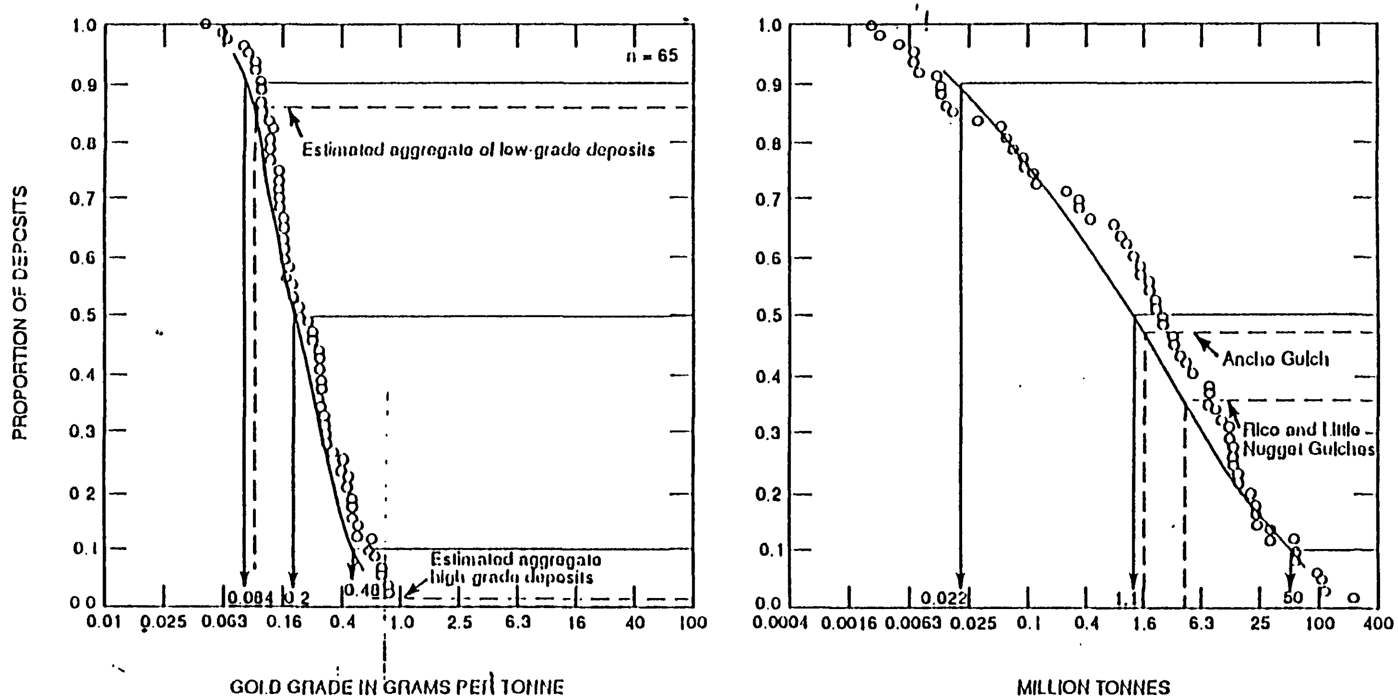


FIGURE 31. --Grades and tonnages of Jicarilla Mountain gold-platinum-group-element placers plotted on the grade and tonnage model (modified from Orris and Bliss, 1986). Silver grades for the deposit model are not known because there are no reported silver grades for placers in the study area.

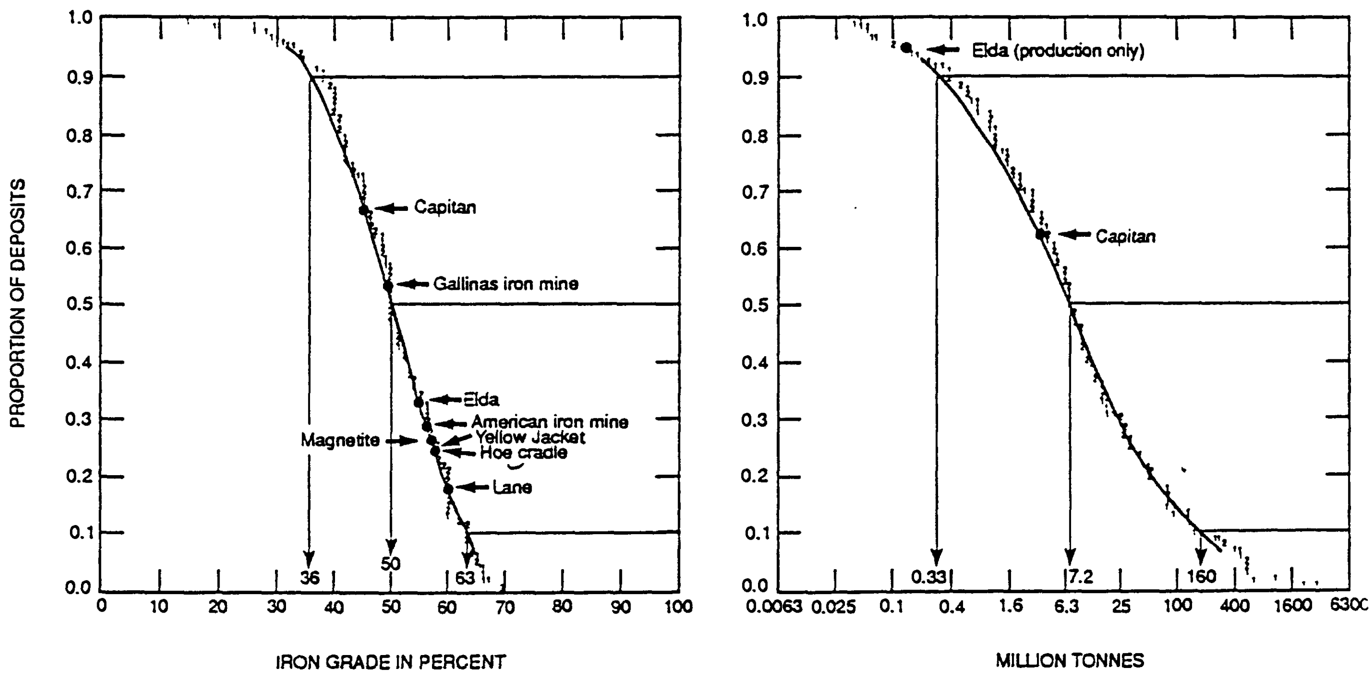


FIGURE 32. --Grades and tonnages of iron skarn deposits in the Roswell Resource Area, plotted on the grade and tonnage model (modified from Mosier and Menzie, 1986).

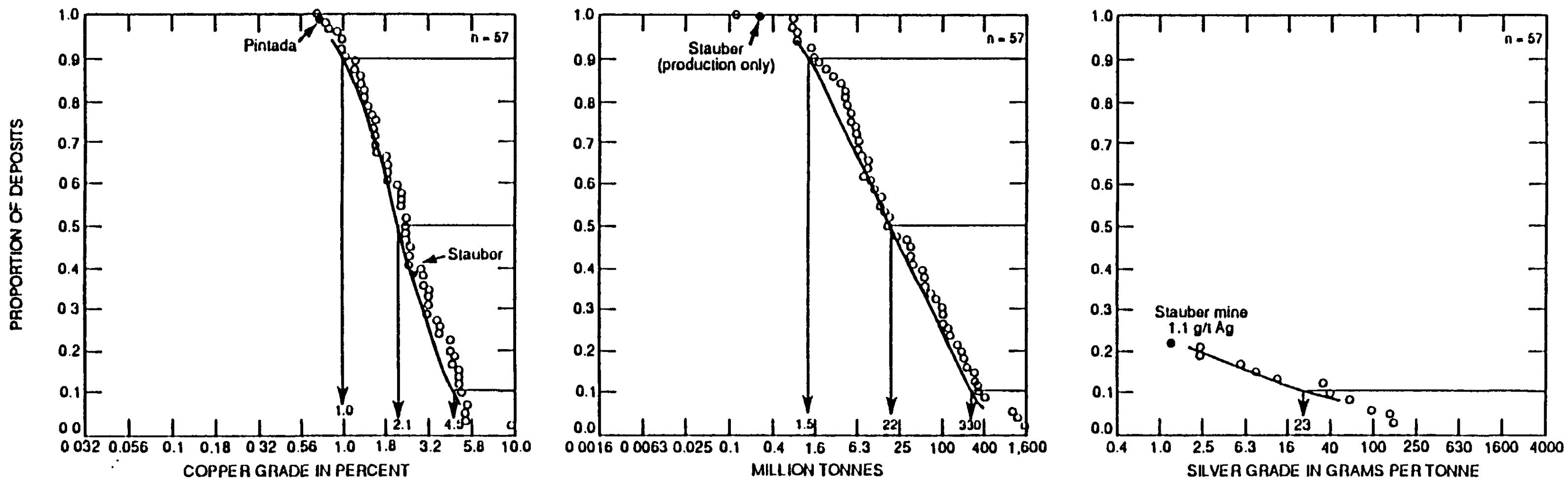
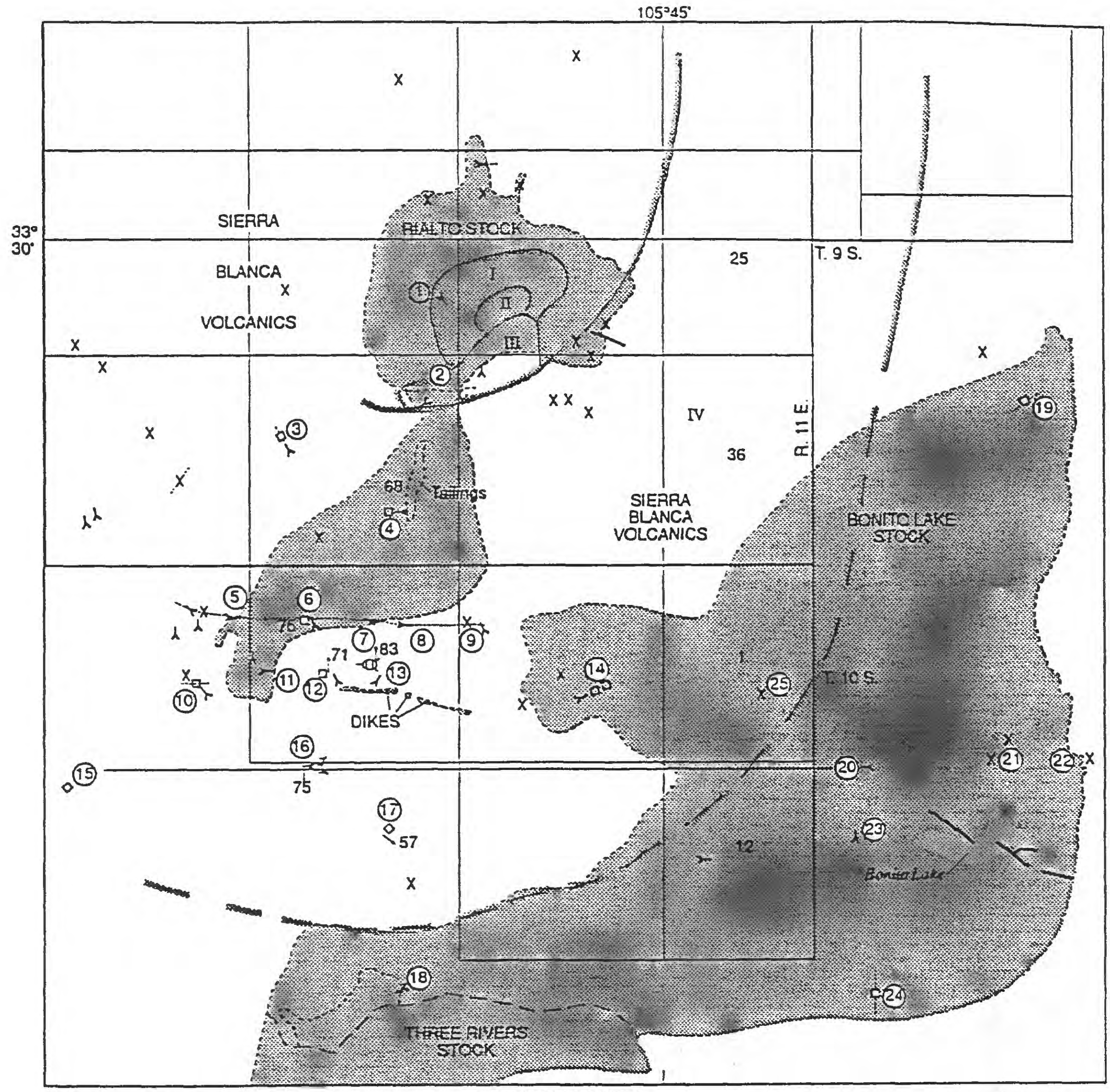


FIGURE 33. --Grades and tonnages of Pintada and Stauber mine production as compared to the grade and tonnage model (Mosier and others, 1986). Production grades and tonnages are calculated from McLemore and North (1985).



EXPLANATION

INDEX TO MINES

1. Fulmer (Rialto Group)
2. Parsons (Hopeful)
3. Old Red Fox
4. Silver King
5. Willis
6. Old Abe
7. Renowned O.K.
8. Crow
9. Martha Washington
10. Argentine
11. Bailey
12. White Swan
13. Spur
14. Washington
15. Silver Spoon
16. Maud
17. Greenville
18. Great Western
19. Water Dog No. 1
20. Soldier
21. Hope
22. Mineral Farms Canyon
23. Christmas
24. Rock No. 1
25. Silver Nugget

Adit
X Prospect
Shaft
Vein quartz with sulfide mineralization

0 1/4 1/2 1 MILE
0 .5 1 KILOMETER

FIGURE 34. --Zonation of the Rialto stock porphyry molybdenum-low fluorine deposit, and mines and prospects within the deposit (after Thompson, 1973). Zone I, magnetite; Zone II, molybdenite; Zone III, copper; Zone IV, lead-zinc.

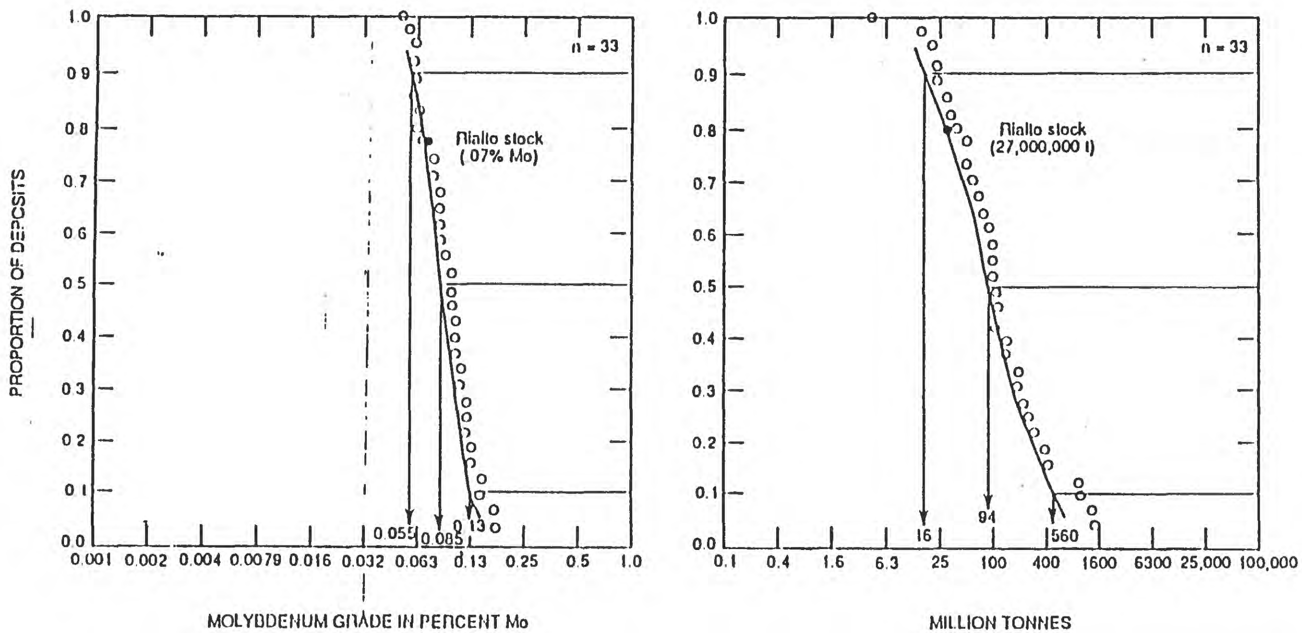


FIGURE 35. --Grade and tonnage of the Rialto stock porphyry-molybdenum low-fluorine deposit as compared to the grade and tonnage model (Mosier and Theodore, 1986).

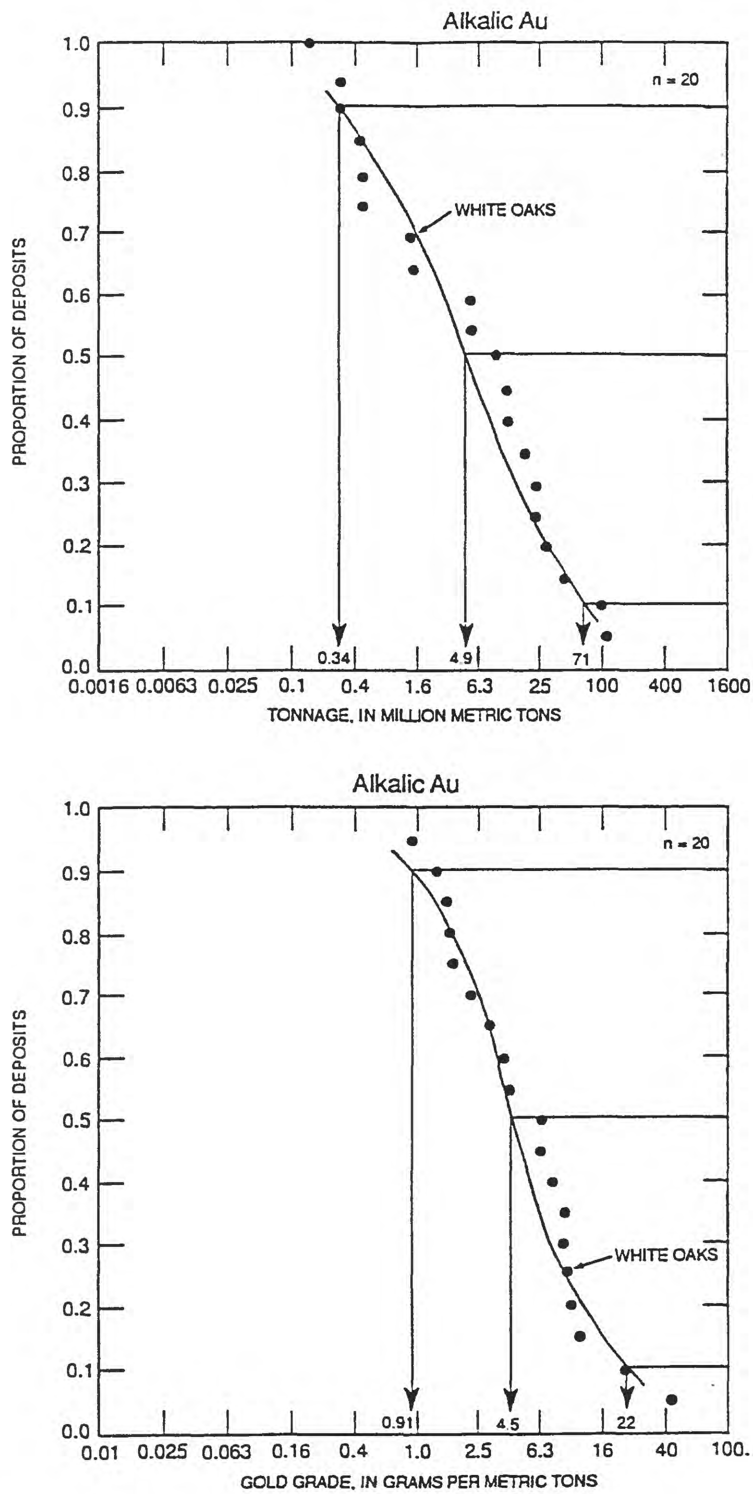


FIGURE 36. –Grade and tonnage of alkaline-hosted gold deposit at White Oaks compared to world model.

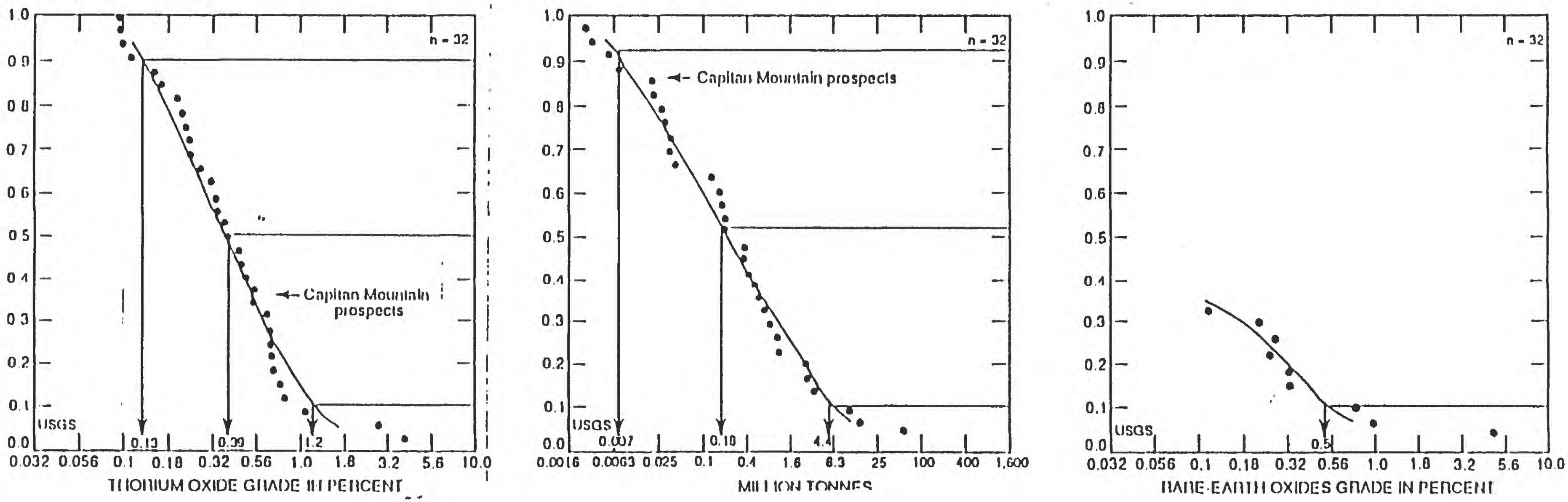


FIGURE 37. --Grade and tonnage of Capitan Mountain deposit compared to the thorium rare-earth vein deposit model (Bliss, 1992).

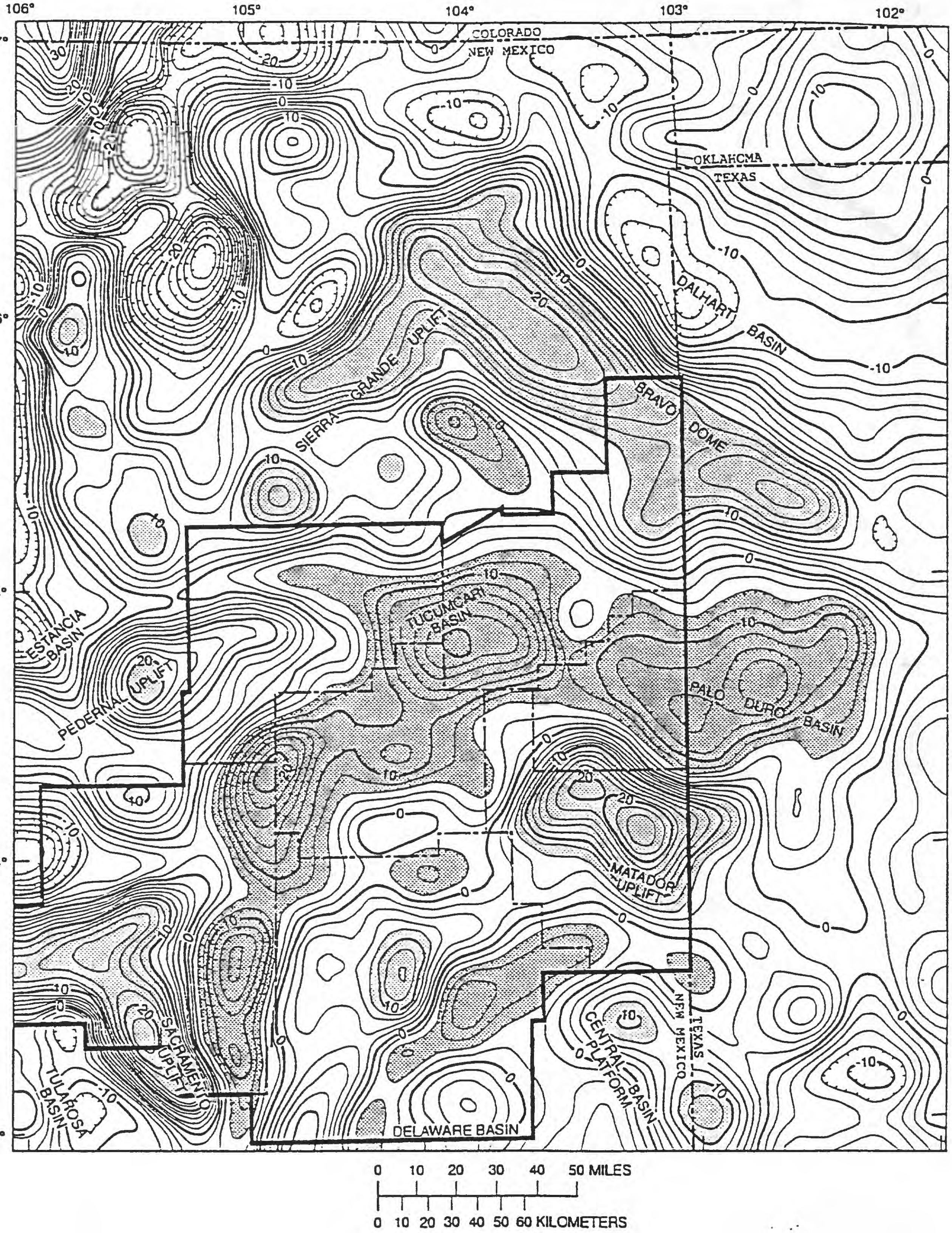


FIGURE 38.--Residual gravity map of eastern New Mexico. Contour interval 2 milligals. A fifth-order polynomial surface was removed from the Bouguer anomaly values to produce this map. A total of 50,000 gravity readings were taken in southeastern New Mexico.

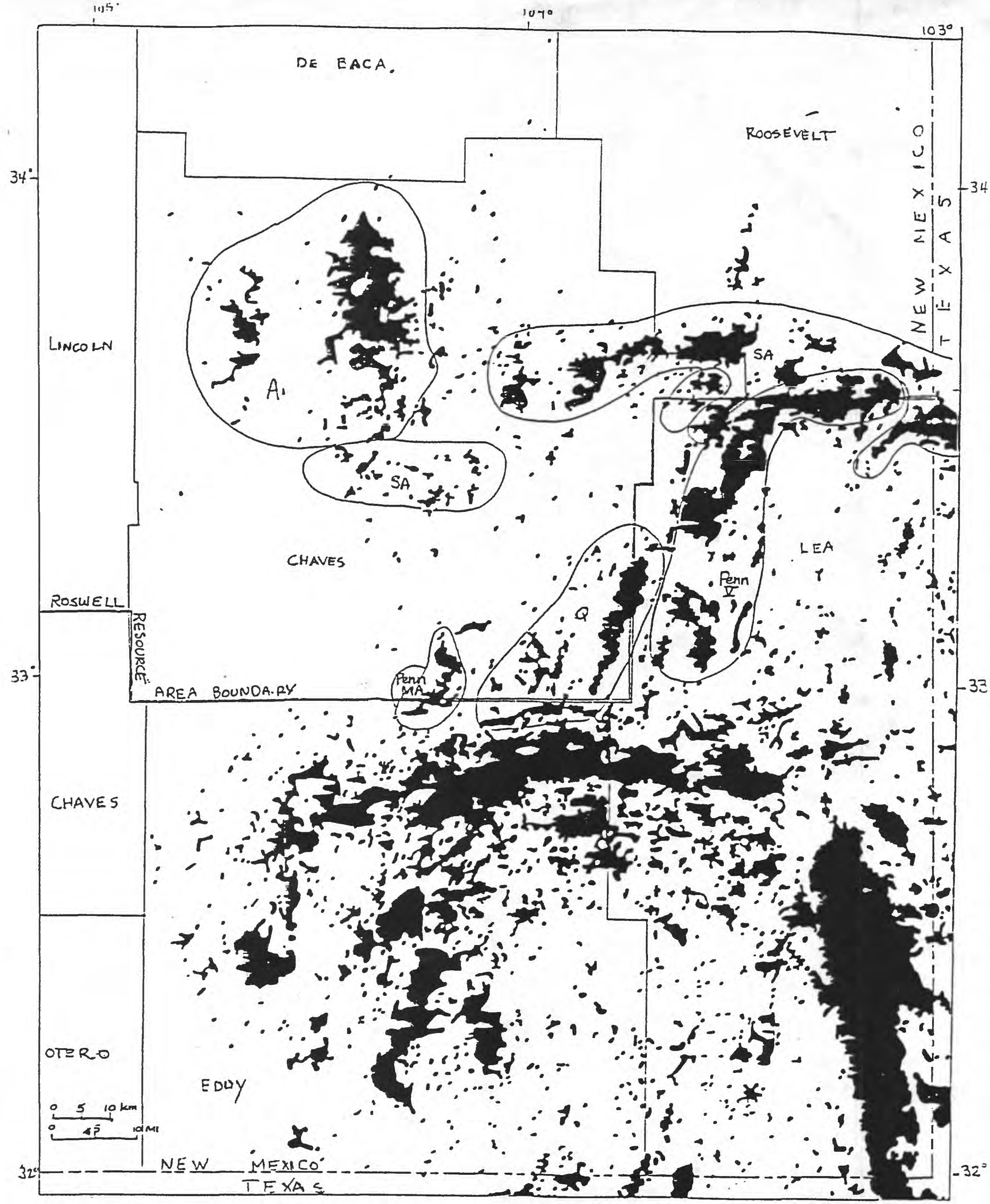


FIGURE 39. --Plan distribution of Pennsylvanian and Permian oil and gas fields of the Roswell Resource Area, New Mexico (modified from Roswell Geological Society, 1988). [Penn V, Virgilian (or lower Cisco) limestone oil fields; SA, Guadalupian San Andres dolomite oil fields; Q, Guadalupian Queen quartz sandstone oil field; Penn MA, Pennsylvanian Morrowan and Atokan quartz sandstone gas field; A, Abo Formation quartz sandstone gas field.]

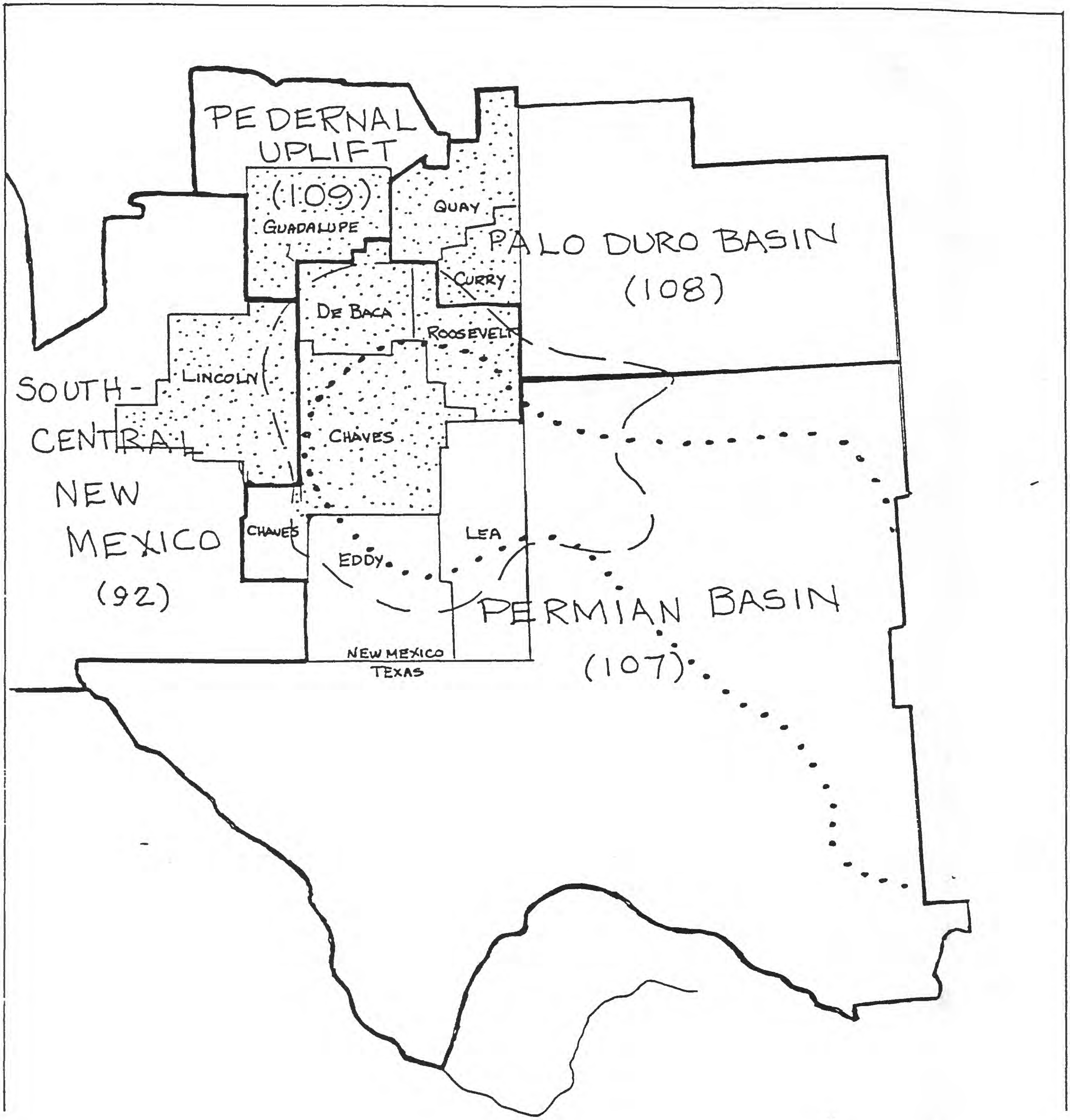


FIGURE 40. --Regional oil and gas provinces of the Permian Basin and vicinity (Mast and others, 1989). Stipple indicates the Roswell Resource Area. Outlined areas are the Northwestern Shelf, Pennsylvanian and Permian province (dashed line), and Northwestern Shelf, pre-Pennsylvanian province (heavy dotted line).

APPENDIX--Geologic and mineral resources information for deposits and occurrences in the Roswell Resource Area, east-central New Mexico

by David M. Sutphin

Mineral abbreviations used in the Appendix 1 are (after Lange and others, 1978):

Actinolite	ACNL	Hematite	HMTT
Allanite	ALNT	Hubnerite	HBNR
Anglesite	ANGS	Kaolinite	KLNT
Azurite	AZRT	Limonite	LMON
Barite	BRIT	Magnetite	MGNT
Bastnaesite	BSNS	Malachite	MLCT
Bornite	BRNT	Molybdenite	MLBD
Chalcoite	CLCC	Phlogopite	PLGP
Chlorite	CLRT	Platinum-group elements	PGE
Chrysocolla	CHRY	Psilomene	PSLM
Clay	CLAY	Pyrite	PYRT
Electrum	ELCM	Pyrolusite	PRLS
Epidote	EPDT	Quartz	QRTZ
Fluorite	FLRT	Silver	SLVR
Galena	GLEN	Sulfides	SLPD
Goethite	GTHT	Titanite	TTNT
Gold	GOLD	Tourmaline	TRML
Gypsum	GPSM	Wolframite	WLFM

Age abbrevations:

Quaternary	QUAT
Tertiary	TERT
Cretaceous	CRET
Jurassic	JUR
Triassic	TRI
Permian	PERM
Ordovician	ORD

Some site coordinates are calculated from small-scale maps and may not be accurate.

N.r., not reported
N.a., not available

OF 92-0261

ROSWELL RESOURCE AREA

COUNTY District Site (* = not in MRDS)	USGS deposit model	Minerals (commodities) reported	Host rock type	Host rock formation or group	Age of host rock	Associated igneous rock type	Ore control	Production	Comments
CHAVES COUNTY									
Stoltz test hole*	Sandstone U	(U)	Continental sediments	Dockum	TRI	---	---	No	Radioactivity in shallow zones.
Beavers pit*	---	(Sand and gravel)	---	---	---	---	---	Yes	Intermittent production.
Chaves County pit*	---	(Sand, gravel, crushed rock)	---	---	---	---	---	Yes	Active mine and mill.
Chaves County Road Dept. pit*	---	(Rock, gravel)	---	---	---	---	---	Yes	Active surface operation.
City of Roswell pit*	---	(Rock, gravel, soil)	---	---	---	---	---	Yes	Intermittent production.
Roswell pit*	---	(Gravel)	---	---	---	---	---	Yes	Intermittent production.
Roswell Ready Mix pit*	---	(Sand, gravel)	---	---	---	---	---	Yes	Inactive.
Walnut Draw gypsum deposit*	Bedded gypsum	GPSM	Marine sediments	San Andres	PERM	---	Chemical precipitation	---	About 60 percent of the deposit is outside the study area.
CURRY COUNTY									
Grier pit*	---	(Caliche)	Continental sediments	---	---	---	---	Yes	Intermittent surface production.
South pit*	---	(Caliche)	Continental sediments	---	---	---	---	Yes	Intermittent surface production.
DeBACA COUNTY									
Cebolo Creek occurrence*	Sandstone U	(U)	Shale, siltstone	Chinle, lower (?)	TRI	---	---	---	Radioactivity in shallow zones.
Sanders pit*	---	(Sand and gravel)	---	---	---	---	---	Yes	Active surface operation.
Steele pit*	---	(Gravel)	---	---	---	---	---	Yes	Intermittent surface operation.
Pecos River Valley gypsum deposits*	Bedded gypsum	GPSM	Marine sediments	Artesia	PERM	---	Chemical precipitation	Yes	Deposit stretches from Arroyo Yeso to Carlsbad.
Sumner Lake gypsum deposit*	Bedded gypsum	GPSM	Marine sediments	Artesia	PERM	---	Chemical precipitation	---	On the southern end of Sumner Lake.
GUADALUPE COUNTY									
Pastura district									
American Uranium prospect*	Sandstone U	(U)	Sandstone	Santa Rosa	TRI	---	Favorable beds	No	.002% U3O8.
Pintada mine	Sediment-hosted Cu	CLCC, MLCT	Sandstone, shale	Grayburg and Queen	PERM	---	Favorable beds	Yes	Production: 1,597 st at 0.67% Cu, .044 oz/st Ag in 1916-17,1969.
Porcupine prospect*	Sediment-hosted Cu	(Cu, Ag, U, Pb)	Sandstone	Santa Rosa	TRI	---	Favorable beds	No	Sandy claystone is radioactive.
Stauber mine	Sediment-hosted Cu	CLCC, MLCT, AZRT	Sandstone	Santa Rosa	TRI		Favorable beds	Yes	Production: 264,357 st at 2.56% Cu, .03 oz/st Ag, and .0087% Pb in 1915-57.
Other deposits									
Branch Ranch prospect*	Sandstone U	(U, V)	Shale, sandstone	Chinle	TRI	---	Carbonized wood fragments	No	U is associated with carbonized wood.
Neafus Ranch prospect*	Sandstone U	(U, V)	Shale, sandstone	Chinle	TRI	---	---	No	Carbonaceous layers a few inches thick.
Santa Rosa railroad cut*	Sandstone U	(U)	Shale sandstone	Chinle	TRI	---	Carbonaceous material	No	Radioactivity in a claystone lens 3 ft thick and 400 ft long.
Santa Rosa tar sands*	Sandstone U	(U, tar sand)	Sandstone	Santa Rosa	TRI	---	Carbonaceous material	Yes	Production: 153,000 st of tar sand in 1930-39.
Santa Rosa gypsum deposit*	Bedded gypsum	GPSM	Marine sediments	Artesia	PERM	---	Chemical precipitation	No	Located south and west of Santa Rosa.
Vaughn region gypsum deposit*	Bedded gypsum	GPSM	Marine sediments	San Andres	PERM	---	Chemical precipitation	No	Deposit covers a 22 by 11 mi teardrop shaped area.

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COUNTY District Site (*= not in MRDS)	USGS deposit model	Minerals (commodities) reported	Host rock type	Host rock formation or group	Age of host rock	Associated igneous rock type	Ore control	Production	Comments
LINCOLN COUNTY									
Capitan Mountains district									
Arabela Mines Mn mine*	Replacement Mn	PSLM, CLAY (KLNT)	Limestone	San Andres	PERM	Alaskite	Intrusive contact	Yes	Post 1959 production.
Barlejon #2 prospect*	Th-REE veins		Alaskite	Capitan Mountains alaskite	TERT	Alaskite	Breccia zone	No	.03-.39% U3O8.
Barry prospects*	Th-REE veins	ALNT, QRTZ, FLRT, TRML, Fe-oxides	Alaskite	Capitan alaskite	TERT	Alaskite	Fractures or shears	No	1.7% Th in biased samples.
Bear Canyon Group*	Th-REE veins	(U)	Alaskite	Capitan Mountains alaskite	TERT	Alaskite	Fractures or shears	Yes	Production: 3 st at .02% U3O8 in 1948-70?
Capitan iron deposit	Fe skarn	MGNT, HMTT, GTHT, EPDT, PLGP	Limestone	San Andres	PERM	Aplite and alaskite	Karst topography, sinkhole	Yes	Resources: 3,000,000 st at 45.6% Fe in 1949.
Capitan Uranium Co. prospect*	Th-REE veins	- - -	Alaskite	Capitan Mountains alaskite	TERT	Alaskite	Fractures	No	.06-.18% U3O8, .35-.100% ThO2.
Copeland Canyon prospect*	Th-REE veins	MGNT	Alaskite	Capitan Mountains alaskite	TERT	Alaskite	Fractures	No	Twice background radioactivity.
Drunzer prospect*	Th-REE veins	ALNT, QRTZ, FLRT, TRML, Fe-oxides	Alaskite	Capitan Mountains alaskite	TERT	Alaskite	Fractures or shears	No	3-inch breccia vein exposed in trench.
El Tigré prospect*	Th-REE veins	ALNT?	Alaskite	Capitan Mountains alaskite	TERT	Alaskite	Fractures or shears	No	Radioactive vein in alaskite.
Fuzzy Nut 1-18 claims*	Th-REE veins	ALNT?	Alaskite	Capitan Mountains alaskite	TERT	Alaskite	Fractures	No	Radioactive vein in alaskite.
Hopeful claims*	Th-REE veins	FLRT	Alaskite	Capitan Mountains alaskite	TERT	Alaskite	Breccia vein	No	Radioactive breccia vein in alaskite.
King prospect*	Th-REE veins	ALNT, QRTZ, FLRT, TRML, Fe-oxides	Alaskite	Capitan Mountains alaskite	TERT	Alaskite	Fractures or shears	No	Several small radioactive anomalies noted.
Koprian Springs*	Th-REE veins		Alaskite	Capitan Mountains alaskite	TERT	Alaskite	Fractures or shears	No	.002-.051% U3O8, .34% ThO2.
Major prospect*	Fe skarn	MGNT, CLRT, ACNL, TMLT	Limestone	San Andres	PERM	Alaskite	Fault zone	No	Resources: 20,000 Fe material in 1944 for Major, Red Wing, Ajax, and Oslo.
McCory prospects*	Th-REE veins	ALNT, QRTZ, FLRT, TRML, Fe-oxides	Alaskite	Capitan Mountains alaskite	TERT	Alaskite	Fractures or shears	No	Up to 64 times background radioactivity.
Mina Tiro Estrella*	Th-REE veins Th-REE veins	ALNT, TTNT	Alaskite	Capitan Mountains alaskite	TERT	Alaskite	Fractures or shears	No	3-4 times background radioactivity.
Monzo group*	Th-REE veins	ALNT	Alaskite	Capitan Mountains alaskite	TERT	Alaskite	Fractures, brecciation	No	.003-.01% U3O8, 3.57% ThO2.
Pine Lodge deposits*	Th-REE veins	ALNT	Alaskite	Capitan Mountains alaskite	TERT	Alaskite	Fractures, brecciation	No	Up to 20 times background radioactivity.
San Pedro-Link-Nob Hill*	Th-REE veins	ALNT	Alaskite	Capitan Mountains	TERT	Alaskite	Fractures	No	Twice background radioactivity.
Silvertone claim*	Th-REE veins	- - -	- - -	alaskite	TERT	- - -	Brecciation	No	.01% U3O8, .04% V2O5.
Tide iron deposit*	Fe skarn	MGNT, HMTT	Alaskite	Capitan Mountains alaskite	TERT	Alaskite	E-W trending fault zone	No	Early development did not determine the size of the deposit.
Wee-Three 1-3*	Th-REE veins	ALNT	Alaskite	Capitan Mountains alaskite	TERT	Alaskite	Fractures	No	.001-.002% U3O8, .17% ThO2
Whettige deposits*	Fe skarn	MGNT	Limestone	San Andres	PERM	- - -	Favorable host rock	No	Two small underdeveloped prospects.
Oscura (Estey) district									
Estey City copper mine	Sediment-hosted Cu	MLCT, AZRT, CLCC SLVR	Arkose	Abo	PERM	- - -	Carbonaceous debris	Yes	Only a few carloads of ore were ever shipped.
Copper prospect 1*	Polymetallic veins	AZRT, MLCT	Granite	- - -	PREC	Granite	Faulting	No	Mineralized fault in granite.
Copper prospect 2*	Polymetallic veins	AZRT, MLCT	Sandstone	Bliss	CRD	Granite	Faulting	No	Mineralized fault in sandstone.
Copper prospect 3*	Polymetallic veins	AZRT, MLCT	Dolomite	El Paso	CRD	Granite	Faulting	No	Mineralized fault in dolomite.

OF 92-0261

COUNTY
District

Site (* = not in MRDS)	USGS deposit model	Minerals (commodities) reported	Host rock type	Host rock formation or group	Age of host rock	Associated igneous rock type	Ore control	Production	Comments
Gallinas district									
All American mine	Polymetallic veins	FLRT, BRIT, BSNS, Cu oxides	Quartzitic sandstone	Yeso	PERM	QRTZ monzonite porphyry; syenite porphyry sill	Brecciated fault	Yes	Production: 129 st FLRT ore in 1949-51.
American Iron mine	Fe skarn	MGNT, HMTT	Limestone	Yeso	PERM	Porphyritic trachyte, and syenite	Limestone xenolith	Yes	Production: 3,944 st with 55.7% Fe in 1942-43.
Big Ben (Sky High) prospect	Polymetallic veins	FLRT, BRIT	Quartzitic sandstone	Yeso	PERM	QRTZ monzonite porphyry; syenite porphyry sill	Brecciated fault	No	Deposits comprised of irregular pods and lenses.
Bottleneck prospect	Polymetallic veins	FLRT, BRIT	Sandstone, limestone	Yeso	PERM	Syenite porphyry; QRTZ monzonite	Breccated fault	No	Composite sample contained 47.94% CaF_2, 21.12% $BaSO_4$, and 25.2% SiO_2.
Buckhorn prospect	Polymetallic veins	Cu minerals, FLRT, BRIT	Sandstone	Yeso	PERM	QRTZ monzonite porphyry; syenite porphyry sill	Brecciated fault	No	Small vein exposed at surface.
Congress prospect	Polymetallic veins	FLRT, BRIT	Sandstone, limestone	Yeso	PERM		Brecciated fault	No	FLRT in irregular pockets along a brecciated fault.
Conqueror mine	Polymetallic veins	FLRT, GLEN, BRIT, CRST, ANGS	Sandstone	Yeso	PERM	QRTZ monzonite porphyry; syenite porphyry sill	Brecciated fault	Yes	Production: 300 st of F, Pb, Cu ore in 1956.
Conqueror No. 4 and Hilltop prospect	Polymetallic veins	FLRT, BRIT	Quartzitic sandstone	Yeso	PERM	QRTZ monzonite porphyry; syenite porphyry sill	Brecciated fault		Composite sample contained 57.4% CaF_2, 21.2% $BaSO_4$, and 20.8% SiO_2.
Deadwood prospect	Polymetallic veins	Cu minerals, FLRT, BRIT	Syenite porphyry	- - -	TERT	QRTZ monzonite porphyry; syenite porphyry sill	Brecciated fault	Yes	A western extension of Red Cloud deposit.
Eagle Nest prospect	Polymetallic veins	FLRT, BRIT, BSNS	Sandstone	Yeso	PERM	QRTZ monzonite porphyry; syenite porphyry sill	Brecciated fault	No	Ore is a dense aggregate of FLRT, BRIT, QRTZ, and CLCT.
Eureka prospect	Polymetallic veins	FLRT, BRIT, CHRY, GLEN	Sandstone, limestone	Yeso	PERM	QRTZ monzonite porphyry; syenite porphyry sill	Brecciated fault	No	Composite sample contained 43.8% CaF_2, 25.5% $BaSO_4$, 10.8% SiO_2, and 5.5% CaO
Gallinas Iron mine	Fe skarn	MGNT, HMTT	Limestone	Yeso	PERM	Porphyritic trachyte and syenite	Favorable host rock	Yes	Production: 6,410 st ore with 48.7% Fe in 1942.
Helen S prospect	Polymetallic veins	FLRT	Sandstone	Yeso	PERM	QRTZ monzonite porphyry; syenite porphyry sill	Brecciated fault	No	Inactive undeveloped occurrence.
Hoosier Girl prospect	Polymetallic veins	FLRT, BRIT, BSNS	Sandstone	Yeso	PERM	QRTZ monzonite porphyry; syenite porphyry sill	Brecciated faults	No	Composite sample contained 54.2% CaF_2, 15.0% $BaSO_4$, 8.2 SiO_2, and 4.5% CaO.
Iron Box prospect*	Fe skarn	MGNT	Limestone and sandston	Yeso(?)	PERM	Monzonite porphyry sill	Intrusive contact	No	Only 4-6 ft thick, low grade.
Last Chance prospect	Polymetallic veins	FLRT, BSNS, BRIT	Sandstone	Yeso	PERM	QRTZ monzonite porphyry; syenite porphyry sill	Brecciated fault	No	FLRT vein in PERM sandstone.
Old Hickory mine	Polymetallic veins	FLRT, BRIT, GLEN, MLCT, BSNS, AZRT	Quartzitic sandstone	Yeso	PERM	QRTZ monzonite porphyry; syenite porphyry sill	Brecciated fault	Yes	Mineralization is in a breccia, vein adjacent a trachyte dike.
Pride 2 and E and M 13*	Polymetallic veins	BSNS	Limestone and sandston	Yeso	PERM	- - -	- - -	No	BSNS veins in Yeso Fm.
Rare Metals prospect*	Fe skarn	MGNT, HMTT, GLEN, FLRT, skarn minerals	Limestone	Yeso	PERM	Syenite porphyry	Intrusive contact	No	Contains a few tons of thousand st at 40-50% Fe.
Red Cloud mine	Polymetallic veins	FLRT, BSNS, BRIT, GLEN, SPLR	Quartzitic sandstone and siltstone	Yeso	PERM	QRTZ monzonite porphyry; syenite porphyry sill	Brecciated fault	Yes	Production: 1,000 st of FLRT cons and 60 st REE cons in the early 1950's.
Summit prospect	Polymetallic veins	FLRT, BRIT	Quartzitic sandstone	Yeso	PERM	QRTZ monzonite porphyry; syenite porphyry sill	Brecciated fault	No	Mineralization is in a 4 ft wide brecciated fault zone.

COUNTY District Site (* = not in MRDS)	USGS deposit model	Minerals (commodities) reported	Host rock type	Host rock formation or group	Age of host rock	Associated igneous rock type	Ore control	Production	Comments
Jicarilla district									
Apex claims*	Alkaline associated Au-Ag-Te	GOLD	---	---	---	---	---	---	About .25 mi SE of Spring mine.
Black Gold mine	Alkaline associated Au-Ag-Te	GOLD, MGNT, PYRT	Granodiorite and monzonite porphyry	---	---	Granodiorite and monzonite porphyry	---	No	About 700 ft of workings show sparse mineralization.
Hoecradle deposit*	Fe skarn	MGNT	---	---	---	---	---	Yes	Production: 590 st with about 60.1% Fe in 1942-43.
Jack iron mines	Fe skarn	MGNT, HMTT	Limestone	San Andres	PERM	Monzonite porphyry	Favorable host rock	Yes	Production: 3,736 st with 55-65% Fe; 1918-21 and 1943.
Jicarilla placers	Placer	GOLD, ELCM, SLVR	Fanglomerate, alluvium	Ogallala (?)	TERT	Granodiorite	Hydrodynamic sorting	Yes	Production: 1,814.32 oz Au and 143 oz Ag in 1933-42.
Lane deposit*	Fe skarn	MGNT	Limestone	San Andres	PERM	Monzonite dike	Favorable host rock	Yes	Production: 70 st with 60.0% Fe in 1943.
Lobner mine*	Fe skarn	MGNT	Limestone	San Andres	PERM	Monzonite	Favorable host rock	No	An undeveloped prospect.
Lucky Strike area*	Alkaline associated Au-Ag-Te	GOLD	Limestone	San Andres	PERM	Monzonite	Intrusive contact	Yes	Production: 82.62 oz Au in 1933.
Magnolite mine	Fe skarn	MGNT, HMTT, KLNT	Monzonite, and limestor	San Andres(?)	PERM	Monzonite	Limestone inclusion in monzonite	Yes	Production: 2,514 st at 57.2% Fe in 1942-43.
Norma deposit*	Fe skarn	MGNT	Limestone	San Andres	PERM	Monzonite sill	Intrusive contact	Yes	Production: 75 st Fe ore in 1942.
Sally mine	Alkaline associated Au-Ag-Te	GOLD, Au-PYRT	Monzonite porphyry	---	TERT	Monzonite porphyry	Intrusive contact	Yes	Deposit consists of numerous QRTZ-PYRT veinlets.
Spring (Gold Stain) mine*	Alkaline associated Au-Ag-Te	GOLD, PYRT	Monzonite sill	---	TERT	Monzonite sill	---	No	About .25 mi NW of Apex mine
Zuni mines*	Fe skarn	MGNT	Limestone	San Andres	PERM	Monzonite porphyry	Intrusive contact	Yes	Production: 629 st Fe ore in1943.
Nogal district									
American mine	Polymetallic veins	GOLD, SLVR, SPLR, GLEN	Monzonite and andesite	Sierra Blanca	TERT	Monzonite	Fault-fracture	Yes	Best mineralization was at intersection of main and minor veins.
Bon group moly prospect*	Porphyry Mo	MLDB	Syenite	Three Rivers	TERT	Syenite		No	---
Bonita claims*	Polymetallic veins	QRTZ, SLPD, CLCP	Andesite	Sierra Blanca	TERT	Andesite	Fault-fracture	No	Up to 20 times background radioactivity.
Commercial mine	Polymetallic veins	CLCP, BRNT, GLEN	Andesite	Sierra Blanca	TERT	Andesite	Fault-fracture	Yes	Deposit is intensely altered and sheared.
Crow mine	Polymetallic veins	GOLD, SLVR, SPLR, GLEN	Andesite	Sierra Blanca	TERT	Andesite and monzonite	Fault-fracture	Yes	Grades .03 Au oz/st, 64.64 oz/st Ag,1.13% Pb,.1% Cu, 3.4% Zn in 1962.
Helen Rae mine	Polymetallic veins	CLCP, GLEN, SPLR	Monzonite and andesite	Sierra Blanca	TERT	Monzonite and andesite	Fault-fracture	Yes	Produced from the same vein as the American mine.
Homestake group	Polymetallic veins	GLEN, SLVR, GOLD	Andesite and diorite	Sierra Blanca	TERT	Andesite and diorite porphyry dikes	Fault-fracture	Yes	Occurs in a brecciated zone adjacent to E-trending dikes.
Maud mine	Polymetallic veins	GOLD, ELCM, MLBD	Andesite	Sierra Blanca	TERT	Andesite	Fault-fracture	Yes	Composite sample contained 7.10%. Pb, .39% Zn, 0.17% Mo, .32 oz/st Au, and 1.28 oz/st Ag.
Parsons mine	Polymetallic veins	GLEN, Ag-GLEN, SPLR	Monzonite	Sierra Blanca	TERT	Monzonite	Breccia	Yes	70,000 to 85,000 st of Au material material were mined from 1900-20's.
Renowned OK mine	Polymetallic veins	MLBD, CLCC, BRNT	Andesite	Sierra Blanca	TERT	Andesite and monzonite	Fault-fracture	Yes	Produced about 25 st of Pb-Ag ore in 1957.
Rialto moly prospect	Porphyry Mo	SLVR, GOLD, GLEN	Monzonite	Sierra Blanca	TERT	Monzonite	Breccia	No	Resources are about 27,000,000 mt of Mo ore.

COUNTY District Site (*= not in MRDS)	USGS deposit model	Minerals (commodities) reported	Host rock type	Host rock formation or group	Age of host rock	Associated igneous rock type	Ore control	Production	Comments
Richardson claims*	Polymetallic veins	- - -	Andesite	Sierra Blanca	TERT	Andesite	Fault-fracture	No	A radioactive vein in volcanic rocks
Silver contact claims	Polymetallic veins	GOLD, SLVR, GLEN	Andesite	Sierra Blanca	TERT	Andesite	Fault-fracture	Yes	Being prospected as late as 1982.
Spur adit*	Polymetallic veins	- - -	Andesite	Sierra Blanca	TERT	Andesite	Fault-fracture	No	3 times background radioactivity.
Surprise prospect	Polymetallic veins	CLCC, MLCT, AZRT	Andesite	Sierra Blanca	TERT	Andesite and syenite	Fault-fracture	No	The principal vein is 5,000 ft long.
Tortolita Canyon vein*	Polymetallic veins	QRTZ, PYRT	- - -	Sierra Blanca	TERT	Radioactive vein in andesi	Fault-fracture	No	Twice background radioactivity.
Turkey group	Polymetallic veins	GOLD, SLVR, CLCC	Andesite	Sierra Blanca	TERT	Andesite and monzonite	Fault-fracture	Yes	Samples contained .02-.08 oz/st Au and .08-.56 oz/st Ag.
Vera Cruz mine	Alkaline associated Au-Ag-Te	GOLD, ELCM	Sandstone and shale	Mesaverde	CRET	Alaskite	Breccia	Yes	Avg grade was about .1 oz/st Au.
Schelerville subdistrict									
Idaho mine*	Polymetallic veins	SLPD, Cu-SLPD	Andesite flows and breccias	Sierra Blanca	TERT	Andesite and basaltic andesite flows	Syenite dike	No	160 st of Cu-Ag ore were shipped.
Junction mine*	Polymetallic veins	Fe, Pb and Cu SLPD, BRIT	Andesite flows and breccias	Sierra Blanca	TERT	Andesite and basaltic andesite flows	E-W dikes	No	Property developed 1934-35, production unknown.
Tecolote Iron district									
Betty prospect*	Fe skarn	MGNT	Limestone	Yeso	PERM	Monzonite	Intrusive contact	No	Very small deposit.
Bond prospect*	Fe skarn	MGNT	Limestone and shale	Yeso	PERM	Monzonite	Intrusive contact	No	MGNT zones 3-30 ft thick.
Consolidated prospect*	Fe skarn	MGNT, HMTT	Sediments	Yeso	PERM	Monzonite dike	Intrusive contact	Yes	Production: 50 st of Fe ore in 1942.
Elda iron mine	Fe skarn	MGNT, HMTT	Limestone	Yeso	PERM	Monzonite	Replacement	Yes	Production: 14,343 st ore with 54.5% Fe in 1915-19.
Iron City prospect*	Fe skarn	MGNT, skarn-type silicates	Limestone	Yeso	PERM	Monzonite	Intrusive contact	No	Deposit is 200 ft long and 2-6 ft thick.
White Oaks district									
Ferro mine*	Fe skarn	MGNT, HMTT, PYRT	Limestone	San Andres	PERM	Lone Mountain syenite	Intrusive contact	Yes	Production: 4,116 st of Fe ore in 1952-53.
Goodnight and Black Knight*	Fe skarn	MGNT	Limestone	San Andres	PERM	Lone Mountain syenite	Intrusive contact	No	Black Knight assayed 43.4% Fe, Good Night 45.1% Fe.
House mines (Prince)*	Fe skarn	MGNT, metatorbernite, GPSM	Limestone	Yeso	PERM	Lone Mountain syenite	Intrusive contact	No	Contains very little minable material.
Lady Godiva mine*	Alkaline associated Au-Ag-Te	GOLD	Monzonite(?)	- - -	TERT	Monzonite(?)	- - -	Yes	Connected to Rita mine at 425 ft level.
Little Mack and Henry Clay mines	Alkaline associated Au-Ag-Te	GOLD, Au-PYRT, ELCM, HBNR	Monzonite	- - -	TERT	Monzonite	Fault-fracture	Yes	Production: 2,579 oz Au in 1879-1951.
Lone Mountain prospect	Polymetallic veins	FLRT	Limestone	Yeso	PERM	Quartz monzonite porphyry	Brecciated fault	No	Chip sample contained 35.5 percent CaF2.
North and South Homestake mines	Alkaline associated Au-Ag-Te	GOLD, Au-PYRT, ELCM, HBNR	Shale and monzonite	Mancos	CRET	Monzonite	Fault-fracture	Yes	Production: 50,039 oz Au in 1879-1951.
Old Abe mine	Alkaline associated Au-Ag-Te	GOLD, Au-PYRT, ELCM, HBNR	Shale and monzonite	Mancos	CRET	Monzonite	Fault-fracture	Yes	Production: 45,745 oz Au in 1879-1951.
Rita mine*	Alkaline associated Au-Ag-Te	GOLD	Monzonite	- - -	TERT	Monzonite	- - -	- - -	Hoisted ore after Homestake's shaft had burned.
Section 2 occurrence*	Orthomagmatic	(U)	Shale	Mancos	CRET	Rhyolite dike	- - -	No	.01% U3O8.
Smuggler mine*	Alkaline associated Au-Ag-Te	GOLD	Monzonite	- - -	TERT	Monzonite	- - -	Yes	Production: 279 oz Au in 1935.
White Oaks Draw and Baxter Gulch placers*	Placer	GOLD	Stream gravels	- - -	TERT	Monzonite	Hydrodynamic sorting	Yes	From1933-41 some placer mining was done.
Yellow Jacket mine	Fe skarn	HMTT, MGNT, LMON, PRLS	Limestone	San Andres	PERM	Monzonite	Replacement of host	Yes	Production: 20,008 st of 58.2% Fe ore 1913-15, 1942.

COUNTY District Site (*= not in MRDS)	USGS deposit model	Minerals (commodities) reported	Host rock type	Host rock formation or group	Age of host rock	Associated igneous rock type	Ore control	Production	Comments
Other deposits									
Fox lode prospect*	Epigenetic barite veins	BRIT, Cu oxides (no FLRT)	Limestone	Yeso(?)	PERM(?)	---	Fault-fracture	No	Sample contained 89.7 percent BaSO4, 2.4 percent CaCO3, 4.2 specific gravity.
Hall (Macho) deposit*	Fe skarn	MGNT	Limestone	San Andres	PERM	Monzonite	Replacement of host	Yes	Produced several thousand tons of Fe ore in 1951-53.
Valley of Fire road cut*	---	---	Shale	Mancos	CRET	Syenite dike	---	No	24 times background radioactivity, 207 ppm U.
Bonnell sand and gravel pit*	---	(Sand and gravel)	Sediments	---	---	---	---	Yes	Active surface operation.
Lietzman pit*	---	(Gravel)	---	---	---	---	---	Yes	Intermittent producer.
Mac rock quarry*	---	(Stone, railroad ballast)	---	---	---	---	---	Yes	Active surface operation.
Pit BP2*	---	(Gravel)	---	---	---	---	---	---	Inactive surface mine.
Tom's gravel pit*	---	(Gravel, base coarse)	---	---	---	---	---	Yes	Active surface operation.
Ancho gypsum deposits	Bedded gypsum	GPSM	Marine sediments	San Andres	PERM	Monzonite porphyry	---	Yes	Quarried in early 1900's.
Cowboy Mesa gypsum deposit*	Bedded gypsum	GPSM	Marine sediments	San Andres, Yeso	PERM	---	---	---	Thin GPSM beds are poorly exposed.
Hasparos Canyon gypsum deposit*	Bedded gypsum	GPSM	Marine sediments	San Andres, Yeso	PERM	---	---	---	Thin GPSM beds are poorly exposed.
Mescalero gypsum deposit*	Bedded gypsum	GPSM	Marine sediments	Yeso	PERM	---	---	---	Most of deposit is outside the study area.
Phillips Hills gypsum deposit*	Bedded gypsum	GPSM	Marine sediments	Yeso, San Andres	PERM	---	---	---	Reports of white GPSM 50-100 ft thick.
Rio Hondo and Rio Ruidoso Valley gypsum deposit*	Bedded gypsum	GPSM	Marine sediments	San Andres, Yeso	PERM	---	---	---	Large production would require underground mining.
Wagon Canyon gypsum deposit*	Bedded gypsum	GPSM	Marine sediments	San Andres, Yeso	PERM	---	---	---	Nearby sample was 98.6 percent GPSM, 1 percent SiO2.
QUAY COUNTY									
Beasley Brothers 4 prospect*	Sandstone U	(U)	Sandstone	Chinle	TRI	---	---	No	---
Bel Aro mine*	Sandstone U	(U)	Sediments	Morrison, basal(?)	JUR	---	Silicified wood	Yes	Production: 30 st of silicified uraniferous wood in the 1950's.
Breen prospect*	Sandstone U	(U)	Sandstone	Morrison, middle	JUR	---	Carbonaceous material	No	LMON and organic(?) material in a 1 ft thick roll.
Eight point claims*	Sandstone U	(U)	Sediments	Morrison, basal(?)	JUR	---	Silicified or carbonaceous wood	No	---
File prospects*	Sandstone U	(U)	Claystone	Redonda, lower part	TRI	---	---	No	8-inch radioactive claystone.
Gilstrip and Trusdel property*	Sandstone U	(U)	Sandstone	Chinle, middle	TRI	---	Carbonized wood fragments	No	Sandstone and limestone-pebble zones contain U.
Good Luck group*	Sandstone U	(U, V)	Sandstone	Chinle, middle	TRI	---	Carbonized wood fragments	Yes	Production: 24 st of ore with 0.10% U3O8 and 0.12% V in 1955-57.
Ima prospect*	Sandstone U	(U)	Sediments	Chinle	TRI	---	---	No	Small radioactive anomaly.
Little Rattler mine*	Sandstone U	(U, Cu, Ag)	Sediments	Chinle, middle	TRI	---	---	Yes	Production: 59 st of ore with .03% U3O8 and .04% V in 1955-56.
Logan prospects*	Sandstone U	(Cu, U, Ag, Au)	Sediments	Chinle	TRI	---	---	No	Large area of radioactive anomalies.

COUNTY District Site (* = not in MRDS)	USGS deposit model	Minerals (commodities) reported	Host rock type	Host rock formation or group	Age of host rock	Associated igneous rock type	Ore control	Production	Comments
Lucky Find 15 prospect*	Sandstone U	(U)	Sediments	Chinle, middle(?)	TRI	---	---	No	---
Red Peak area prospects*	Sandstone U	(U)	Shale	Chinle (Cuervo)	TRI	---	---	No	Uranium is in a thick red shale.
Richardson Ranch prospects*	Sandstone U	(U)	Sediments	Morrison, middle	JUR	---	Silicified or carbonaceous wood	No	Associated with silcified wood, bone, or carbonaceous wood.
San Jon area*	Sandstone U	(U, Cu, Ag)	Sediments	Chinle	TRI	---	---	---	Large area of radioactive anomalies.
Smith Ranch prospect*	Sandstone U	(U)	Sediments	Chinle, middle	TRI	---	---	No	---
Strawn prospect*	Sandstone U	(U)	Sediments	Morrison, middle	JUR	---	---	No	Associated with silicified wood or bone.
Troutman Ranch*	Sandstone U	(U)	Sandstone	Chinle, middle	TRI	---	---	No	.06% U3O8 in sample.
Wallace Ranch prospect*	Sandstone U	(U)	Sediments	Chinle, middle	TRI	---	---	Yes	---
Ute Creek copper deposits	Sediment-hosted Cu	MLCT, AZRT, CLCC	Shaly sandstone	Dockum	TRI	---	---	Yes	Several low-grade deposits are in the area.
Bruhn gravel pit*	---	(Sand and gravel)	Sediments	---	---	---	---	Yes	Active surface operation.
Caprock pit*	---	(Caliche)	Sediments	---	---	---	---	Yes	Intermittent surface mining.
Duke pit*	---	(Caliche)	Sediments	---	---	---	---	Yes	Intermittent surface mining.
Ragland pit*	---	(Caliche)	Sediments	---	---	---	---	Yes	Intermittent surface mining.
ROOSEVELT COUNTY									
Nunn pit*	---	(Caliche)	Sediments	---	---	---	---	Yes	Intermittent surface mining.
Sadler pit*	---	(Gravel)	Sediments	---	---	---	---	Yes	Intermittent surface mining.
Valley Tolar pit No. 1*	---	(Crushed rock, sand, gravel)	Sediments	---	---	---	---	Yes	Active surface operation.

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ADDENDUM TO MAP A EXPLANATION OPEN-FILE 92-0261:

Qab = Qal
TKcm = TKc
Tid and Tvf = Tv
Ku = KT_ru and Kmmd
Kt = KT_ru
J = Jme
T_r = $T_r$cs
Pag = Pa
M_z = M_zu
Psf - Psg
Py = Pu
M-Є = MЄu
pЄ = pЄu

Note: A digital version used to prepare this geologic map (modified from New Mexico Geological Society, 1982) in either color or pattern has been released as an ASCII file (LaRock and Moore, 1992).

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