UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

LONG-TERM REGULATORY COMPLIANCE

GEOLOGY AND HYDROLOGY OF THE CARLSBAD POTASH AREA, EDDY AND LEA COUNTIES, NEW MEXICO

By

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Open-file report
1972

Prepared under
Agreement No. AT(40-1)-4339
for the
Division of Waste Management and Training
U.S. Atomic Energy Commission

This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards or nomenclature.

CONTENTS

CONTENTS--Continued

CONTENTS--Continued

ILLUSTRATIONS

TABLES

GEOLOGY AND HYDROLOGY OF THE CARLSBAD POTASH AREA, EDDY AND LEA COUNTIES, NEW MEXICO

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ABSTRACT

The potash mines of southeastern New Mexico are in a sparsely populated area 15-30 miles east of Carlsbad. Topographic relief is low, surface drainage poor, and collapse features common. The climate is semiarid.

Sedimentary rocks attain thicknesses of more than 20,000 feet and range in age from Ordovician to Quaternary. The area includes the northern end of the Delaware basin and the largely buried Capitan Reef. The basin contains as much as 13,000 feet of Permian strata. The oldest exposed rocks are of Late Permian age, but drilling has provided much data on the buried older rocks. The principal structures are broad gentle features related to late Paleozoic sedimentation: the northern Delaware basin, a shelf north and west of the basin, and a central basin platform to the east. These structures were tilted eastward before Pliocene time, have been inactive since, and now show a general eastward dip of less than 2°.

The salt deposits are in the Late Permian Ochoan Series composed of a thick salt-bearing evaporite lower part (Castile, Salado, and Rustler Formations) and a thin non-salt-bearing upper part (Dewey Redbeds).

The Castile Formation consists largely of interlaminated gray anhydrite and brownish-gray limestone, but includes much rock salt. It is about 1,500-1,600 feet thick along the southern edge of the potash area; it thins northward to about 1,000 feet near the margin of the Delaware basin and tongues out in the southernmost parts of the northwest shelf. All the salt is concentrated in a thick middle member which lies 200-300 feet above the base of the formation.

The Salado Formation, the main salt-bearing unit of the potash area, ranges in thickness from about 1,900 feet in the south to about 1,000 feet in the north. The formation is characterized by thick persistent units of rock salt alternating with thinner units of anhydrite and polyhalite. Thin seams of claystone underlie the anhydrite and

polyhalite unit, and there are a few beds of sandstone and siltstone at large intervals. The Salado Formation is divided into three informal units: a lower and an upper salt member, generally free of sylvite and other potassium and magnesium evaporite minerals; and the McNutt potash zone, generally rich in these minerals.

The Rustler Formation mostly anhydrite and rock salt, thins from 300 to 400 feet in the southern part of the area to about 200-250 feet in the northern part. Some dolomite is present in the upper and lower parts of the formation, and thin to thick units of sandstone and shale are interbedded at long to short intervals.

The Dewey Lake Redbeds at the top of the Ochoan Series consist of reddish-brown siltstone and fine-grained sandstone. The formation is 250-550 feet thick in the potash area.

Three main hydrologic units control the ground-water hydrology of the Carlsbad potash mining area: the Pecos River, the water-bearing strata overlying the Salado Formation, and the Capitan Limestone and other water-bearing strata underlying the Salado. The distribution and development of large dissolution features, particularly in the Nash Draw and Clayton Basin areas, exert a major effect on the occurrence and movement of the ground water. The Pecos River receives nearly all of the ground-water outflow from the area. Most of that outflow reaches the Pecos near Malaga Bend.

The main water-yielding units overlying the Salado Formation are the basal solution breccia zone and the Culebra Dolomite Member of the Rustler Formation, the Santa Rosa Sandstone, and the alluvium. The basal solution breccia zone is the hydrologic unit most significant in the solution of halite from the upper part of the Salado Formation. The easternmost extent of evaporite solution in the potash mining area is roughly at the common boundary between Ranges 30 and 31 E. The formations above the Salado Formation seem to be connected hydrologically and can be considered a single multiple aquifer system. Solution activity and associated collapse, subsidence, and fracturing have increased the overall permeability of the rocks and the interformational movement of water in the aquifer system.

Ground water in the formations above the Salado moves generally southward and southwestward across the potash mining area toward the Pecos River. Although the total amount of ground water discharging to the Pecos River is not known, it has been estimated that 200 gallons per minute enter the river from the basal solution breccia zone.

The potentiometric and water-table contours outline a series of ground-water ridges and troughs which are imposed on the regional southward to southwestward pattern of ground-water movement. A large southwestward-plunging ground-water trough extends from Malaga Bend northeastward roughly through Nash Draw to beyond the mining area in the vicinity of Laguna Plata. Another much smaller trough is east and southeast of the Project Gnome site.

The Salado Formation has an intergranular porosity and permeability that ranges from low to virtually none. Locally, fractures and solution openings impart a spotty formational permeability. In the potash mining area, the Salado Formation is dry except for water in the leached zone at the top of the formation and small pockets of water or water and gas encountered occasionally during mining.

The Cambrian to Permian sedimentary rocks underlying the Salado Formation contain water of brine composition and are under high artesian pressure. These rocks are not exposed in the potash mining area but lie deeply buried throughout much of southeastern New Mexico and western Texas. In the potash mining area the elevations of the potentiometric surfaces of different zones of these rocks range from a few feet to a few hundred feet above or below the land surface.

INTRODUCTION

The U.S. Geological Survey, on behalf of the Atomic Energy Commission, has summarized the available geologic and hydrologic information on the Carlsbad, N. Mex., potash area. The purpose of this summary is to furnish the Atomic Energy Commission with data that would be useful to them in their evaluation of various geologic formations for the disposal of radioactive wastes. The project was started on April 1, 1972, and completed on June 30, 1972.

In preparing this report we have drawn liberally on published reports and on unpublished file data of the U.S. Geological Survey. We have benefited from the full cooperation of R. S. Fulton, Regional

Mining Supervisor, U.S. Geological Survey, Carlsbad, N. Mex., and D. M. Van Sickle, Regional Geologist, U.S. Geological Survey, Roswell, N. Mex. We had the pleasure of discussing the objectives of this proje with Donald Baker, Director, New Mexico Bureau of Mines and Mineral Resources, and with Frank Kottlowski and Roy Foster, also of that organization. Discussions and underground trips with William Stanley of the U.S. Potash Company, and Karl Ehlers of the Duval Company were also very helpful in our work.

GEOGRAPHY

Location and population

The potash mines of southeastern New Mexico are in eastern Eddy County and westernmost Lea County. Most of the mines lie along a north-trending line 15 miles east of the city of Carlsbad and 25-45 miles north of the Texas border (fig. 1). Two mines are 10 miles farther east.

The area is sparsely populated. Populations given here are estimates for Jan. 1, 1972 (Rand McNally and Co., 1972). Eddy County has a population of 39,800 and Lea County 48,800. Other than Carlsbad (20,500), the only cities of 1,000 or larger population within 50 miles of the mines are Hobbs (25,800), Artesia (10,300), Lovington (8,900), Eunice (2,600), Jal (2,600), and Loving (1,200). Except for widely scattered ranch and farm houses, the only habitations within 20 miles

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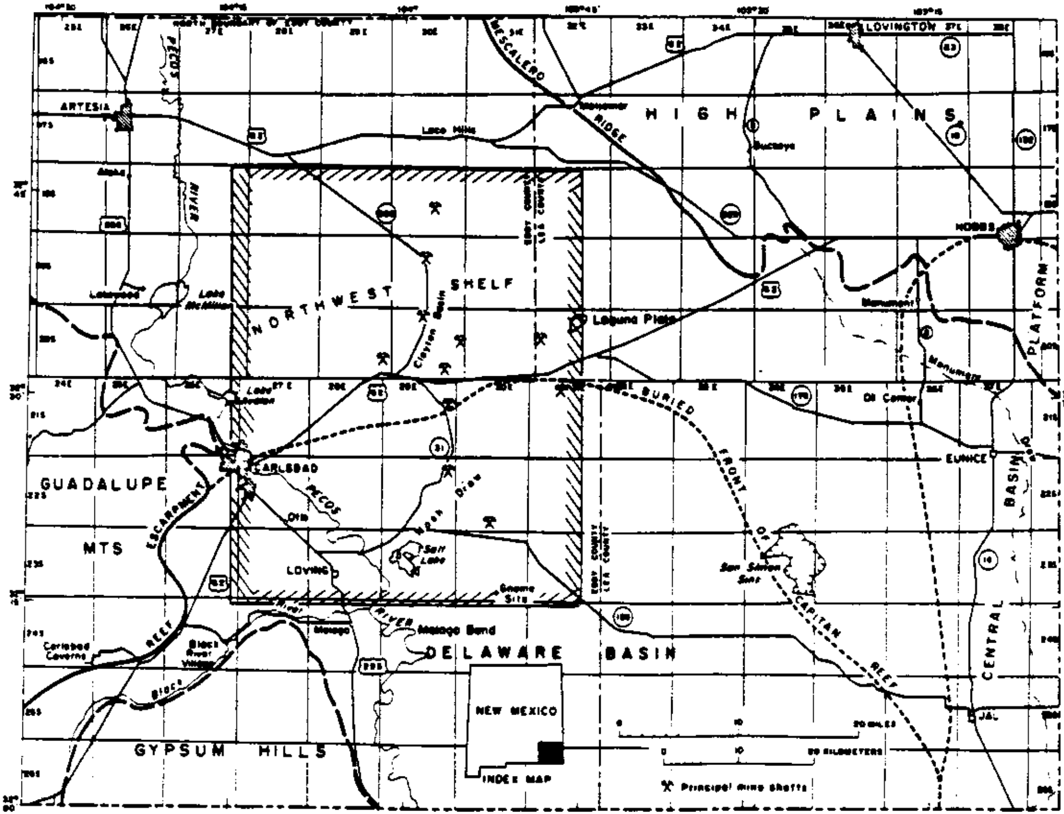

Figure 1.— Map of the vicinity of the potash mines, southeastern New Mexico. Northern boundary of Delaware basin is defined by Reef Escarpment and buried front of Capitan reef. Area of figure 4 outlined by hachures.

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of the mines are in Carlsbad, Loving, and the small communities of Malaga, Otis, Loco Hills, and Maljamar. Population is highly dependent on the petroleum and potash industries, and any large increase other than through possible expansion of these industries seems improbable.

Surface water

The Pecos River, which rises in northeastern New Mexico and ultimately joins the Rio Grande at the Mexican border, is the only through-going perennial stream in this area. Here and farther south the Pecos receives almost all the surface discharge and at least the greater part of the subsurface discharge from the area. Surface drainage from most of the area is poor. The only significant continuously flowing tributary of the Pecos is Black River, south of Carlsbad. The abundant small intermittent streams generally drain into depressions produced by sand dunes or by solution subsidence where the water evaporates or sinks into the subsurface. Of the intermittent streams, the longest is in Monument Draw, which drains southward along the eastern edge of Lea County. It is rare for such generally dry channels to carry continuous flows of water, as the runoff from thunder showers ordinarily sinks into depressions in the floor.

The Pecos River, small reservoirs behind two dams between Carlsbad and Loving, and a small part of Salt Lake, east of Loving, are the only bodies of perennial surface water within 14 miles of any potash mine. The northern edge of Salt Lake is 4 miles southwest of the International Mineral and Chemical Corp. mine. Other lakes (or "lagunas") east of the Pecos contain water only after heavy rains. Lakes McMillan and Avalon and the smaller reservoir on the river at the east edge of Carlsbad are 15 miles or more from the nearest mine.

Topography

The topography of the area (fig. 1) falls easily into four large divisions: the eastern Guadalupe Mountains and its foothills; the High Plains; isolated areas of low hills, principally south of Carlsbad and southwest of Eunice; and widespread pediments and alluvial plains, north, east, and southeast of Carlsbad. Collapse features locally modify the topography throughout the region.

Guadalupe Mountains.--The Guadalupe Mountains form a moderately dissected plateau, gently inclined to the northeast (Hayes, 1964). South of Carlsbad the mountains are bounded abruptly on the southeast by the Reef Escarpment, the face of an exhumed Permian reef that bordered the Delaware basin. This striking topographic and stratigraphic feature emerges from the subsurface near Carlsbad. It becomes steeper and higher southwestward from Carlsbad and culminates in Guadalupe Peak (8,751 feet), 50 miles from the city. Northwest of Carlsbad, the margin of the mountains is far less spectacular; the northeastern slc there descends gradually to the pediments that flank the Pecos River.

High Plains.--The High Plains are a large remnant of the deposit surface on top of the Pliocene Ogallala Formation. The surface of tl plains is remarkably even and slopes east-southeast about 15 feet per mile. It is underlain by a thick layer of caliche, which is mantled in places by thin soil. West of Hobbs and Lovington, the plains are sharply bounded by a southwest-facing erosional scarp, 100-300 feet high, known as Mescalero Ridge. South of Hobbs, the boundary is only vaguely defined (Nicholson and Clebsch, 1961).

Low hills.--The Gypsum Hills, a group of low rounded hills erode from gypsiferous Permian rocks, occupy much of the area between the P River and the Reef Escarpment, 20 miles south of Carlsbad. Farther north, small hills locally project above the piedmont surfaces flanki the escarpment. In Lea County, two low ridges, north and west of San Simon Sink may preserve outlying remnants of the High Plains surface (Nicholson and Clebsch, 1961).

Pediments and alluvial plains.--Over most of the area shown on figure 1, the ground surface has low relief and slopes gently (20-40 feet per mile) away from the borders of the Guadalupe Mountains and the High Plains toward the Pecos River or locally toward Black Riv and Monument Draw. Included, in general, is all the large area east the Pecos River and south and west of the High Plains, the area near Artesia from the river west to the foothills of the Guadalupe Mountains, and the area south of Carlsbad between the Pecos River, the Gypsum Hills, and the Reef Escarpment.

The basic form of almost all the ground surface of the region is erosional and consists of Pleistocene pediments and partial pediments that have been modified to varying degrees. Nearly all the surface east of the Pecos River, including the vicinity of the potash mines, is a pediment or group of coalesced pediments of probable early Pleistocene age (Morgan and Sayre, 1942, p. 35). This surface was modified during and since its formation by solution-collapse features. It has been dissected locally by streams, and large parts of it are mantled by shifting or stabilized sand dunes.

Along the Pecos River and west of the river, the surface is younger than that to the east and consists of a complex of three terraces that commonly rise like broad low steps from the river to the foothills or to the escarpment of the Guadalupe Mountains (Fiedler and Nye, 1932, p. 10-12). The upper two terraces are interpreted as remnants of Pleistocene pediments (Horberg, 1949, p. 472; Morgan and Sayre, 1942, p. 35), whereas the lowest and youngest terrace was produced by moderate entrenchment of the river and its major tributaries into narrow discontinuous alluvial plains.

Collapse features.--Collapse features produced by subsurface solution are varyingly common throughout the region. They are most abundant east of the Pecos River in parts of the widespread old pediment. Solution occurs where unsaturated circulating ground water passes through or along the contacts of layers of salt, gypsum, anhydrite, or, to less extent, carbonate rock. These soluble rocks predominate in the Late Permian Ochoan Series, which underlies all the area east of the Pecos River.

The collapse features range in size from small sinks to depressions many miles long. Indeed, the present course of the Pecos River was probably determined by a train of coalesced Pleistocene sinks captured by a headward-working tributary of the Rio Grande (Morgan and Sayre, 1942, p. 37). Other conspicuous expressions of ground-water solution include the subsidence of the floor beneath the alluvium of the Roswell-Artesia basin to as much as 140 feet below the bedrock outlet of the basin south of Artesia (Morgan and Sayre, 1942, p. 37), the several abrupt changes in flow in the Pecos River within 20 miles north of Carlsbad (Morgan and Sayre, 1942, p. 37), Nash Draw and Clayton Basin close to the potash mines east of Carlsbad, and San Simon Sink southwest of Eunice.

Climate

The climate of nearly the whole region is semiarid. The average annual precipitation ranges from about 12 to 13 inches near the Pecos River and Jal to almost 16 inches at Hobbs. In the Guadalupe Mountains, precipitation rises to about 22 inches near the summit. Most precipitation is from local thundershowers that occur from June to October. The variation in the yearly total is large.

The relative humidity in the region is low. Winters are mild with little snow, and summers are warm. The average July temperature near Carlsbad is a little over 80° F. Windstorms, mainly in the spring of the year, may be severe.

Industry

Mineral production in Eddy and Lea Counties has been nationally significant, and, as of 1967, Lea County ranked first in the State in value of production. The petroleum, gas, and potash industries have dominated the economies of the two counties for several decades. All yearly production values given below are abstracted or derived from data compiled by Stotelmeyer (1969).

Production values of crude petroleum, natural gas, natural-gas liquids, and natural gasoline totaled $72.4 million in 1967 in Eddy County. Of this, $54.8 million was crude petroleum. In Lea County, the production value of crude petroleum alone, largely from the central and southern parts of the county, was $247 million in 1967.

The production is gradually increasing. Exploration is active and is particularly spurred by increasing demand for natural gas. Sanger and Saultz (1971, p. 1039), in discussing exploration in 1970 in the district of West Texas and eastern New Mexico, stated that the Delaware basin, "...still in the early stages of its exploratory history, continued to be very active and to have the greatest potential... Deep gas reserves from Devonian through Ordovician (Ellenburger) continue to be of prime consideration."

The potash mines east of Carlsbad are the principal source of potash available within the United States and constitute all of the production in New Mexico. The total value of potash produced since 1932 is $1.75 billion. In 1966, the value was well over $100 million (Stotelmeyer, 1969). Since then, foreign competition has grearly reduced production, and some mines are closed. Decline in the industry resulted in reduction in the population of Carlsbad from 25,500 in 1960 to an estimated 20,500 in 1972 (Rand McNally and Co., 1972). Large reserves of potash remain, and the future of the industry seems to depend on demand, which is influenced greatly by the extent of foreign competition.

Agriculture over most of this dry region consists solely of the grazing of cattle and sheep. Irrigated farms concentrated along the Pecos River near Artesia and south of Carlsbad account for a large part of the total agricultural income. There is dry farming on the High Plains.

Tourist dollars are an important part of the local economy. Carlsbad Caverns, White Sands, and other nearby natural features draw many thousands to the area each year.

Access

The vicinity of the potash mines is readily accessible by highway, railroad freight, and scheduled air service. The mines are served by hard-surface State or federal highways that provide easy year-round access from Carlsbad. Federal highways extend from Carlsbad in several directions. Spur lines of the Santa Fe Railroad serve the mines, connecting via Carlsbad with the main line at Clovis, N. Mex., about 180 miles to the northeast. Carlsbad has scheduled air service to El Paso, Albuquerque, and Dallas-Ft. Worth via Texas International Airlines.

STRATIGRAPHY

The potash mines in southeastern New Mexico (fig. 1) are in an area of great stratigraphic significance. Sedimentary deposits ranging in age from Ordovician to Quaternary attain total thicknesses exceeding 20,000 feet. The area includes the northern end of the Delaware basin, a Late Permian depositional trough with Pennsylvanian and earlier Permian antecedents. The edge of the basin is commonly defined as the front of the largely buried Capitan Reef. As much as 13,000 feet of Permian strata was deposited within the area of the basin, which constitutes the most complete succession of the Permian in North America. The oldest rocks exposed in the area are of Late Permian age, but drilling has provided abundant information on still older rocks.

The text that follows is largely limited to brief discussions of sedimentary environments, gross thicknesses, relations between stratigraphic units, and occurrences of petroleum. Lithologic descriptions and thicknesses of individual units are shown on the accompanying illustrations.

Precambrian basement

The depth of the Precambrian basement ranges from as little as 7,000-8,000 feet below the surface in the northwestern corner of the area and easternmost Lea County to more than 20,000 feet in southernmost Lea County. Drill data from scattered localities indicate that the basement consists of granitic, metasedimentary, metavolcanic, and volcanic rocks (Flawn, 1954 and 1956, p. 25-29; Hayes, 1964, p. 5; Foster and Stipp, 1961, p. 17, 19-29). The Precambrian rocks are generally overlain by Ordovician strata that lapped northwestward onto a positive area in northern New Mexico and Colorado. Locally, near the eastern boundary of Lea County, late Paleozoic uplift caused erosion of all older Paleozoic rocks, and Permian strata lie directly on basement.

Pre-Permian Paleozoic deposition

From Ordovician through Pennsylvanian time, marine sediments accumulated slowly but fairly continuously in the southeastern corner of New Mexico. Deposition was in and marginal to broad, nearly flat, subsiding basins that were northern arms of the Ouachita trough. This trough passed through Oklahoma and central and trans-Pecos Texas and connected with open sea in the vicinity of the present gulf coast or the coast of southern California. In Early Pennsylvanian time, the initial rise of a median ridge that was to be known as the central basin platform of Permian time (fig. 1) divided an earlier very wide basin into the ancestral Delaware basin and the Midland basin farther east. The various Paleozoic basins were areas of especially active subsidence whose surfaces were generally lower than those on the more stable shelves, platforms, or arches bounding them. Total deposition was thickest in the central part of the Delaware basin where subsidence was greatest, but the deposits of some time intervals, notably the Pennsylvanian Period, were thickest on the margins.

The total thickness of the pre-Permian sedimentary rocks is 5,000-5,500 feet in the immediate vicinity of the potash mines. The rocks thicken southeastward to more than 7,000 feet in southern Lea County and thin northwestward to about 3,300 feet near the middle of the northern edge of Eddy County. The rocks are predominantly shale and carbonates (fig. 2). Rocks of Mississippian and Pennsylvanian age are dominantly shale in the central parts of the basins of deposition and carbonates along the edges. Middle Ordovician and Lower Pennsylvanian sandstones a few hundred feet thick occur in the vicinity of the potash mines and the Gnome site.

Rocks of Ordovician, Silurian-Devonian, and Pennsylvanian age form important petroleum reservoirs beneath the central basin platform and the northwest shelf (fig. 1). Production from rocks of these ages in the northern Delaware basin is widely scattered and interest is increasing in deep exploratory drilling there.

Permian deposition

Wolfcampian, Leonardian, and Guadalupian Series.--Over a large area in the general vicinity of Carlsbad, the total thickness of the Wolfcampian, Leonardian, and Guadalupian Series is 8,000-9,000 feet. The section thins gradually northward from the mines. The rocks are noted for remarkably complex lateral changes in facies.

The subsidence that defined the ancestral Delaware basin in Pennsylvanian time accelerated in Early Permian Wolfcampian time and continued at a high rate through Guadalupian time. During much of this interval, the basin extended a few tens of miles northwest of the late Guadalupian limits defined by the Capitan reef of that age. The subsiding basin was covered to varying depths by marine water and received deposits of shale, fine-grained sandstone, and dark-colored limestone. The rock column for this interval (fig. 2) is representative of the type of deposition in the northern part of the basin. Light-colored shallow-water carbonates generally bounded the basin on the shelves to the west and north, and the platform to the east. Reefs or banks of less cohesive skeletal material very commonly composed the basinward edges of these carbonates (fig. 3), and submarine talus formed steep slopes descending to the floor of the basin. As the reefs grew upward, some also grew basinward, overriding their talus.

Close behind the reefs and banks, the contemporaneous shelf rocks (fig. 3) consist of bedded dolomite, subordinate amounts of limestone, shale, and sandstone, and locally a little anhydrite. The gradational contact between shelf and reef facies, like that between reef and basin facies, commonly transects bedding as it rises in the section basinward. Farther back of the reefs, the dolomite of the upper part of the Guadalupian Series (the Artesia Group) and, to much less extent, that of the lower Guadalupian and Leonardian Series tends to give way increasingly to anhydrite, formed in shallow evaporative lagoons.

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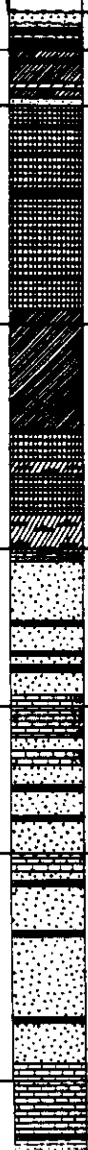
SYSTEM	SERIES	GROUP	FORMATION (WHERE DIFFERENTIATED)	LITHOLOGY	THICKNESS, IN FEET	DESCRIPTION
QUATERNARY			Dune sand, Gatuna, and Dewey Lake Redbeds		290	Sand, clay, and sandstone, unconformable on redbeds.
PERMIAN	Ochoan		Rustler		360	Anhydrite or gypsum and subordinate salt, dolomite, and fine clastics.
			Salado		1,600±	Mainly halite and argillaceous halite. These rocks, thinner layers of sulphate minerals (chiefly anhydrite and polyhalite), and minor claystone, siltstone, and sandstone occur in cyclic sequences, 2-30 feet thick. Potash ore in irregularly lenticular to tabular bodies near middle. Generally 1,600-2,000 feet thick near Gnome site and southern potash mines; thins northward over buried Capitan Reef to 700-1,200 feet near northern mines. Thinner farther north.
			Castile		1,600+	Mainly anhydrite, generally interlaminated with calcite in central and lower parts of formation. Two intervals of fairly pure halite, generally 200-350 feet thick, persist throughout northern Delaware basin. Minor limestone. Thins abruptly shelfward within vicinity of mines and elsewhere at margins of basin; no more than a thin tongue crosses buried Capitan Reef. Thickness fairly uniform within basin.
	Guadalupian	Delaware Mountain	Bell Canyon		1,150±	Brown and gray sandstone and minor limestone and shale. Grade at edges of Delaware basin, including vicinity of potash mines, into reef of light-gray Capitan Limestone, as much as 2,000 feet thick. Behind the reef, dolomite, siltstone, sandstone, and anhydrite of upper Artesia Group is equivalent and similar in thickness to Bell Canyon.
			? Cherry Canyon		1,050±	Gray and brown sandstone, limestone, and minor shale. Near northern-most mines and elsewhere along margin of basin, it grades laterally into carbonate reef (Goat Seep Reef) or bank and then, behind the reef, into dolomite, anhydrite, and fine clastics of lower Artesia Group and upper San Andres Formation.
			? Brushy Canyon		1,600±	Gray sandstone and a little brown and black shale and brown limestone. Thins north of potash mines and gives way to mainly dolomite (lower San Andres Formation) on shelf to north. Laps out against ancient arch west of basin.



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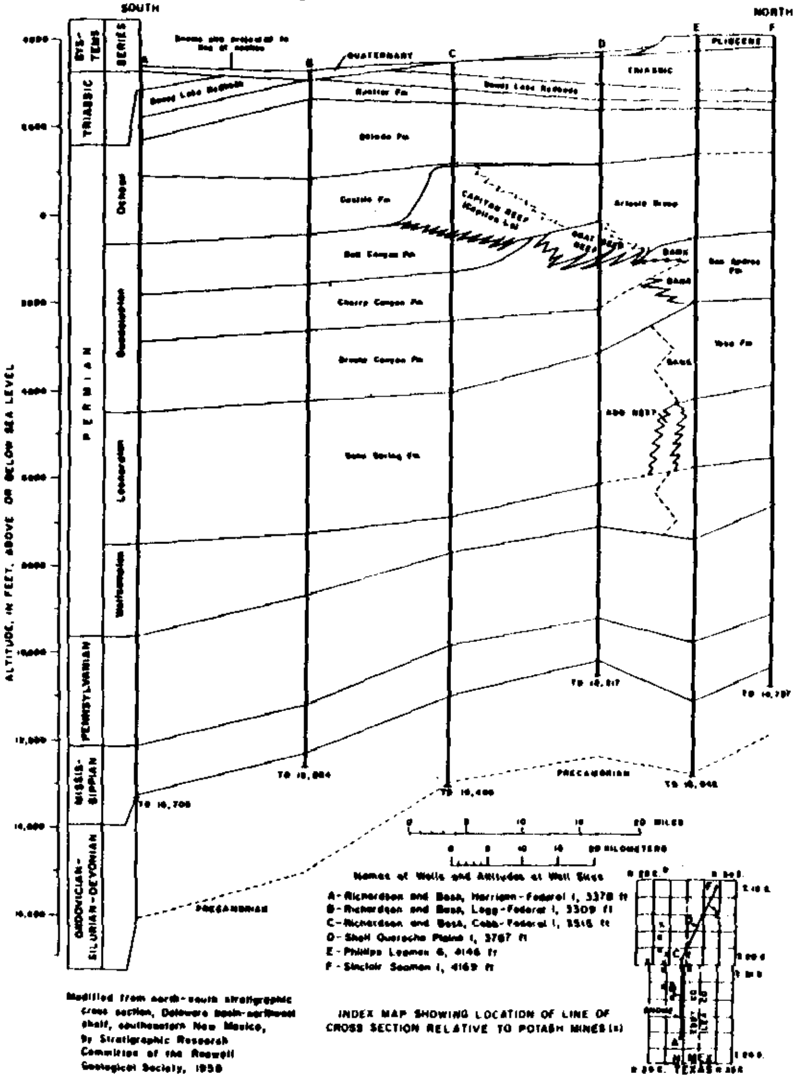

Figure 3.-- Generalized geologic cross section from south to north through the vicinity of the Gnome site and the potash mines, Eddy and Lea Counties, New Mexico

The reefs bounding the northern edge of the Delaware basin progressed from a position north of the present potash mines, in Leonardian and early Guadalupian time, to a position within the mining area in late Guadalupian time (fig. 3). Elsewhere on the margins of the basin there was a similar basinward progression. At the end of Guadalupian time, the Capitan Reef almost completely encircled the basin, restricting southern access to the sea and setting the stage for basinal evaporite deposition.

The northwest shelf, north of the Delaware basin, and the central basin platform, east of the basin, have been important producers of petroleum from Permian rocks. Extensive pools in sandstone and carbonates of the Artesia Group and the San Andres Formation are concentrated in a belt immediately above and behind the buried Capitan Reef, but there has been significant production from almost all parts of the Wolfcampian, Leonardian, and Guadalupian section in various a on the shelf and platform. Established pools within the northern Delaware basin are more scattered and are principally in sandstones of the Delaware Mountain Group.

Ochoan Series.--The floor of the Delaware basin in early Ochoan time is generally estimated to have been at least 1,200 feet below the top of the Capitan Reef, which almost encircled it. While many hundreds of feet of Castile Formation evaporites accumulated in the basin, apparently little accumulated in the reef and back-reef areas. Probably rather late in Castile time, the basin was filled to the extent that a thin tongue of anhydrite extended locally across the bounding reef and onto the shelf. The uppermost part of the Castile intertongues reefward into basal halite of the Salado Formation (Jones, 1954, p. 108-109; Jones and Madsen, 1968, pl. 2).

The Salado Formation is one of the principal deposits of halite on the North American continent. It overlies the Castile conformably in the Delaware basin and extends over the Capitan Reef to the north and east, far beyond the limits of the area here described. Whether the Salado once extended west of the basin is unknown. The Salado sea was, in general, even more saline than the sea of Castile time. Lacking a shield of carbonate reefs, it received, however, considerable fine clastic sediment. Its halite deposits are generally less pure than those of the Castile.

After widespread deposition of the Salado salt, the sea water freshened somewhat, and anhydrite again dominated deposition during Rustler time (table 1). The Rustler Formation is very largely coextensive with the Salado in this area. In the subsurface of the northern Delaware basin and of the shelf to the north, the Rustler appears to be conformable to the Salado (Jones, 1954, p. 110; 1960, p. 12), from which it is commonly separated by a layer of solution breccia, discussed later in this report.

Table 1.--Generalized section of rocks and sediments of latest Permian (post-Salado) and younger age in the northern Delaware basin and on its northern and eastern margins

System	Series	Formation	Thickness (feet)	Description	Variations in thickness and distribution
Quaternary	Holocene	Dune sand, alluvium, playa deposits, and travertine	0-300	Light-brown to pale-reddish-brown partially stabilized fine- to medium-grained dune sand. Alluvial sand, silt, and gravel. Playa deposits of mainly reworked alluvium and dune sand. Travertine as spring deposits.	Dune sand, as much as 60 feet thick, discontinuously covering much of area between Pecos River and High Plains. Thick alluvium limited to vicinity of rivers.
				Unconformity	
	Pleistocene(?)	Gatuna	0-300	Mainly reddish-orange or pale-red very fine to medium-grained sand and silt. Locally some gravel and clay and, uncommonly, gypsum and fresh-water limestone. Bedding commonly obscure and discontinuous. Mostly capped by caliche. Local high permeability.	Discontinuous and highly variable in thickness over large area southwest of High Plains and mainly east of Pecos River, in Eddy County and probably Lea County. Mostly less than 100 feet thick.
				Unconformity	

Table 1.--Generalized section of rocks and sediments of latest Permian (post-Salado) and younger age in the northern Delaware basin and on its northern and eastern margins--Continued

System	Series	Formation	Thickness (feet)	Description	Variations in thickness and distribution
Tertiary	Pliocene	Ogallala	0-300	Chiefly white, gray, and reddish-brown fine-grained sand, which locally has calcite cement. Subordinate gravel, silt, and clay. Lenticular, discontinuous bedding. Mainly capped with caliche. Highly permeable.	Underlies High Plains and much of Lea County farther south. Probably absent from Eddy County except for northeast corner.
				Unconformity	
Triassic	Upper Triassic	Chinle(?)	0-1,200	Reddish-brown and greenish-gray claystone and subordinate amounts of reddish-brown siltstone and fine-grained sandstone. Some secondary gypsum. Low permeability.	Thickest in eastern Lea County; erosionally thinned westward to wedge out near eastern edge of Eddy County.

Table 1.--Generalized section of rocks and sediments of latest Permian (post-Salado) and younger age in the northern Delaware basin and on its northern and eastern margins--Continued

System	Series	Formation	Thickness (feet)	Description	Variations in thickness and distribution
Triassic	Upper Triassic	Santa Rosa	0-300	Mainly pale-reddish-brown, pale-red and gray fine- to medium-grained commonly cross-stratified sandstone. Lenses of pebble conglomerate. Local thin layers of reddish-brown siltstone and claystone. High local permeability.	Absent near and west of Pecos River and locally farther east.
				Unconformity	
Permian	Ochoan	Dewey Lake Redbeds	0-400	Reddish-orange to reddish-brown fine-grained sandstone, siltstone, and shale. Sandstone and siltstone are commonly clayey. Thin lamination and small-scale cross lamination common. Permeability generally low.	Mainly 200-300 feet thick in vicinity of Gnome site and potash mines; locally absent. Thins gradually northward. Absent west of Pecos River.

Table 1.--Generalized section of rocks and sediments of latest Permian (post-Salado) and younger age in the northern Delaware basin and on its northern and eastern margins--Continued

System	Series	Formation	Thickness (feet)	Description	Variations in thickness and distribution
Permian	Ochoan	Rustler	0-500	Mostly anhydrite. Considerable salt, commonly silty or clayey, occurring in central part of Delaware basin and tends to lens out at margins. Two dolomite layers, a basal sandstone, and several thinner layers of fine clastics are widespread. Main aquifer in Carlsbad area.	Thins very gradually northward. Thickness ranges from 200 to 500 feet in vicinity of Gnome site and mines due to variable subsurface solution, which increases westward.

The Rustler represents the last Permian saline sea and the upper layer of a remarkable sequence of predominantly evaporite rock of Ochoan age. The entire sequence is as much as 3,500 feet thick in the northern part of the basin. The thickness drops rapidly to about 1,500 feet on the shelf near the northern potash mines and decreases more gradually farther north.

After the sea withdrew, the Dewey Lake Redbeds were deposited on broad mudflats over the former sea bed. The appearance of medium-scale cross lamination in sandy lenses in the upper part of the formation probably indicates a gradual change to fluvial conditions (Vine, 1963, p. 23) as the final episode in the long complex history of the Permian deposition.

Except for dolomite and sandstone layers in the Rustler Formation, the Ochoan Series generally has very low permeability. The little oil produced from lower Ochoan evaporites apparently escaped from underlying sandstone (Adams, 1965, p. 2148).

Triassic and Cretaceous deposition

Fluvial deposition resumed in Late Triassic time, when the Santa Rosa Sandstone and the finer grained redbeds of the Chinle(?) Formation formed on flood plains in a very large area over and beyond the borders of the Delaware basin. The Jurassic Period is not represented by deposition in this region and was a time of erosional removal of Triassic rocks west of the basin.

Late in Early Cretaceous time, a shallow sea advanced from the south and covered southeastern New Mexico. It soon withdrew leaving behind a thin deposit of limestone and sandstone. The only remnants of this deposit in the vicinity of the northern Delaware basin are in very small areas in easternmost Lea County, in the western Gypsum Hills, and perhaps on the crest of the Reef Escarpment (Hayes, 1964, p. 38).

Tertiary and Quaternary deposition

No early or middle Tertiary deposits are known to be present in the region. Cretaceous deposition was followed by broad uplift in the vicinity of the Guadalupe Mountains and farther north and by erosion of Cretaceous and Triassic rocks to form a surface of low relief sloping gently east and southeast. In Pliocene time, this surface extended from near or within the present Guadalupe Mountain area and from the uplands north of that area southeastward into Texas. It was mantled by the fluvial Ogallala Formation, whose upper surface of deposition is fairly well preserved on the High Plains today. There are no definite remnants of the Ogallala west of easternmost Eddy County, but gravels in the Pecos valley and on high parts of the Guadalupe Mountains have been interpreted as belonging to this formation (Bretz and Horberg, 1949).

Most authors believe that the Pecos valley was formed in Quaternary time, after Ogallala deposition. Solution subsidence, the coalescing of solution depressions by surface erosion and further solution, and headward erosion by the Pecos River and its tributaries contributed to the formation of the valley. After much erosion, a period of aggradation in the valley mantled the slopes and filled depressions with the Gatuna Formation, whose sediment is largely of local origin. Renewed downcutting by streams and subsurface solution and resultant subsidence have continued to the present and have been accompanied by intermittent local accumulations of pediment and terrace alluvium and playa deposits.

STRUCTURE

General features

The rocks in the general vicinity of the potash mines (fig. 1) are for the most part little deformed, and they have been tectonically stable since Tertiary time. The principal structural units are broad features related to late Paleozoic sedimentation: the northern Delaware basin, the shelf north and west of the basin, and the central basin platform to the east (fig. 1). The small part of the Guadalupe Mountains included in the area, though topographically high, is structurally part of the shelf. The major structures were tilted gently eastward mainly during pre-Pliocene time. The tilt produced a general eastward dip of no more than 2° (figs. 4 and 5).

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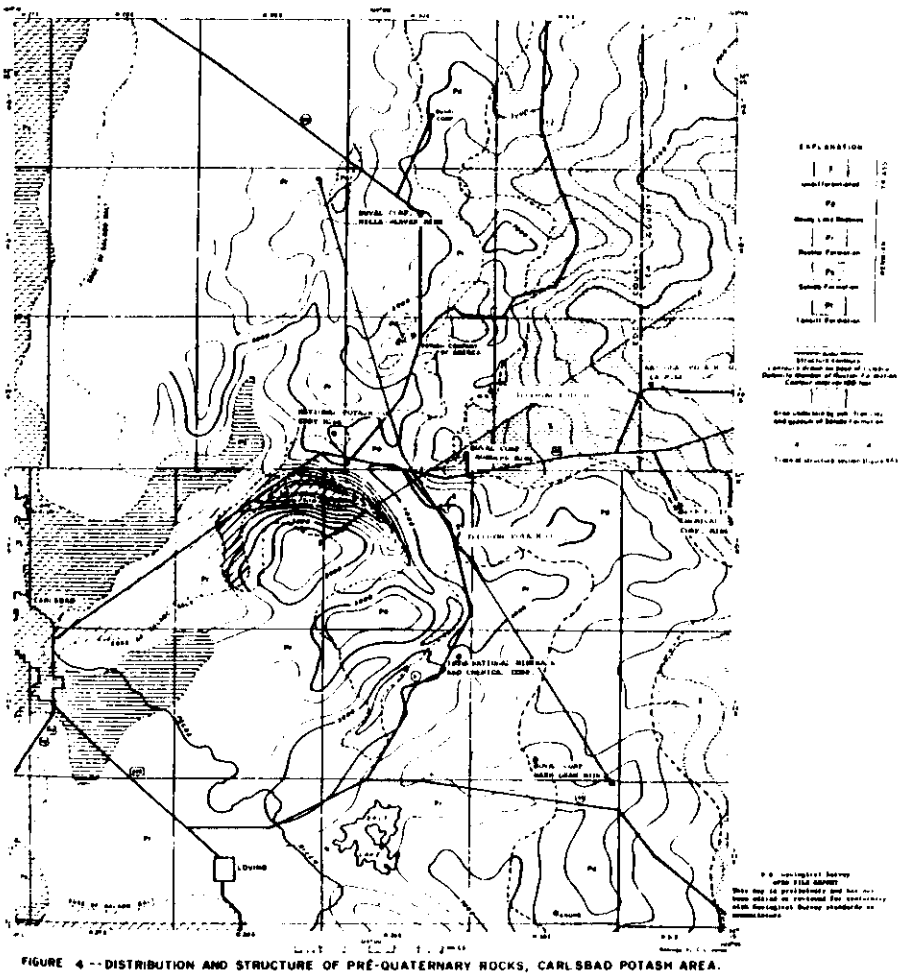

FIGURE 4 --DISTRIBUTION AND STRUCTURE OF PRÉ-QUATERNARY ROCKS, CARLSBAD POTASH AREA.

Delaware basin

The Delaware basin was first defined in Early Pennsylvanian time, when an earlier very broad basin was divided by initial uplift of a large median ridge that became the central basin platform of Permian time. The basin subsided relative to the bounding platform and shelf until Late Permian time, when its history as an active structur feature ended.

The form of the northern part of the basin, as defined by contours on the surface of the Precambrian floor (Foster and Stipp, 1961), is a broad asymmetrical trough, trending north and plunging south. The axis is in central Lea County, roughly parallel to the central basin platform. The eastern slope of the trough rises rapidl to the platform, whereas the western slope is much gentler.

As in any gradually subsiding basin, the older sediments are downwarped in a form like that of the basement floor, and the warpin dies out upward in the basin section (fig. 4A). The Late Permian Ochoan rocks and the Triassic rocks exposed in the basin today do no reflect basinwide warping, and their major structural feature is the regional eastward slope mentioned above. This slope is 75-100 feet per mile in proximity to the Gnome site and the southern potash mine

Disruption of the regional slope of the Ochoan and younger rock is minor. The vicinity of the Gnome site and the southern mines is apparently representative in its scattering of open folds, domes, and small faults, which may be, in part, of tectonic origin. Deep-seated faults with more than 20 feet of vertical displacement are rare if not absent there (Jones, 1960, p. 16). Near the western edge of the basin and the present upper course of the Black River, Cenozoic tectonism may be involved in a northwest-trending monoclinal flexure. Kelley (1971, pl. 5) showed 600 feet of relief across this monocline on the upper surface of the Bell Canyon Formation. Several minor high-angle faults cutting the Castile Formation in the same part of the basin and two inferred faults at the northwestern edge of the basin (Kelley, 1971, p. 48-51) are most probably products of solution subsidence. Subsurface solution has produced many other minor faults and numerous local flexures in the near-surface rocks, as well as the many sinks and larger depressions. In addition, small surficial domes that are attributed to differential solution of salt or to expansion of anhydrite during hydration are numerous (Vine, 1960).

The generally simple surface structure of the basin is doubtless somewhat deceptive. A fault zone in the Guadalupe Mountains may have extended southeastward into the western edge of the basin, below the younger monocline described above, and may have been active during Mississippian to Early Permian time (Hayes, 1964, p. 42). Pennsylvanian deformation, for which there is widespread evidence in eastern New

Mexico and western Texas, may be represented elsewhere in the subsurface and rapid Early Permian subsidence of the basin was accompanied by widespread block faulting within it (Adams, 1965, p. 2144).

Northwest shelf

The regional structural slope in that part of the shelf north and west of the Delaware basin (fig. 1) is as much as 200 feet per mile in the Guadalupe Mountains and generally no more than 100 feet farther east. In the vicinity of the northern potash mines, this slope is interrupted locally by minor domes, folds, monoclinal flexures, and faults similar to structural features described near the southern mines. A difference here is that some of the domes are probably of depositional origin, resulting from irregularities in Guadalupian carbonate deposition (Motts, 1972). Nowhere, here or near the southern mines, are there "strong or well-defined zones of folding or faulting representing response to compressive or tensional forces" (Jones and Madsen, 1968, p. 9).

Beyond the vicinity of the mines, the shelf north of the basin includes a few more strongly expressed structural features. Several miles northwest of Artesia, a buried northeast-trending fault, offsetting Upper Permian rocks along a distance of about 30 miles, is probably part of a prominent set of northeast-trending shear zones that extends far to the north. Movement on these zones was initiated in Carboniferous or earlier time and may have been basically right lateral (Kelley, 1971, p. 44-48). Another buried member of this set may pass immediately southeast of Lake McMillan (Roswell Geological Society, 1968, fig. 9). A long low east-trending arch in Late Permian rocks the Artesia-Vacuum arch, passes a little south of Artesia. It is at least largely the product of differential compaction over the Abo Reef of Early Permian age.

In the part of the Guadalupe Mountains included in the area discussed, monoclines and folds are the prominent structures. A buried broad fold or arch of Leonardian and early Guadalupian age trends northeast a little behind the present Reef Escarpment (Hayes, 1964, p. 42-43). It apparently controlled the location of growth of the Goat Seep and Capitan Reefs. Much later, probably during Tertiary time, monoclinal flexing contributed to the basinward dips in the Late Permian rocks of the escarpment. Other folds, on the ridge above the escarpment and also about 12 miles west of Carlsbad, are of early Tertiary or perhaps older age.

Other than minor surficial deformation related to solution and hydration of evaporites, the entire shelf in this area appears to have been stable in Quaternary time.

Central basin platform

The central basin platform, whose western edge is included in the area discussed here, has an eventful history involving more intense deformation than that of the basin and shelf.

In latest Mississippian or Early Pennsylvanian time, the area was deformed to an elevated emergent fold belt, trending north-northwest. The belt may have been bounded by high-angle faults and may have a horst structure (Adams, 1965, p. 2143). After submergence and deposition in Middle and part of Late Pennsylvanian time, renewed orogeny further elevated the area and "sharpened, compressed, and faulted the folds" (Hills, 1963, p. 1717-1718). Uplift continues strongly through Wolfcampian time and then slowed. Since filling of the Midland and Delaware basins in Late Permian time, the platform has been structurally stable.

GEOLOGY OF SALT DEPOSITS--OCHOAN SERIES

All the salt deposits in the Carlsbad potash area are in the Ochoan Series of Late Permian age. The Ochoan consists entirely of sedimentary rocks, but it has two distinct parts--a thick lower section of salt-bearing evaporites and a thin upper section of red beds. The lower section includes, in ascending order, the Castile, Salado, and Rustler Formations, whereas the upper section consists entirely of the Dewey Lake Redbeds. The Castile Formation is confined to the Delaware basin in the southern half of the potash area and is known only in the subsurface (fig. 4A). The three younger formations form the pre-Quaternary bedrock across the greatest part of the area (fig. 4) and, although they are largely covered by extensive dune sand, caliche, and alluvial deposits, they are well known from the countless boreholes drilled in exploration for potassium salts and petroleum.

Exposures of Ochoan evaporites in the potash area are exceedingly poor for stratigraphic studies or any other investigations requiring precise knowledge of the composition, sedimentary structures, or thickness of the three evaporite formations. This is true because of the considerable lithic and structural changes that have accompanied extensive evaporite solution and removal by meteoric waters. Solution of halite and other readily soluble salts has been complete to depths of several hundred feet, and all anhydrite and other soluble calcium salts have been weathered to gypsum. The removal of soluble salts has resulted in a great reduction of formation thicknesses and in much subsidence and accompanying brecciation of all residual gypsum and overlying deposits. Consequently, the entire area of evaporite outcrop is in reality a "regolith" liberally dented and creased by numerous sinks, fissures, and linear solution valleys.

Castile Formation

The lower part of the Ochoan Series is represented in the Carlsbad potash area by the Castile Formation. The Castile was named and defined by Richardson (1904, p. 43) to include several hundred feet of gypsum that overlies the Bell Canyon Formation and underlies the Rustler Formation at the surface in the western part of the Delaware basin. Somewhat later, the interval represented by gypsum at the surface was found by drilling to consist of a much larger sequence of evaporites in the subsurface, including mostly anhydrite in the lower parts of the evaporite sequence and mostly rock salt in the upper part. For a time the two parts of the evaporite sequence were classed as lower and upper members of the Castile, but they were considered to be separate formations. Finally, Lang (1935) restricted the name Castile to the lower part of the sequence and applied the name Salado to the upper part. Regionally, the criterion most commonly used to differentiate one formation from the other is the predominance of anhydrite in the Castile and the predominance of halite in the Salado.

The Castile Formation underlies the southern half of the potash area at depths ranging from about 500 feet in the west to almost 3,200 feet in the east. The nearest outcrops of the formation are in the Gypsum Hills in southern Eddy County, N. Mex., about 16 miles southwest of the potash area. In that area the Castile consists of interlaminated white gypsum and dark-brownish-gray limestone and some laminated brownish-gray limestone and a little brown dolomite. Near the center of the Gypsum Hills the formation dips beneath the Salado Formation and gypsum gives way to anhydrite in the subsurface.

In the subsurface of the Carlsbad potash area, the Castile Formation is readily divisible into three informal members. The tripartite subdivision includes a lower and an upper anhydrite member separated by a thick salt member (fig. 4A). The three members are distinctive, are conformable, and constitute laterally persistent rock units in the potash area and over wide sections of the Delaware basin. Near the margin of the basin, however, the three members merge into a single wedgelike mass of anhydrite that rapidly thins to a narrow tongue and extends across the basin margin for a few miles before thinning out in the southern part of the northwest shelf.

The lower anhydrite member of the Castile Formation gradationally overlies the Bell Canyon Formation in the Delaware basin, but overlaps the Capitan Limestone along the margin of the basin. Within the area of overlap, the lower member of the Castile is presumed to die out abruptly, in part by pinchout against the Capitan Limestone and in part by lateral gradation into laminated limestone that grades in turn into massive limestone of the Capitan. The member ranges in thickness from 210 to 230 feet in the southern parts of the potash area, but thickens northward and attains thicknesses of 320-380 feet a short distance from the overlap of the Capitan Limestone. The predominant rock in the member is interlaminated gray anhydrite and brownish-gray limestone. A few beds of dark-gray and brownish-gray limestone, a few inches to several feet thick, are persistent in the lower and middle parts of the member; some are practically of basinwide extent.

The middle member of the Castile Formation is a salt-rich lentil that forms a widespread, lithologically distinct stratigraphic marker. The member is 550-700 feet thick in the southern part of the Carlsbad potash area, but thickens northward and attains thicknesses of 800-1,000 feet along a broad 2- to 3-mile-wide belt that parallels th margin of the Delaware basin. North of this belt, the member terminates, in part by lateral gradation to anhydrite and in part by intertonguing with anhydrite (fig. 4A). The member is predominant rock salt, but it contains thin to thick layers of interlaminated anhydrite-limestone rock. The thickest of these layers averages abou 100 feet, and it divides the member into two almost equally thick salt beds. The lower of the two beds is free of interlaminated anhydrite-limestone layers, whereas the upper bed includes several o these layers, some of which are 2-5 feet thick.

The upper member of the Castile Formation is an anhydrite-rich unit that exhibits the most lithologic complexity. It consists mainl of interlaminated anhydrite-limestone; but massive anhydrite and roc salt are present in appreciable amounts and there are lesser amounts of dolomite and magnesite. The member includes a northward-thinning tongue of magnesitic anhydrite that overlaps the Capitan Limestone along the margin of the Delaware basin and extends a few miles into the northwest shelf (fig. 4A). The main body of the member is

700-800 feet thick in the southern part of the potash area, but thins northward and is as little as 150-300 feet thick in the areas near the margin of the Delaware basin where the underlying salt member is thickest.

The Castile Formation is overlain by the Salado Formation. The contact between the two formations has been considered to be an angular unconformity (Adams, 1944, p. 1608). Contrary to this interpretation, subsurface studies in the Carlsbad potash area and elsewhere in the Delaware basin show that the upper beds of the Castile grade laterally into, and intertongue with, the lower beds of the Salado. In this transitional sequence, the Castile intertongues with successively older rocks of the Salado, causing a gradual stratigraphic descent in the top of the Castile, which is responsible for the decrease in the thickness of the upper member of the Castile from about 800 feet in the southern part of the potash area to about 150 feet and less in the central part of the area and then to 0 in the northern part.

Salado Formation

Considerable economic significance is attached to the Salado Formation because it contains the potash deposits for which the Carlsbad area is well known among geologists. The deposits are the dominant source of the potassium salts mined in the United States, and their wide extent suggests that they will maintain this ranking for years to come. Deposits containing sylvite (KCl)--the main potassium mineral of economic importance--have been mined at 11 localities (fig. 1), but they underlie practically the entire eastern half of the potash area and extend eastward beneath much of southwestern Lea County, N. Mex. (fig. 6). The Salado also contains many deposits rich in polyhalite [$K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$] that are extensive and widely distributed but lack the economic importance of the sylvitic deposits. The polyhalitic and sylvitic deposits are fairly important elements in the stratigraphy of the Salado Formation, and a special section of this report (appendix A) summarizes some details of their distribution and geology.

The Salado Formation, named by Lang (1935), is the oldest unit in the Ochoan Series that crops out in the Carlsbad potash area. The main exposures of the formation are near Lake Avalon, north of Carlsbad, N. Mex. Here the Salado overlies the Tansill formation and underlies the Rustler Formation, but the stratigraphic relations cannot be determined positively from examination of the outcrop. The Salado appears to overlie the Tansill Formation conformably and to grade upward into the Rustler Formation. The lower part of the Salado grades laterally southward into the upper part of the Castile Formation. The gradational contact between the Salado and the

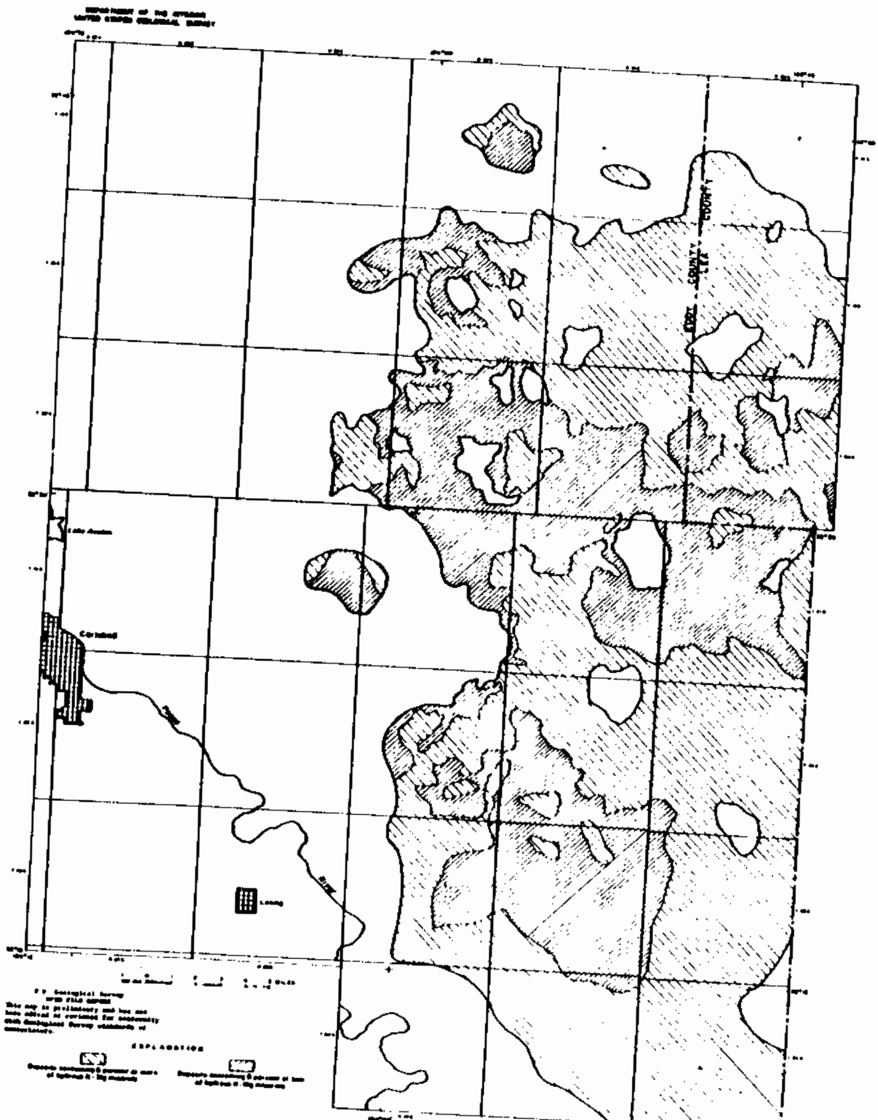

FIGURE 6 —DISTRIBUTION OF SYLVITIC POTASH DEPOSITS, CARLSBAD POTASH AREA.

Castile rises in stratigraphic position from north to south and is depicted schematically on the geologic structure sections (fig. 4A)

East of the outcrop, the Salado Formation underlies the centr part of the potash area at depths of 250-700 feet. In general, th depth to the Salado increases with distance from the outcrop, and it is as much as 1,600 feet at the northeast corner of the area an about 1,000 feet at the southeast corner.

The Salado Formation is characterized by thick persistent uni of rock salt alternating with thinner units of anhydrite and polyhalite (fig. 7). Thin seams of claystone underlie virtually all the anhydrite and polyhalite units, and there are a few thin beds of sandstone and siltstone at long intervals. All the anhyd units and beds of clastic rocks are distinctive members that serv as stratigraphic marker beds; two are formally named rock units. The widespread Cowden Anhydrite Member, named for the North Cowde oilfield in Ector County, Tex. (Giesey and Fulk, 1941), lies 90-200 feet above the Castile Formation. The Vaca Triste Sandst of Adams (1944) near the middle of the Salado Formation is a quartz- and clay-rich unit of fragmental rocks contrasting sharp with adjacent beds of crystalline evaporite rocks.

In exposures of the Salado Formation along the west side of Carlsbad potash area, all the salt has been removed by solution the anhydrite and polyhalite have been altered to gypsum. The alteration of the evaporite rocks extends to depths ranging from 260 feet to almost 1,600 feet below the surface and is responsible for a fourfold to sixfold reduction in the thickness of that part of the Salado and for a change in composition from dominantly rock salt in the subsurface to dominantly gypsum in the outcrop. The contact between the two highly dissimilar parts of the formation, known locally as the "base of leached zone" and also as the "top of salt," is highly irregular, with many closed depressions and isolated pinnacles (fig. 8). The contact dips generally eastward but rises in stratigraphic position from the base of the Salado near the west side of the potash area to the top of the formation near the Eddy-Lea County line at the east side of the area. The altitude of the contact ranges from a high of slightly more than 3,200 feet near the northwest corner of the area to a low of slightly less than 1,500 feet at the south edge of the area.

The maximum thickness of the Salado Formation in the potash area is slightly more than 2,000 feet in a northwestward-trending zone that parallels the margin of the Delaware basin at the Eddy-Lea County line (fig. 9). The thickness of the Salado decreases slowly southward within the basin, but diminishes rather rapidly northward and westward from the zone of maximum thickness. The northward

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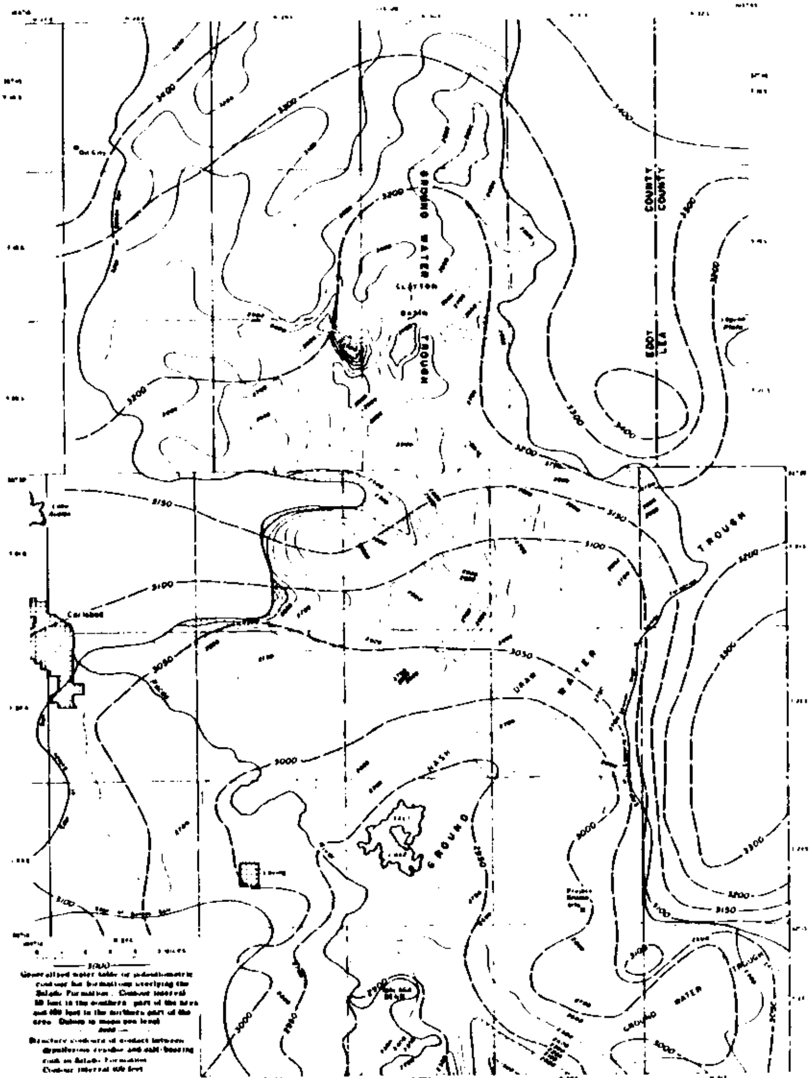

——— 3000 ———
Generalized water table or potentiometric contour for formations overlying the Salado Formation. Contour interval 50 feet in the southern part of the area and 100 feet in the northern part of the area. Datum is mean sea level

Structure contours of contact between gypsiferous residue and salt-bearing rock in Salado Formation
Contour interval 100 feet

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Figure 8 -- Structure contours on contact between gypsiferous residue and salt-bearing rock in Salado Formation, and water table and potentiometric contours in formations overlying the Salado Formation

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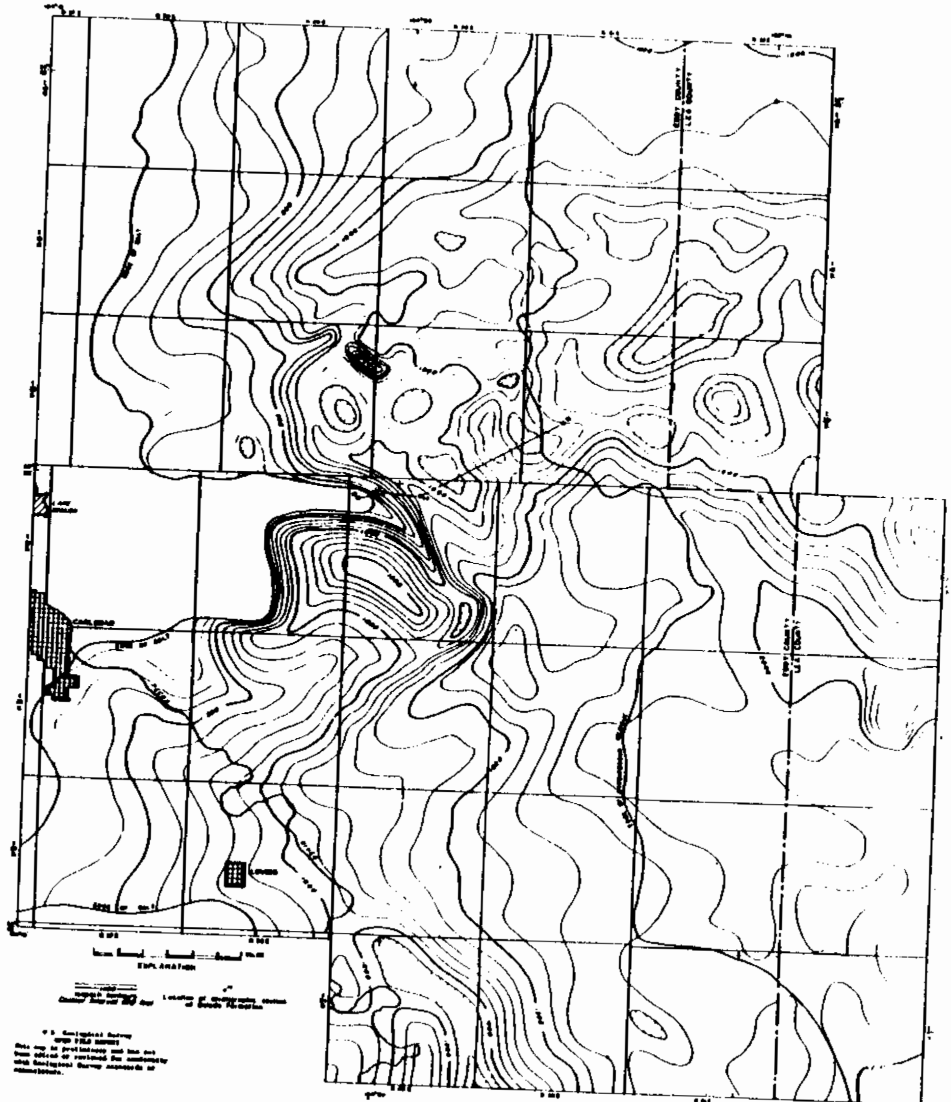

FIGURE 5 -- CONTOUR MAP SHOWING THICKNESS OF SALADO FORMATION

reduction is part of a broad pattern of regional change in thickness at or near the south edge of the northwest shelf area, whereas the westward reduction is related largely, if not entirely, to evaporite solution and removal by meteoric waters. Within the shelf area, local reductions in thickness are sharp over pre-Salado knolls or "highs" at the Getty, Barber, Halfway, and other small oilfields which appear as domal features on the structure map of southeastern New Mexico published by Stipp and Haigler (1956).

The Salado Formation is divided into three informal units: a lower salt member, a potash-rich member, known locally as the McNutt potash zone, and an upper salt member (fig. 7). The three members are conformable, are laterally persistent rock units, and are about equally rich in rock salt, anhydrite, polyhalite, magnesit and clastic rocks. In fact, they are generally similar in virtuall all but one respect. The lower and upper members are almost entirel free of sylvite and other potassium and most magnesium evaporite minerals over much of the Carlsbad potash area, whereas the McNutt zone is generally rich in these minerals over much of the area and contains several extensive sylvite-bearing potash deposits of econo importance. These deposits are the obvious lithologic feature that sets the McNutt potash zone apart from the lower and upper members of the Salado and makes it a fairly natural stratigraphic unit. Th deposits are restricted to a few small groups of mineralized salt beds or ore zones which are scattered at irregular but fairly short intervals through parts of the McNutt zone (fig. 10). Nearly all the deposits in the McNutt zone are mineralogically complex and contain a host of hydrous minerals that are thermally reactive at fairly low to moderate temperatures (table 2).

Rustler Formation

The Rustler Formation, named by Richardson (1904), is the youngest salt-bearing unit in the Ochoan Series. The formation is mainly exposed in inliers scattered irregularly through the central and western parts of the Carlsbad potash area. It is overlain by the Dewey Lake Redbeds. The contact between the two formations is obscured in outcrops by slumping and warping due to evaporite hydration, solution, and removal by meteoric waters. From subsurface studies, however, it appears that the formations are unconformable at places near the western edge of the Dewey Lake Redbeds. The discordance and hiatus are not great and they disappear eastward. Over broad sections of the area the Rustler and the Dewey Lake appear to be conformable.

In the subsurface below the zone of ground-water penetration, the Rustler Formation is mostly anhydrite and rock salt (fig. 11).

Table 2.--Evaporite minerals in sylvite and polyhalite deposits in the Carlsbad potash area (Modified from Berg, 1970)

[M, melting; B, boiling; Dec, decomposition; Deh, dehydration; T, transition]

Mineral	Formula	Thermal effects and temperature (°C)				
		M	B	Dec	Deh	T
Anhydrite	$CaSO_4$	-	-	-	-	1,193
Aphthitalite	$[(K, Na)_3Na(SO_4)_2]$	940	-	-	-	437
Bloedite	$Na_2Mg(SO_4)_2 \cdot 4H_2O$	670	-	625	110* 220*	-
Carnallite	$KMgCl_3 \cdot 6H_2O$	160* 425*	190	-	230	-
Glauberite	$Na_2Ca(SO_4)_2$	944	-	520-540	-	-
Halite	$NaCl$	800	-	-	-	-
Kainite	$KMgSO_4Cl \cdot 3H_2O$	-	-	490-540	160* 277*	425
Kieserite	$MgSO_4 \cdot H_2O$	1,124	-	-	340	-
Langbeinite	$K_2Mg(SO_4)_3$	930	-	-	-	-
Leonite	$K_2Mg(SO_4)_2 \cdot 4H_2O$	760	-	-	140* 180*	580
Loeweite	$Na_{12}Mg_7(SO_4)_{13} \cdot 15H_2O$	670	-	625	220	-
Magnesite	$MgCO_3$	-	-	350	-	-

Table 2.--Evaporite minerals in sylvite and polyhalite deposits in the Carlsbad potash area (Modified from Berg, 1970)--Continued

Mineral	Formula	Thermal effects and temperature (°C)				
		M	B	Dec	Deh	T
Picromerite	$K_2Mg(SO_4)_2 \cdot 6H_2O$	760	125	-	140* 180*	580
Polyhalite	$K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$	880	-	-	310-320	-
Sylvite	KCl	770	-	-	-	-
Thenardite	Na_2SO_4	884	-	-	-	240
Vanthoffite	$Na_6Mg(SO_4)_4$	800	-	515	-	-

* Mineral has more than one phase.

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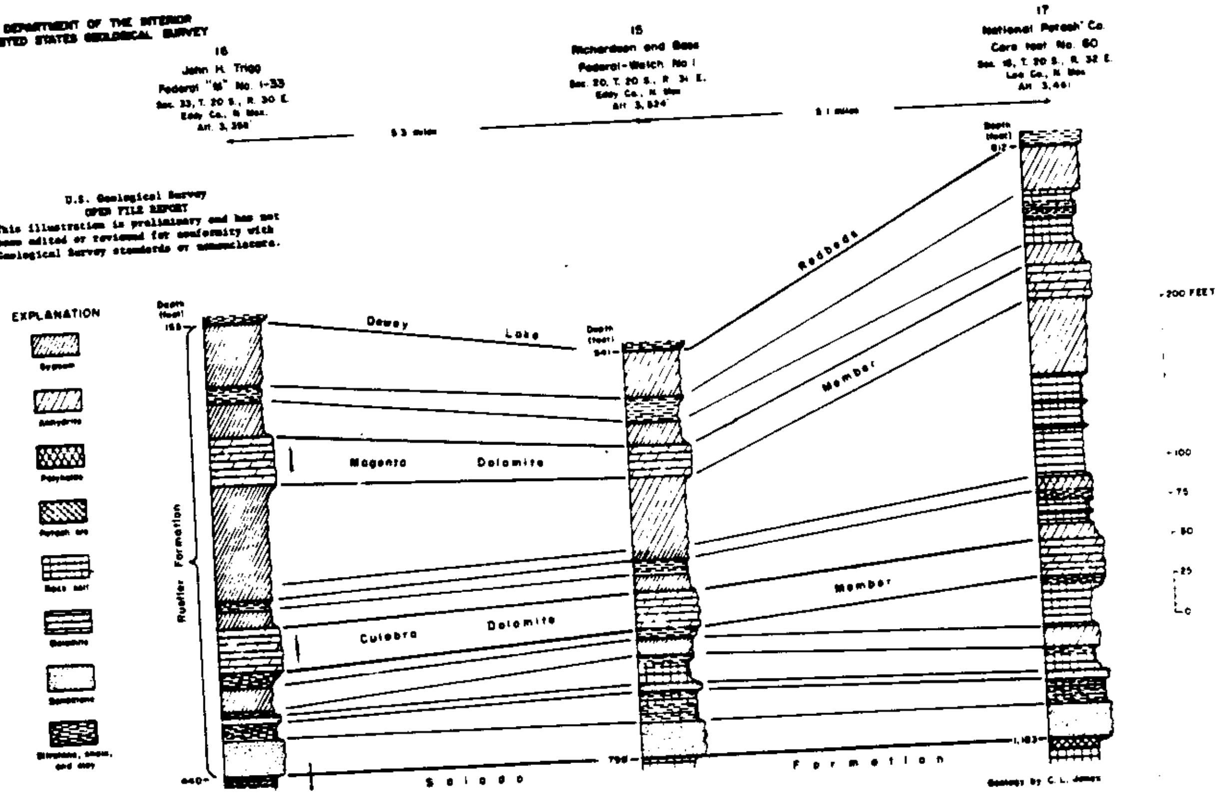

FIGURE 11.--COLUMNAR SECTIONS OF RUSTLER FORMATION, CARLSBAD POTASH AREA

Some polyhalite is commonly present near the middle of the formation, and thin to thick units of sandstone, siltstone, and shale are interbedded at long to short intervals. Dolomite is present in the lower and upper parts of the formation and forms distinct stratigraphic marker beds which have wide and persistent development in the potash area and other sections of southeastern New Mexico. The dolomite in the lower part of the formation is known as the Culebra Dolomite Member and that in the upper part as the Magenta Dolomite Member (Adams, 1944, p. 1614).

The Rustler Formation reaches a maximum thickness of about 500 feet in the eastern part of the potash area. The formation thins toward the outcrop in the central part of the area (fig. 12). Here the formation generally ranges in thickness from about 200 feet to 400 feet, but its thickness varies considerably over short distances. The variable thickness is due in great part to the leaching of salt and the hydration of anhydrite by meteoric waters. In general, the removal of salt accounts for a marked reduction in the thickness of the formation, and the hydration of anhydrite results in an increase of thickness (fig. 11).

Dewey Lake Redbeds

The Dewey Lake Redbeds, named by Page and Adams (1940), is the youngest unit in the Ochoan Series, but unlike all other members of the Ochoan it is entirely free of rock salt and other evaporite rocks.

The Dewey Lake consists entirely of siltstone and fine-grained sandstone, and generally ranges in thickness from about 400 feet to 550 feet. It is exposed in low bluffs in the central and eastern parts of the potash area (fig. 4) and is unconformable with overlying Triassic rocks.

GROUND-WATER HYDROLOGY

Three main hydrologic units control the ground-water hydrology of the Carlsbad potash mining area. These are: (1) the Pecos River, which receives the ground-water outflow from the project area; (2) the water-bearing strata overlying the Salado Formation; and (3) the Capitan Limestone and other water-bearing strata underlying the Salado Formation. The distribution and development of large solution features, particularly in the Nash D aw and Clayton Basin areas, exert a major effect on the occurrence and movement of the ground water.

Pecos River

The Pecos River receives nearly all the natural discharge of ground water that moves through the rocks of the potash mining area. The principal places of natural ground-water inflow are at Carlsbad, where water derived from the Capitan Limestone discharges to the river or to the alluvium bordering the river, and near Malaga Bend (fig. 1), where highly mineralized water is discharged from the Rustler Formation to the river. Between Carlsbad and Malaga Bend the river receives water from the alluvium, except in areas where pumping has lowered the water table below river level.

Water-bearing units overlying Salado Formation

A small amount of ground water occurs in all the geologic formations overlying the Salado Formation, but the main aquifers or water-yielding units are the Culebra Dolomite Member and basal solution breccia zone of the Rustler Formation, the Santa Rosa Sandstone, and the alluvium. Locally, the Gatuna Formation yields water to wells. In the area west of and near the Pecos River, water from the alluvium is utilized extensively for irrigation purposes. East of the river, in the potash mining area, only a few wells have encountered potable water. The yields of the wells are generally low and most are used for the watering of livestock. The Culebra Dolomite Member occurs throughout much of the area and is the main source of water tapped by stock wells. The basal solution breccia zone of the Rustler Formation, often referred to as the "brine aquifer," is the unit that is most significant in the solution of the halite in the upper part of the Salado Formation. Table 3 summarizes the hydrology of the geologic formations overlying the Salado Formation.

The formations above the Salado Formation seem to be connected hydrologically and can be considered as constituting a single multiple-aquifer system (figs. 4A, 8). How perfectly this aquifer system is developed is an open question and cannot be determined from the existing hydrologic information, although the levels of water standing in wells are sufficiently uniform that potentiometric and water-table contours can be constructed throughout the area (fig. 8). This water table and potentiometric surface ranges from less than 200 feet to about 1,400 feet above the contact between the gypsiferous residue and salt-bearing rock in the Salado Formation (fig. 13).

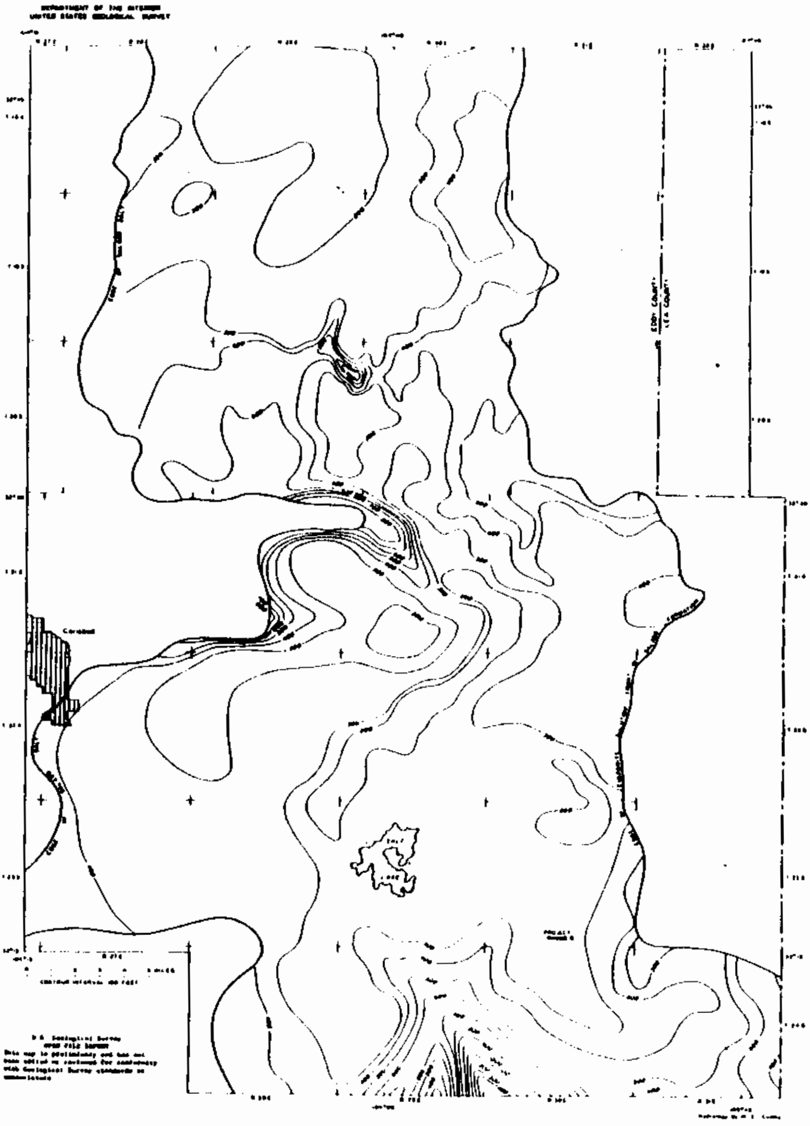

Figure 13.—Height of water table above contact between [illegible] and salt-bearing rock in [illegible] Formation

Solution activity and associated collapse, subsidence, and fracturing have increased the overall permeability of the rocks and enhanced the interformational movement of water in the aquifer system. The solution action in the area of the potash mines also has detrimentally affected the chemical quality of the ground water. Analyses of well water indicate that the ground water in the mining area contains much higher amounts of dissolved substances than does the water of the surrounding region of New Mexico; this distributional relationship is indicated best by the total dissolved solids (fig. 14) and chloride (fig. 15).

Ground water in the formations above the Salado Formation moves generally southward and southwestward across the potash mining area toward the Pecos River (fig. 8). Most of the discharge of the ground water takes place in the reach of the Pecos River near Malaga Bend. This discharge is from about 850 square miles of the mining area north of Project Gnome site and from at least an additional 400 square miles lying to the northeast of the mining area. Although the total amount of ground water discharging to the Pecos River is not known, Theis and others (1942, p. 69) estimated that 200 gallons per minute entered the river from the basal solution breccia zone.

The potentiometric and water-table contours outline a series of ground-water ridges or highs and troughs or lows (fig. 8), which are imposed on the regional southward to southwestward pattern of ground-water movement. A large southwestward-plunging ground-water trough

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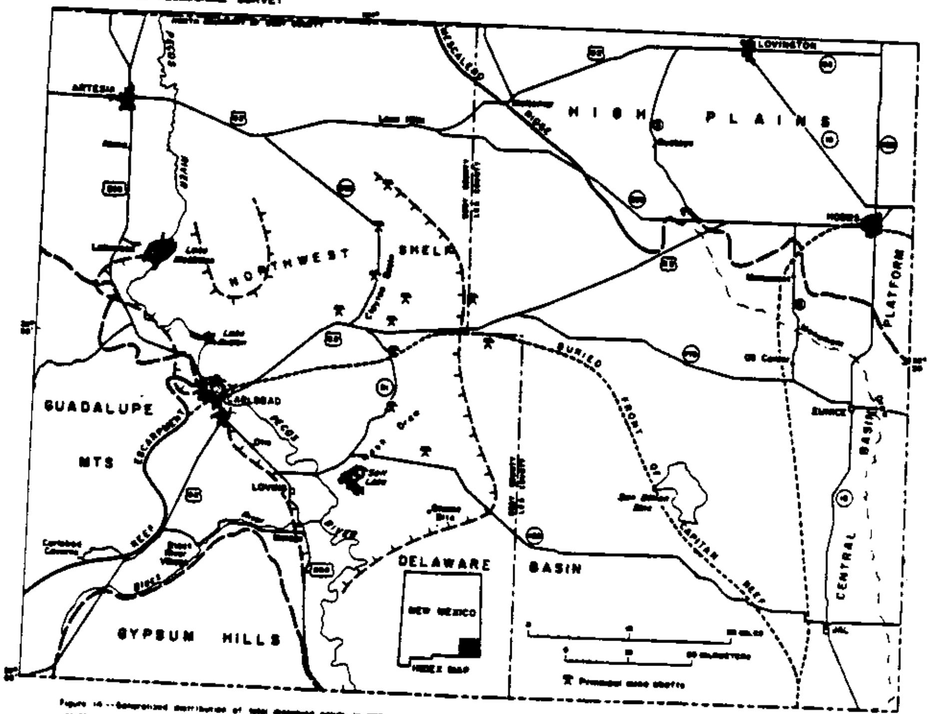

Figure 14.--Generalized distribution of total dissolved solids in [illegible] water in the rocks overlying the Salado Formation, Carlsbad mining area and adjacent region of southeastern New Mexico. Hachures indicate area where ground water usually contains more than 2,500 ppm of dissolved solids. Data compiled from Bjorklund and Motts (1959), Cooper and Glanzman (1971), Cox (1967), Hendrickson and Jones (1952), and Nicholson and Clebsch (1961).

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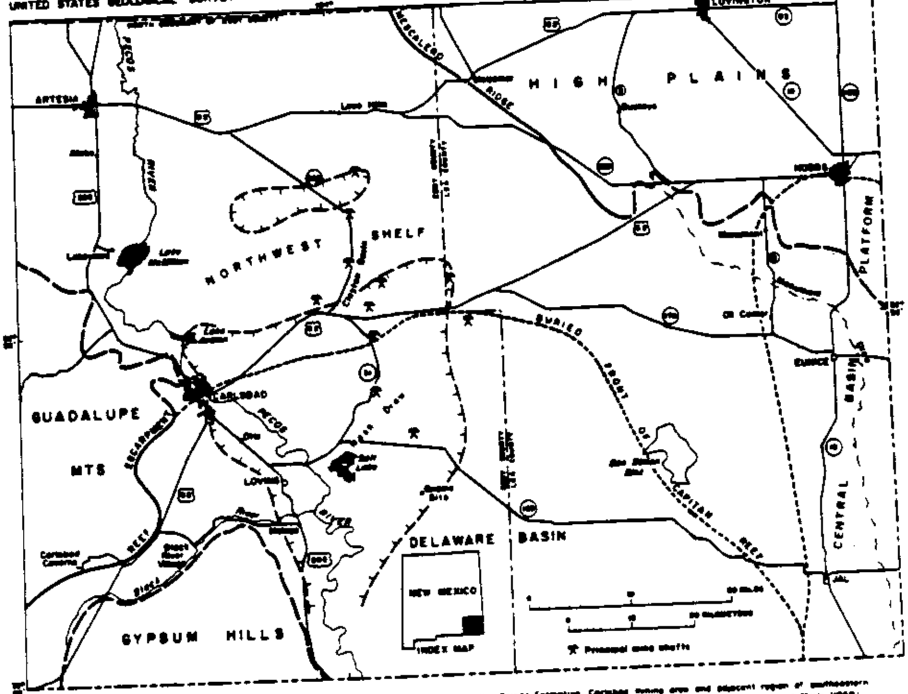

Figure 19.--Generalized distribution of chloride in well water in the rocks overlying the Salado Formation, Carlsbad mining area and adjacent region of southeastern New Mexico. Hachures indicate area where ground water usually contains more than 500 ppm of chloride. Data compiled chiefly from Bjorklund and Motts (1959), Cooper and Glanzman (1971), Cox (1967), Hendrickson and Jones (1952), and Nicholson and Clebsch (1961).

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extends from Malaga Bend northeastward roughly through Nash Draw to the vicinity of Laguna Plata. Another much smaller trough is east-southeast of the Project Gnome site and extends from the southeastern part of T. 24 S., R. 30 E. east-northeastward across T. 24 S., R. 31 E., to T. 23 S., R. 32 E. A southward-plunging trough is in the area of Clayton Basin. Water moves southeastward toward the center of this trough from the northwestern part of the mining area, southward from the northern border region of the mining area, and southwestward and westward from a narrow ground-water ridge between Clayton Basin and Laguna Plata. South of Clayton Basin the trough is not a well-defined hydrologic feature. Much of the water in the trough does not move directly toward the Pecos River from the Clayton Basin area. Instead, the water is diverted south-southeastward through the rocks underlying Quahada Ridge into the ground-water trough in the Nash Draw area (see Gatuna Formation, table 3), where it joins water moving southwestward toward the Pecos River.

Salado Formation

The Salado Formation has an intergranular porosity and permeability that ranges from low to virtually none (Stevens and others, 1970, table 1). Locally, fractures and solution openings impart a spotty formational permeability. In the potash mining area, the Salado Formation is dry except for small pockets of water or water and gas that have been encountered occasionally during mining and test-drilling operations and for water present in the leached zone developed at the top of the formation. Some of the water and gas pockets are confined under high pressure. In much of the mining area ground water moving through the basal part of the Rustler Formation has formed a leached zone along the top of the Salado Formation (fig. 4A). In places, the leached zone extends more than 200 feet into the Salado Formation. Most of the dissolved solids in the brine in the basal solution zone of the Rustler Formation has been obtained from the leached zone.

G. O. Bachman (written commun., 1972) estimates that during the past 5 million years..."salt has been dissolved laterally in the vicinity of Carlsbad, New Mexico, at an average rate of about 3 1/2 to 4 miles per million years... This conclusion is based on the fact that the distance from the eastern front of the Guadalupe Mountains to the present western limit of major salt beds is about 18 to 20 miles and on the following assumptions: (1) the Ogallala Formation formerly extended across the Pecos River valley at least as far as the front of the Guadalupe Mountains, (2) the Pecos River valley in the vicinity of Carlsbad has been formed since Ogallala time, and (3) the Ogallala Formation has been eroded and the Permian salt dissolved from this area during the past 5 million years. It does not seem probable that salt extended much farther west than the front of the Guadalupe Mountains before Ogallala time; if the salt was less extensive before Ogallala time this estimate is conservative."

Strata underlying Salado Formation

The Permian to Cambrian sedimentary rocks underlying the Salado Formation contain water of brine composition and are under high artesian pressure. These rocks are not exposed in the potash mining area, but they lie deeply buried in the subsurface throughout much of southeastern New Mexico and western Texas. McNeal (1965, figs. 1-7) showed that in the potash mining area the elevation of the potentiometric surfaces of different zones (excluding the Capitan Limestone of these rocks ranges from a few feet to a few hundred feet above or below the land surface. At Project Gnome site where the average elevation of the land surface is about 3,400 feet, the potentiometric surfaces are at elevations between 3,400 and 3,800 feet, which is 600-1,000 feet above the top of the halite in the Salado Formation. the direction of the slope of the potentiometric surfaces differs somewhat, but it is generally to the east or northeast in southeastern New Mexico.

The Capitan Limestone and associated dolomitic part of the Yates and Tansill Formations form the topmost aquifer in the strata beneath the Salado Formation. These formations crop out or lie at shallow depths southwest of Carlsbad, but they are deeply buried east of the city near the potash mines (fig. 4A). The Capitan Limestone comprises a giant reef 1-2 miles wide that extends northeastward and eastward from Carlsbad across the mining area; the Yates and Tansill Formations adjoin the north side of the Capitan Limestone reef. West of the Pecos River, the Capitan Limestone is developed as a source of water for the city of Carlsbad and for irrigation. East of the river only a few water wells penetrate this unit or the Yates and Tansill Formations. East of the Pecos River, water in the Capitan Limestone and in the Yates and Tansill Formations is under strong artesian pressure. According to Halpenny and Greene (1962, table 2), the potentiometric surface of water in these units is largely above the land surface in the area east of the Pecos River (figs. 4, 4A). Within an area that extends 14 miles east-northeast of Carlsbad, some of the water in the Yates and Tansill Formations may move upward, mix with water in the Rustler Formation, and aid in the solution of halite, gypsum, and anhydrite in the Rustler and Salado Formations. The distribution of chloride shown on figure 15 is consistent with the concept that upward movement of water does take place.

POTASH MINES

History of mining

The potash mines in Eddy and Lea Counties, N. Mex., produce about 84 percent of the potassium minerals mined in the United States. Mining activity in the area began in 1931 after the disclosure by the Federal Government in 1926 that large tonnages of potassium-bearing minerals were present in Permian strata near Carlsbad, N. Mex. Peak production was reached in 1966. The higher grade commercial ore in the area is nearing depletion and most of the seven producing companies have less than a 10-year supply. Large low-grade deposits remain, but their recovery may not be competitive with the Canadian production. Recent production cutbacks resulted in a reduction of employment that has seriously affected the economy of the Carlsbad area.

Location of mines

Most of the potash mines in the Carlsbad district have been develop on deposits in a north-trending belt 10-12 miles east of Carlsbad. Nine mines have been developed along this trend. Two mines have been opened on deposits 6-8 miles farther east, near the Eddy-Lea County line (fig. 16).

The mines are owned and operated by the Teledyne Potash Co. (a subsidiary of Continental American Royalty Co.), Potash Company of America (a division of Ideal Basic Industries, Inc.), Duval Corporation, International Minerals and Chemical Corporation, Southwest Potash Co.,(a subsidiary of Freeport Sulphur Co.),and Kerr-McGee Chemical Corp.

At the present time, eight mines operate in the district (figs. 4, 16). Three mines are closed, Wills-Weaver (Duval), Saunders (Duval), and Lea (National). The Teledyne Potash No. 3 mine is scheduled for closure in August 1972.

Methods of prospecting and exploration

All prospecting and exploration in the district has been done by holes drilled from the surface. Most of the holes were drilled into the top of the Salado by means of churn or rotary drilling rigs. The holes were completed through the ore zones with a diamond drill. Casing was set in the upper part of the hole and cemented into the top of the salt. The casing and cement seal prevented water from the Rustler and younger rocks from entering the hole. After the holes were completed and sampled, the casing was pulled and the holes plugged with cement from bottom to top. In some of the earlier drilling the lower parts of the holes were plugged with mud, but those parts above the top of the salt were filled with cement. It can be assumed that all exploration holes drilled for potash have been effectively sealed.

The density and distribution of the exploration and development drilling are shown on figure 17. In general, the pattern and density of drilling reflects the position or the economic limits of the potash deposits. Outside the densely drilled areas the ore horizons in the Salado are probably composed of halite and only minor amounts of potash.

Mining methods

The bedded potash deposits are nearly flat lying over large areas; therefore, modified coal-mining methods have been used in extracting the ore. The ore-bearing horizons are reached through vertical shafts from which main entries are driven into the ore bodies. Pans of rooms and pillars are developed off the main entries.

The main entries are generally 15-20 feet wide and 8 feet high. Where double entries are driven, they are spaced 50-55 feet apart. The breakthroughs are about 7 feet high, 32-34 feet wide, and are driven on 100- to 150-foot centers. The average room sizes are 34 x 42 feet. The height of the rooms, determined by the thickness of the ore beds being mined, ranges from 4-10 feet.

Each ore body is developed to its economic limits by the above method. This cycle of mining is referred to as "first mining" and results in an ore recovery of about 50-55 percent.

Second mining or final mining is the removal of pillars and the retreating from the outer edges of the developed area toward the main haulageways and shafts. When this mining cycle is completed, the tot ore recovery approaches 85-90 percent.

Final mining results in the removal of pillar support and the eventual subsidence of the mined areas. Reentry into the caved areas is not possible.

Shafts

Twenty-five shafts have been sunk at the sites of the 11 mines in the district (fig. 4). The shaft locations and other pertinent data are shown in tabular form on table 4. None of the shafts has been abandoned or decommissioned. Nearly all shafts are concrete or steel

Table 4.--Shaft location index, Carlsbad potash mining district

Name and shaft numbers	Sec. Twp. Rg.	Location	Depth (feet)	Dimensions	Lining
Teledyne Potash Co.					
No. 1	12-21S-29E	1500 ft N., 2500 ft W. of SE. cor. sec. 12	1,062	5 1/2 ft x 20 ft	Wood lagging to top of salt.
No. 2	13-21S-29E	719 ft S., 137 ft W. of S. 1/4 cor. sec. 12	1,000	5 1/2 ft x 15 ft 10 in.	....Do....
No. 3	13-20S-30E	648 ft W., 1300 ft N. of SE. cor.	1,188	15 ft diameter	Concrete into salt.
No. 4	13-20S-30E	1399 ft N., 1218 ft W. of SE. cor.	1,180±	36 in. Interior diameter	Steel casing into salt.
Potash Company of America					
No. 1	4-20S-30E	1660 ft N., 2230 ft W. of SE. cor.	1,086	5 ft 8 in. x 16 ft 4 in.	Concrete into salt.
No. 2	4-20S-30E	2204 ft N., 2678 ft W. of SE. cor.	985	5 ft 8 in. x 16 ft 4 in.	....Do....
No. 3	17-20S-30E	80 ft S., 1040 ft E. of W. 1/4 cor.	764	15 ft diameter	....Do....
International Minerals and Chemical Corp.					
No. 1	12-22S-29E	416.43 ft S. of N. line, 2127.42 ft W. of E. line	1,086	7 ft x 21 ft	....Do....
No. 2	1-22S-29E	2150.77 ft S. of N. line, 121.63 ft W. of E. line	985	7 ft x 21 ft	....Do....
No. 3	11-22S-29E	2438.87 ft N. of S. line, 2265.12 ft W. of E. line	940	7 ft x 21 ft	....Do....
No. 4	23-22S-29E	379.64 ft S. of N. line, 2627.07 ft W. of E. line	856	7 ft x 21 ft	....Do....
Duval Corp.					
No. 1	35-20S-30E	300 ft S., 675 ft W. of NE. cor.	1,559	6 ft x 18 1/2 ft	....Do....
No. 2	35-20S-30E	600 ft S., 675 ft W. of NE. cor.	1,463	6 ft x 18 1/2 ft	....Do....
No. 3	22-18S-30E	593.02 ft N., 2932.78 ft W. of SE. cor.	1,087	14 ft diameter	Concrete to ore zone.
No. 4	22-18S-30E	487.97 ft N., 3213.78 ft W. of SE. cor.	989	9 ft diameter	....Do....
No. 5	33-22S-30E	376.6 ft S., 1495 ft W. of NE. cor.	1,020	14 ft diameter	....Do....
No. 6	33-22S-30E	280 ft S. 46° W. of No. 5 shaft	920	12 ft diameter	....Do....
National Potash Co.					
No. 1	18-20S-32E	651.35 ft S., 2149.01 ft W. of E. 1/4 cor.	1,806	18 ft diameter	....Do....
No. 2	18-20S-32E	971.46 ft S., 2148.96 ft W. of E. 1/4 cor.	1,760	15 ft diameter	....Do....
No. 3	25-20S-29E	2638 ft N., 2894 ft E. of SW. cor.	846	15 ft diameter	....Do....
No. 4	25-20S-29E	2868 ft N., 2664 ft E. of SW. cor.	826	12 ft diameter	....Do....
Southwest Potash Co.					
No. 1	9-19S-30E	955.50 ft N., 430.30 ft W. of SE. cor.	1,089	15 ft diameter	Concrete into salt.
No. 2	9-19S-30E	555.00 ft N., 430.30 ft W. of SE. cor.	927	20 ft diameter	....Do....
Kerr-McGee Chemical Corp.					
No. 1	4-21S-31E	727 ft N., 2550 ft W. of SE. cor.	1,700	15 ft diameter	Concrete to ore zone
No. 2	4-21S-31E	250 ft N., 3 ft 8 1.3 in. W. of No. 1 shaft	1,700	8 1.2 ft diameter	Steel casing into salt.

lined and have standard hoisting and auxiliary equipment capable of handling large tonnages of mined material. At each shaft the aquifers above the Salado Formation have been sealed with cement grout, water rings and sumps have been constructed, and pumps installed to handle water seepage from the grouted areas. At several of the shafts pumping is no longer required, and at others the amount of water pumped is minimal. The effectiveness of the methods employed to control the water in the shaft areas is evidenced by the fact that the records show that no water has entered the mine workings.

Part of the investigations for the Gnome project showed that the Farm Chemical Resources Development Corp. shaft in eastern Eddy County had been abandoned and contained water. Water-level measurements were made in this shaft during October and November 1961 and in December 1961 after the Gnome device was detonated on December 10, 1961. At the time the measurements were made the water level stood at 1,687 feet below the surface or 13 feet above the bottom of the shaft. Presumably the source of the water was the aquifer in the Rustler Formation. During the period of inactivity the water had overflowed the sump and collected in the shaft. The collar was constructed high enough above ground level to prevent surface water from draining into the shaft.

The shaft has since been equipped with the usual complement of machinery and is now in operating condition. It is listed on table 4 as Kerr-McGee Chemical Corp. No. 1.

It is reported that the shafts, with the possible exception of Teledyne Potash Co. No. 1 and No. 2, are in excellent condition.

Extent of mine workings

Forty years of large-tonnage mining in the relatively thin-bedded ore deposits in the district has resulted in an extensive maze of underground workings. The mine workings in the district cover an area in excess of 45 square miles. The average height of the workings away from the vicinities of the shafts and the main entries is about 7 feet. The floors and backs are generally flat or gently sloped because the mining methods and the mine layouts are designed to follow the nearly flat regional dip of the beds.

The mined areas are irregular in shape but most are elongate in a north-northeast direction. This configuration reflects the variation of the potash content of the ore beds and not the continuity of the enclosing salt beds. In other words, these are chemical variations, or chemical facies within a single bed, and are not variations in the regional sedimentation.

Ore has been mined from four beds or zones in the Salado Formation. The most extensive workings are in the lowest or "First" ore zone, which is between 650 and 800 feet below the top of the Salado. Nine mines in the district have produced ore from this zone. Teledyne Potash Co. No. 1 has produced from the "First" and "Fourth" ore zones. International Minerals and Chemical Corp. has produced from the "First," "Fourth," and "Fifth" zones. Duval's Nash Draw mine has produced from the "First" and "Tenth" zones. National Potash Co.'s Lea mine and the Kerr-McGee Chemical Corp. mine have produced from the "Tenth" ore zone. The approximate stratigraphic positions of the ore zones are shown in figure 10.

Stability of mine workings

The entries, rooms, and pillars developed during the "first cycle" mining are designed to insure stability commensurate with safe and efficient mining practice. Back failure may occur where the back is only a few inches to a foot below a clay seam. The unsupported salt beds have a tendency to pull away from the clay bed because of the loose bond between the two rock types. Back falls are controlled by the judicious and extensive use of bolting.

Caving and subsidence

During final mining most of the pillar support is removed and the worked-out areas gradually subside or cave. More than 50 percent of the mined areas are now caved (fig. 16). In those mines where mining has been completed, the subsidence is nearly 100 percent of the mined height.

In most caved areas the subsidence is reflected in the overlying surface by the development of gentle depressions. Fracturing at the surface in the subsidence areas cannot be accurately mapped or determined because of the cover of unconsolidated surficial materials. Some fracturing has been noticed in the paved highways that cross the subsided areas.

Although detailed studies of the subsidence areas have not been made, some speculations concerning the mechanism involved can be made. Subsurface observations of the subsiding areas indicate that the rocks above the mined areas move slowly downward as a simple cohesive block after final mining is completed. Fracturing may well occur in the subsiding block, particularly in the dolomite beds above the Salado, but the pattern is not known. The unique physical properties of the salt prohibits the development of open fractures. The fractures formed are tight or quickly sealed by flowage or recrystallization of the salt. The absence of water seepage into the mines in the areas of subsidence is indicative of the self-sealing character of the salt beds.

Further evidence for the cohesiveness of the subsidence block is that mining is currently being carried on in two mines in ore beds about 50 and 100 feet above the bottoms of the caved blocks or lower mining levels. The ore beds being mined have suffered no noticeable structural deformation other than the sag and elevation changes due to the subsidence.

No data are available on the effect that subsidence has had on the movement of water in the aquifers above the Salado.

Gnome shaft and workings

The Gnome site and shaft are near the center of sec. 34, T. 23 S., R. 30 E., Eddy County, N. Mex. (fig. 16). The shaft was sunk by the U. S. Atomic Energy Commission as a part of the Plowshare program. Only a brief summary of the geology and description of the mined areas is given in this report. Details can be obtained from reports on Project Gnome (U. S. Geol. Survey, 1962).

The Gnome shaft was sunk to a depth of 1,202 feet. The shaft is circular in plan, has an inside diameter of 10 feet, and is lined with reinforced concrete to a depth of 722 feet. It penetrated about 200 feet of surficial and Pleistocene deposits and 1,000 feet of Permian rocks. The top of the salt is about 650 feet below the collar of the shaft. The bottom of the shaft is in salt about 550 feet below the top of the Salado Formation. Rocks exposed in the shaft are shown on table 5. The shot chamber is connected to the shaft by two parallel drifts each approximately 1,100 feet long. The drifts and chamber are near the base of the upper third of the salt section. About 1,000 feet of massive salt is estimated to be present below the bottom of the shaft and drift.

The Gnome shaft was abandoned and sealed by the AEC in November 1968. The decommissioning of the shaft was done under the surveillance of Reynolds Electrical and Engineering Co. and is reported on by Tappan and Lorenz (1969). All materials giving a contact radiation dose rate of more than 0.1 milliroentgens per hour were removed from the surface and placed in the shaft or flushed as a brine slurry down a drill hole that intersected one of the drifts.

Table 5.--Rocks exposed in the Gnome shaft

Name	Lithology	Age	Depth below surface (feet)	Thickness (feet)
Alluvial bolson deposits	Unconsolidated sand	Holocene	0-43	43.0
Gatuna Formation	Friable sandstone and conglomerate	Pleistocene(?)	43-91.9	48.9
Dewey Lake Redbeds	Thin-bedded siltstone	Permian	91.9-294	202.1
Rustler Formation:		....do........	294-651.2	357.2
Forty-niner Member	Chiefly gypsum and anhydrite	....do........	294-361.3	67.3
Magenta Dolomite Member	Silty dolomite	....do........	361.3-382.2	20.9
Tamarisk Member	Chiefly anhydrite and gypsum	....do........	382.2-495.5	113.3
Culebra Dolomite Member	Dolomite	....do........	495.5-523.5	28.0
Lower member	Chiefly clay and silt with some gypsum and anhydrite	....do........	523.5-651.2	127.7
Salado Formation:		....do........	651.2-1,202	550.8
Upper leached member	Chiefly claystone and siltstone	....do........	651.2-709.3	58.1
Unleached Salado Formation	Chiefly impure halite rock with some anhydrite, polyhalite, and siltstone	....do........	709.3-1,202	492.7

The shaft contains contaminated metal scrap, one dump truck, four mine cars, a hoist man-cage, and various other materials, including a considerable amount of contaminated soil and salt muck. The report does not state how far up the shaft the contaminated materials extend. Uncontaminated soil was placed in the upper part of the shaft to within 5 feet of the surface, and a permanent plug was formed by filling the last 5 feet with concrete.

In addition, all test drill holes were plugged with cement to the top of the Salado.

Because of the conditions that now exist at the shaft, the Gnome shaft or drifts probably cannot be safely and economically rehabilitated.

Solution mining activities

The Kansas City Testing Laboratory was the first of two companies to conduct experimental solution mining projects in the Carlsbad area. This experimental project involved attempts to establish a connection between two boreholes about 200 feet apart in the NW 1/4 sec. 22, T. 20 S., R. 29 E. The project was started during the late 1940's and ended during the 1950's.

During the mid-1960's Continental Oil Co. conducted an experimental solution mining project in the Carlsbad area (Davis and Shock, 1970). Four test holes were drilled in the SW 1/4 sec. 12, T. 19 S., R. 30 E., about 3 1/2 miles east of the Southwest Potash Co. shaft.

The drilling pattern was in the shape of an equilateral triangle with a fourth hole in the center, 200 feet from the apex wells. The wells were drilled to a depth of 1,150 feet and were completed in the "Third" ore zone of the Salado Formation. Subsurface connections between wells were established by hydraulic fracturing from the center or injection well.

During the life of the experiment an elliptical cavity 280 feet long and about 80 feet wide at its broadest part and 5-10 feet deep was formed. About 175,000 cubic feet of salts were removed. The shape and size of the cavity was determined by a sonar survey.

The wells were cased and cemented into the top of the Salado to prevent water from the near-surface aquifer entering the holes. Presumably these holes were plugged with cement when the project was completed.

OIL AND GAS PRODUCTION

Oil was first produced in Eddy County, N. Mex., from the famous Artesia pool which was discovered in 1924. Since that time there has been a steady increase in the production of oil and gas in southeastern New Mexico. The oil and gas fields in Eddy and Lea Counties are the most productive in New Mexico. As of 1966, the fields in Eddy County had produced almost 197,000,000 bbls (barrels) of oil and 112,000,000 MCF (thousand cubic feet) of gas. The production from Lea County was about 1,700,000,000 bbls of oil and 2,600,000,000 MCF of gas.

Lea County, with more than 60 percent of the total oil and gas sales in the State, ranks first among all counties in the United States in the value of hydrocarbon production. The producing wells are concentrated in an arcuate belt that in general reflects the position of the buried reef that marks the transition zone between the Delaware basin and the northwest shelf area and the central basin platform.

The most productive oil and gas zones are in the Permian rocks lying below the Castile Formation. However, some production has come from upper, middle, and lower Paleozoic strata in the eastern, western, and northeastern part of the area. The producing zones for the oil and gas pools in Eddy and Lea Counties are shown in table 6.

Production in the vicinity of Carlsbad is mostly from rocks of Guadalupian age, particularly the Grayburg and San Andres Formations, from the rocks of Leonardian and Wolfcampian age, and from rocks of Pennsylvanian age. The distribution of wells and developed oil and gas fields as of 1964 are shown on figures 18 and 19. In general, the wells near the west margin of the Delaware basin are 8,000-10,000 feet deep, most of those in the vicinity of the potash mines are from 1,500 to 3,000 feet deep, and many wells are more than 3,000 feet deep. In the more central and eastern part of the basin, the depths of the wells generally are 4,000-14,000 feet. The deepest well in the Delaware basin, drilled 21,275 feet to basement, encountered large reserves of gas condensate in several zones and probably is the first of many wildcats that will be drilled in the relatively unexplored deeper parts of the basin.

Table 6.--Nomenclature of oil- and gas-producing zones, southeastern New Mexico
(From Stipp and others, 1956, p. 29-30.)

SYSTEM	SERIES	STRATIGRAPHIC UNIT Basin	STRATIGRAPHIC UNIT Shelf	LEA COUNTY POOLS	EDDY COUNTY POOLS
PERMIAN	OCHOA	Rustler	Rustler		
PERMIAN	OCHOA	Salado	Salado		
PERMIAN	OCHOA	Castile			Glenn
PERMIAN	Guadalupe	Bell Canyon	Tansill		Hale, Scanlon
PERMIAN	Guadalupe	Bell Canyon	Yates	Arrow, Baish, Corbin, Eaves, Eumont, Gem, Halfway, Jalmat, Lusk, Lynch, North Lynch, Rhodes, San Simon, Teas, Wilson, North Wilson.	Aid, Barber, Benson, Burton (ABD), Cedar Hills, Empire, Getty, Hackberry, Lusk, W. Lusk, P.C.A., Russell, Shugart (Black River, Dark Canyon, Fenton - Delaware Basin Malaga, Santa Nina)
PERMIAN	Guadalupe	Bell Canyon	Seven Rivers	Arrow, Bowers, Cooper Jal, Eaves, Eumont, South Eunice, East Hobbs, Jalmat, Langlie Mattix, Leonard, Tonto, Watkins, West Wilson.	Aid, Angell, Empire, Fren, McMillen, Palmillo (ABD), Turkey Track - Seven Rivers.
PERMIAN	Guadalupe	Cherry Canyon	Queen	Arrow, Caprock, North Caprock, Cooper Jal, Corbin, Dollarhide, Eumont, Langlie Mattix, South Leonard, Pearsall, Penrose Skelly, Young.	Culwin, Grayburg - Jackson, Highlonesome, McMillan, Shugart, North Shugart. Turkey Track, East Turkey Track, Loco Hills - Queen.
PERMIAN	Guadalupe	Cherry Canyon	Grayburg	Arrowhead, Eunice-Monument, Hardy, Hobbs, Maljamar, East Maljamar, North Maljamar, South Maljamar, Penrose Skelly, Roberts, Skaggs, Vacuum, Watkins.	Anderson, Artesia, Cave (ABD), Dayton, East Dayton (ABD), Grayburg-Jackson, South Highlonesome, Leo, Loco Hills, Maljamar, Millman, Premier, Red Lake, Robinson, Square Lake, Turkey Track.
PERMIAN	Guadalupe	Cherry Canyon / Brushy Canyon	San Andres	Eighty Four Draw, Eunice-Monument, Garrett, Hobbs, East Hobbs, House, Littman, Lovington, West Lovington, Maljamar, East Maljamar, North Maljamar, Sawyer, Vacuum.	Anderson, Artesia, Atoka, Dougherity, Forest, Grayburg-Jackson, Grayburg - Keely, Henshaw, South Highlonesome, Loco Hills, Logan Draw, Maljamar, Nichols, Red Lake, Robinson, Square Lake.
PERMIAN	Leonard	Bone Spring	"Glorieta" Sandstone	Justis, Lovington, Monument, Maljamar, Paddock.	
PERMIAN	Leonard	Bone Spring	Yeso, includes Sandy Member	Blinebry, East Hobbs, Monument, Terry.	
PERMIAN	Leonard	Bone Spring	Yeso, includes Sandy Member	Tubb	
PERMIAN	Leonard	Bone Spring	Yeso, includes Sandy Member	Dollarhide, Drinkard, Fowler, Hobbs, House, Nadine, Skaggs, Warren, Weir.	
PERMIAN	Wolfcamp	Abo - Hueco	Abo - Hueco	Anderson Ranch, East Caprock, Denton, D-K, Gladiola, King, Lovington, Townsend, Tulk, Wantz.	
PENNSYLVANIAN				Allison, Bagley, Bough, Cass, Crossroads, Edison, Hightower, Lazy J, East Lovington, Mescalero, Moore, Saunders, South Saunders, Shoe Bar.	
MISSISSIPPIAN		"Mississippi limestone"	"Mississippi limestone"	Denton	
DEVONIAN				Anderson Ranch, Bagley, Bronco East Caprock, Crossroads, Denton, Dollarhide, Echol, North Echol, Gladiola, Hightower, Knowles, South Knowles, Maljamar, Mescalero, Moore, Shoe Bar, Teague.	
SILURIAN		Fusselman	Fusselman	Dollarhide, Fowler, McCormick.	
ORDOVICIAN	Upper	Montoya	Montoya	Cary	
ORDOVICIAN	Middle	Simpson	Simpson	Hare, South Hare, Teague, Warren, North Warren.	
ORDOVICIAN	Lower	Ellenburger	Ellenburger	Brunson, Dollarhide, Fowler, Teague	
PRECAMBRIAN					

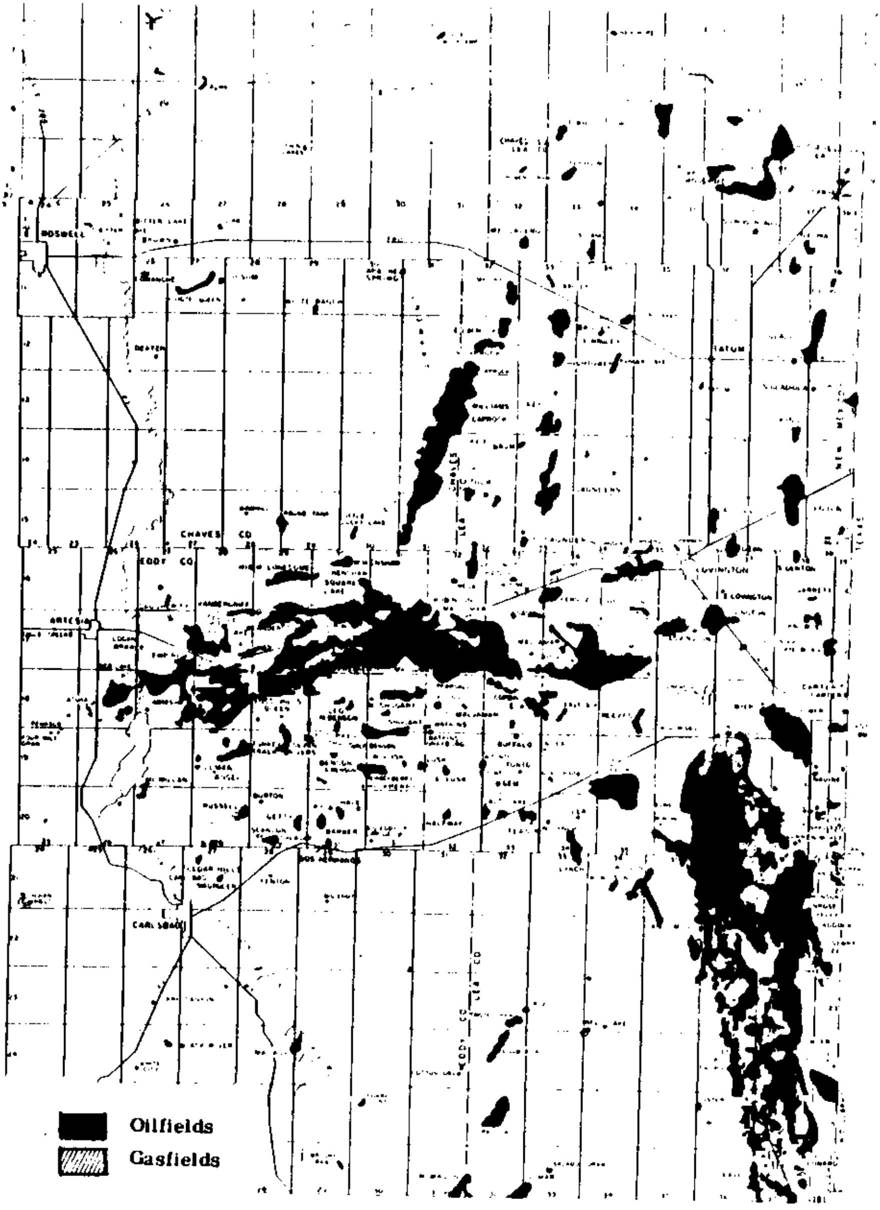

Figure 19. --Map of oil and gas fields in southeastern New Mexico.

Southeastern New Mexico is now a well-established oil- and gas-producing area. The general geology is well known, but unexplored large areas still remain. The search for stratigraphic traps and favorable structures in the deeper parts of the Delaware basin undoubtedly will result in the discovery of new fields. The area will probably continue to be one of the most actively explored areas in the nation because of the high success ratio.

CONCLUSIONS

That part of the Carlsbad potash area in Tps. 21, 22, 23, and 24 S., Rs. 31 and 32 E., has the lowest density of drill holes for potash, oil, and gas, is farthest from the dissolution front in the salt section, has a substantial thickness of consolidated cover above the salt section, and contains the maximum thickness of Salado Formation salt at reasonable depths below the surface. Some of the mined-out potash mines may provide useful storage.

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