# *Economic geology of the Carlsbad potash district, New Mexico*

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# ECONOMIC GEOLOGY OF THE CARLSBAD POTASH DISTRICT, NEW MEXICO

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**Abstract**—New Mexico produced 83% of domestic potash and 27% of domestic consumption in 1992. Fertilizer used 95% of U.S. production; 5% was used in chemicals. The potash industry of New Mexico produces sylvite (KCI), langbeinite ($K_2SO_42Mg(SO4)_2$) and artificial $K_250_4$. Sylvite grade in New Mexico decreased from 20-25% $K_20$ in the 1950s to about 14% today. The average grade of langbeinite (first produced in 1940) remains 8-10% $K_20$. Reserves in the Known Potash Leasing Area (KPLA) will sustain production for 25 to 35 years and represent 57% of domestic reserves. Potash horizons extend far outside the KPLA, but none are economic. Commercial potash occurs in the middle or McNutt Member of the Salado Formation (Upper Permian Ochoan Stage). The potash distribution in the Salado is asymmetrical, suggesting a reflux model related to a bar-restricted marine embayment with dense brine underflow toward the bar. The dominantly seawater brine was magnesium-rich, producing primary carnallite or polyhalite, later recycled into the modern complex salt assemblage. The 400–ft-thick McNutt Member dips about I° east and contains 11 of 12 potential ore zones in the Salado. Potash zones are 3-10 ft thick and contain minable sylvite and/or langbeinite, together with halite and accessory minerals. The zones are consistent laterally, but are locally interrupted by barren halite (salt horses) formed later by undersaturated migrating fluids. Room-and-pillar mining, with pulled pillars, recovers >90% of the potash from depths ranging from 885 to 1400 ft by continuous-mining coal equipment or drilling and blasting. Beneficiation is by various separation, flotation, crystallization, leaching and heavy-media circuits optimized for each ore. The mineralogy and proportion of clay minerals, up to 7% of the ore, influence optimum milling procedures and ore grade cutoff. Agriculture, petroleum and nuclear waste disposal affect production of potash from southeastern New Mexico. Agricultural demand for fertilizer is a complex interaction between weather and climate, advances in crop genetics, soil science, farming practices, GNP of importing nations, farm income, population growth, efficient distribution systems, freight rates and backhauls, substitutes, taxes and tariffs. Petroleum companies compete for petroleum under potash and the Waste Isolation Pilot Project (WIPP) led to withdrawal of potash reserves.

## INTRODUCTION

Potash is the common industrial term for potassium in various combinations with sodium, magnesium, chloride and sulfate (Table 1). Potassium is one of the three essential plant nutrients; it is the "K" in the "NPK" fertilizer rating, with nitrogen (N) and phosphorus (P). The potassium in potash is reported as $K_20$ eq. wt % ($K_20$ hereafter), although potassium oxide is not directly present in natural potassium salts (Table 2). For potash fertilizers, $K_20$ is closest chemically to the form of potassium used by plants (Sullivan and Michael, 1986) and is the best means to compare fairly the diverse mineralogy of potash.

Important natural, commercial, soluble potassium salts are sylvite and langbeinite. Sylvinite, a mixture of sylvite and halite, is the typical ore mined in the Carlsbad Potash District (CPD) in southeastern New Mexico (Fig. I). The CPD is near the northeastern border of the Delaware basin (Fig. 1) and contains the largest domestic potash reserves. Soluble potash occurs primarily in Eddy and Lea Counties, which contain the only potash mines in the state. The Potash Enclave (Fig. 2), also designated the Known Potash Leasing Area (KPLA), consists of part of the CPD where federal and state lands require competitive bidding for mineral leases under BLM management.

The KPLA lies between Carlsbad and Hobbs, and comprises about 425 mi2 (Cheeseman, 1978). The area underlain by other salts and less soluble potash minerals, such as polyhalite, is much larger than the KPLA (Fig. I). The Salado Formation underlies about 58,000 mi2, halite about 37,000 mi2 and polyhalite about 27,000 mi1 (Jones, 1972). Areal limits of the CPD are determined by drilling to the north, east and south. The CPD is bounded on the west by dissolution truncation of shallow Salado evaporites by circulating ground water in the Pecos River drainage basin (Griswold, 1982).

Potassium products (Table 2) from New Mexico are muriate of potash (KCI; also called MOP, muriate or sylvite by industry), langbeinite (K,SO4·2Mg(SO4)2, called sulfate of potash magnesia or SOPM) and manufactured potassium sulfate (K2504, called sulfate-of-potash or SOP). MOP, sold in various grades (Table 3), comprises about 70% of New Mexico potash output; SOPM and SOP account for the remaining 30%. IMC Fertilizer (IMC), the largest producer in the CPD, supplies all

three types of soluble potash salts (Table 2); other producers are more specialized.

The United States ranked fourth in world potash production (1.94 million st) in 1992. New Mexico accounted for about 83% of domestic production (1.61 million st), supplied about 27% of domestic consumption (Table 4) and has about 57% of domestic reserves (Searls,

TABLE 1. Evaporite minerals and rocks of the Carlsbad Potash District (after Griswold, 1982).

| Mineral or Rock | Formula | Equivalent wt % | | | |
|---|---|---|---|---|---|
| | | K | KCl | $K_2O$ | $K_2SO_4$ |
| Anhydrite* | $CaSO_4$ | -- | -- | -- | -- |
| Arcanite | $K_2SO_4$ | 44.88 | -- | 54.06 | 100.00 |
| Bischofite | $MgCl_2 \cdot 6H_2O$ | -- | -- | -- | -- |
| Bloedite | $Na_2SO_4 \cdot MgSO_4 \cdot 4H_2O$ | -- | -- | -- | -- |
| Carnallite* | $KCl \cdot MgCl_2 \cdot 6H_2O$ | 14.07 | 26.83 | 16.95 | -- |
| Erytrosiderite | $2KCl \cdot FeCl_3 \cdot H_2O$ | 23.75 | 45.28 | 28.61 | -- |
| Glaserite | $K_3Na(SO_4)_2$ | 35.29 | -- | 42.51 | 78.63 |
| Glauberite | $Na_2SO_4 \cdot CaSO_4$ | -- | -- | -- | -- |
| Gypsum* | $CaSO_4 \cdot 2H_2O$ | -- | -- | -- | -- |
| Halite* | $NaCl$ | -- | -- | -- | -- |
| Hydrophilite | $KCl \cdot CaCl_2 \cdot 6H_2O$ | 13.32 | 25.39 | 16.04 | -- |
| Kainite* | $MgSO_4 \cdot KCl \cdot 3H_2O$ | 15.71 | 29.94 | 18.92 | -- |
| Kieserite* | $MgSO_4 \cdot H_2O$ | -- | -- | -- | -- |
| Langbeinite* | $K_2SO_4 \cdot 2MgSO_4$ | 18.84 | -- | 22.70 | 41.99 |
| Leonite* | $K_2SO_4 \cdot MgSO_4 \cdot 4H_2O$ | 21.33 | -- | 25.69 | 47.52 |
| Mirabilite | $Na_2SO_4 \cdot 10H_2O$ | -- | -- | -- | -- |
| Polyhalite* | $K_2SO_4 \cdot MgSO_4 \cdot 2CASO_4 \cdot 2H_2O$ | 12.97 | -- | 15.62 | 28.90 |
| Schoenite | $K_2SO_4 \cdot MgSO_4 \cdot 6H_2O$ | 19.42 | -- | 23.39 | 43.27 |
| Sylvinite* | $KCl + NaCl$ | -- | -- | 10-35 | -- |
| Sylvite* | $KCl$ | 52.44 | 100.00 | 63.17 | -- |
| Syngenite | $K_2SO_4 \cdot CaSO_4 \cdot H_2O$ | 23.81 | -- | 28.68 | 53.06 |
| Tachyhydrite | $CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O$ | -- | -- | -- | -- |

Only sylvite and langbeinite are presently ore minerals. Hydrated potassium minerals are not amenable to existing concentration methods.
*Common minerals and rocks in the Carlsbad Potash District.

TABLE 2. K₂O equivalent wt. % of commercial potash minerals (after Searls, 1985; Adams and Hite, 1983; and Sullivan and Michael, 1986).

| Chemical Compound | Chemical Formula | Mineral Name | Industry Name | Max $K_2O$ Eq. wt % | Grades $K_2O$ Eq. wt % | Remarks |
|---|---|---|---|---|---|---|
| Potassium chloride | KCl | sylvite | MOP, sylvite, muriate | 63.18 | 61% (USA) 60% ⌉ 50% ⊢ World 40% ⌋ 30% | Coarse grades used to match sizes N-P ingredients to minimize segregation |
| Potassium chloride + sodium chloride | KCl+NaCl | "sylvinite" | --- | ≈35 | --- | Easily mined with continuous miners |
| Potassium/magnesium double sulfate | $2MgSO_4 \cdot K_2SO_4$ | langbeinite | SOPM, sulfate of potash magnesia | 22.70 | 22% 21.5% | Preferred for tobacco, paper, potato, sugar beet, and citrus crops to prevent chloride burn; harder to mine than chlorides |
| Potassium sulfate | $K_2SO_4$ | arcanite | SOP | 54.06 | 50% | Preferred for tobacco, paper, potato, sugar beet and citrus crops to prevent chloride burn; mostly manufactured, some natural |
| Potassium nitrate | $K_2NO_3$ | nitre | --- | --- | --- | Natural is only 14% $K_2O$ (admixture) crude salt mixed with $NaNO_3$; mostly manufactured, some natural |
| Potassium chloride | KCl | manure salts | --- | 19 | --- | Manufactured |
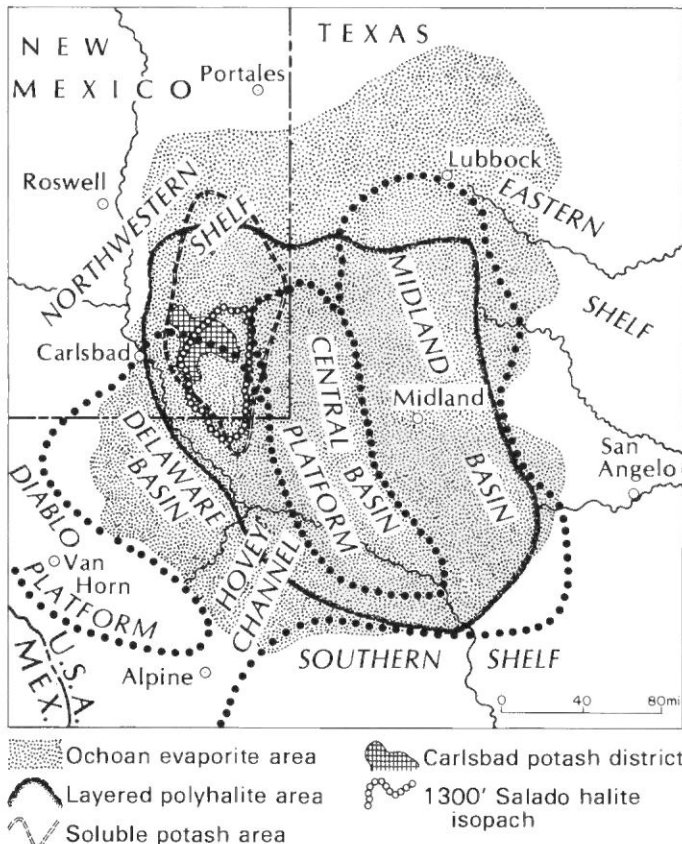


FIGURE 1. Location of the Carlsbad Potash District in the southwestern United States and its relation to the regional subsurface geology (after Lowenstein, 1988; Austin, 1980; Jones, 1972).



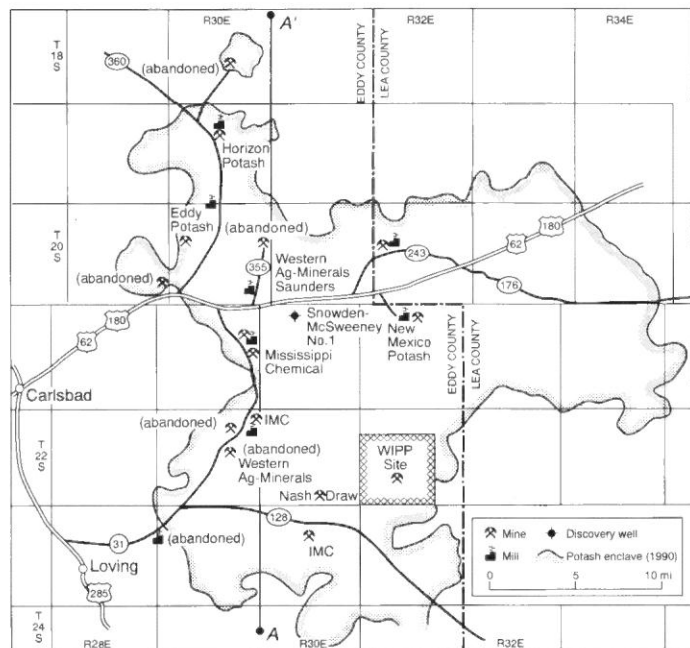FIGURE 2. Active, inactive and abandoned potash facilities in Eddy and Lea Counties, southeastern New Mexico showing general outline of the Potash Enclave (KPLA) as of 1984. Only minor adjustments have occurred since (oral comm., U.S. Bureau of Land Management, Minerals Management Service, June 1990). Cross section shown in Fig. 3 (A-A′) is approximately along the east side of R30E (north) and R29E (south).

TABLE 3. Particle-size grades of muriate of potash (MOP, muriate, sylvite), langbeinite (SOPM) and sulfate of potash (SOP) products (after Searls, 1985).

| Grade | Minimum K₂O equiv. wt. % | Approximate particle size range[1] | | Type of potash | Remarks |
|-------|------------|------|-------------|----------------|---------|
|       |            | Mesh[2] | Millimeters |                |         |
| Granular | 61, 50, 22 | 6-20 | 3.35-0.85 | Muriate & sulfates | --- |
| Blend[3] | 60 | 6-14 | 3.35-1.18 | Muriate | Replaces granular and coarse grades |
| Coarse | 60 | 8-28 | 2.4-0.6 | Muriate | --- |
| Standard | 60, 50, 22 | 14-65 | 1.2-0.21 | Muriate & sulfates | --- |
| Special Standard | 60 | 35-150 | 0.4-0.11 | Muriate & sulfate | Canada only |
| Soluble/Suspension | 62 | 35-150 | 0.4 - 0.11 | Muriate | --- |
| Chemical | 63 | NA | NA | Muriate | --- |

[1]From approximately 2% to 98% by wt. % cumulative
[2]Tyler standard
[3]blend = new grade with midpoint between 8 and 10 mesh introduced by Canadian producers
NA = not applicable

1993). The remaining 73% of consumption was imported primarily (91%) from Saskatchewan, Canada. Domestic potash production is composed of about 75% as muriate, 20% as sulfate or langbeinite and 5% in other forms (Searls, 1993). About 95% of soluble potash minerals are used in fertilizer, so potash trends closely parallel agricultural supply and demand (Searls, 1993). Most of the additional 5% is used in chemicals (O'Driscoll, 1990), mainly aqueous electrolysis of potash to po-. tassium hydroxide. Potassium chemicals are used in medicines, pharmaceuticals, salt substitutes, soap, matches, glass and storage batteries.

## HISTORY

The following discussion of potash mining history draws heavily on Walls (1985) and on Williams-Stroud et al. (1993). Early large scale use of potash started in Germany in the mid-nineteenth century. The modern U.S. potash industry is primarily a product of a World War I embargo on German potash—the only large source—that drove prices to over $500/st. Wartime potash (for saltpeter) was produced at over 100 plants, mainly in Nebraska and California, each with very small output. Bedded potash was discovered in 1925 in Eddy County, NM, in Snowden McSweeney Well No. I on a V. H. McNutt permit near the center of the mined portion of the KPLA (Fig. 2; T2 IS, R30E).

Potash was cored in April 1926 and the Federal Potash Exploration Act was passed in June.

The American Potash Co. was formed in 1926 for potash exploration in southeastern New Mexico. A 1062-ft shaft was started in December 1929 and completed in 1930, and the first commercial potash from New Mexico was shipped in March 1931. Assets of American Potash, incorporated in 1930 as United States Potash Co., are owned by Mississippi Chemical Corp. (Table 5). The Potash Company of America (PCA) formed in 1931 and completed a shaft in early 1934. The Santa Fe Railroad constructed a 20-mi spur from Carlsbad to the mine; later spurs were run to other mines and mills. The PCA mine is now operated by Eddy County Potash. By 1934, at least II companies were exploring for potash in southeastern New Mexico. In 1936, Union Potash & Chemical Co., Texas Potash Co., Independent Potash & Chemical Co., New Mexico Potash Co. and the Carlsbad Potash Co. merged into what is now IMC Fertilizer, Inc. and began producing sylvite, langbeinite and $K_2SO$., in 1940.

Domestic production supplied virtually all potash in the United States between 1941 and 1949. New Mexico produced about 1,000,000 st of marketable potash containing 525,000 st of $K_2O$ in 1941. New Mexico was the largest domestic potash producer in 1944, furnishing 85% of U.S. consumption. In 1949, active exploration by several companies

TABLE 4. Potash statistics for calendar years 1980 to 1992 (data modified from J. P. Searls, U.S. Bureau of Mines, oral comm. June 1990 and June 1993, and U.S. Bureau of Mines Mineral Commodity Reports, Mineral Commodity Profiles and Mineral Yearbooks (1980–1993).

| Calendar Year | Marketable U.S. Production (1000 st) | N.M. Share of U.S. Production (%) | N.M. Share of U.S. Consumption (%) | Apparent U.S. Consumpt. (1000 st) | Import Reliance (%) | Avg. Price marketable potash ($/st K₂O) | Value U.S. production of marketable potash FOB mine (million $) |
|------|-------|----|----|-------|----|-------|-----|
| 1980 | 2,468 | 83 | 29 | 6,999 | 71 | $152 | 375 |
| 1981 | 2,377 | 84 | 29 | 6,849 | 71 | $154 | 365 |
| 1982 | 1,967 | 82 | 29 | 5,647 | 71 | $127 | 250 |
| 1983 | 1,575 | 87 | 24 | 5,699 | 76 | $121 | 190 |
| 1984 | 1,724 | 90 | 23 | 6,638 | 77 | $145 | 250 |
| 1985 | 1,429 | 87 | 21 | 5,904 | 79 | $129 | 185 |
| 1986 | 1,325 | 82 | 20 | 5,338 | 80 | $106 | 140 |
| 1987 | 1,391 | 87 | 22 | 5,609 | 78 | $119 | 165 |
| 1988 | 1,677 | 89 | 26 | 5,803 | 74 | $155 | 260 |
| 1989 | 1,758 | 89 | 28 | 5,678 | 72 | $159 | 280 |
| 1990 | 1,888 | 89 | 28 | 6,012 | 72 | $138 | 260 |
| 1991 | 1,928 | 85 | 28 | 5,778 | 72 | $158 | 305 |
| 1992* | 1,879 | 83 | 27 | 5,852 | 73 | $172 | 323 |

*Estimates by J. P. Searls, U.S. Bureau of Mines.

TABLE 5. Changes in potash property ownership in the Carlsbad Potash District since the mid-1980s.

| Circa 1985 | | Circa 1992 |
|---|---|---|
| AMAX | --------------------------------> | Horizon Potash |
| Duval | --------------------------------> | Western Ag-Minerals |
| IMC | --------------------------------> | IMC Fertilizer |
| Kerr McGee | --------------------------------> | New Mexico Potash |
| Mississippi Chemical | ----------------------> | Mississippi Chemical |
| National Potash | --------------------------------> | Mississippi Chemical* |
| PCA -------> Ideal Basic ------> Lundberg ----> | | Eddy Potash |

*Operates compactor and loading facilities on site only

resulted in production in 1951 by Duval Texas Sulfur Co. via two mine shafts at the Wills-Weaver property. The potash operations of Duval are now Western Ag-Minerals. Southwest Potash Corp., now controlled by Horizon Potash Corp., began operation in 1952. The shaft of National Potash Co. (now Mississippi Chemical Corp.) in Lea County, NM, was completed in 1956 and production started in 1957. The Kerr-McGee facility, completed in 1957, delayed operation until 1965 and is now New Mexico Potash Corp.

Minable potash was discovered in Saskatchewan, Canada, in 1952, but many factors prevented major production until the late 1950s with exports to the United States commencing in 1962. In 1964, U.S. domestic consumption exceeded domestic production permanently. The highest production year for New Mexico potash was 5.7 million st KCl or 3.3 million st $K_2O$ in 1966. Production has decreased steadily as lower-cost Canadian potash has supplied an increasing share of U.S. potash consumption. The cross-over years were 1970 and 1971, when imports first exceeded domestic production. A low of 1.3 million st of $K_2O$ was produced in 1986 in the United States. Overall U.S. potash capacity utilization declined from 83% (1984) to 61% (1985); this is significant because total capacity also declined during this period.

A dumping finding against Canadian producers by the International Trade Commission in 1987 and the 1988 antidumping agreement between the U.S. Department of Commerce and Canadian producers reversed the downward trend and revitalized the industry in New Mexico. Mississippi Chemical was reactivated in 1988 after several years on standby. Price increases after the 1988 antidumping agreement with Canada allowed AMAX to continue operation until its mine was purchased by Horizon in 1992 and has increased reserves at other properties in the Carlsbad Potash District. Large exports by the former USSR has again depressed prices and demand in 1992-93. The impact of Canadian, Russian and other competition, declining reserves and grades and
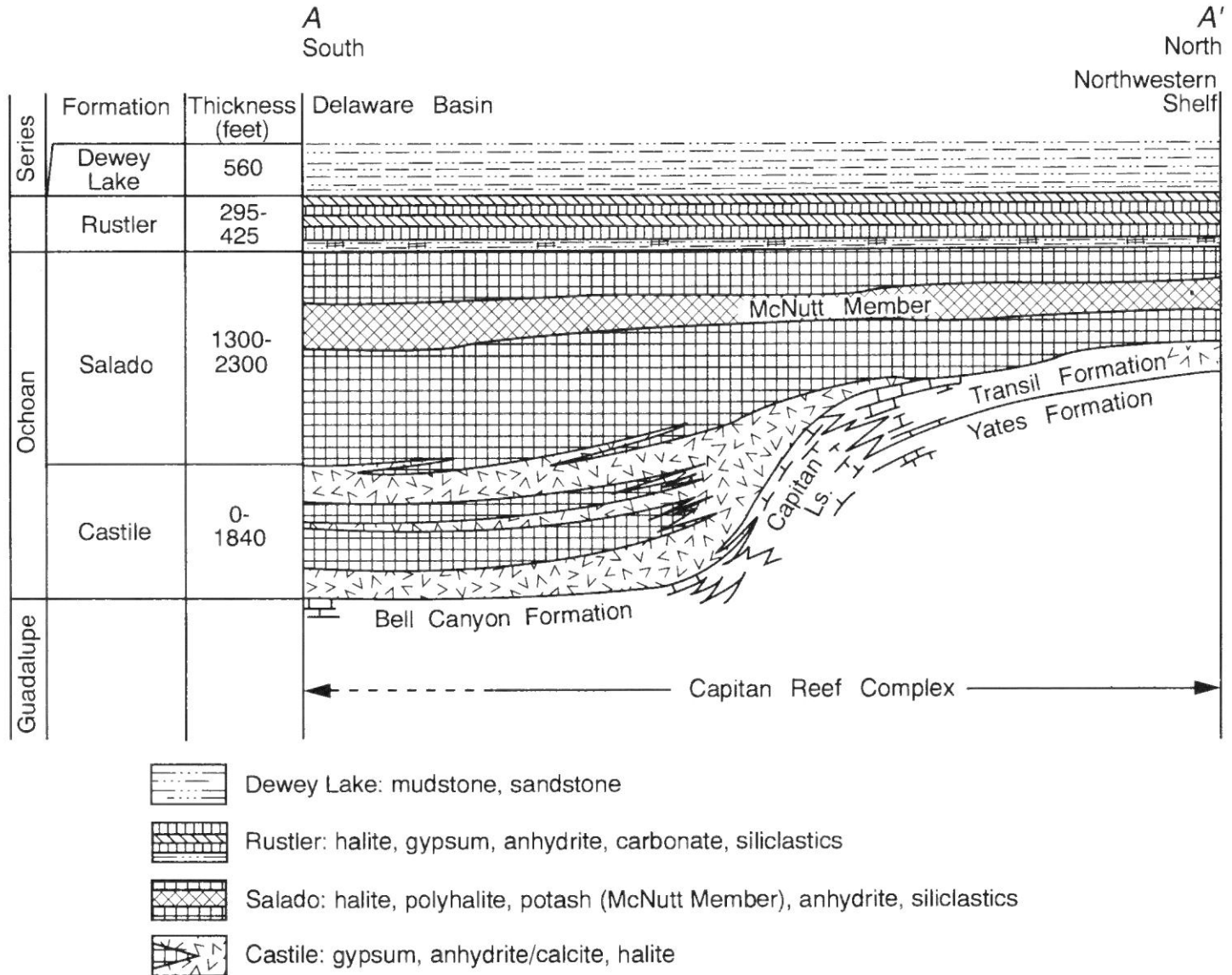


FIGURE 3. Diagrammatic north-south cross section (A-A' on Fig. 2) and stratigraphic relationships of the northern edge of the Delaware Basin, southeastern New Mexico (after Austin, 1980; Jones, 1972).

increased mining costs, led to many changes in ownership since 1985. Only Mississippi Chemical and IMC remain of the older companies (Table 5).

## GEOLOGY
### Overview

Potash-bearing evaporites occur in Ochoan (Upper Permian) marine rocks in the Delaware basin portion of the Permian basin of west Texas and southeast New Mexico. The Ochoan includes four formations (Fig. 3; Lowenstein, 1988): (1) the Castile Formation (oldest)—halite and banded anhydrite/limestone; (2) the Salado Formation—potash (mainly the McNutt Member), halite, muddy halite, anhydrite, polyhalite, dolostone and mudstone; (3) the Rustler Formation—halite, gypsum, anhydrite, siliclastic rocks, dolostone and limestone and (4) the Dewey Lake redbeds (youngest)—siliclastic mudstone and sandstone. The Castile and basal portions of the Salado have extensive sections of laminated limestone/anhydrite cyclic couplets or "banding" (Madsen and Raup, 1988). Anhydrite interbeds in the Salado show extensive lateral con

tinuity, although often replaced by polyhalite, allowing recognition of 43 marker beds in the CPD (Jones et al., 1960).

The Salado Formation, up to a maximum of 2200 ft thick, is an evaporite sequence dominated by 650 to 1300 ft of halite and muddy halite in the Potash Enclave (Lowenstein, 1988). It hosts 12 ore zones, 1 I in the middle or McNutt Member (Fig. 4) and the 12th in the upper member. The area underlain by the 12 ore zones is about 1900 mi$^2$ (Lowenstein, 1988; Jones, 1972). The Salado Formation represents repeated cyclic drawdown and brine concentration in a shallow, marginal-marine basin with an intermittent inlet (Hovey Channel) to the southwest (Fig. 1). The Salado Formation and McNutt Member exhibit vertical stacks of two cycles (Type I and II; Fig. 5) on a larger scale (Lowenstein, 1988) than cycles in the Castile. Potash salts are not included in the cycles because they are secondary, as shown by their displacive and crosscutting textures and distribution independent of host lithology (Lowenstein, 1988). Relative subsidence was necessary to allow the stacks to develop at least 46 Type I cycles in the Salado (Jones et al., 1960).
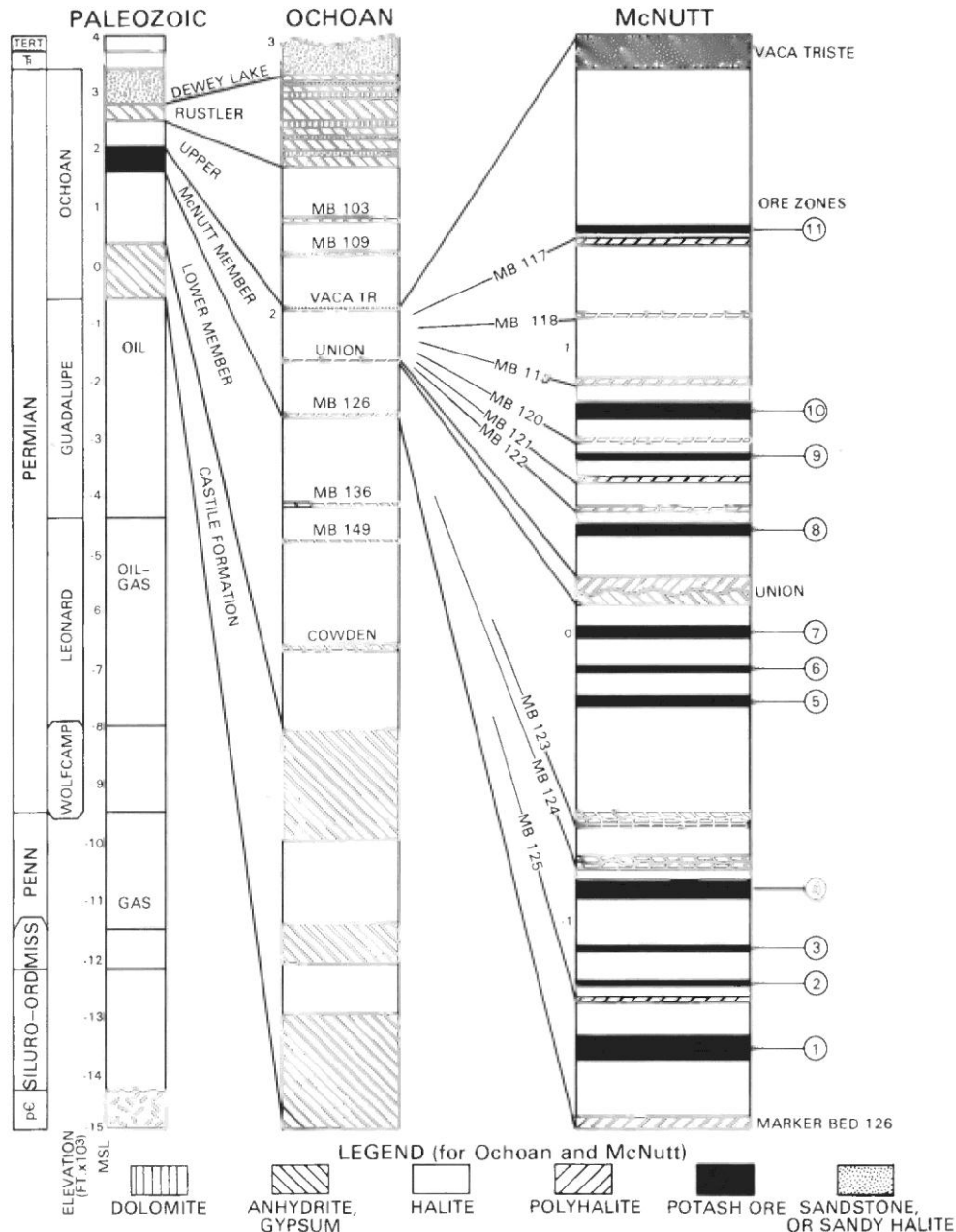


FIGURE 4. Regional stratigraphic column with expanded sections of the Ochoan Evaporite and McNutt Member of the Salado Formation (after Griswold, 1982).
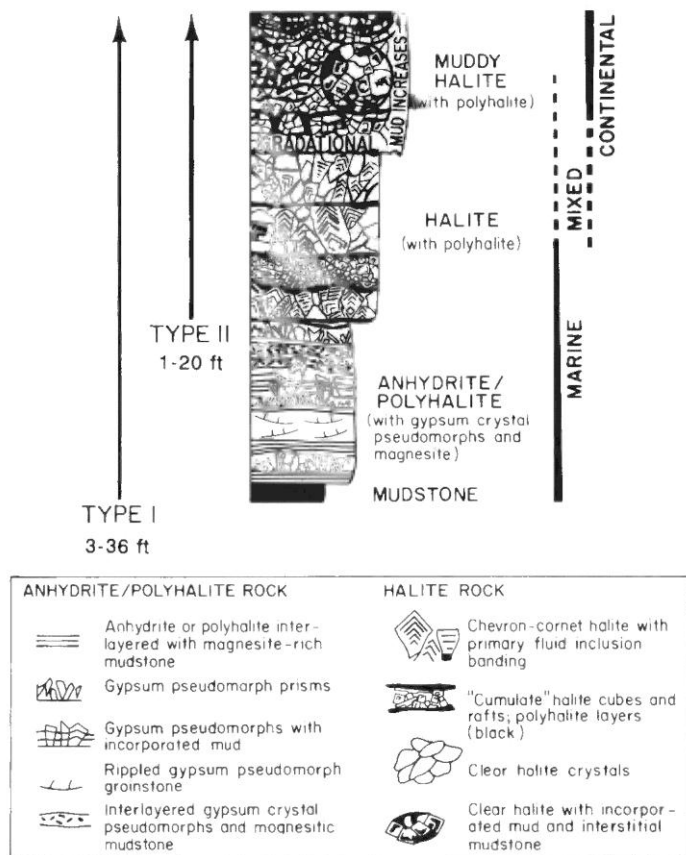
FIGURE 5. Vertical cyclic sequences in the McNutt Member of the Salado Formation, with diagnostic sedimentary structures and textures and interpreted inflow waters (after Lowenstein, 1988).

The Type I cycle in the Salado is marine dominated (seawater) and consists of an upward sequence, 3-36 ft thick, of calcareous/siliclastic mudstone, anhydrite/polyhalite after gypsum, halite and muddy halite. These record basin shallowing and brine concentration upward during progression from a stratified perennial lake or lagoon to a shallow ephemeral saline lake. The Type I cycle is related to sea level rise relative to the Salado basin and is not as common as Type **11** cycles (Lowenstein, 1988).

The Type ll cycle is mainly continental (meteoric water) with some seawater from seepage or residual brines (brackish water). A Type II cycle is related to a drop in sea level and is volumetrically more important and more numerous than Type I cycles. It is 1-20 ft thick and consists of halite grading upward into muddy halite. One or more Type II cycles separate Type I cycles, yielding vertically stacked sedimentary packets representing a maximum time interval of $10^5$ yrs per cycle. The Type Il cycle is similar to the upper portion of a Type I cycle. The Type Il shows no evidence of prolonged subaqueous exposure compared to Type I and has no anhydrite-gypsum, polyhalite or mudstone layers. The cumulative thickness of Type II exceeds that of Type I in the McNutt (Lowenstein, 1988).

The possible occurrence of minable potash salts in other parts of New Mexico, particularly in the Salado Formation, is not a strong possibility. Austin (1980) and others confirmed the presence of potash salts in the Salado Formation outside the KPLA, but found neither the quantity nor the required mineralogy to be exploitable. This limitation could change, particularly if companies employ solution-mining or other advanced techniques.

## McNutt Member

The McNutt Member of the Salado dips about 1° to the east within the Carlsbad Potash District and is about 400 ft thick (Griswold, 1982).

The McNutt contains evaporite minerals consisting of sylvite and langbeinite, together with halite, muddy halite and accessory leonite, kainite, carnallite, polyhalite, kieserite, bloedite and anhydrite (Table 1). In addition, the McNutt Member consists of nonevaporite minerals such as primary alkali feldspar, hematite, and quartz, and secondary magnesite, illite, clinochlore, talc, talc-saponite, corrensite and a continuum from very uniform to completely random interstratified clinochlore-saponite (Lowenstein, 1988; Bodine 1978). All clay minerals appear to be well crystallized, with sharp x-ray diffraction maxima. The characteristic illite-kaolinite-dioctahedral smectite assemblage of normal clay-mineral detritus reacted extensively with evaporite brines and recrystallized into trioctahedral clay assemblages by incorporating magnesium from brines during transport and after deposition from migrating fluids (Bodine, 1978).

Mudstone and siliclastic sediment in the muddy halite of the McNutt Member were derived from erosion of the surrounding basin margin dominantly to the north and east (Lowenstein, 1988). Lowenstein (1988) confirmed previous observations that the present potash salts formed later than the primary evaporite cycles and their overall distribution is independent of host lithology.

Potash ore zones are 3-10 ft thick and are laterally consistent except where interrupted by salt horses, collapse features (Bachman, 1984) and igneous dikes (Calzia and Hiss, 1978). Original finely detailed sedimentary features are mostly obliterated by postdepositional authigenesis and recrystallization (Griswold, 1982). Commercial deposits were created in some localities by undersaturated fluids moving through the zones, but in other areas late fluids have destroyed ore, producing barren halite (salt horses). The McNutt Member is absent in the subsurface just west of the present mines (Fig. 2).

Ore zone 1 (Fig. 4) accounted for about 80% of past potash production, but it is essentially mined out at currently economic depths. Production is now chiefly from ore zones 3, 4, 5 and 10, which successively overlie zone 1. Mine levels in zone 7 are on standby. Langbeinite is produced from mixed sylvite and langbeinite ores in zones 4 and 5 (Table 6; Harben and Bates, 1990). Near the shallow westem boundary of the KPLA, only ore zone 1, stratigraphically lowest, oldest and richest in potash, has not been removed. A typical mixed ore from the Salado in the CPD contains 60% halite and 30% sylvite (usually together as sylvinite), with 5% langbeinite, 2% polyhalite and 2% insolubles (Cheeseman, 1978).

The average sylvite ore grade in New Mexico decreased from 25-30% $K_2O$ in the 1950s to about 14% today; langbeinite ore now averages 8-10% $K_2O$. Potash ore reserves are large within the district and should last for at least 25 to 35 years (Table 7) at current extraction rates. Mississippi Chemical reports reserves that will last much longer. Other properties, such as Horizon Potash, are closer to exhaustion under 1993 potash market conditions.

## OVERVIEW OF POTASH-EVAPORITE ORIGIN

The majority of potash-bearing bedded salt deposits originate from evaporation of either seawater or mixtures of seawater and other brines in restricted marine basins (Schmalz, 1969). The brine depth in an ancient evaporite basin underwent fluctuations related to sea level, ground-water inflow, precipitation and meteoric runoff. Saline minerals could be deposited in deep or shallow water, sometimes including subaerial exposure (Williams-Stroud et al., 1993).

During evaporation of normal seawater, carnallite ($KCl \cdot MgCl_2.6H_2O$) rather than sylvite (KCI) precipitates due to the high concentration of magnesium in seawater. Potash ore zones often are near the tops of halite beds in relatively thin layers because the potash is precipitated from brines of higher salinities occurring near the end of the evaporation sequence and later than halite beds. The sodium-to-potash ratio in seawater is about 27:1 so halite is highly abundant compared to potash. Carnallite in a salt sequence can be altered to sylvite by the reaction of magnesium-poor brine or meteoric water. In many instances, this diagenetic process occurs shortly after deposition of the carnallite layer, as in the case of potash deposits in Thailand (Hite, 1982). However, mixing of marine brines with other brines or with meteoric water may

TABLE 6. General mineralogy and minability of ore zones with presently producing companies in the Carlsbad Potash District (after Griswold, 1982; Searls, oral comm. June 1990).

| Ore zone | Marker bed near base* | General mineralogy | Producing company | Minability |
|---|---|---|---|---|
| Eleventh | MB 117 | Mostly carnallite, minor sylvite, leonite | ----- | Not commercial to date |
| Tenth | MB 120 | Sylvite, sylvinite | New Mexico Potash, IMCF | Second best in the district; high-clay content (6-7%) |
| Ninth | MB 121 | Carnallite, kieserite, sylvite | ----- | Not commercial to date |
| Eighth | Union | Sylvite | ----- | Moderate reserves; important in future; high clay |
| Seventh | ----- | Sylvite, sylvinite | Mississippi Chemical | Moderate reserves; moderate clay (3-4%) |
| Sixth | ----- | Carnallite, kieserite, etc. | ----- | Not commercial to date |
| Fifth | MB 123 | Sylvite, langbeinite | IMCF | Moderate reserves; trace clay (1%) |
| Fourth | ----- | Langbeinite, sylvite | IMCF, Western Ag-Minerals | Principal source of langbeinite; mixed ore |
| Third | ----- | Sylvite, sylvinite | Horizon, Eddy Potash | Ranks 3rd in production of sylvite |
| Second | MB 125 | Carnallite, kieserite, etc. | ----- | Not commercial to date |
| First | MB 126 | Sylvite, sylvinite | Eddy Potash | Was the major sylvite-producing zone, now nearly mined out |

*Base of marker bed; see Figure 4

produce evaporite deposits without carnallite. Nonmarine evaporite deposits are known with minerals very similar to those in marine evaporites (Lowenstein et al., 1989) yielding further complication.

Most subbasins of high-grade potash salts are found near the basin center surrounded by successively less soluble salt facies (symmetrical model), but some potash is restricted to the margins of the basin (asymmetrical model). An asymmetrical evaporite distribution, such as that in the Ochoan Delaware basin, could be formed by the reflux model

TABLE 7. Active potash mines in New Mexico, showing estimated capacity, average ore grade and mine life at the average 1992 price of $81.14/st product (J. P. Searls, U.S. Bureau of Mines, oral comm. 1993).

| Operator | County | Product Capacity (st/yr[1]) | Ore grade (% K$_2$O) | Mine life (yrs) |
|---|---|---|---|---|
| Eddy Potash Inc.[2] | Eddy | 550,000 | 18 | 4 |
| Horizon Potash Co. | Eddy | 450,000 | 12 | 6 |
| IMC Fertilizer, Inc. | Eddy | 1,000,000[3] | 11[3] | 33 |
| Mississippi Chemical | Eddy | 300,000 | 15 | 125 |
| New Mexico Potash[2] | Eddy | 450,000 | 14 | 25 |
| Western Ag-Minerals[4] | Eddy | 400,000 | 8[5] | 30 |

[1]May not be operating at full capacity
[2]Owned by Trans-Resource, Inc.
[3]Muriate, langbeinite, and sulfate combined
[4]Owned by Rayrock Resources of Canada
[5]Langbeinite only

as first described by Ochsenius (1888) and others later (Lowenstein, 1988).

In the reflux model, a shallow bar, or sill, across the mouth of the basin (proximal end) restricts the flow of seawater, which evaporates into a salt-precipitating brine. The dense brine, with maximum concentration at the distal end, sinks to the bottom and sets up an undercurrent of higher density brine back toward the proximal (sill) end. The sill, which restricts the inflow of seawater, allows inhibited flow of evaporation-concentrated brines back to the ocean. The least soluble salts are precipitated toward the sill and the most soluble components precipitate in the deeper parts of the basin. The result is lateral facies changes in a tabular deposit that are due to the asymmetrical salinity gradients in the brine.

The soluble potassium salts of the Salado Formation and the McNutt Member formed by recycling of either primary carnallite or polyhalite, by migrating Mg- and Ca-poor fluids (Bodine, 1978), or by reactions in place based on changing brine composition, pressure or temperature. Thus, neither ore minerals, such as sylvite and langbeinite, nor most gangue potash minerals, such as leonite or kainite, are primary in the Salado. Alteration of evaporites is complex and may be syndepositional, postdepositional or retrograde (Suwanich, 1991). Petrographic and textural relationships and chemical analysis of fluid inclusions of associated halite in potash evaporites suggest that sylvite is primary in some basins (Lowenstein and Spencer, 1990; Wardlaw, 1972). If so, magnesium in the brines must have been removed, perhaps due to the enrichment of calcium from other brines. Enrichment of seawater with respect to calcium will result in early depletion of sulfate with gypsum/anhydrite precipitation and will prevent deposition of magnesium sulfates by restricting available sulfate. The magnesium sulfate-poor potash deposits probably precipitated from brines that were high in calcium and constitute 60% or more of known potash basins (Hardie, 1991) although the Salado represents magnesium-rich potash deposition.

## MINING

The high solubility of potash ores under New Mexico climates limits them to the subsurface, hence all mines in the CPD are underground. Mine depths range from about 885 to 1400 ft. These room-and-pillar mines are relatively clean, dry and orderly because the beds being exploited are relatively shallow, regular, tabular and nearly flat. Room-and-pillar mining is flexible and allows selective mining (Sullivan and Michael, 1986) so salt horses are easily bypassed and ore grade control is good. The location of barren salt horses is unpredictable, but they comprise up to 10% of the ore horizons and must be avoided. Low concentrations of methane are rarely encountered but relief holes are drilled in ceilings to dissipate nitrogen (Williams-Stroud et al., in press). All mines in the CPD consist of at least two shafts for safety and ventilation, and older mines have three or more shafts because working faces are now 3-5 mi from the main shaft (Searls, 1985).

Continuous mining equipment adapted from coal mining is used to mine most potash ore, although blasting is increasingly used. Beds as thin as 4 ft are mined with mechanical mining machines called drum miners. Some harder ores, particularly langbeinite, require mechanical undercutters to prepare the working face for drilling and blasting, usually with ANFO (ammonium nitrate and fuel oil). In all cases, mechanical loaders, underground crushers and conveyor belts are used to handle broken ore. Room-and-pillar methods remove 60-75% of the ore during initial mining. Subsequent removal of most of the support pillars allows extraction to exceed 90% (Sullivan and Michael, 1986).

## MILLING

Mills in the CPD produce potash by combinations of separation, flotation, crystallization, leaching and heavy media circuits related to specific ore. Output from these circuits is dried in fluid bed or rotary dryers and sized over screens to yield final products. Potash ore is ground to break up sylvite-halite agglomerates (Searls, 1985) followed by froth flotation (Fig. 6). Frothers such as cresylic acid, pine oil or alcohol are added to the slurry. Sylvite is floated from halite in an
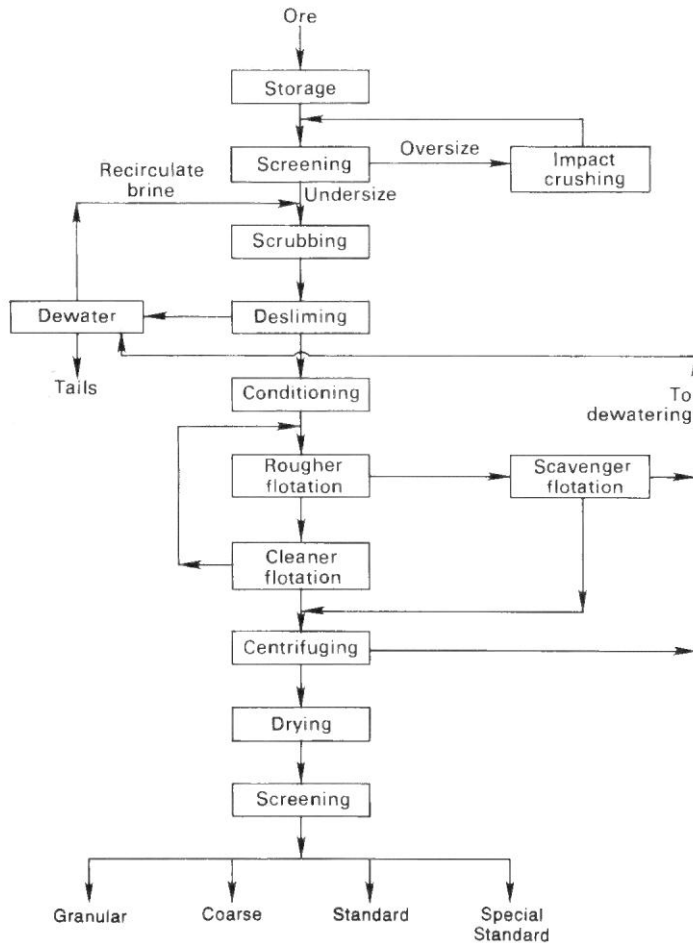
FIGURE 6. Simplified potash flotation circuit (Sullivan and Michael, 1986).



FIGURE 7. Simplified potash crystallization circuit (Sullivan and Michael, 1986).

aqueous solution saturated with both sodium and potassium chlorides at pulp densities of 20-35% solids; recovery generally exceeds 80%. Collectors typically are hydrochloride and acetate salts of aliphatic amines with carbon chain lengths of 12 to 24. IMC uses heavy media separation on sylvite/langbeinite ore prior to flotation and produces potassium sulfate by reacting potassium chloride with various sulfate materials including langbeinite. Western Ag-Minerals washes langbeinite ore to leach more soluble gangue without a flotation stage. Fine-grained MOP from flotation must be coarsened by compaction between rollers, crushed and sized to bulk-blended fertilizer specifications.

The abundance and mineralogy of clay minerals are significant in processing potash ores, in particular, the clay-rich 10th ore zone. Clay-size particles (slimes), composed dominantly of clay minerals, make up from a trace to about 10% of ore zones in the CPD. Each mill is designed for a specific slimes content in its feed stock (Fig. 7). For example, the Mississippi Chemical mill can handle up to 4.5% slimes, thus some ore zones cannot be processed efficiently in all plants. Beneficiation by dissolution and vacuum recrystallization is used on clay-rich or fine-grained ores. This method is used by New Mexico Potash whose ores contain about 7% clay (Searls, 1985).

Clay minerals preferentially interact with the amines used to coat sylvite in sylvinite ores and frothers used in flotation cells (Searls, 1985). This is a result of the large surface areas of clays, their residual charges, adsorption, absorption and colloid formation. Expandable trioctahedral clay minerals such as corrensite, saponite and clinochlore-saponite have more surface area than other clay minerals and can form colloids with the brines of either the flotation or crystallization circuits. These characteristics of clay minerals interfere with beneficiation and increase chemical use.
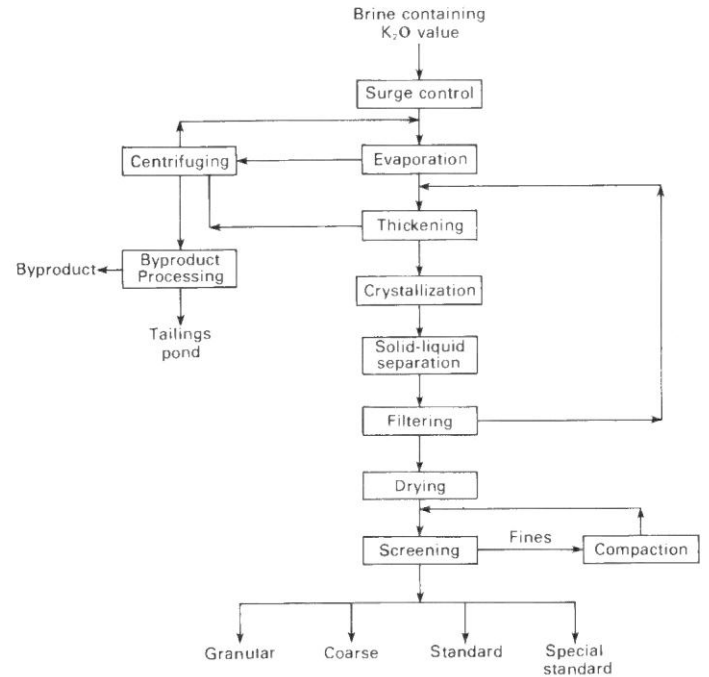
Potash tailings in the CPD, largely halite and clay, are stored or disposed of on the surface. Solid wastes are piled and monitored for salt leakage, which is minimal owing to the semiarid climate. Brines are evaporated in impoundments or in an expanded natural saline lake/ saltpan. Methods for returning tailings to the mine are being studied but are more likely to be initiated in potash districts less price sensitive than the CPD.

## OVERVIEW OF ECONOMIC FACTORS

Activity by other industries, like agriculture, petroleum and nuclear waste storage, can affect the production of potash from southeastern New Mexico. The main use of potash as a fertilizer ties it to cyclic trends in the agricultural industry. These trends are related to complex interactions between weather and climate, advances in crop genetics, soil science, farming practices, GNP of importing nations, farm income, population growth, efficient distribution systems, freight rates and back-hauls, substitutes (Williams-Stroud et al., in press), taxes and tariffs. Decisions to drill for petroleum below potash beds, hence rendering the potash unminable, are made by the Bureau of Land Management (BLM), which manages the federal and state land within the Potash Enclave in consultation with representatives of the potash and petroleum industries (Searls, 1992). The BLM historically has decided in favor of preserving potash reserves rather than petroleum production unless the petroleum well can be drilled from outside the KPLA. Also impacting the potash industry is the Waste Isolation Pilot Project (WIPP) at the southeast boundary of the KPLA (Fig. 2). Potash close to the WIPP facility is presently excluded from mining.

The development of substantial, low-cost potash in other countries, particularly Canada, inhibit exploitation of lower grade, higher cost resources in the CPD. This development was at the expense of many Carlsbad producers whose Canadian mines, with large low-cost reserves in a new mining district, were nationalized leaving them with small high-cost reserves in a mature mining district. A protected domestic potash mining industry is possible, but not likely, because Canada, a close and friendly neighbor, is our principal foreign source of potash.

The potash industry is also subject to overcapacity worldwide. In 1990, capacity utilization ranged from 40% to 100% and averaged about 75% (Williams-Stroud et al., in press). Overcapacity is buffered mainly by withheld Canadian production (about 60% capacity utilization to

prop up prices), transportation limits and unique potash products that yield semiprotected markets to some fortunate producers.

## REFERENCES

Adams, S. S. and Hite, R. J., 1983, Potash; *in* Lefond, S. J., ed., Industrial minerals and rocks, 5th edition: Society of Mining Engineers of AIME, New York, p. 1049-1077.

Austin, G. S., 1980, Potash in New Mexico: New Mexico Geology, v. 2, p. 7-9.

Bachman, G. 0., 1983, Regional geology of Ochoan evaporites, northern part of the Delaware Basin: New Mexico Bureau of Mines and Mineral Resources, Circular 184, 22 p.

Bodine, M. W. Jr., 1978, Clay mineral assemblages from drill core of Ochoan evaporites, Eddy County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 159, p. 21-31.

Calzia, J. P. and Hiss, W. L., 1978, Igneous rocks in northern Delaware Basin, New Mexico and Texas: New Mexico Bureau of Mines and Mineral Resources, Circular 159, p. 39-45.

Cheeseman, R. J., 1978, Geology and oil/potash resources of Delaware Basin, Eddy and Lea Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 159, p. 7-14.

Griswold, G. B., 1982, Geology overview of the Carlsbad Potash Mining District: New Mexico Bureau of Mines and Mineral Resources, Circular 182, p. 17-21.

Harben, P. W. and Bates, R. L., 1990, Industrial minerals: geology and world deposits: Industrial Minerals Division, Metal Bulletin Plc., Worcester Park, Surrey, U.K., p. 205-216.

Hardie, L. A., 1991, On the significance of evaporites: Annual Reviews of Earth and Planetary Sciences, v. 19, p. 131-168.

Hite, R. J., 1982, Progress report on the potash deposits of the Khorat Plateau, Thailand: U.S. Geological Survey, Open-file Report 82-1096, p. 48-66.

Jones, C. L., 1972, Permian basin potash deposits, southwestern United States; *in* Geology of saline deposits: UNESCO, Earth Science Series 7, Proceedings Hanover Symposium, 1968, p. 191-201 (reprinted *in* Brokaw, A. L., Jones, C. L., Cooley, M. E. and Hayes, M. E., 1972, Geology and hydrology of the Carlsbad potash area, Eddy and Lea Counties, New Mexico: U.S. Geological Survey, Open-file Report 4339-I, Appendix A).

Jones, C. L., Bowles, C. G. and Disbrow, A. E., 1960, Generalized columnar section and radioactivity log, Carlsbad potash district: U.S. Geological Survey, Open-file Report, 25 p.

Jones, C. L., Bowles, C. G. and Bell, K. G., 1960a, Experimental drill-hole logging in potash deposits of the Carlsbad District, New Mexico: U.S. Geological Survey, Open-file Report, 22 p.

Lowenstein, T. K., 1988, Origin of depositional cycles in the Permian "saline giant": the Salado (McNutt zone) evaporites of New Mexico and Texas: Geological Society of America Bulletin, v. 100, p. 592-608.

Lowenstein, T. K., Spencer R. J. and Pengxi, Z., 1989, Origin of ancient potash evaporites: clues from the modern nonmarine Qaidam Basin of western China: Science, v. 245, p. 1090-1092.

Lowenstein, T. K. and Spencer, R. J., 1990, Syndepositional origin of potash evaporites: petrographic and fluid inclusion evidence: American Journal of Science, v. 290, p. 1-42

Madsen, B. M. and Raup, **O.** B., 1988, Characteristics of the boundary between the Castile and Salado Formations near the western edge of the Delaware Basin, southeastern New Mexico: New Mexico Geology, v. 10, p 592-608.

O'Driscoll, M., 1990, Minerals in the U.S. southwest-breaking rocks in the hot sun: Industrial Minerals, No. 270, p. 52-87.

Ochsenius, K., 1888, On the formation of rock salt beds and mother liquor salts: Philadelphia Academic Society Proceedings, Part 2, p. 181-187.

Searls, J. P., 1985, Potash: U.S. Bureau of Mines, Bulletin 675, p. 617-633.

Searls, J. P., 1992, Potash; 1991: U.S. Bureau of Mines, Annual Report, 16 p.

Searls, J. P., 1993, Potash; *in* Mineral commodity summaries, 1993: U.S. Bureau of Mines, p. 132-133.

Schmalz, R. F., 1969, Deep water evaporite deposition: a genetic model: American Association of Petroleum Geologist Bulletin, v. 53, p. 798-823.

Sullivan, D. E. and Michael, N., 1986, Potash availability-Market economy countries-a minerals availability appraisal: U.S. Bureau of Mines, Information Circular 9084, 32 p.

Suwanich, P., 1991, Relationships between soluble and insoluble minerals in the McNutt•Member, Salado Formation, Delaware Basin, New Mexico [M.S. independent study]: Socorro, New Mexico Institute of Mining and Technology, 98 p.

Walls, J. M., 1985, Overall view of Carlsbad potash: Unpublished manuscript, New Mexico Bureau of Mines and Mineral Resources, 9 p.

Wardlaw, N. C., 1972, Unusual marine evaporites with salts of calcium and magnesium chloride in Cretaceous basins of Sergipe, Brazil: Economic Geology, v. 67, p. 156-168.

Williams-Stroud, S. C., Searls, J. P. and Hite, R. J. (in press), Potash resources; *in* Can⁻, D. D., ed., Industrial minerals and rocks; 6th ed.: Littleton Colorado, Society for Mining, Metallurgy and Exploration, Inc.
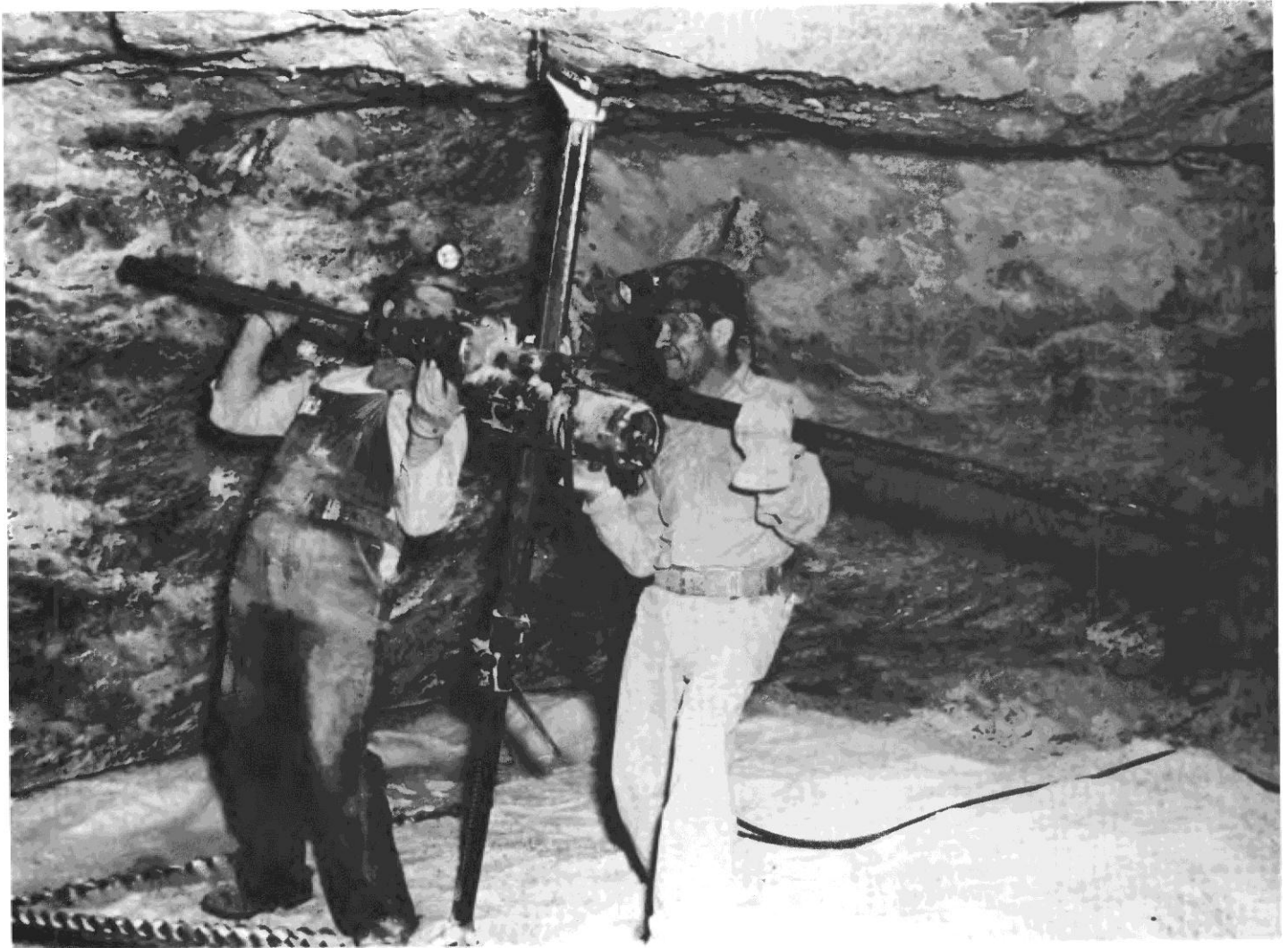
Two International Mineral and Chemical Corporation workers use an A-6 drill to make shot holes in undercut face of potash ore zone, Salado Formation. Photographer unknown, c. 1946. Courtesy of Southeastern New Mexico Historical Society of Carlsbad.