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GEOLOGY OF THE TENTH POTASH ORE ZONE: PERMIAN SALADO FORMATION, CARLSBAD DISTRICT, NEW MEXICO

ROBERT C.M. GUNN

AND

JOHN M. HILLS

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ABSTRACT

The Tenth potash ore zone is a bedded evaporite deposit in the Permian (Ochoan) Salado Formation in the Carlsbad district, Eddy and Lea counties, New Mexico. The rocks of the Tenth ore zone were precipitated in the supersaline part of the Permian basin and range from 6 to 10 feet (1.8 to 2.1 meters) in thickness. This report gives the results of a 1975 study of the Tenth ore zone in the Duval Corporation's Nash Draw mine; the Kerr-McGee Chemical Corporation's potash miner; the National Potash Company's Lea mine; and the Noranda Exploration Inc. drill cores.

The Tenth ore zone lithofacies include halite rock, sylvinite and carnallitite. Brines from the saline environment intruded the supersaline environment, dissolved primary carnallite and released potassium and chloride ions which reprecipitated as sylvite before burial. The boundary between the sylvite and halite facies is marked by erosional salt horses, and a change from green to brown clay in the gangue.

After burial, autogenetic events due to pressure and an intrusion of Tertiary basalt removed some potential ore. A fault created a salt horse. Brines, in intercrystalline cavities, crystallized as pegmatitic pods of sylvinite or as salt horses. Hematite, characteristically found as rims around sylvite crystals, was lost during recrystallization. The rims were corroded in places where sylvite was metasomatically replaced by carnallite. When sylvite was replaced by langbeinite, leonite or kieserite, remnant hematite rims are present.

INTRODUCTION AND PURPOSE OF THIS STUDY

Potash is the potassium oxide equivalent which serves a standard for comparison of potassium compounds in the world fertizlier market. The carlsbad district (Fig. 1) contains the largest soluble potash resource in the United States (Jones, 1975).

Bailey (Smith, 1938) identified sylvite (KCI) from the Snowden-McSweeney No. 1 McNutt oil test in Section 4, Range 30E, Township 21S. The Unites States Potash Company produced the first refined potash product in 1931 from property now mined by Mississippi Potash Incorporated (Fig. 2).

The purpose of this investigation was to determine the relationship between sylvinite and the gangue rock in the Tenth potash ore zone. The Tenth ore zone is the name given to a group of three evaporite beds below 610 feet (190 meters) the top of the Salado Formation (Upper Permian) (Fig. 3). All the potash in this zone does not qualify as ore at the present time, but the non-ore portion may constitute an important future potash resource.

Gunn gathered the field data for this report in the spring and summer of 1975. He was employed by Noranda Exploration Inc., and logged 35 drill cores from below the 120 Marker Bed, through the younger Tenth ore zone to above the 119 Marker Bed. Gunn also observed the Tenth ore zone underground where it is mined: Duval Corporation, Nash Draw Mine; the Kerr-McGee potash mine; and the National Potash, Lea mine. An x-ray defractometer was used to identify the minerals.

Location of Area Investigated

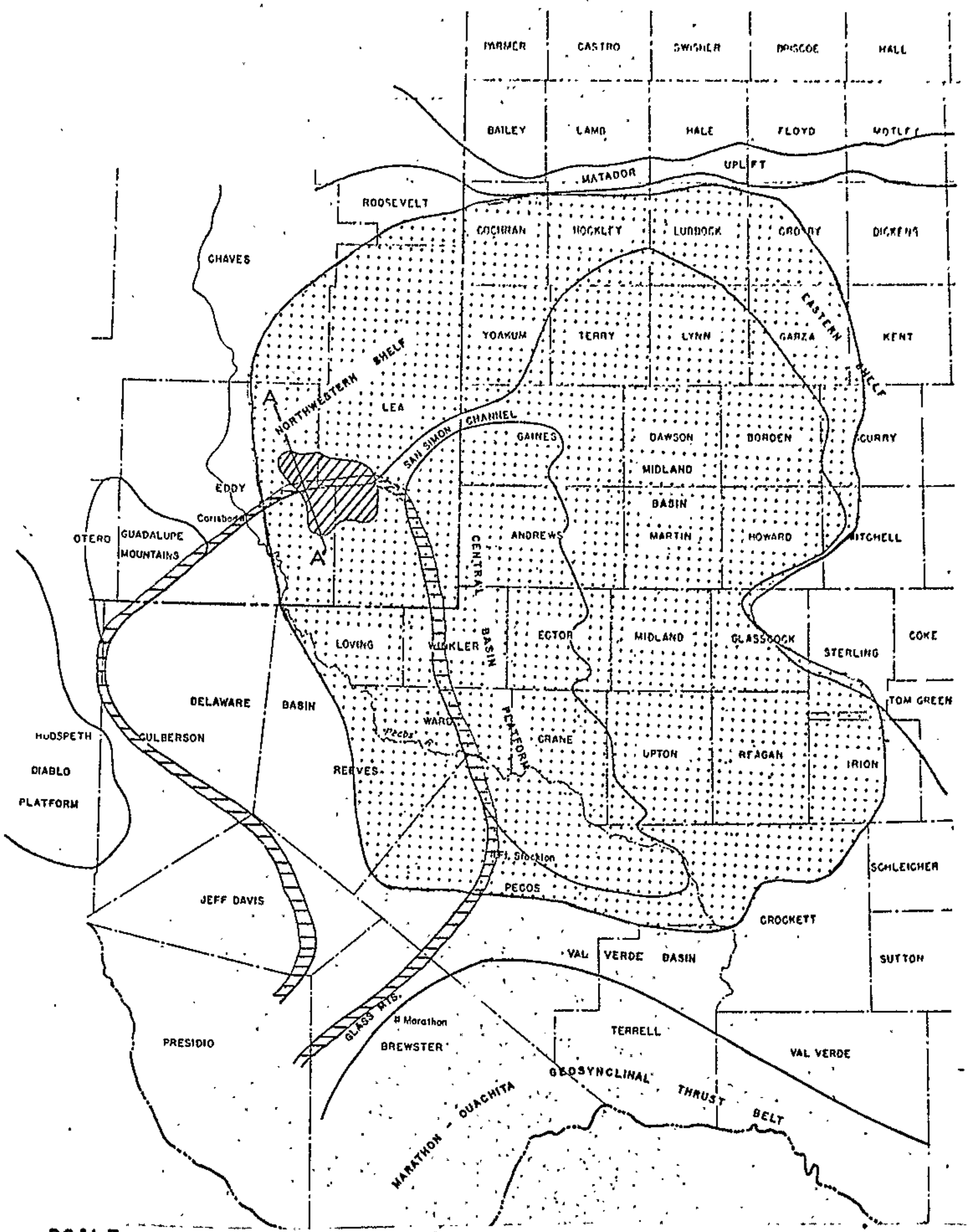
The Carlsbad district is located in Lea and Eddy Counties in southeastern New Mexico (Fig. 1) about 15 miles (24 kilometers) east of the City of Carlsbad. Figure 2 shows the limits of mining in the district and the location of drilling done by Noranda Exploration, Inc.

Seven companies are presently mining in the district. The names of the mines and their shaft locations are as follows:

1. Amax Chemical Corporation, Section 9, Township 19S, Range 30E.
2. Duval Corporation
   Willis Weaver mine, in Section 22, Township 18S, Range 30E; Saunders mine, in Section 35, Township 20S, Range 30E; and Nash Draw mine, in Section 33, Township 22S, Range 30E.
3. International Minerals and Chemical Corporation, in Sections 1, 11, 12, 23, Township 22S, Range 29E.
4. Kerr-McGee Chemical Corporation, in Section 4, Township 21S, Range 31E.
5. National Potash Company
   Lea mine, in Section 18, Township 20S, Range 32E; and Eddy mine, in Section 25, Township 20S, Range 29E.
6. Potash Company of America, Division Ideal Basic Industries Incorporated, in Sections 4, 17, Township 20S, Range 30E.

Fig 1

The Salado Formation and its relationship to the structural features of the Permian basin (data compiled from Adams, 1970, p. 247; Galley, 1958, p. 439; Hills, 1972, p. 2305; Jones, 1954, p. 108; and Jones, 1972, p. 192).



SCALE

Miles: 0, 50, 100

Kilometers: 0, 80, 160

LEGEND

Outline of Carlsbad district

A–A′ Geologic cross-section Fig.

Upper Guadalupian Capitan reef

Limit of Salado Formation

Limit of structural provinces

Figure 2. Limits of mining in the Carlsbad district* and location of Noranda Exploration, Inc. drilling.

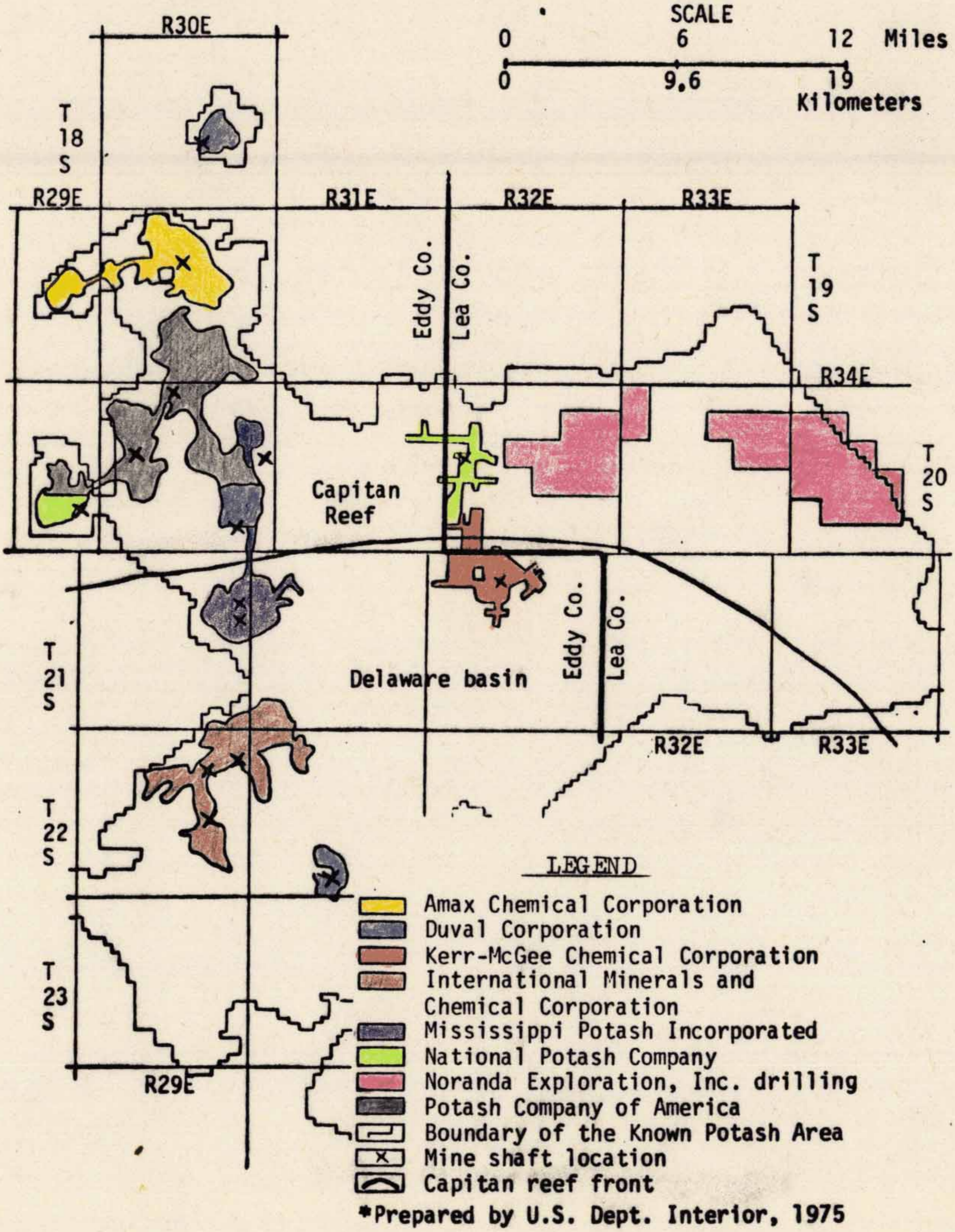
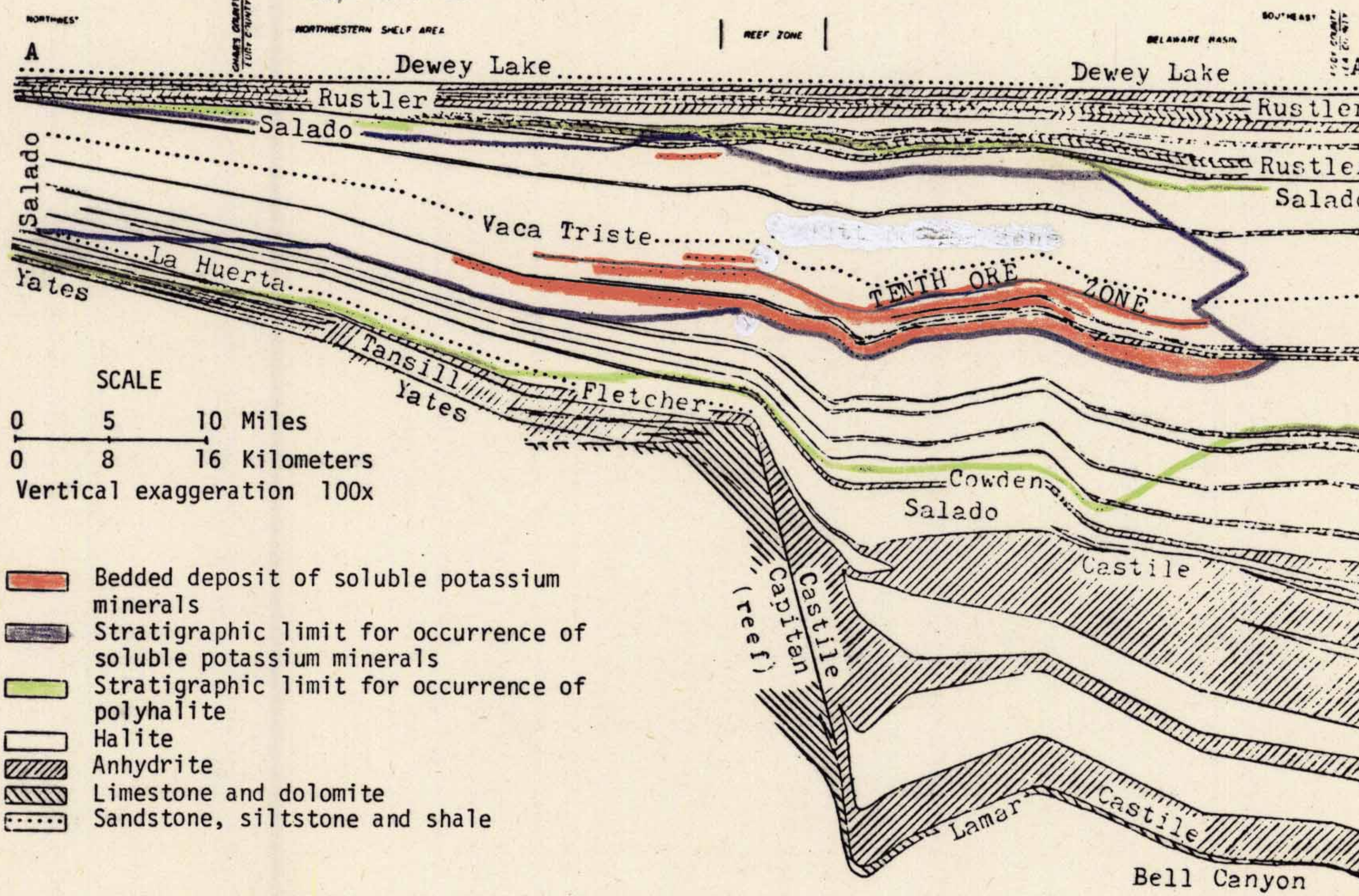


Figure 3. Composite geologic cross-section of the Ochoan series (Upper Permian) in the Carlsbad district as shown in Figure 1 (adapted from Jones, 1954, p. 108).



7. Mississippi Potash, Incorporated, in Sections 12, 13, Township 21S, Range 29E, and in Section 13, Township 20S, Range 30.

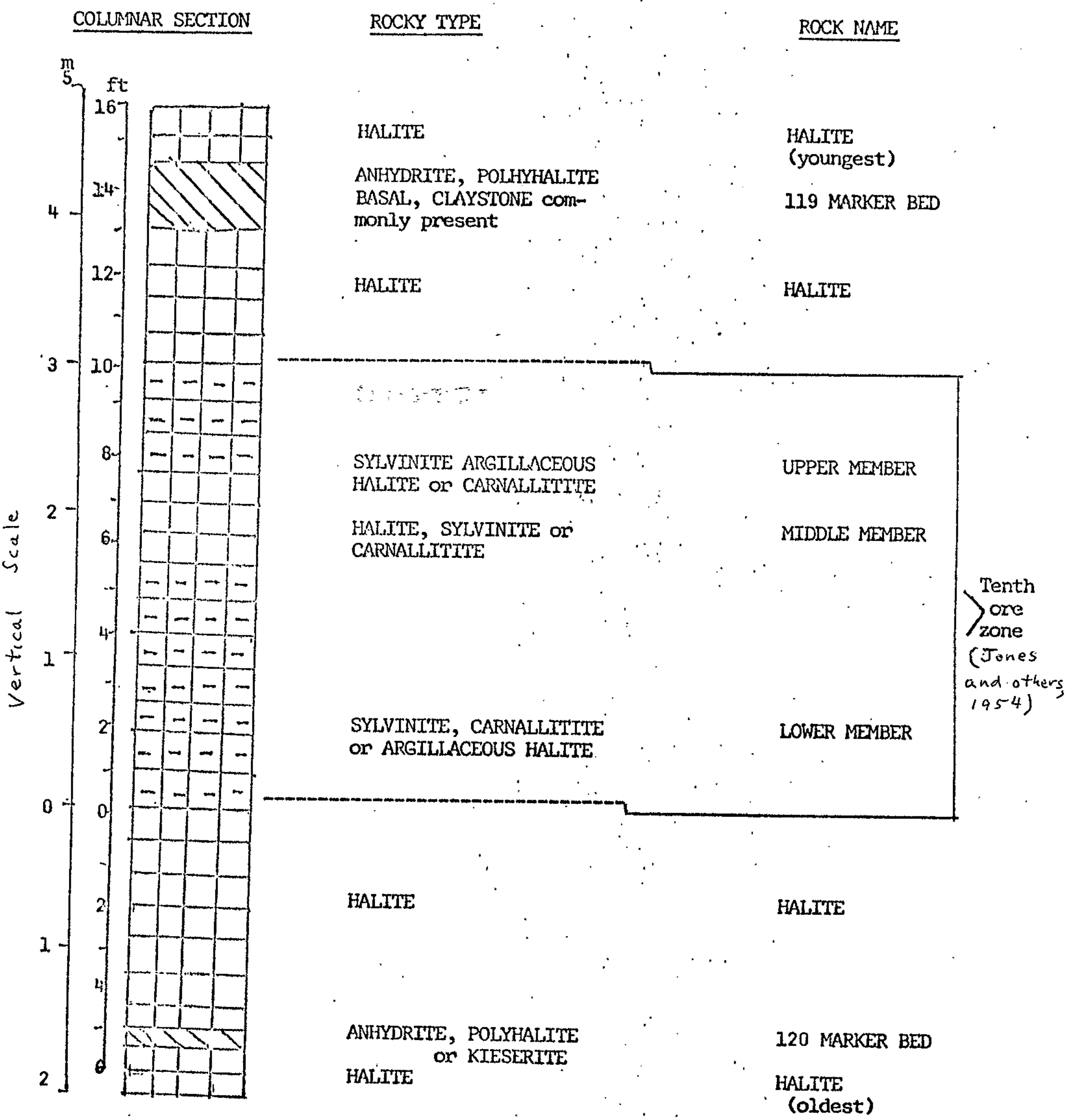
GEOLOGICAL SETTING

The Tenth potash ore zone deposit forms part of the Permian upper Salado Formation in the Delaware basin of west Texas and southeast New Mexico. This basin is surrounded by the Upper Permian Capitan reef and is separated from the Midland basin by an uplift known as the Central Basin platform (Cartwright, 1930, p. 970) (Galley 1958). The area discussed in this study is on the extreme northeast edge of the Delaware basin (Fig. 1) and overlies,in part, the Capitan reef.

The Tenth ore zone (Fig. 4) is a tripartite cluster of strata containing potassium minerals. It is underlain and overlain by halite beds. The whole assemblage is underlain by the 120 Marker Bed composed of distinctive anhydrite, polyhalite and kieserite. Overlying the upper halite bed is the 119 Marker Bed containing anhydrite, polyhalite and basal claystone. The vertical interval between the two marker beds is about 16 feet (4.9 meters).

The Noranda Exploration property lies north of the Capitan reef front. Here the Tenth ore zone and the 120 Marker Bed beneath it dip to the east-southeast. The 120 Marker Bed dips 2 to 3 degrees per mile to the east-southeast on the west side of the property and 1 to 2 degrees per mile to the east-southeast on the east (Fig. 2). However the dip of the Tenth ore zone is to the south between the National Potash, Lea mine located over the Capitan reef and the Kerr-McGee

Fig. 4 Stratigraphic column of the Tenth ore zone and important related evaporite beds



potash mine on the northeast edge of the delaware basin (Fig. 2). The change in dip direction may be the result of diagenetic evaporite compaction in the Delaware basin.

Salado Formation

The Salado Formation (Fig. 3) was named by Lang (1935) from the subsurface section in the Means Number 1 well on the Pinal dome, Loving County, Texas. It conformably overlies the Castile Formation in the Delaware basin, and is unconformably overalin by the Rustler Formation.

The extent of the Salado Formation and its relationship to the structural provinces in the Permian basin are shown in Fig. 1. The northern and eastern margins of the Salado Formation contain clastic material and may be close to the original depositional limit. The southern edge of the Salado Formation is truncated by Cretaceous beds along the front of the Marathon-Ouachita geosynclinal thrust belt. The western boundary of the Salado Formation is truncated by late Permian erosion followed by solutioning during Cenozoic time due to the underflow of the Pecos River. Thus, the western limit of deposition of the Salado is unknown.

In the Salado Formation, the sedimentation cycle is as follows:

top ↑	argillaceous halite stratum
	halite stratum
	sulfate marker bed
	claystone stratum
↓ bottom	sandstone and siltstone

This cycle is not always complete. Individual strata are persistent laterally for miles. All beds but the claystone stratum range from 1 foot to 30 feet (0.3 to 9 meters) in thickness. The claystone units vary from a thin film to 5 inches (13 centimeters) in thickness. Clastic rocks form a very small part of the Salado Formation.

OBSERVATIONS

The rock types associated with the Tenth ore zone are halite, argillaceous halite and sulfate. The following detailed description of the rock types is based on observation of Noranda Exploration, Inc. drill core and exposures of the Tenth ore zone in mine workings. The color designation is in accordance with the rock color chart of the Geological Society of America.

Halite Rock

Halite rock is associated with the poorly mineralized middle member of the Tenth ore zone and with the barren beds between the tenth ore zone and the 119 and 120 Marker Beds (Fig. 4). This type of rock commonly contains 0.8% to 0.5% clay. Halite rock is also associated with salt horses in all members of the Tenth ore zone.

The halite rock in commonly milky white (N9) or colorless, but it is also reddish-orange (10 R 6/6), yellowish-orange (10 YR 6/6), very light gray (N8), very dusky purple (5P 2/2) and dark blue in color. The milky halite crystals derive their color from minute fluid inclusions trapped within the crystals. The crystals are euhedral to subhedral and range in size from 0.2 to 0.8 inches (0.5 to 2.0 centimeters).

The reddish-orange halite occurs in bands 1.0 to 2.0 inches (3.0 to 5.0 centimeters) in thickness immediately above the 119 Marker Bed. Adams (1967. p. 64) believes the reddish-orange color in halite is due to minute polyhalite inclusions. This sulfate deposition pattern is reflected in the individual reddish-orange halite bands. A thin stringer of polyhalite usually makes a sharp basal contact with underlying occluded polyhalite contained in a halite band.

Argillaceous Halite Rock

The argillaceous halite rock differs from halite rock only in the presence of insoluble, mainly clay minerals in amounts ranging from 1% to 100%. The argillaceous halite occurs as an lithofacies of the upper and lower members of the Tenth ore zone. When argillaceous halite forms the matrix for sylvite crystals, then the entire rock is termed sylvinite. The average percentage of insolubles in the upper and lower members of the Tenth ore zone is 2.6% and 4.7%, respectively. Analyses of the insolubles from this type of rock from the district indicate the presence of quartz, illite, chlorite and corrensite clays (Grim and others, 1969), as well as talc (Bailey, 1949). The clay is either pale green (10 G 6/2) or moderate brown (5 YR 3/4).

Schaller and Henderson (1932 p. 25) assayed the iron in both colors of clay. Both colors of clay contained about 1% ferrous iron but the brown clay contained 5.15% ferric iron or 11.7 more ferric iron than the green clay.

In Duval Corporation's Nash Draw mine, the base of the lower member of the Tenth ore zone is usually moderate brown argillaceous halite rock rather than sylvinite. The color of the clay in sylvinite is pale green even where recrystallization has occurred. Twelve miles northeastward, in a Noranda Exploration, Inc. drill core, the base of the lower member of the Tenth ore zone is carnallitite, a mixture of carnallite and halite. The basal brown clay is altered to pale green clay at the carnallite-clay contact. The green color indicates the iron in the clay is chemically reduced. The bitterns probably leached out the ferric iron and precipitated it as hematite plates in sylvite and carnallite. These solutions probably also carried the carnallite into the lower member of the Tenth ore zone.

Where the 119 Marker Bed is at least 1.5 feet (0.45 meters) thick, a fractured claystone seam averaging 1 inch (2.5 centimeters) in thickness occurs beneath it. This claystone seam thins out and disappears before the overlying sulfate part of the 119 Marker bed disappears laterally.

Sulfate Rock

The sulfate rock type includes anhydrite ($CaSO_4$) and polyhalite ($2Ca\text{-}SO_4\text{-}MgSO_4\text{-}K_2SO_4\text{-}2H_2O$). No evidence of original gypsum crystallization is seen in the 119 and 120 Marker Beds or in the Tenth ore zone between these beds. Other sulphate minerals are langbeinite, kieserite and leonite, but they do not form widespread rock units in the study area. The 119 and 120 Marker Beds are excellent stratigraphic markers because of their easy identification and broad geographic range. In 1952 the United States Geological Survey standardized the stratigraphic terminology in the district based on 143 sulfate marker beds. (Table I).

The 119 and 120 Marker Beds are commonly composed of massive, finely crystalline, laminar, nodular or vuggy anhydrite, polyhalite or anhydrite and polyhalite. Halite is often present as nodules or thin bands and clay is present in trace amounts. Anhydrite is light gray (N7) in color and polyhalite ranges from dark reddish-brown (10 R 3/4) "brick red," to moderate orange pink (10 YR 8/4 and 5 YR 8/4). In one Noranda drill core a thin band of anhydrite is sandwiched between pale green claystone seams at the base of the 119 Marker Bed. The clay separates the anhydrite from the polyhalite part of this Marker Bed.

M.P. Scroggin of Duval Corporation made a chemical analysis of three samples of the 119 Marker Bed collected by Gunn in the Nash Draw mine. The moderate orange pink (10 YR 8/4) sample from above mineable Tenth ore zone was 89.58% polyhalite and 3/40% anhydrite. The moderate orange pink (10 R 7/4) sample from

Table I. Comparison of systems of nomenclature for marker beds and ore zones - Salado Formation; for locations, see Fig. 4 (from U.S. Geol. Survey)

Revised 12/19/52	OLD	Smith	Schaller	USPC	PCA	IM&CC	DS&PC	SWPC	FSC*	NFU*
12th Ore Zone	13th Ore Zone									
Marker Bed # 100	100	1								
101	101	1								
102	102	2								
103	Top Anhy.									
104	-	3								
105	104	4								
106	-									
107	105	5								
108	106	6								
109	107	7								
110	108	8								
111	109	9								
-	110	10								
112	-									
113	111	11								
114	-									
115	112	12	Poly. #3	-	-	-	#112	#112		
116	113	13	Poly. #4	-	Poly.D	-	#113	#113		
Vaca Triste Sand Member										
11th Ore Zone	12th Ore Zone									
117	114	14	Poly. #5	-	Poly.X	-	#114	#114		
118	115	15	Poly. #6	-	Poly.Y	-	#115	#115		
119	116	16	Poly. #7	-	Poly.Z	-	#116	#116		
10th Ore Zone	11th OZ	17	Carn. #1	#1	J	#1	#117	-		
120	118	18	Poly. #8	-	Poly.H	-	#118	#118		
9th Ore Zone	10th Ore Zone		-	-	I	-	-	-		
121	-	-	-	-	-	-	-	-		
122	119	19	Poly.#9	-	Poly.G	-	#119	#119		

FSC: Freeport Sulfur Company (Kermac Potash Corporation) *For logs submitted after 12/17/52 Revised U.S.G.S. system will be used.

NFU: National Farmers Union (National Potash Corporation) *For logs submitted after 12/17/52 Revised U.S.G.S. system will be used.

Table I (Continued)

Revised 12/19/52	OLD	Smith	Schaller	USPC	PCA	IM&CC	DS&PC	SWPC	FSC	NFU
8th Ore Zone	9th	20	Sylvite #1	#1A	K	-	#120	-		
Union Anhydrite	-	-	-	-	-	Union	Union	-		
7th Ore zone	-	#20A	-	#2	1-1	-	-	-		
6th Ore Zone	-	21	Sylvite #2	-	-	-	#121	-		
5th Ore Zone	-	22	Sylvite #3	#2A	1-2	#2	#122	-		
123	123	23	Anhy. #1	-	Q	Q	#123	#123		
124	124	24	Anhy. #2	A	Anhy.A	A	124	#124		
4th Ore Zone	-	25	Sylvite #4	#3	M-1	#2	#125	#125		
3rd Ore Zone	-	25A	Sylvite #5	#3A	M2-M4	#3A&	#126	)		
		26				3B		)#126		
2nd Ore Zone	-	27	Sylvite #6	#3B	M-5	-	-	)		
125	127	-	-	SalmonPoly.E Poly.	-	-	#127	#127		
1st Ore Zone	-	28	Sylvite #7	#4	N	#4	#128	#128		
126	129	29	Poly. #10	-	Poly.F	#129	#129	#129		
127	130	30	-	-	-	-	-	-		
129	131	31	-	-	-	-	-	-		
130	132	32	-	-	-	-	-	-		
131	133	33	-	-	-	-	-	-		
132	134	34	-	-	-	-	-	-		
133	135	35	-	-	-	-	-	-		
134	136	36	-	-	-	-	-	-		
135	137	37	-	-	-	-	-	-		
136	138	38	-	-	-	-	-	-		
137	-	-	-	-	-	-	-	-		
138	-	-	-	-	-	-	-	-		
139	139	39	-	-	-	-	-	-		
140	140	40	-	-	-	-	-	-		
141	141	41	-	-	-	-	-	-		
142	-	42	-	-	-	-	-	-		
143	-	43	-	-	-	-	-	-		
Cowden	Cowden	-	-	-	-	-	-	-		
Anhydrite	Anhydrite	-	-	-	-	-	-	-		
LaHuerta	LaHuerta	-	-	-	-	-	-	-		
Siltstone	Siltstone	-	-	-	-	-	-	-		
Fletcher	Fletcher	-	-	-	-	-	-	-		
Anhydrite	Anhydrite	-	-	-	-	-	-	-		

above the margin of a salt horse was 81.14% polyhalite and 5.75% anhydrite. The moderate reddish orange (10 R 6/6) sample above a salt horse was 87.84% polyhalite and 5.16% anhydrite. The unreported material needed to make each analyses 100% is mainly halite, with minor insoluble clay. These data indicate that polyhalite - anhydrite lithofacies do not vary significantly whether the 119 Marker Bed overlies the ore zone or a barren lithofacies.

Where the 119 Marker Bed is thick (Table II), it commonly has a basal claystone seam and the sedimentary structure of the Marker Bed changes from mosaic to bedded to nodular polyhalite and anhydrite.

The other extreme in marker bed structure is seen where the 119 Marker Bed is thin (Table II), the bedded structures dominate and the contacts above and below are sharp. There is no evidence of a gradual increase or decrease in sulfate accumulation such as would be expected for minerals which accumulate below a brine from which they precipitate. There is no evidence of erosion of the underlying halite and no basal claystone seam. In one core of the 119 Marker Bed with a fine-grained anhydrite matrix, there were 0.05-0.08 inch (1-2 millimeters) rounded sand size grains of anhydrite. Subrounded polyhalite pebbles are present in the argillaceous halite lithofacies of the lower member of the Tenth ore zone, and are probably derived from erosion of the older consolidated 120 Marker Bed.

Rocks of the Tenth Ore Zone

The Tenth ore zone is being mined for its sylvinite rock in the Duval Corporation's Nash Draw mine; the National Potash's Lea mine; and the Kerr-McGee potash mine. Schwerdtner (1964, p. 1109) defined sylvinite as a rock composed of a mixture of sylvite (KCI) and halite (NaCl) with minor amounts of carbonates, sulfates and clay.

Table II Vertical change in deposition of sulfate rock (based on Noranda Exploration drill core).

Thick Deposit (119 Marker Bed)	Thin Deposit (119 Marker Bed) (120 Marker Bed)
Nodular	No deposition
Distorted Nodular	" "
Distorted Bedded Nodular	" "
Bedded Nodular	Bedded Nodular
Streaky Laminated, Bedded Massive	Streaky Laminated, Bedded Massive
Bedded Massive	Bedded Massive
Bedded Mosaic	No deposition
Distorted Nodular Mosaic	" "
Nodular Mosaic	" "

Interpretation of Structures in Marker Beds

Thick Deposit	Thin Deposit
Environment of precipitation and deposition of anhydrite, polyhalite, with an average thickness of 1.5 feet (0.49 meters)	Restricted environment of accumulation of transported anhydrite, polyhalite, and kieserite, with an average thickness of 0.4 feet (0.1 meters)

Terminology from Maiklem and others, 1969.

Jones (1972) grouped sylvinite deposits on the basis of sylvite concentrations as follows: massive deposits, lens deposits and disseminated deposits. The massive deposits are stratiform, with gradational lower boundaries and sharp upper boundaries as seen in the members of the Tenth ore zone (Pl. I). The lens deposits are erratic, discordant bodies ranging in size from a few centimeters to a meter in thickness. They consist almost entirely of sylvite and resemble pegmatitic salt horses. The disseminated sylvite deposits disappear gradually into halite or argillaceous halite rock. The sylvite in the halite which envelops the Tenth Ore zone is dissiminated. These deposits may be the result of precipitation of halite and minor sylvite from different levels in the Ochoan sea brine. For example, a sylvite crystal with an eroded red rim containing hematite, was seen in halite rock below the Tenth ore zone. The sylvite partially dissolved because it was unstable in the less saline halite facies.

In the National Potash's, Lea mine, and the Noranda drill core carnallitite and hartsalz are present in the Tenth ore zone. Schwerdtner (1964, p. 1109) defined carnallitite as a rock consisting of a mixture of carnallite (KCl-M_gCl_2-$6H_2O$) halite and possible sylvite and minor amounts of carbonates, sulfates and clay. Clark (1924, p. 225) defined hartsalz as a rock composed of a mixture of Kieserite (M_gSO_4-H_2O) in sylvinite rock. The tenth ore was mapped before December 19, 1952 as various ore zones : Eleventh by U.S.G.S., Seventeenth by Smith, Carnalite #1 by Schaller, Number 1 by U.S. Potash Corp. and International Minerals and Chemical Corp., Number 117 by Duval Corp., and the "J" by Potash Company of America (Table I).

Mineralogy of the Tenth Ore Zone

The minerals with which this study is concerned are: sylvite, carnallite and minor amounts of kieserite, langbeinite, leonite and epsomite, listed in order of decreasing abundance. These minerals are found in host rocks of halite or argillaceous halite.

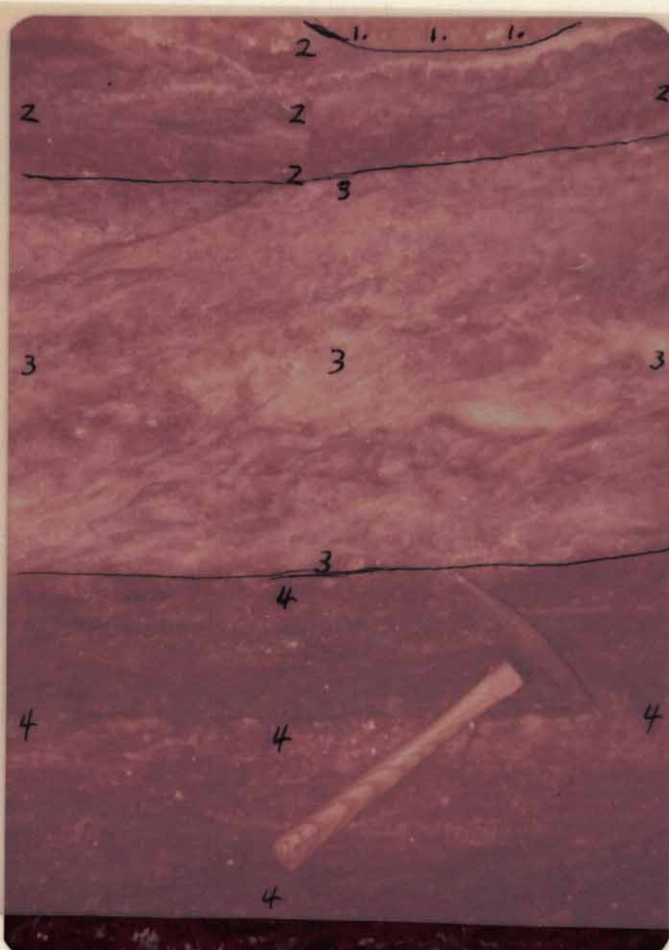
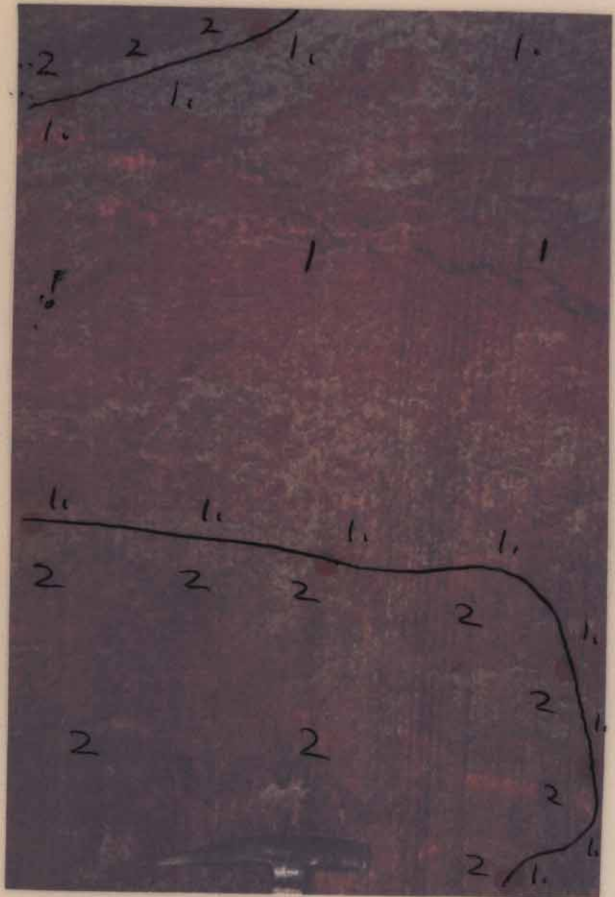


Plate I. Duval Corporation, Nash Draw mine — Tenth ore zone exposure on working face in sylvinite lithofacies.

1. 119 Marker Bed (polyhalite)
2. Upper member of the Tenth ore zone
3. Middle member of the Tenth ore zone
4. Lower member of the Tenth ore zone

Plate II. National Potash Company, Lea mine — Carnallitite replaces sylvinite in lower member of the Tenth ore zone

1. Base of middle member of the Tenth ore zone
2. Lower member of the Tenth ore zone.
3. Hartsalz where kieserite alters to epsomite when exposed to mine air.
4. Carnallitite cross-cuts sylvinite (5) and hartsalz (3) at margin of carnallitite metasomatic salt horse



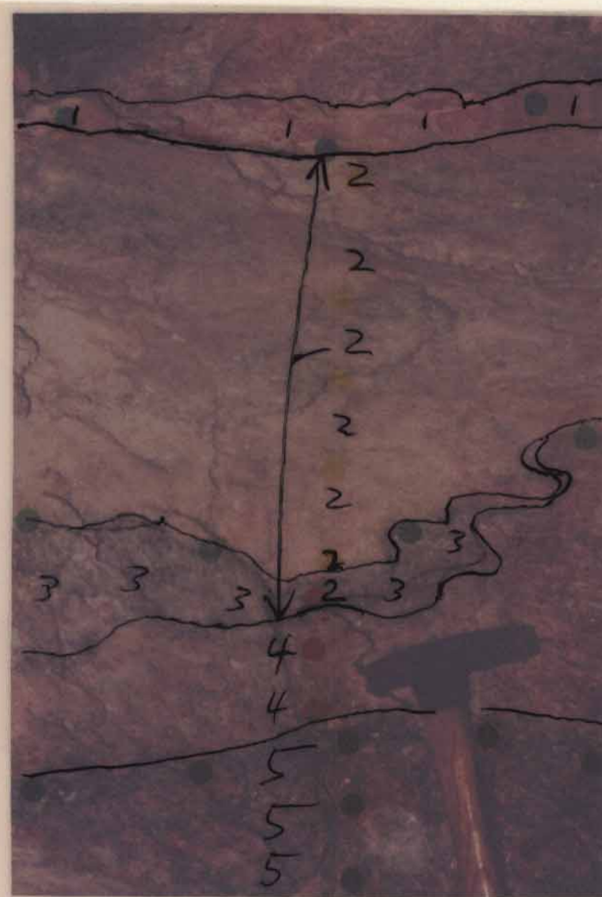


Plate III Kerr-McGee potash mine - ore gangue contact

1. Sylvinite, green clay gives it a gneissosity
2. Brown argillaceous halite rock forms a lithofacies salt horse. Sylvinite thins and wedges out in direction of pick end of hammer.

Plate IV Duval Corporation, Nash Draw mine - erosion of the Tenth ore zone,

1. 119 polyhalite Marker Bed
2. Where Tenth ore zone is eroded, halite infill forms an erosional salt horse.
3. Residual green clay at the contact between the top of the middle member of the Tenth ore zone and halite rock. This is an erosional contact because the halite rock is in contact with the upper member further to the right of the part shown in the photograph and in contact with the lower member further to the left.
4. Middle member
5. Lower member

Sylvite, the ore mineral in the Tenth ore zone, is present as coarse to pegmatitic, subhedral to euhedral crystals. These are usually clear or a milky color when filled with fluid inclusions. Sylvite can be distinquished from halite by its bitter taste. Sodium cobaltinitrate reagent forms a yellow precipitate on sylvite and not on halite. Schaller and Henderson (1932) idsntified microscopic size hematite (Fe_2O_3)plates occluded in the margin of the sylvite crystals. When this hematitic red rim on sylvite is completely or partially absent, the sylvite crystal is either corroded or has been recrystallized.

Carnallite is present in the Tenth ore zone and is associated with the 119 and 120 Marker Beds. Clear, colorless carnallite found in the middle member of the Tenth ore zone is interpreted as primary and it has no exterior crystal faces. Secondary carnallite is occurs in this zone and varies in color from dark yellowish-orange (10 YR 6/6) to dusky red (5 R 3/4). According to McIntosh and Wardlow (1968), the intensity of color in carnallite is related to the density of iron oxide inclusions which are present as hematite plates.

Kieserite, langeinite and leonite are associated with sylvinite in the lower member of the Tenth ore zone. Kieserite occurs as a sedimentary precipitate with sylvinite at the top of the lower member of the Tenth ore zone in the National Potash, Lea mine. It alters to epsomite on the mine pillars due to exposure to mine air at 55^{0}F (13^{o}C.). Kieserite is also found along faults and fractures where it replaces sylvite. Pegmatitic crystals of langbeinite and leonite fill local fractures in the ore zone in the Duval Corporation's NashDraw mine. When these three potassic sulfate minerals replace sylvinite, floating remnant hematite rims indicate the former presence of sylvite.

GEOLOGIC HISTORY AND INTERRRETATION OF THE TENTH ORE ZONE DEPOSITS

The Tenth ore zone is a sedimentary evaporite deposit of the supersaline environment of the Ochoan Permian basin. Evaporite lithofacies depend on such factors as distance from the ocean connection, configuration of the depositional floor and thermal water currents. The separation of polyhalite Marker Beds from the sylvite and carnallite facies by halite facies, shown in this study, indicates that polyhalite should be included in the saline rather than the supersaline environment of deposition. The area of supersaline environment probably included little more than the Carlsbad district (Fig. 5).

The cross section (Fig. 3) after Jones (1954) shows the relationship of the repeated marine flooding of the Permian basin in Ochoan time. The channels in the salinity of the water and its temperature are reflected in the evaporite beds. During late Ochoan time the evaporation of the brines of the northeastern part of the Delaware basin went nearly to completion. The result was the precipitation of the potash salts of the Tenth ore zone.

The sylvinite and carnallite rocks in the Tenth ore zone extend in an east-west direction from National Potash's Lea mine, Sec. 18, T. 20 S, 4. 32E, through the Noranda Exploration property, a distance of 15 miles (24 kilometers). They extend at least 21 miles (34 kilometers) in a north-south direction (Jones, 1972; p. 199). These data indicate that from the time of deposition of the 120 Marker Bed to the end of deposition of the 119 Marker Bed in the Permian basin, the supersaline bittern extended over some 315 square miles. The gentle dips on the top of the 120 Marker Bed seem to indicate that the Tenth ore zone accumulated in a shallow basin. Since no evidence of karst topography is seen at the top of the ore zone,

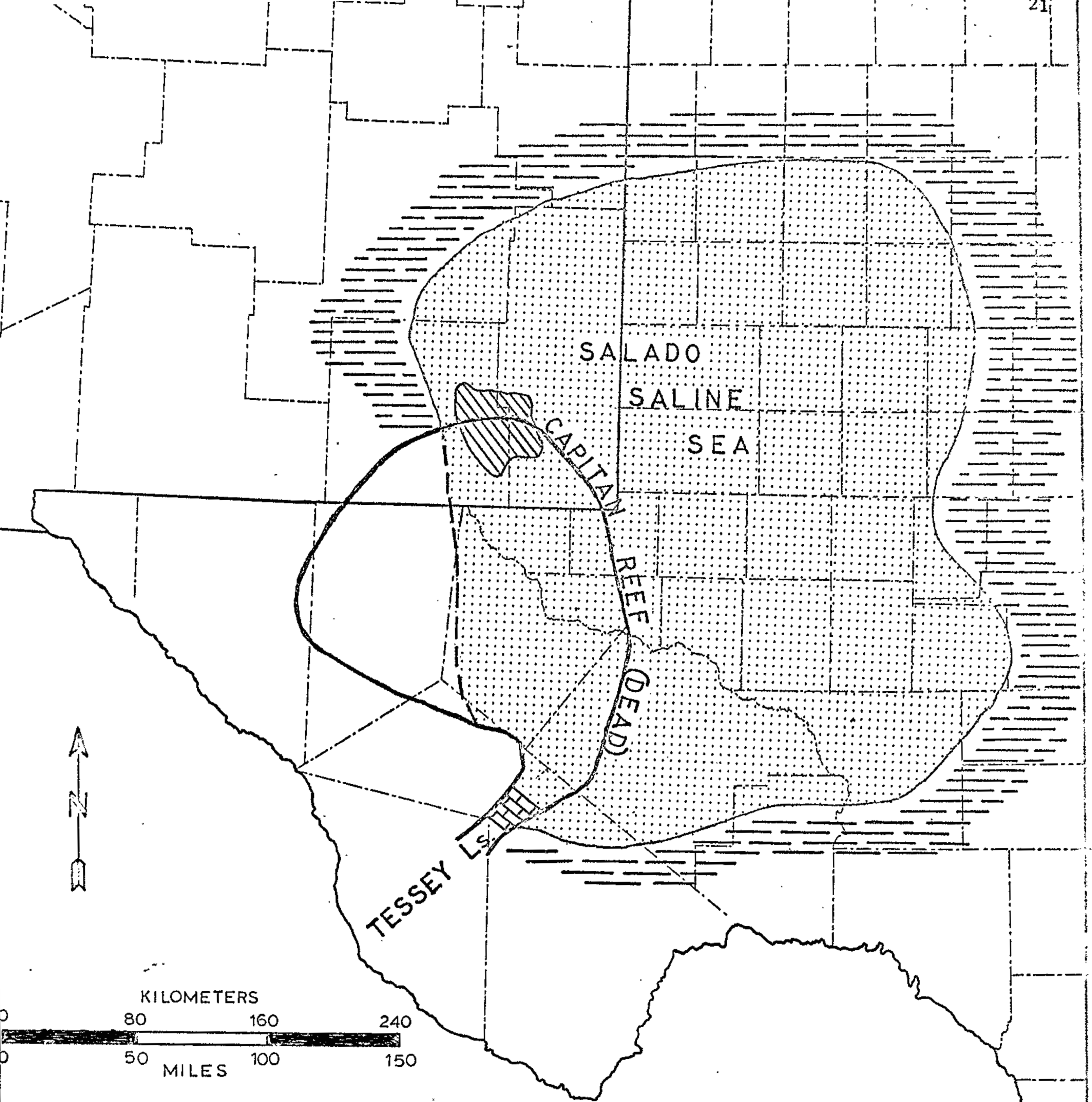


Fig. 5

PALEOGEOGRAPHY
EARLY AND MIDDLE OCHOA TIME

TERRESTIAL AND BRACKISH WATER DEPOSITS

UPPER SALADO SUPERSALINE POTASH BRINES

the bittern which precipitated the Tenth ore zone was still present at the close of deposition. Thus, it appears that the Tenth ore zone rocks accumulated in a broad, shallow basin wet by a concentrated bittern from which potassium salts were deposited.

Precipitation history of the Tenth ore Zone

The precipitation history of the Tenth ore zone and its related evaporite beds is shown in Figures 6 and 7. The vertical sequence of evaporite beds is summarized in Table II.

The oldest lithological unit studied is the halite rock underlying the 120 Marker Bed (Fig. 4). This halite is commonly homogeneous but sometimes it is banded with sulfate inclusions. The banded halite shows a gradual increase in sulfate upward to the conformable contact with the overlying 120 Marker Bed. The anhydrite was precipitated in a brine of salinity from 199 to 427 parts per thousand (Scruton, 1952). Then it was probably altered gradually to polyhalite and to kieserite in localities where the brine was more saline. Polyhalite appears to be largely a secondary mineral after anhydrite, but minor amounts may be primary. The thickness and sedimentary structures of the 119 and 120 Marker Beds indicate that many nearly monomineralic sulfate beds were transported and winnowed by currents over an extensive area.

The basal bed of the halite rock above the 120 Marker Bed occasionally is banded and is probably conformable with the underlying marker bed.

Where there is no banding in the halite rock, the 120 Marker Bed may have been deposited during an hiatus in halite precipitation. This hypothesis is supported by the occurrence of minor corroded sylvite crystals disseminated in the halite rock which probably crystallized in the denser, lower part of the brine.

Figure 6. Interpretation of marker bed lithofacies based on 119 and 120 Marker Bed data (from Noranda Explorations drill core and Jones, 1954, p. 109).

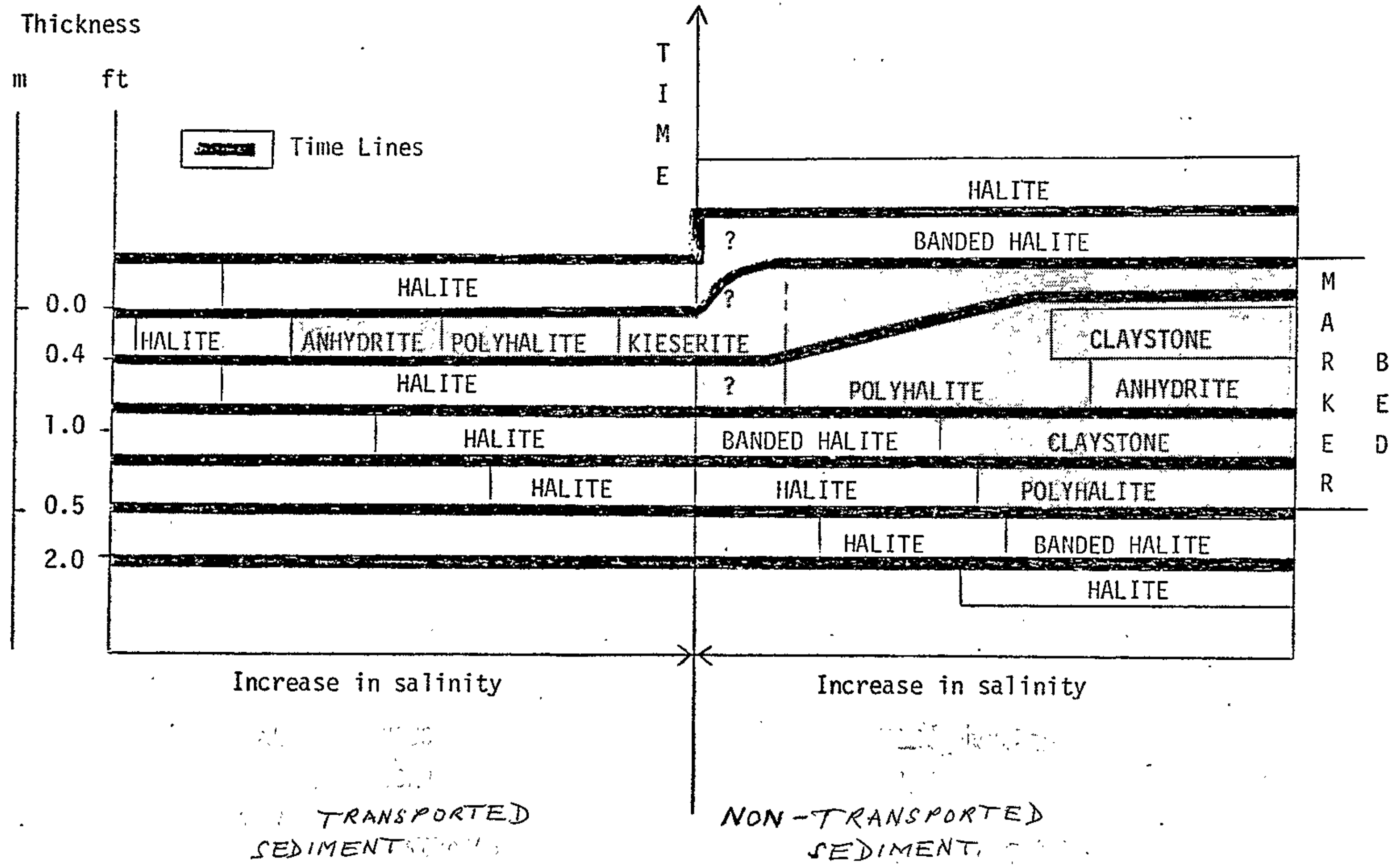
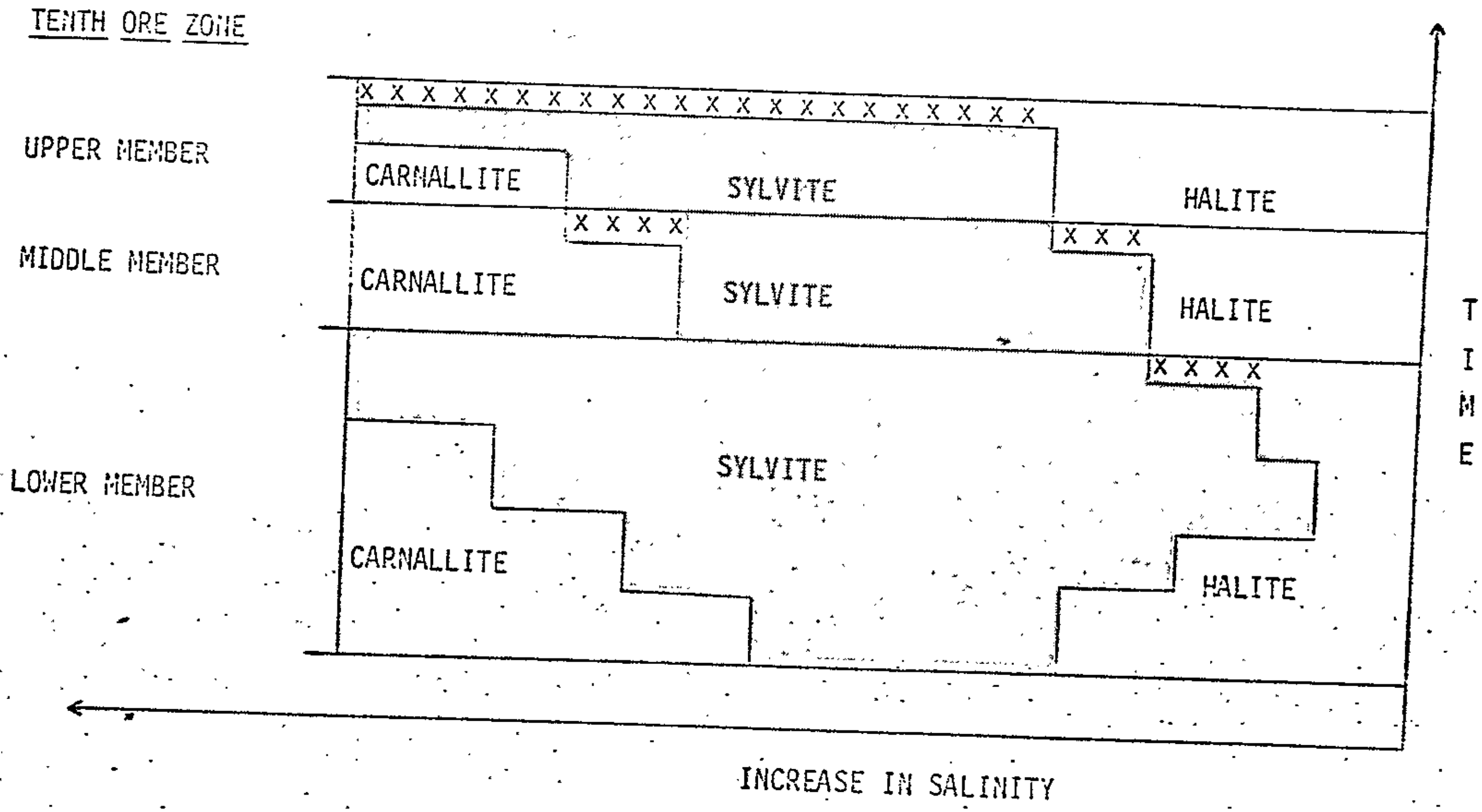


Fig. 7. Interpretation of Tenth ore zone mineral facies which reflect precipitation from Permian basin sea brine (data from Noranda Explorations drill core and mine tours of the Tenth ore zone).



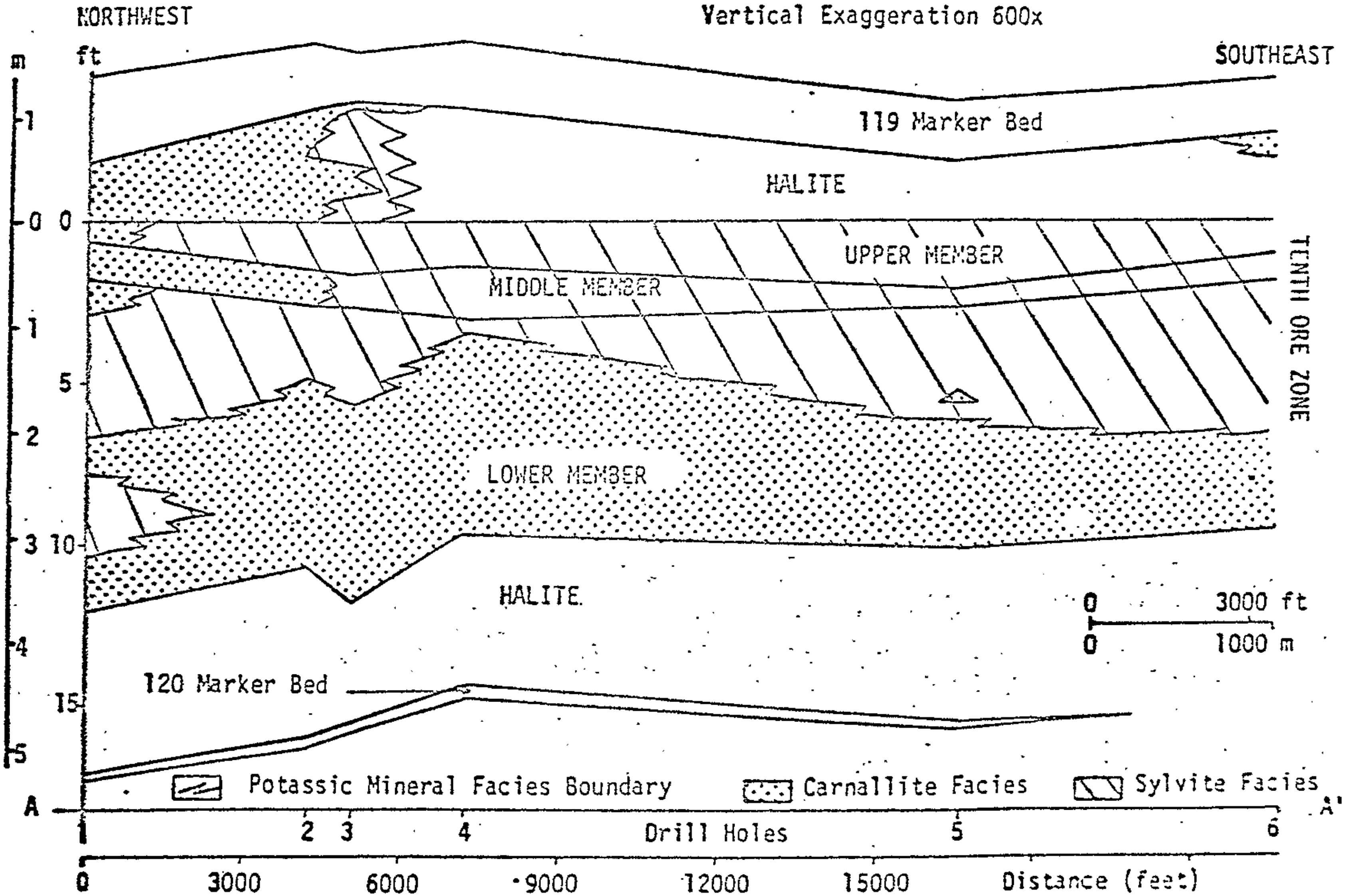
x x x Clay accumulation due to solution when less saline brine was in contact with precipitate from more saline brine.

TABLE VII

Precipitation of the Tenth ore zone and related evaporite beds.

ROCK TYPE	RELATIVE BRINE SALINITY Decreasing Salinity High 5→4→3→2→1 Low	EVIDENCE
HALITE (youngest)	3	Banded halite, minor sulfates decrease upward
ANHYDRITE, POLYHALITE	2	Nodular to bedded habit indicates more stability upward; little or no clay.
BASAL CLAYSTONE	1	Maximum evaporite clay accumulation and halite solution; not alluvium.
HALITE	3	Trace potassic menerals, locally cross-cut Tenth ore zone.
SYLVINITE	4	Residual clay accumulation, recrystallization at high salinity.
CARNALLITITE	5	Carnallitite-sylvinite lower contact is sharp because brine which precipitated carnallitite transgressed chemically stable sylvinite. Upper contact is gradational as return to lower salinity
SYLVINITE underlain by CARNALLITITE	4 5	Residual clay accumulation at high salinity with recrystallization. Carnallitite in basal part of Tenth ore zone with no brown clay probably represents remnant primary sedimentation not re-precipitated as sylvinite.
HALITE	3	Trace corroded sylvite crystals and nodules of polyhalite at top; minor halite bands at base.
ANHYDRITE, POLYHALITE	2	Bedded to bedded nodular structures and no basal claystone indicates transported deposit.
HALITE (Oldest)	3	Usually banded; trace clay.

Fig. 8 Geologic cross-section of the Tenth ore zone and related evaporite beds from A (center of Sec. 11, T 20S, R 33E to A' (center of Sec. 21, T 20S, R 34E) where the top of the upper member of the Tenth ore zone is used as a datum plane (from Noranda Exploration, Inc. drilling (Fig. 2)).



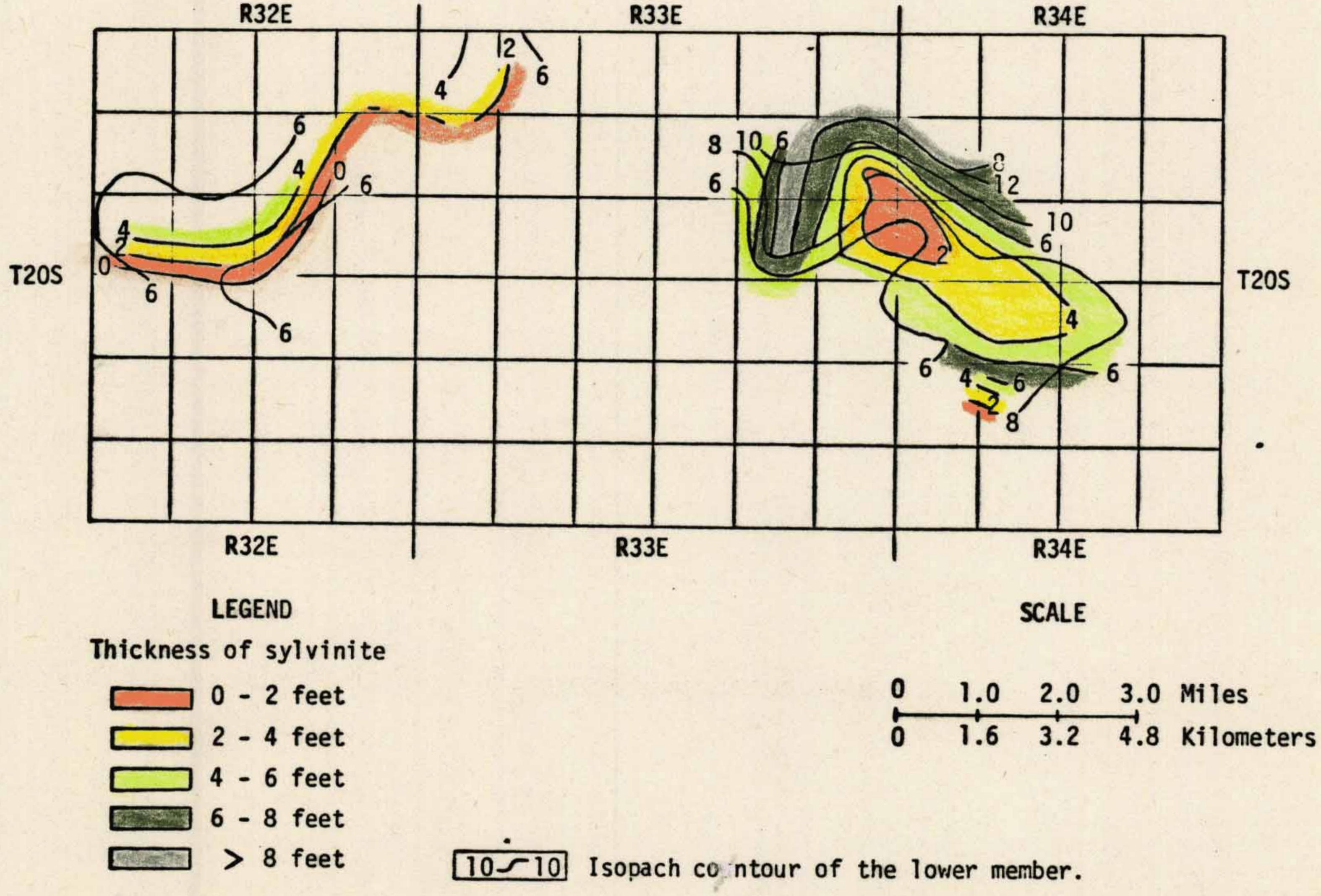
The corroded sylvite was probably partially dissolved during the diagenesis because it was out of equilibrium with the host rock. The halite rock is overlain conformably by the lower member of the Tenth ore zone (Fig. 8).

The lower member of the Tenth ore zone (Fig. 9) is marked by disseminated clay which probably accumulated as the result of continual solution and recrystallization of the evaporite pile in highly saline conditions before burial. The salinity where precipitation of the chloride salts takes place is thought to be greater than 532 parts per thousand (Scruton, 1953). Halite is always present because sodium and chloride ions were in excess of the other elements in the bittern.

The lithofacies of the lower member of the Tenth ore zone grade from argillaceous halite upward to sylvinite and to carnallitite reflecting increasing brine salinity during deposition. The lithofacies boundary between carnallitite and sylvinite is obscured by post-burial carnallite metasomatism. Argillaceous halite sometimes forms an envelope around a thinning wedge of sylvinite at this lithofacies boundary. There is a stratiform association of kieserite with sylvite in the National Potash, Lea mine at the top of the lower member. The lower member of the Tenth ore zone has a sharp conformable upper contact with the non-argillaceous middle member.

The middle member of the Tenth ore zone exhibits the same lithofacies as the lower member except that there is usually no clay accumulation. Thus, the middle member is probably conformable with the lower member. Locally there is a greater concentration of clay where the sylvinite and argillaceous halite of the lower member are overlain by the halite rock of the middle member due to minor salt solution. There is no evidence of even minor salt solution where sylvinite in the lower member is overlain by sylvinite and carnallitite of the middle member.

Figure 9. Isopach map of the lower member of the Tenth ore zone and its relationship to the thickness of sylvinite in the lower member, Lea County, New Mexico (from Noranda Exploration, Inc. drilling (Fig. 2)).



10 10 Isopach contour of the lower member.

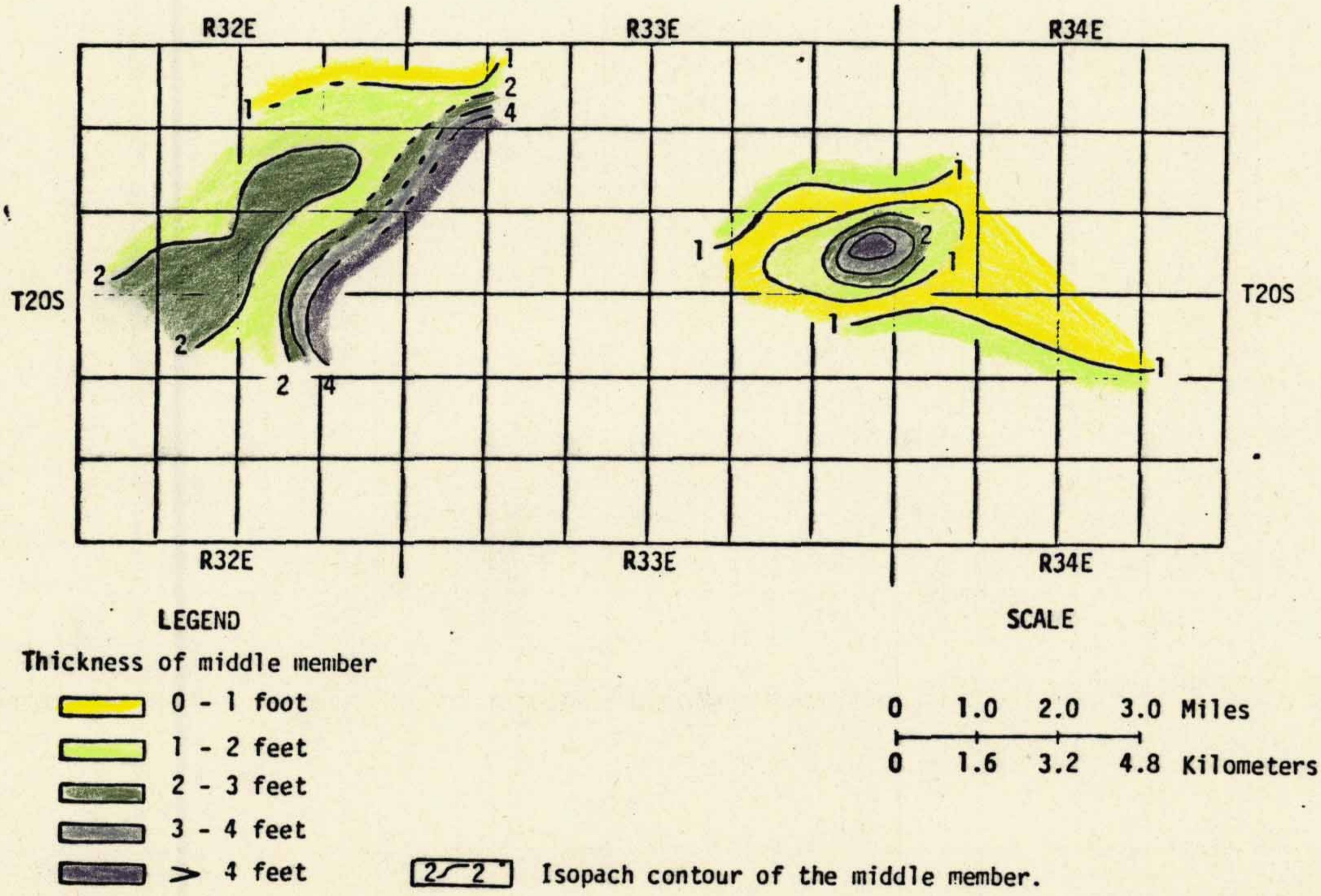
During the deposition of the middle member, the chloride salts appear to have been in a stable environment, protected from repeated solution, recrystallization and accumulation of insolubles. This would be true if they were covered by a thick layer of brine. Therefore, the sea level in the basin was probably higher during accumulation of the middle member than for the other members of the Tenth ore zone and maintained a brine layer over the precipitating potash salts.

The parts of the middle member (Fig. 10) thicker than 3 feet (1 meter) are in the carnallite facies. The areas of carnallite concentrations in the middle member coincide with the concentration of carnallitite or minor sylvinite in the lower member (Fig. 9). The brine which precipitated the carnallitite in the middle member probably accumulated in gentle depressions in the lower member. The middle member is conformably overlain by the upper member. This interpretation is supported by the gradual increase in clay concentration upward toward the contact but no definite claystone bed is present.

The upper member of the Tenth ore zone is composed of halite, sylvinite and carnallitite lithofacies and is similar to the argillaceous lower member. The increase in clay content over the middle member may be due to a drop in sea level and a concomitant increase in wind-born dust. The upper member is conformably overlain by halite rock. The sylvite and carnallitite lithofacies of this stratum in Noranda drill holes Number 1 and Number 2 is relatively minor. The halite is commonly nonargillaceous and sometimes it is banded near its upper contact with the 119 Marker Bed.

The 119 Marker Bed is present as anhydrite and polyhalite. Like the 120 Marker Bed, it becomes more anhydritic toward to northern margin of the Carlsbad district. It conformably overlies the halite rock in places where the halite is banded and there is no claystone seam present. The Claystone seam at the base of

Figure 10. Isopach map of the middle member of the Tenth ore zone, Lea County, New Mexico(from Noranda Exploration, Inc. drilling (Fig. 2)).



the 119 Marker Bed probably represented residual material left at a local disconformity. During the hiatus evaporites were eroded and clay accumulated in water of such low salinity that no evaporite minerals could precipitate. As the water salinity increased, sulfates accumulated above the claystone seam. The clay appears to have prevented the anhydrite from altering to polyhalite. The 119 Marker Bed is conformably overlain by banded halite rock.

Jones (1954, p. 109) reported that lithofacies of the Marker Bed change from the Delaware basin to the Northwestern shelf as follows: anhydrite to polyhalite to kieserite; or anhydrite to glauberite to polyhalite to kieserite. In the Noranda property, these lithofacies change in reverse manner on the Northwestern shelf north to the limits of the district as follows: Kieserite to polyhalite to anhydrite. Anhydrite may have altered to polyhalite and kieserite with increasing salinity in suppersaline environment (Fig. 6). However, if this alteration is due to upward migration of potassic brine from the Tenth ore zone, then it should be found in Duval Corporation's Nash Draw mine twelve miles to the southeast where the 119 Marker Bed and the Tenth ore zone have the least vertical separation. It was not found there. Therefore, the alteration of anhydrite to polyhalite was not the result of migrating upward through the underlying potash ore zones.

The saline sequence shows an increase in brine salinity from the time of deposition of the 120 Marker Bed to the top of the middle member of the Tenth ore zone. The high concentration of carnallite in this member reflects the existence of a brine with the highest salinity in the supersaline environment. From the time of deposition of the upper member of the Tenth ore zone to that of the claystone seam in Marker 119 the water salinity decreased to a level such that no potash salts precipitated. The claystone marks a disconformity and the completion of an uninterrupted evaporite cycle.

Claystone accumulated at a disconformity as the result of solution of underlying halite rock. If the claystone seam is enveloped by polyhalite, then slow reduction in brine salinity caused sulfate and halite to precipitate simultaneously before the hiatus which caused the disconformity occurred. When deposition resumed and salinity increased, halite and sulfate precipitated together to build a mosaic structure which was then subjected to current action, and a decrease in brine salinity with solution of halite. Anhydrite has a low solubility so that is accumulated as a bedded almost monomineralic sediment. As salinity increased, sulfate precipitation decreased and halite became the dominant mineral above the Marker Bed. This evaporite sedimentation would explain the sedimentary current structures in the Marker Bed.

Scruton (1953) reported that sulfate and halite precipitate together over a salinity range of 353 to 427 parts per thousand. A sharp basal contact of polyhalite on occluded polyhalite in halite may indicate that the salinity dropped below 353 parts per thousand and no halite precipitated. If the brine salinity increased to 427 parts per thousand, sulfate and halite accumulated together. Than as the brine gradually evaporated to higher salinity only halite precipitated. This explains the upper gradational contact between polyhalite bearing orange halite and the colorless pure halite.

Schaller and Henderson (1932) believed that all the polyhalite was formed by replacement of anhydrite because irregular remnants of magnesitic anhydrite are enclosed in the polyhalite. The polyhalite crystals and multigrained aggregates project into the anhydrite as elongate crystals or vein-like tongues with scalloped margins convex toward anhydrite. A possible chemical reaction is:

(Magnesitic Anhydrite) + (Brine) $\rightleftharpoons$ (Polyhalite) + (Brine)

$$Ca_2Mg(SO_4)_3 + (2K^+_{(aq)} + SO_4^{=}{}_{(aq)} + 2H_2O) \rightleftharpoons K_2Ca_2Mg(SO_4)_4 + (2H_2O)$$

The iron present in the sylvite probably did not result from alteration from carnallite, but from 0.17 ppm Fe^{++} found in sea water saturated to the point of carnallite deposition (Braitsch, 1971). Adams (1967) found the content of iron in the red rims to be 1,800 to 1,300 ppm by weight. Therefore, there is about 10,000 times more iron concentrated by sylvite red rims than is present in carnallite. Bacteria (Flint and Gale, 1958) and algae (Morris and Dickey, 1957) may have been important in the concentration of iron.

According to Borchert and Muir (1964, p. 223) the primary mineralogy in the Carlsbad district was carnallite + halite, or carnallite + halite + epsomite. Sylvite was absent probably because it cannot precipitate under equilibrium conditions by evaporation in the temperature range of 11°C to 72°C (52°F to 106°F) before caranallite (Stewart, 1963). The sea temperature in Recent time is rarely above 25°C (77 F) according to Horne (1969) and the Permian sea in this region was probably not much above this average. Thus, sylvite was not a primary deposit. It was probably the result of leaching of carnallite by an undersaturated brine, which became saturated with potassium. Then sylvite precipitated with other salts (Schwerdtner, 1964) as sylvinite or hartzsalz such as is present in the National Potash's Lea mine at the top of the lower member of the Tenth ore zone.

Autogenetic Events

Autogenetic events refer to changes in the Tenth ore zone and its related evaporites due to pressure after burial. Because of relatively shallow depths, temperature was not an important factor. The autogenetic events are summarized in Table IV.

The gneissic banding, as observed in the Tenth ore zone sylvinite, is interpreted to be the result of pressure (Stewart, 1963). The claystone seam usually found in the basal part of the 119 Marker Bed is folded and fractured. Halite, sylvite and carnallite have migrated laterally along the top and bottom surfaces of the 119 and 120 Marker Beds. This migration of bitterns is commonly accompained by metasomatism which is not confined to evaporite lithofacies but cuts across evaporite beds. For example, a dusky-red carnallite aggregate may extend from the lower member into the middle member.

Nitrogen gas pressure may have contributed to this migration and metasomatism. Brine filled cavities under nitrogen gas pressure are often found during mining. The source of the nitrogen is unknown.

Intercrystalline brines are still present in the potash ores. Greenwald and Howarth (1937) measured traces to 3.0 oz (86 grams) of brine exuded during compression of 29.2 pound (13.2 kilogram) samples of sylvinite from a depth of 900 to 1000 feet (270 to 310 meters).

Salt Horses in the Tenth Ore Zone

A salt horse is a mining term used in the Carlsbad district to indicate a gangue salt body which breaks the continuity of the ore zone. In the Tenth ore zone, the salt horses studied are composed of carnallite, halite, argillaceous halite and kieserite. Salt horses in the National Potash, Lea mine; the Kerr-McGee

TABLE IV

Autogenetic events in the Tenth ore zone and related evaporite beds.

ROCK TYPE	ALTERATION (⟶)	
HALITE (Youngest)	----------	No evidence
ANHYDRITE, POLYHALITE	Anhydrite ⟶ Polyhalite	Polyhalite envelopes around anhydrite and protected by clay (Schaller and Henderson, 1932)
BASAL CLAYSTONE	Brecciated	Fracture-filling by carnallite and sylvite between claystone fragments.
HALITE	----------	No evidence
SYLVINITE or CARNALLITITE	Sylvinite ⟶ Carnallitite	Corroded hematite-rimmed sylvite is surrounded by carnallite
HALITE or CARNALLITITE	Halite ⟶ Carnallitite	Dusky red carnallite migrates upward from lower member
SYLVINITE or CARNALLITITE	Sylvinite ⟶ Carnallitite	Sylvinite stratum and sylvite crystals float in carnallitite and carnallite
	or Hartsalz	Remnant hematite rims from sylvite in kieserite
HALITE	----------	No evidence
ANHYDRITE, POLYHALITE	Anhydrite ⟶ Polyhalite	120 Marker Bed found as both anhydrite and polyhalite (Schaller and Henderson, 1932)
	⟶ Hartsalz	Hartsalz forms envelopes around polyhalite
HALITE (Oldest)	----------	No evidence

Potash mine; the Duval Corporation, Nash Draw mine; and the Noranda core can be divided into four types: metasomatic, structurally controlled, lithofacies, and erosional. The type of salt horse exposed at the mining face determines what exploration method is used.

A metasomatic salt horse is an irregularly shaped discordant body with a sharp contact with the ore and with a pegmatitic texture. There is little clay present in the horse, except on its margins where it accumulated during salt horse recrystallization. The size and distribution of this type of salt horse are unpredictable. No slumping or collapse is observed around the salt horse, so it is probably formed by the metasomatic alteration after burial of the Tenth ore zone. (Pl. II) The source of the metasomatic solutions is probably brine trapped during burial and released during phase changes of the buried salt minerals. A continuation of the Tenth ore zone is likely to be found by drilling horizontally through a metasomatic salt horse because it is a local secondary feature.

A structurally-controlled salt horse originates by faulting and folding of the Tenth ore zone. In the National Potash's Lea mine, the Tenth ore zone was subjected to isoclinal folding associated with a reverse fault. Which elevated the lower member about 5 feet (1.5 meters) higher than its normal position. Gangue halite rock was carried by this fault into the plane of mining operations, but the ore resumes with in a short horizontal distance. The cause of the folding and faulting is unknown. The position of the Tertiary basalt dike (Jones and others, 1973).is thought to be structurally controlled. It removed ore in the Kerr-McGee mine.

A lithofacies salt horse is an irregular - shaped and randomly sized concordant body. Due to variations in brine salinity at the time of deposition of the

Tenth ore zone, different lighofacies variations in the of the same geologic subzone accumulate. For example, the contact zone between the sylvinte ore and an argillaceous halite horse in the lower member is a lateral thinning wedge of sylvinite enveloped by argillaceous halite Pl. III. The argillaceous halite horse contains rounded, disseminated polyhalite pebbles, no sylvite, and the color of the clay is moderate brown (5 Y 4/4). In contrast, the sylvinite ore contains no polyhalite pebbles and the clay is pale green (10 G 6/2). In an interval of 40 feet (10 meters) in the Kerr-McGee mine drift there is a transition from the argillaceous halite horse to the sylvinite ore in the lower member of the Tenth ore zone. A continuation of the Tenth ore zone is not likely to be found by penetration of this type of salt horse because it is a laterally extensive primary sedimentary feature.

An erosional salt horse is an angular unconformable body. The halite rock above the Tenth ore zone cuts across the upper (Pl. IV), middle and most of the lower member of the Tenth ore zone in part of the Duval Corporation, Nash Draw mine. Clay is highly concentrated in the halite above sylvinite at the contact between the halite rock and the lower member of the Tenth ore zone. It appears that dilute brines dissolved and eroded troughs in the margin of Tenth ore zone sylvinite. The halite rock of the horse fills the trough in contrast to the sylvinite or argillaceous halite rock. A sink feature with channel entries on all sides, as described by Baar (1974), would fit into this classification, but this geologic phenomena is probably not present in the study area, because the Tenth ore zone does not exhibit any karst features such as those in Ethiopia (Holwerda and Hutchinson, 1968). A continuation of an economic thickness of the Tenth ore zone is not likely to be found by penetration of this type of salt horse because the erosion is a primary sedimentation feature at the margin of sylvinite sedimentation.

SUMMARY AND CONCLUSIONS

The Tenth ore zone is a bedded evaporite potash deposit in the Upper Permian (Ochoan) Salado Formation in the Carlsbad district. Sylvinite is mined in the Duval Corporation's Nash Draw mine; the Kerr-McGee Chemical Corporation's potash mine; and the National Potash Company's Lea mine; and it is present in the International Minerals and Chemical Corporation's potash mine; and in an area explored by Noranda Exploration, Inc.

The Tenth zone ore mineral is sylvite and the marketed product is muriate of potash. The Tenth ore zone was intersected by the Noranda Exploration drilling, but the exploration failed to find enough tonnage of ore to support a new mine development.

The Ochoan Series is dominated by evaporitic sediments which accumulated in a restricted saline sea within the Permian basin. The potash evaporites were precipitated in a supersaline environment. Structural contours on the top of the 120 Marker Bed indicate that the Tenth ore zone was deposited on a broad, flat basin. The regional southeast dip may be due to downward movement on the west side of the fault separating the Delaware basin from the Central Basin platform.

The Tenth ore zone is part of a cyclic sequence of beds in which cycles of evaporation and deposition were interruped and renewed as the brine concentration in the basin changed. A brine of high salinity transgressed from the Northwestern shelf into the Delaware basin whenever marine circulation in that basin became restricted because of a fall in sea level. The brine moved in the opposite direction at times when the basin became open to marine circulation and the sea level rose. Northeasterly movement of the brines may have been facilitated by the eastward tectonic tilting of the Delaware basin in late Permian time. During these transgressions and regressions, evaporitic sediments of differing composition precipitated from brines of various salinities and accumulated on the floor of the basin.

A cycle of evaporite precipitation started with the sulfate facies (120 Marker Bed). This bed is overlain conformably by halite rock and then by a series of increasingly younger, more saline evaporite strata of various facies: halite, sylvite and carnallite of the lower member of the Tenth ore zone, and sylvite and carnallite of the middle member. The middle member is overlain conformably by an upper member composed of increasingly younger, less saline evaporite strata of various facies; sylvite and carnallite, halite and then sulfate (119 Marker Bed). A claystone seam is commonly associated with the 119 Marker Bed and marks a local discondormity caused by salinity so low that no evaporite minerals precipitated. Clay concentration in the supprsaline environment seems to be a function of the number of solutions and recrystallizations an evaporite bed is subjected to before burial.

The lithofacies of the 120 Marker Bed grade from anydrite and polyhalite deposited in a saline environment to kieserite in a superline envornment. Anhydrite was probably the primary sulfate mineral which was partially altered after it was carried by currents into environments of different salinity. The 120 and 119 Marker Beds have a wide distribution because once anhydrite and polyhalite have formed, they are hard and nearly insoluble. Thus they will survive transport by water currents. Since these marker beds are not contemporaneous with the ore zone, they do not indicate the continuation of mineable ore.

The Tenth ore zone ranges from 6 to 10 feet (2 to 3 meters) in thickness. Favorable mining conditions occur when the sylvite facies of all members of the Tenth ore zone occur one on top of the other. This does not always happen because each member precipitated from a bittern with a different salinity distribution.

Carnallite was precipitated from the bittern with the highest salinity and density, which gravitated into the depressions in the underlying strata. Carnallite is usually found in localities where the Tenth ore zone is unusually thick. Often brines undersaturated in carmallite dissolve the carmallite amd release the potassium ions which recombine in brines of higher salinity as sylvite with minor amounts of kieserite. Therefore the sylvite facies often forms alteration shells around incompletely replaced the carnallite facies.

The lack of clay in the middle member of the Tenth ore zone is probably due to a rise in sea level and less dust transport, for the depth of the brine does not restrict sylvite formation. The lack of karst features indicates that the Tenth ore zone was always below sea level before burial.

Autogenetic events occurred in the Tenth ore zone due to pressure after burial. The claystone seam at the base of the 119 Marker Bed was fractured. Buried intercrystalline brines caused minor recrystallization, such as gneissic banding, while brine in cavities, often under nitrogen gas pressure, caused major recrystallization forming pegmatitic pods of ore and salt horses.

Carnallite metasomatic replacement of sylvinite and sylvite to produce carnallitite was common. Characteristic red rims of hematite plates are found around sylvite crystals. The hematite plates migrate to the edge of the recrystallized sylvite zones. Corrosion of the hematitic rims or their presence "floating" in langbeinite, leonite or kieserite is evidence of metasomatic replacement of sylvite.

The clay in the sylvite facies is characteristically pale green, in contrast to brown clay in the halite facies. Carnallite metasomatism caused the brown clay to be chemically reduced to green clay through leaching of the ferric iron from the brown clay by the bittern. The ferric iron recombines as hematite plates in carnallite and sylvite.

The facies relationships of evaporite minerals and their alterations can be used to explain the presence of absence of sylvinite, and help to reduce the risk involved in reaching for sylvinite ore.

Carnallite associated with some of the sylvinite ore cause recovery problems in the mill. The insoluble content of the Tenth ore zone is too great to permit economical solution mining. A Tertiary basalt dike drilled on the Noranda property may form a costly barrier to underground mining as it has in the Kerr-McGee potash mine.

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