DEPARTMENT OF MINES
SOUTH AUSTRALIA

REPORT ON OVERSEAS VISIT (APRIL-JULY, 1964)

PART II - EVAPORITES, BRINES, SULPHUR

by

R.K. Johns
Senior Geologist

Rep.Bk.No. 60/45
G.S. No. 3097
D.M. 305/65

10th March, 1965

INTRODUCTION

While overseas during the period April to July, 1964 the writer visited in addition to phosphate deposits, most of the major potash mines and a number of evaporated-salt, rock salt, brine and sulphur operations in North America, Europe and Israel to study the occurrence, exploration and exploitation of what are, to Australia, mostly exotic mineral deposits. However, this may not always be so. There are generally no surface indications of highly soluble evaporite minerals and their discovery depends on drilling; thus, discovery is often largely a matter of chance.

It is interesting to trace the history of discovery and exploitation of potash from 1861 to after World War I, when Germany was the sole world source, until the present time.

Though Searle's Lake (California) was discovered in 1862 and was first exploited in 1873 fractional crystallization technology was insufficiently advanced to provide domestic U.S. needs. The situation was little changed by the discovery in 1912 during oil drilling operations of potash brines and non-commercial potash salts in West Texas. However, the discovery in 1925 of sylvite in oil-well cuttings from the same basin in New Mexico led to intensive core drilling and to the establishment of a sound U.S. potash industry based at Carlsbad. Between the wars, Germany, France, U.S.A. and U.S.S.R. emerged as the main sources of supply. In 1943 oil-well drilling operations in the Esterhazy Basin in Saskatchewan (Canada) led to the discovery and production (in 1962) of what has now proved to be the largest potash deposit in the world. Drilling for oil has also located exploitable potash bearing evaporite sequences near Moab (Utah), in northeastern England, Spain, Poland and North Africa.

The discovery and exploitation of sulphur, both as a caprock component of some of the salt domes of the Gulf of Mexico area and as a recovered product from sour natural gas in Alberta (Canada) and at Lacq (France) also resulted from the search for oil and gas.

The various mines and plants visited and details of geological setting of the deposits are described below with some general data relating to occurrence. In Fig. 1 is shown the route taken and the localities visited.

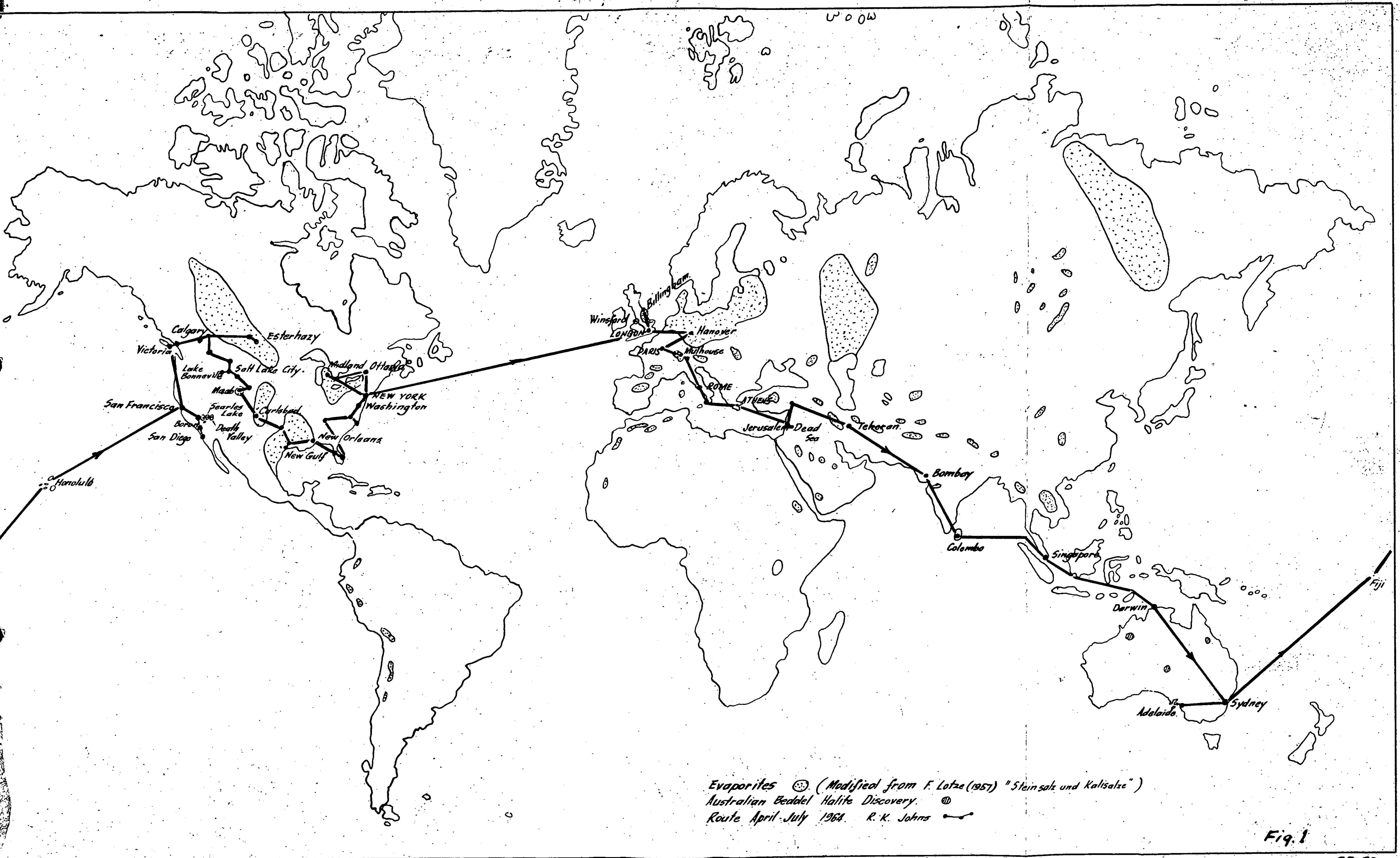

Fig. 1

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EVAPORITES

General Occurrence

Evaporites are more common and widespread than is generally recognized. In North America they are present in all Palaeozoic and later systems (excepting possibly the Cambrian): In Europe salt deposits are found in the Devonian, Permian, Triassic, Jurassis and Tertiary, and only the Carboniferous is entirely salt free; in Asiatic Russia they are also found in the Cambrian, Ordovician, Silurian and Cretaceous Systems. In the general sense evaporites may comprise deposits resulting from evaporation of seawater under restricted environmental conditions, or from desiccation of salt lakes and playas - in the latter the salts may have been derived from cyclic sources, from the weathering of rocks of the drainage basin or from volcanic sources.

In discussing restricted marine occurrences Krumbein* (1951) points out that "widespread and recurrent deposition of evaporites during essentially all parts of the Palaeozoic and later eras suggests that conditions favouring excessive evaporation of seawater occurred. . . . . . on many occasions. The lateral gradations of the evaporites into normal marine deposits in many instances, implies that large parts of the continent had normal climatic conditions simultaneously with the formation of evaporites in restricted areas. Hence, there seems no need for calling upon "general aridity" during a geologi period to account for its evaporites. Rather, the implication for historical geology is that tecto-environmental conditions for evaporites were of common occurrence, and that the evaporites fit into the climatic picture of any period as normally expected phenomena to be found on shelves, intracratonic basins and in miogeosynclines . . . . .(but) rare or absent among typical eugeosynclinal deposits."

The evaporation of seawater in basins, marginal salt pans, salinas, lagoons or of relict seas depends on a restriction of the environment which may be caused by biogenic (reefs), physiographic (regressive strand lines, barrier beaches) or tectonic controls. The major contained elements are

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* Krumbein W.C., (1951) Occurrence and lithologic associations of evaporites in the U.S. Jour.Sed.Pet.21 (2) pp. 63-81.

For other references see:

Stewart, F.H., (1963) Marine evaporites. U.S.G.S. prof.pap. 440-Y.

those of seawater, precipitated in a definite order dependent on their solubility. Evaporation normally leads to successive layers that are rich in carbonates (Ca, Mg), sulphates (Ca) and finally chlorides (Na with K and Mg). Primary lateral variations result from a number of factors: distance from the shoreline, distance from the open ocean, influence of rivers, depth of water, configuration of the depositional floor, rate of subsidence, thermal currents, periodicity of intake of seawater or freshwater, changes in temperature and whether opportunity is given for precipitation of the various salts and in particular of the highly soluble bittern salts. Pene-contemporaneous and postconsolidation changes introduce further variations.

Solid Phase Potash

Potassium salts are commonly referred to as "Potash". Commercially the most important of these salts is sylvite (KCl) while the ore mined is an intimate physical mixture of KCl and NaCl called sylvinite. Potash statistics are reported as the amount of potassium oxide (K_2O) to which a salt in question is equivalent. Pure muriate (KCl) is equivalent to 63.18% K_2O but most commercial muriate is equivalent to about 60% K_2O. Other naturally occurring potassium salts are tabled below.

SALT	FORMULA	% OF K	CHEMICAL EQUIVALENT IN TERMS OF POTASH (K_2O)
(Potassium metal)	K	100	120
Sylvite	KCl	52	63
Arcanite	K_2SO_4	45	54
Langbeinite	$K_2SO_4 \cdot 2MgSO_4$	19	23
Polyhalite	$K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$	13	16
Carnallite	$KCl \cdot MgCl_2 6H_2O$	14	17
Kainite	$KCl \cdot MgSO_4 \cdot 3H_2O$	16	19
Glaserite	$Na_2SO_4 \cdot 3K_2SO_4$		

Potash data are reported in short tons (2000 lbs.)

Potash is one of the basic plant nutrients indispensable to plant life and some 94% of all production is consumed in fertilizers. The total world consumption is growing at about 5% annually. The production of potash in the "Free World" in 1963 increased by 14.5% over that of 1962, to a total of almost 10.5 million tons though it still remained in short supply. Over 90% of the total world demand was filled by U.S.A., West Germany, East Germany, France, U.S.S.R. and Canada while the remainder was supplied by Spain, Sicily, Poland, Israel, Morocco, the Congo, Chile, Jordan, and Ethiopia.

In 1963 the following production was reported (in millions of short tons potash equivalent) - U.S.A. (2.60), West Germany (1.95), East Germany (1.75), U.S.S.R. (1.24), France, Alsace (1.67). Canada is expected to become the largest producer in the world within several years; in 1963 output totalled 664,000 tons.

The price of standard potash (60% minimum K_2O) in bulk at works ranges from $30 to $40 per ton.

In 1963 Australia imported 64,000 tons of KCl and 9,500 tons of K_2SO_4 for fertilizer usage.

1. <u>West Germany - Hanover - Zechstein Basin</u>

23rd June, 1964 to 27th June, 1964.

Erich Hofrichter }
Axel Hermann } - Bundenstalt für Bodenforschung, Hanover.

Palaeogeographic History of the N.W. German Zechstein Upper Permian Basin.

The Zechstein Basin (fig. 2) is an extensive epicontinental basin comprising a thick sequence of Upper Permian evaporites, the basement of which is composed of Devonian, Carboniferous and Lower Permian Rocks. The Zechstein Sea, during transient states of cut off and evaporation, underwent four major depositional cycles resulting in thick sequences of salt (fig. 3). At the base, these cycles consist of clastic deposits; these are generally succeeded by carbonates, sulphates and chlorides and in the recessive part are generally terminated by anhydrite.

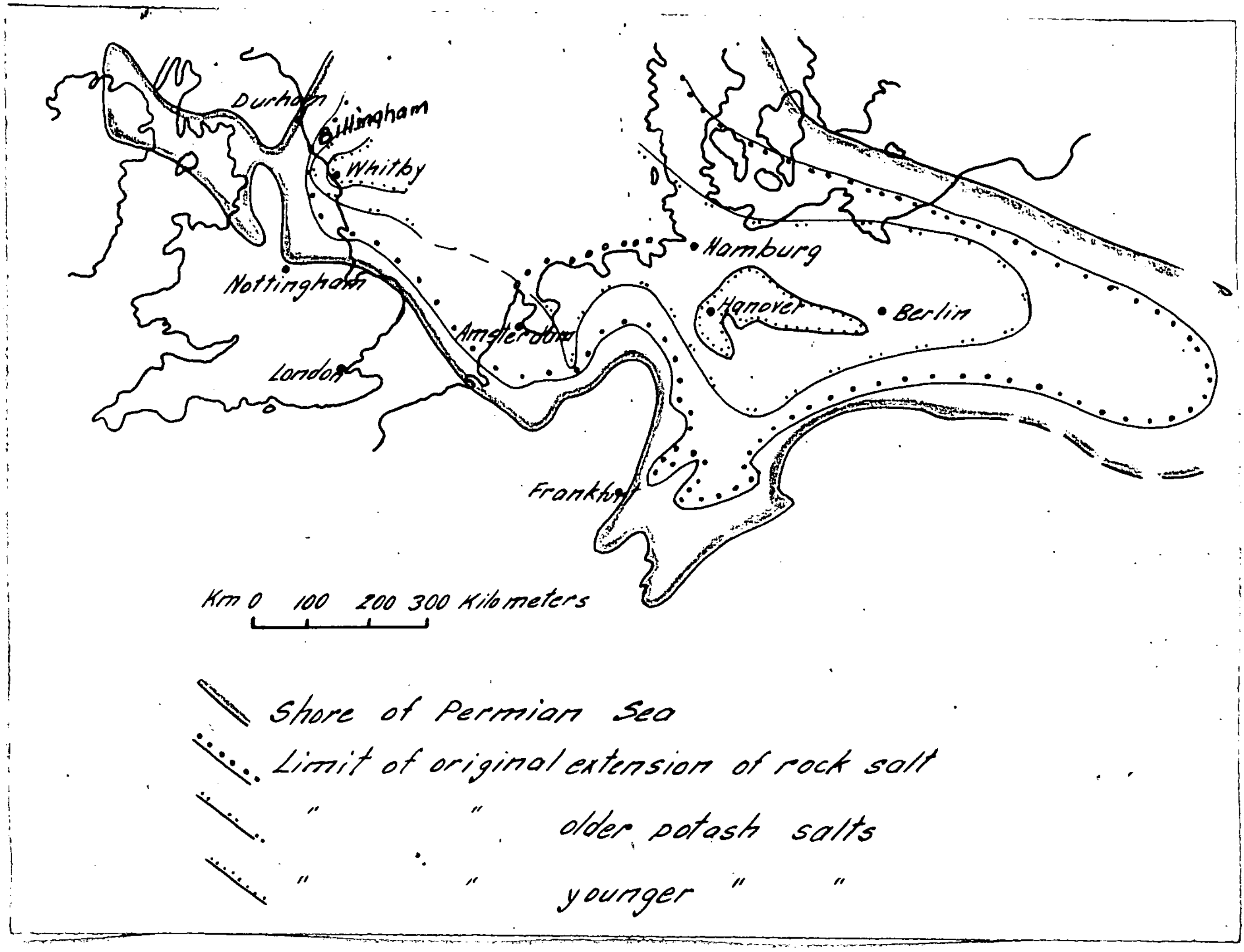

Fig. 2: Zechstein Basin - Permian salt deposits in Northwestern Europe and British Isles.

The "Zechstein" is overlain by Bunter sandstone, a shallow water semicontinental deposit; red terrigenous materials which came from the south and southeast are over 3,000 feet in thickness and include some rock salt. Then follows the marine Muschelkalk; during this phase a temporary cut-off took place resulting in separation of more rock salt. During the upper and Middle Keuper brackish estuarine conditions were prevalent once more. These are succeeded by Jurassic and Cretaceous marls, limestone and chalk and Tertiary clays.

The stratigraphic sequence is shown in Table 1.

GERMAN ZECHSTEIN SEDIMENTATION AND STRATIGRAPHY

AFTER G. RICHTER - BERNBERG 1963

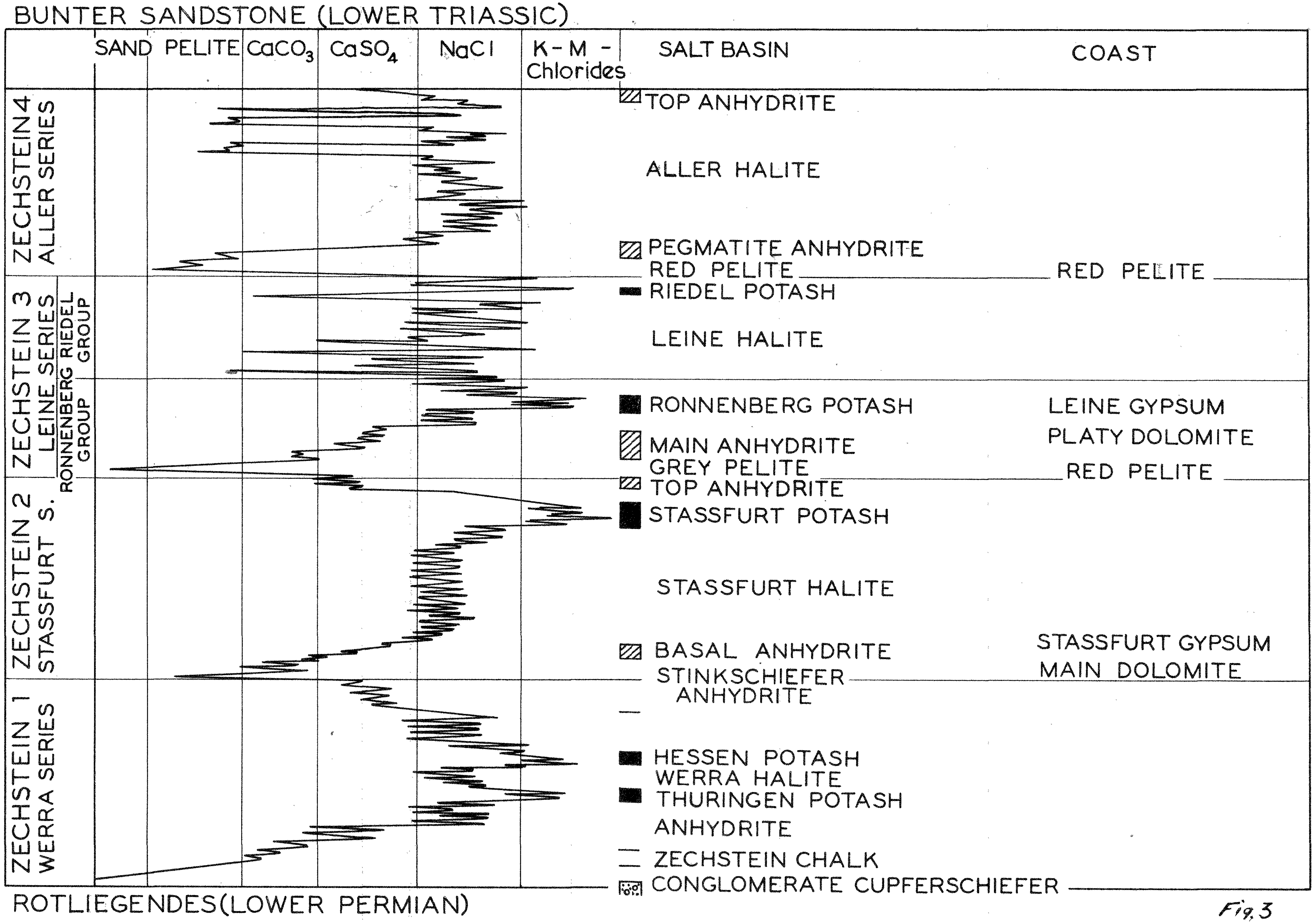

Fig. 3

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German Zechstein Sedimentation and Stratigraphy

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Exd.	Date 24/9/64

Approved

Passed

Director

No. | Amendment | Exd. | Date

TABLE 1.

STRATIGRAPHIC SEQUENCE - NORTHWEST GERMANY

SYSTEM			MAIN LITHOLOGY	THICKNESS (ft.)
Quaternary			sand, gravel	450 - 900
Tertiary			clay	3000 - 5500
CRETACEOUS	Upper Cretaceous	Danian Maestrichtian Campanian Santonian Coniacian Truronian Cenomanian	chalk, limestone marls	1500 - 5500
	Lower Cretaceous	Albian Aptian Barremian Hauterivian	clays, marls	- 3600
		Valangiman Wealden	clay, marls, sandstones	
JURASSIC	Upper Jurassic	U. Malm. (Portlandian)	Limestone, marls, salt	- 5000
		M. Malm. (Kimmeridgian)	Marls, limestone, sandstone.	
		L. Malm. (Oxfordian)	Clay, limestone	
	Middle Jurassic (Dogger)	Callovian Bathonian Bajocian Adlenian	Clay, marls, sandstone	600 - 3000
	Lower Jurassic (Lias)		Clay,marls, oil shales	1200 - 4500
TRIASSIC	Keuper	Rhaetian Middle Keuper Lower Keuper	Clay, sandstone marls, salt Clay, marls, dolomite	1500 - 1800
	Muschelkalk		limestone, dolomite, salt	600 - 1200
	Bunter	Upper B. Middle B. Lower B.	sandstone, clay, salt sandstone, clay clay, sandstone	1500 - 3000
PERMIAN	Zechstein	Aller Series Leine Series Stassfurt Series Werra Series	salt, anhydrite,potash dolomite, clay	3600
	Rotliegendes		sandstone, clay,salt	600 - 3000
CARBONIFEROUS	Upper Carboniferous	Stephanian Westphalien Namurian	sandstone,shale,coal seams	5000
	Lower Carboniferous		?	?

Tectonic Features

The southern boundary of the Basin is formed by mountainous regions (including the Harz) where the tectonic structures are characterized by fault blocks along the borders of which salt has frequently risen.

Where the salt thickness elsewhere exceeds a certain thickness anticlines and salt domes having a NNE-SSW or NW-SE trend have been formed (Figs. 4 and 5). The tectonic structure of the Mesozoic in N.W. Germany is entirely modified by the specific movement of the Permian salt and it influences all economic mineral deposits including groundwater.

(a) The first oil fields in the area were discovered at the flanks of salt domes, the cores of which consist of Zechstein salt.

(b) Migration of this salt can be dated back to the Jurassic and the sedimentary iron ores typical of central Germany have an origin attributed to synsedimentary faulting consequent on the rise of salt. The transgressive conglomerates are rich in iron.

(c) Near Stassfurt are located potash deposits which were identified in 1843 and in 1861 became the first to be economically exploited in the world. Other localities have since been opened up. Halite is being recovered by mining and also by solution at a number of centres.

(d) Copper shales which have been known since the Middle Ages (e.g. Mansfeld) occur at the base of the formation.

(e) Carbonate rocks of the Zechstein constitute the most significant German natural gas deposits.

The Zechstein cycles

There are four sedimentary cycles represented more or less throughout the region and named Zechstein 1, Zechstein 2, Zechstein 3 and Zechstein 4. Each of these individual cycles of progressive evaporation starts with a clastic sediment (conglomerate at the margin of the basin, sand silt, mudstone, pelite). Then follows a carbonate phase (limestone/dolomite), a sulphate phase (anhydrite/gypsum), and chlorides. Halite is generally of great thickness and is succeeded finally by bittern salts (potassium, magnesium: sulphates and chlorides).

Prior to the deposition of a new cycle a recessive sequence (generally only thin) is developed. The diagram (Fig. 3) illustrates the progress of precipitation which, due to palaeoclimatic and palaeogeographic factors, does not proceed in a straight line, although the principle of the sequence from less soluble to more soluble salt can be clearly recognized.

At the margin of the basin and within the region of shallow-water areas in the central parts of the basin carbonates have been deposited in considerable thickness. At these places are developed bryozoa reefs in Zechstein 1 and algae reefs in Zechstein 2 and 3. Towards deeper water these massive light coloured carbonate rocks (90 - 200 feet in thickness) change laterally in facies to dark, stratified limestones or dolomites. In the deepest parts of the basin these may be replaced by a thin bed of highly bituminous "stinkschiefer". This change of facies from Main Dolomite to "stinking dolomite" to "stinking shale" from the margin and proceeding to the deeper parts of the basin is particularly obvious in Zechstein 2.

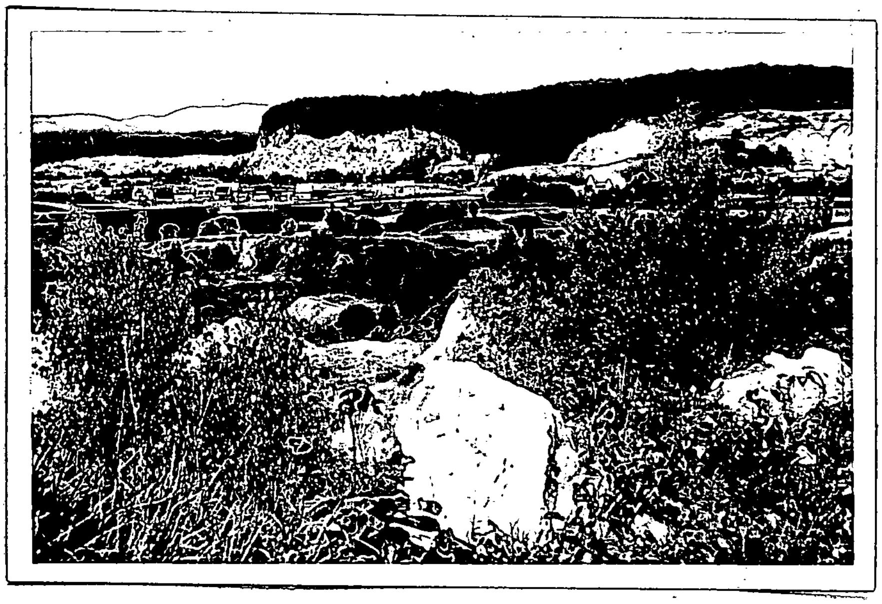

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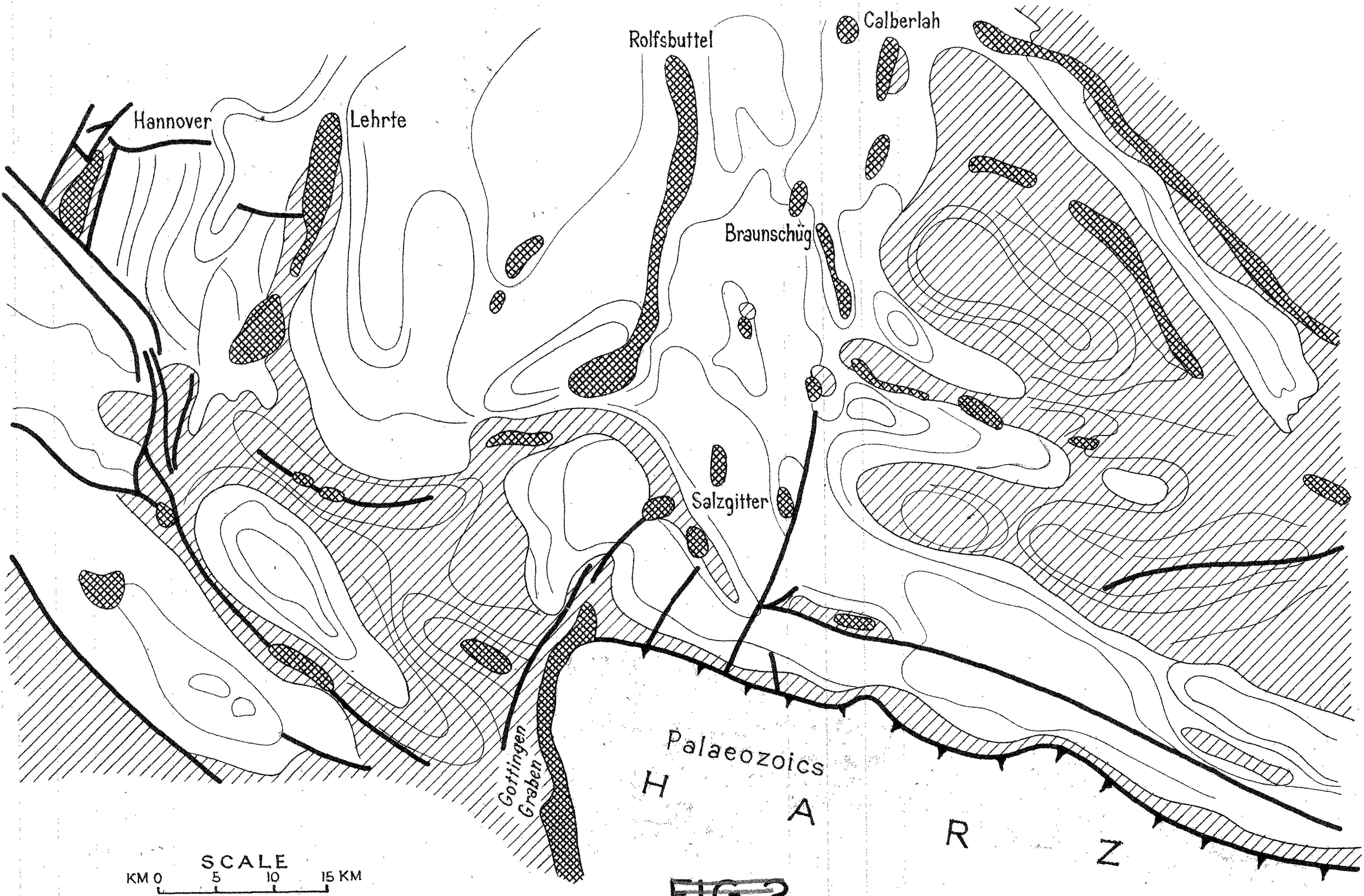
Fig. 6 Anhydrite, gypsum quarries at Sachsenstein by Bad sachse, Harz Mountains.

The marginal "coast-line" carbonate rocks are normally succeeded by light coloured massive anhydrite up to 1500 feet in thickness (Fig. 6); towards the centre of the basin these change laterally to thin and extremely finely stratified dark anhydrites.

In the cycles Zechstein 2, 3 and 4, beds of halite range from 600 to 2,000 feet in thickness. In Zechstein 1, however, halite was precipitated

STRUCTURAL GEOLOGICAL MAP OF THE HARZ FORELAND

(AFTER H.J.MARTIN - 1963)



~~FIG. 2~~

Zechstein (diapir mainly at surface)....... ▩

Triassic.......................... ▨

Jurassic, Lower & Upper Cretaceous ..... ☐

Fault .... —

Fig. 4

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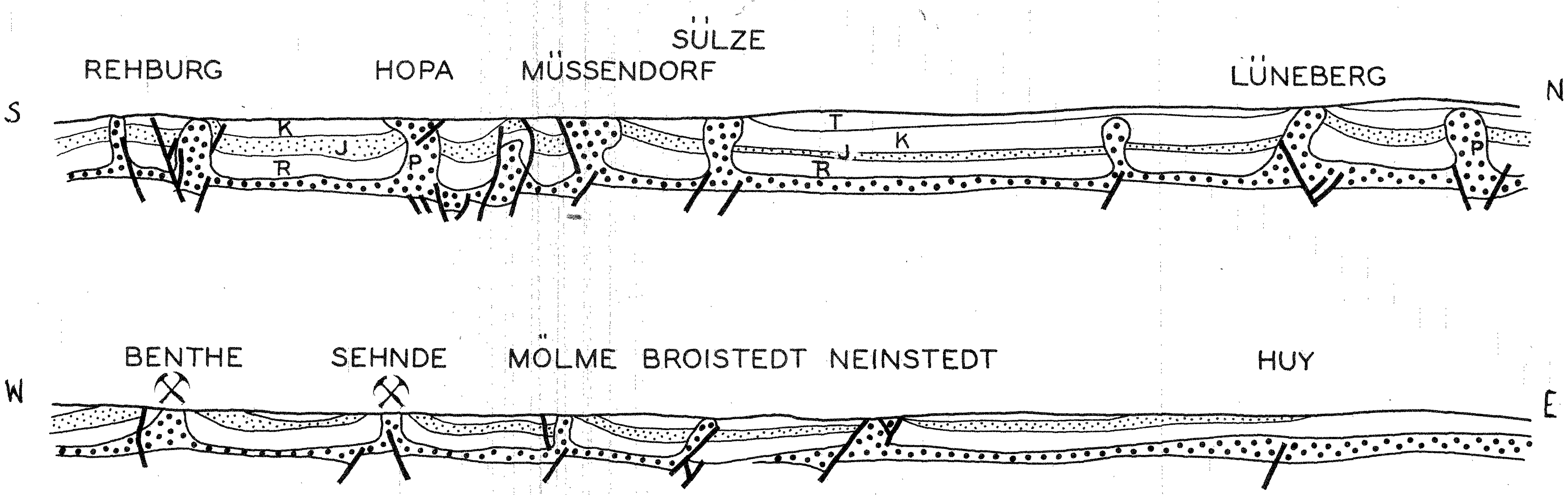
ZECHSTEIN DIAPIRS IN N.W. GERMANY

AFTER G. RICHTER – BERNBURG 1963



LEGEND

T	TERTIARY
K	CRETACEOUS
J	JURASSIC
R	TRIASSIC
P	PERMIAN – ZECHSTEIN SALT
╱	FAULT

SCALE IN KILOMETRES

Fig. 5

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Zechstein Diapirs in N.W. Germany

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only in a confined local "trap" behind a ridge and it is assumed that brine which was almost concentrated in sodium chloride was returned from the main basin in Northern Germany to the ocean. It is considered that halite has generally been precipitated rather quickly after having reached concentration.

The potash salts (and K-Mg-salts) represent bitterns of maximum salinity and appear as interbeds ranging up to 30 feet in thickness within the considerable amount of salt. The famous Stassfurt seam attains a thickness of 75 feet.

The mineable potash beds in Zechstein 1 are restricted to the Hessen - Thuringen sub basin in the South. Seam Stassfurt in Zechstein 2 is widely distributed in northern Europe, in Denmark and in north eastern England. Drilling undertaken in Yorkshire indicates that this bed is 15 feet thick and lies at a depth of 3800 feet (see under Billingham, anhydrite). The seams Ronnenberg and Reidel among other lesser ones in Zechstein 3 are lenses well mineable over wide areas though not in others.

Potassites in Zechstein 1 and 2 are composed predominantly of sylvite (KCl), Carnallite ($KCl.MgCl_2.6H_2O$) and Kieserite ($MgSO_4.H_2O$) and change rather quickly in facies. The seams of Zechstein 3 are mostly sylvinites free of Mg salts. The complex salts generally occurring in the potash zone are the result of extensive secondary changes involving transformation and replacement, rather than simple precipitation from an evaporating sea.

Tectonic disturbance of Zechstein Salts

Dislocation of the salt beds has depended largely on the thickness of overburden and genuine salt domes are widely distributed in northern Germany where the Cenozoic - Mesozoic cover attains a thickness of 6,000 to 12,000 feet.

South of Hanover a relation between salt domes and tectonics of the Mesozoic cover is conspicuous and a clear dependence of diapirs on faults of mostly dilatation character is evident e.g. salt has injected the faults of the Gottingen Graben in spite of the fact that the overlying sediments total less than 4,500 feet (Fig. 4).

The linear extended form of the salt bodies east of Hanover is related to SSW-NNE trending faults although elsewhere the relation of diapirism to pre-existing faults is not always obvious. In most cases the ascent of the salt began gradually, as can be demonstrated by thickness variations in the Mesozoics, but immediately piercement took place this was very quick and almost explosive.

During these movements the salt formation was intensively folded and developed structures featured by highly viscous fluids. Nevertheless, the internal structures of the salt bodies can be analysed provided the stratigraphic characteristics of the different salts are known.

The salt domes exposed by mining have been studied in great geological detail and the following features are characteristic.

(a) The cores of the diapirs are built up by the older salt formation (Stassfurt halite - Na_2).

(b) The salts of Zechstein 2 and 3 "coat" the core with many folds having steep (almost vertical) axes, showing normal or inverted inclination and at times drape folds.

(c) The structures may be extremely complex with flowage of the salt resulting in thickening of the beds in some places and severe attenuation elsewhere presenting problems in exploration and mining the potash seams.

(d) The tops of the salt domes are usually affected by leaching processes which take place below the ground surface through the action of groundwater. This results in the development of a flat plane on the top of the salt (salt table) which is covered by a caprock of gypsum (see Fig. 14).

This destruction of saline rocks is called "subrosion".

Inspection of Zechstein Formation.

The writer was guided on tours underground at the Lehrte salt dome (20 Km. east of Hanover) and at the Benthe salt dome (10 Km. west of Hanover) by Dr. Erich Hofrichter when many of the features described above were inspected. In company with Drs. Hofrichter and Axel Hermann, one day was spent traversing the route indicated on the locality plan (Fig.7) to visit the marginal facies of the Zechstein formation.

(a) Lehrte Salt Dome. The Bergamannssegen Mine visited is one of four mines operated by Wintershall Co. on the northern lobe of

LOCALITY PLAN HANNOVER-HARZ
Showing
SALT DOMES, MINES, ROUTES TAKEN

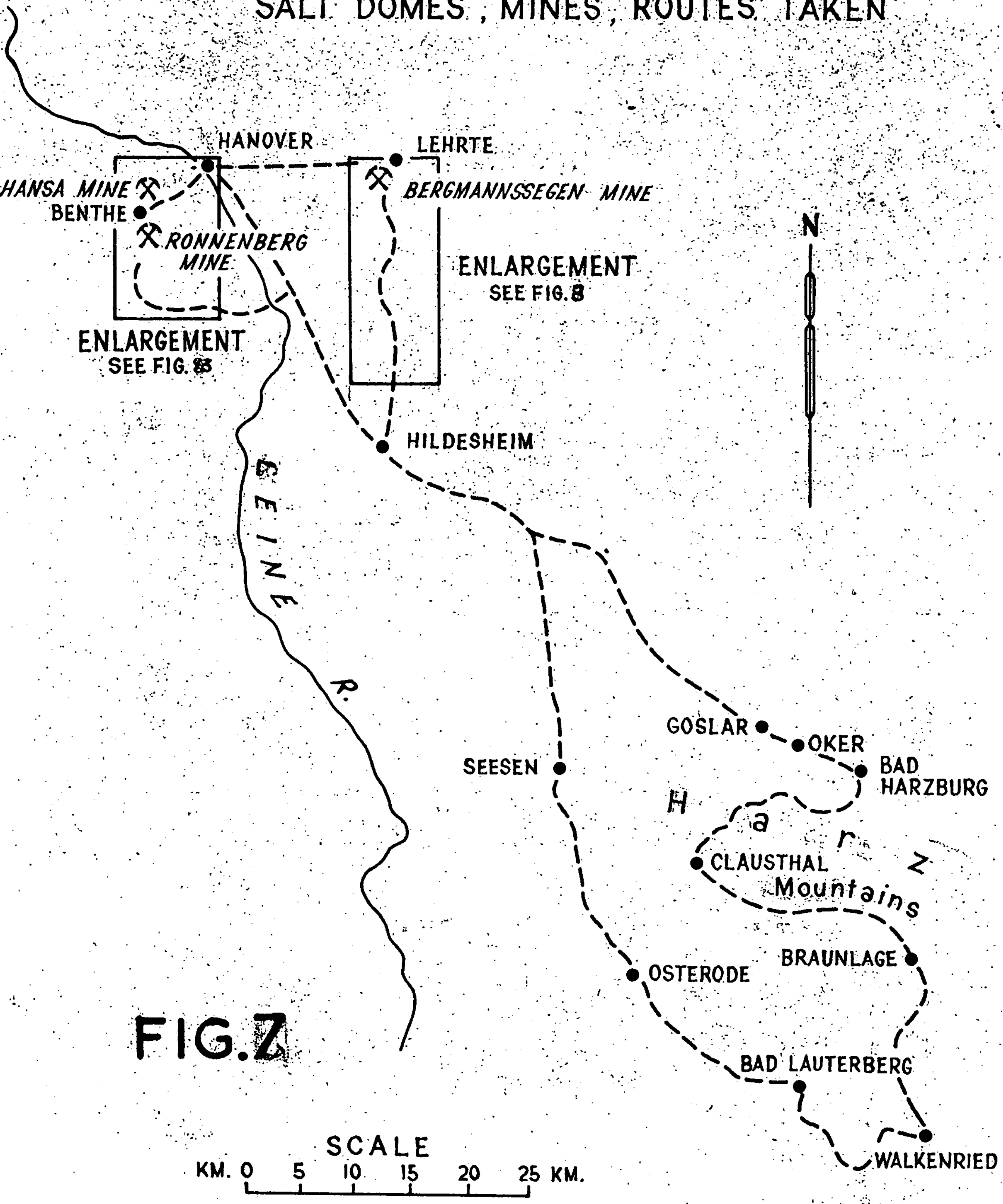

FIG. Z

S.A. DEPARTMENT OF MINES						
Approved	Passed	Drn.	LOCALITY PLAN-HANNOVER-HARZ Showing SALT DOMES, MINES, ROUTES TAKEN	D.M.	Scale As Above	
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the Lehrte - Sehnde (- Sarstedt) salt dome. The dome strikes NNE-SSW and is some 25 Km. in length and 1 to 4 Km. in width. The southernmost lobe is connected to the Leinetal anticline.

The area of the salt dome is marked by a depression caused by subrosion and subsidence in otherwise gently undulating country. The operating mines include Bergmannssegen, Hugo, Erichseggen and Ottoshall and are interconnected underground.

Geologic details are shown in Figs. 8, 9, and 10. The stratigraphic section exposed in the mine includes salt formations of Zechstein 2, 3 and 4 with the potash beds Stassfurt (Hartsalz), Ronnenberg and Riedel (sylvinites) and the locally developed seam Bergmannssegen. Drape folds with steeply dipping axes (more complicated in the deeper levels) are features of the structure.

The 580 m. and 900 m. levels of the Mine Bergmannssegen were inspected. Enormous piles of waste resulting from the separation of sylvite from the ore by fractional crystallization mark the mine centres (Figs. 11, 12). Trackless mining equipment is used extensively with some ore haulage undertaken by electric trains.

(b) <u>Benthe Salt Dome.</u> On the salt dome of Benthe/Hanover there are two operating companies - Vereinigte Kaliwerke Salzdetfurth Co. (Hansa Mines) and the Kalichemie Co. (Ronnenberg Mines).

The salt dome has ascended at the intersection of several major faults (see Fig. 13).

Levels have been established at the 427 m., 514 m., 601 m., 701 m., 801 m., 901 m., and 1001 m. levels. The 601 and 1001 metre levels were inspected. The internal structures of the salt body show drape folds with vertical axes also folds with horizontal axes, progressive and recessive precipitation, varves in halite, and indications for interformational resolution.

The plane affected by subrosion is under 300 ft. of cover. The structure of the dome is illustrated in Figs. 13 and 14, while Figs. 15, 16, 17 and 18 typify underground features.

31109

Fig. 11 Potash Mine Bergmannssegen-Hugo, Lehrte Salt dome, Hanover. Haulage shaft, separation plant and waste pile of salt etc.

31110

Fig. 12 Main shaft, Bergmannssegen Mine, Hanover.

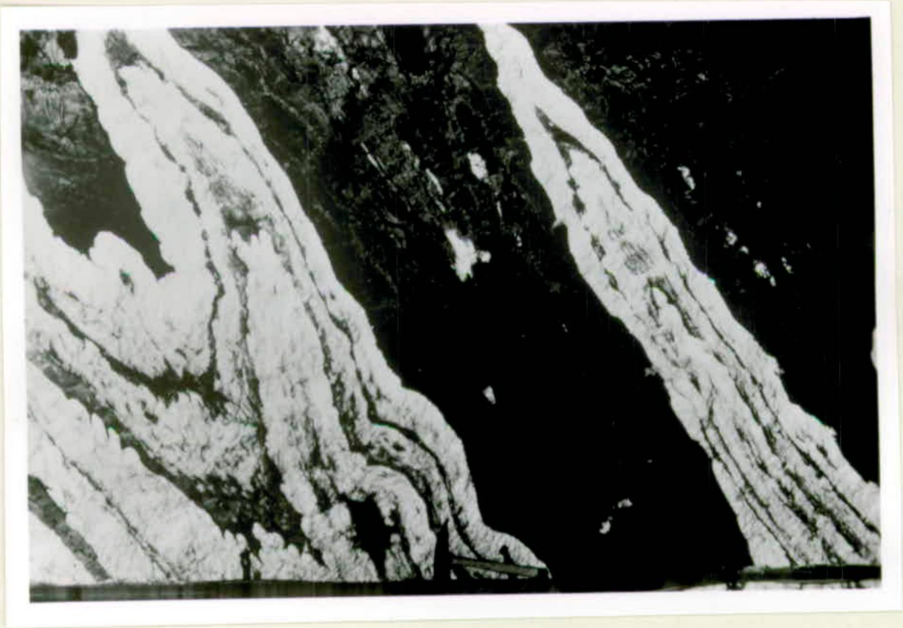

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Fig. 15 Plastic flowage of salt beds, Neuhof.
(R. Russell photo)

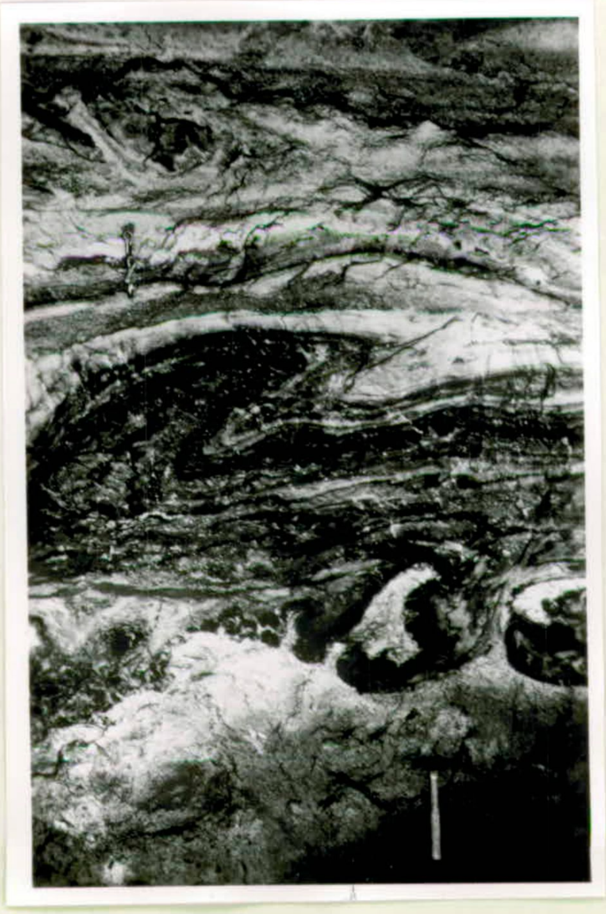

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Fig. 16 Folding in salt - carnallite beds, Neuhof.
(R. Russell photo)

31113

Fig. 1~~8~~7 Leinne salt enclosing Ronnenberg potash seam, Ronnenberg. Potash seam exposed on right side of roof of drive above electric cable. (R. Russell photo)

31114

Fig. 18 Plastic folding in salt, enclosing fractured and disjointed shale, Neuhof (R. Russell photo)

SALT DOME OF LEHRTE - SARSTEDT
(AFTER C.DIETZ - 1955)

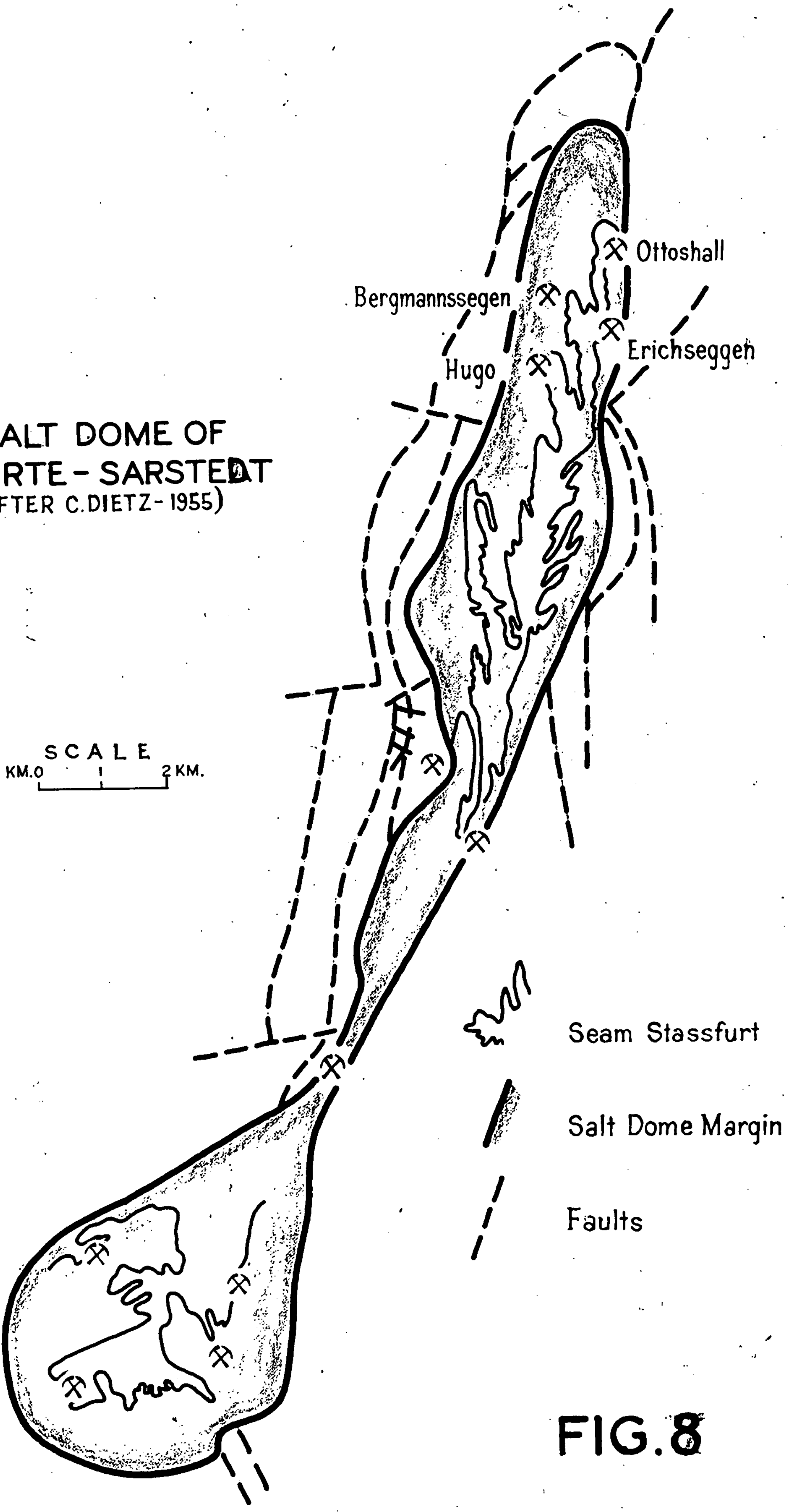

FIG.8

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SALT DOME OF LEHRTE
CROSS SECTION

(AFTER C. DIETZ, 1955)

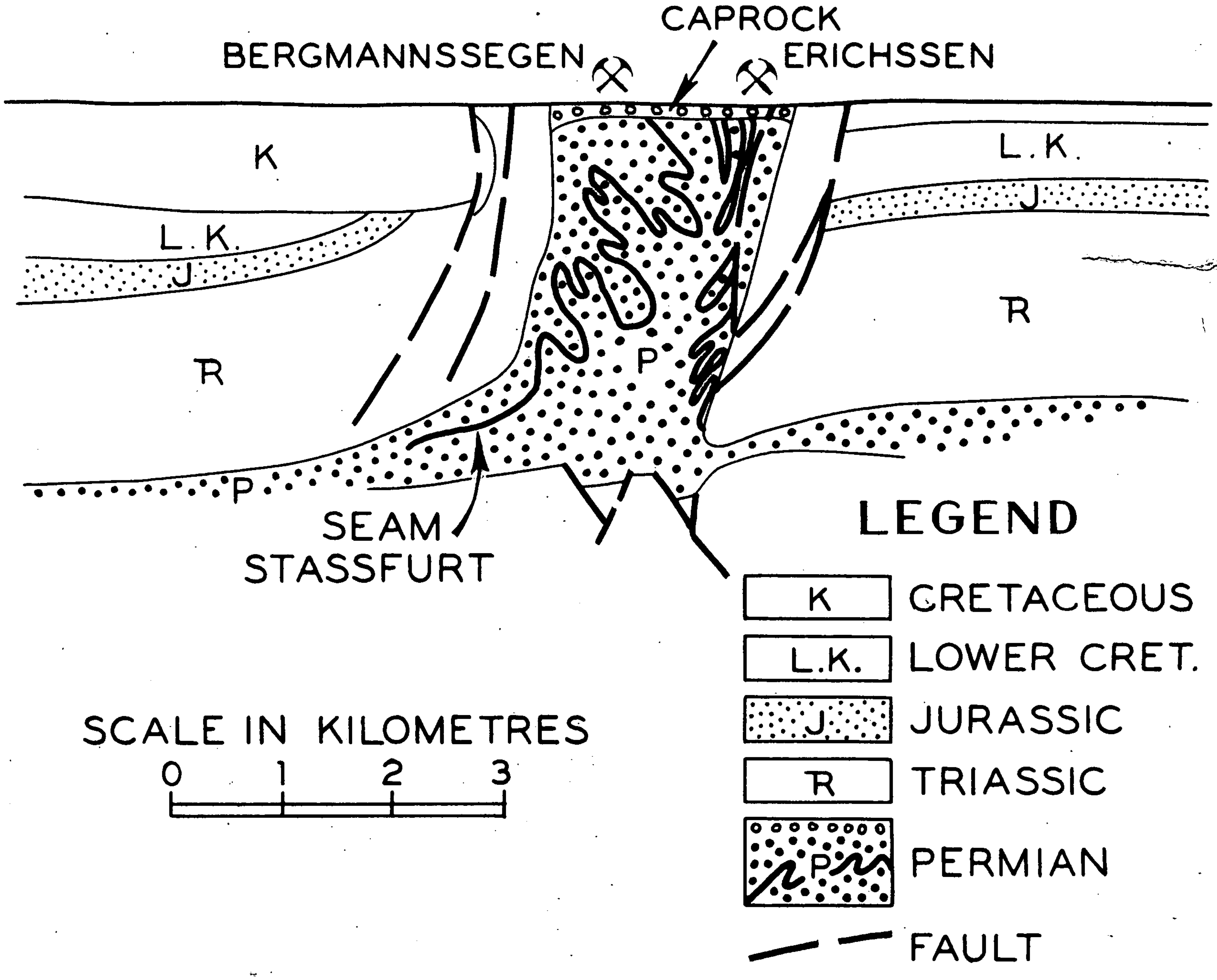
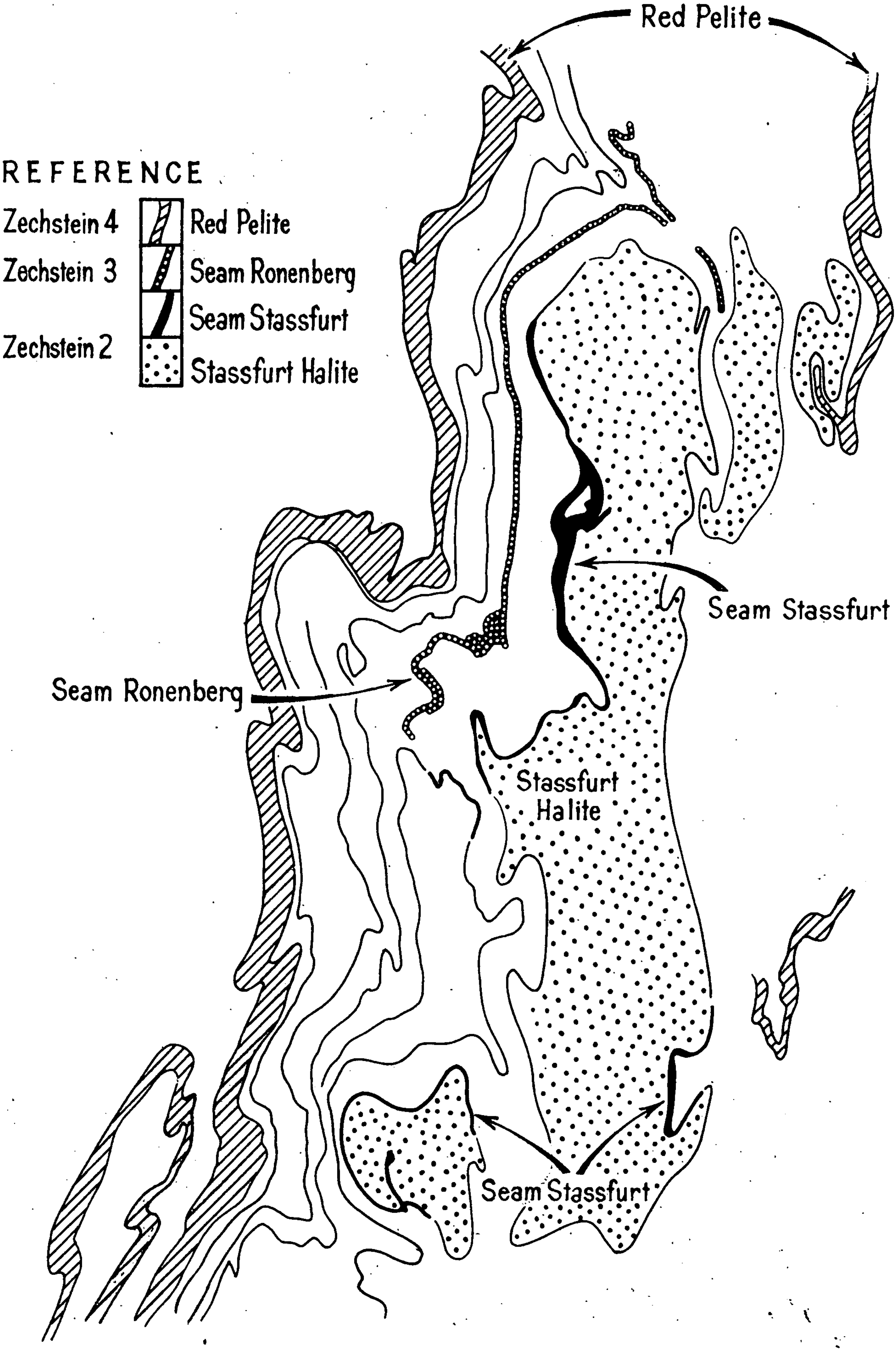


Fig. 9



POTASH MINE BERGMANNSSEGEN HUGO
GEOLOGICAL MAP OF 580 M. LEVEL
(After H. Roth – 1955)

Fig. 10

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HORIZONTAL SECTION OF THE BENTHE SALT DOME AT 600M. BELOW THE SURFACE

(After O. Ahlborn & G. Richter - Bernburg, 1955 & C. Dietz, 1959)

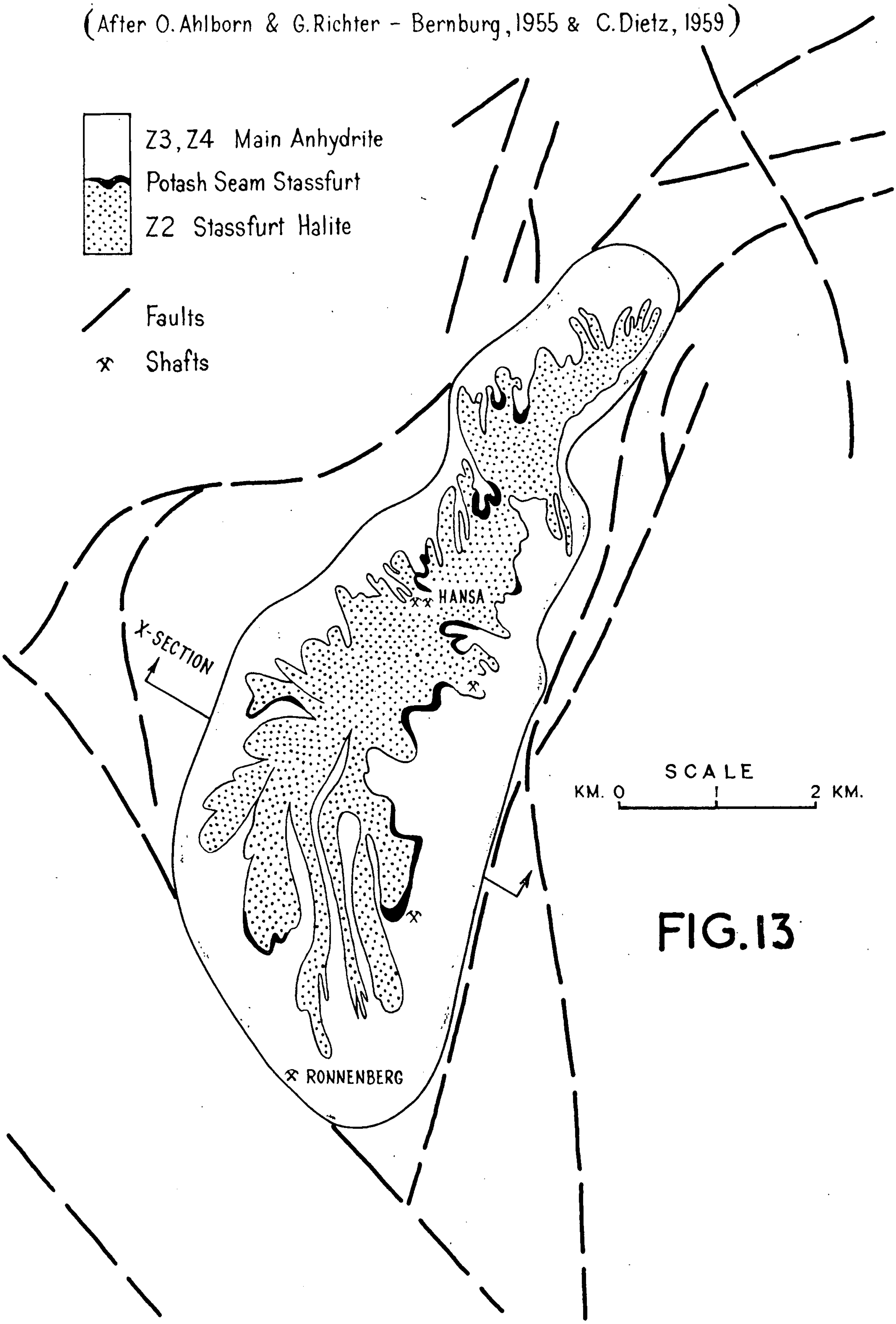

FIG. 13

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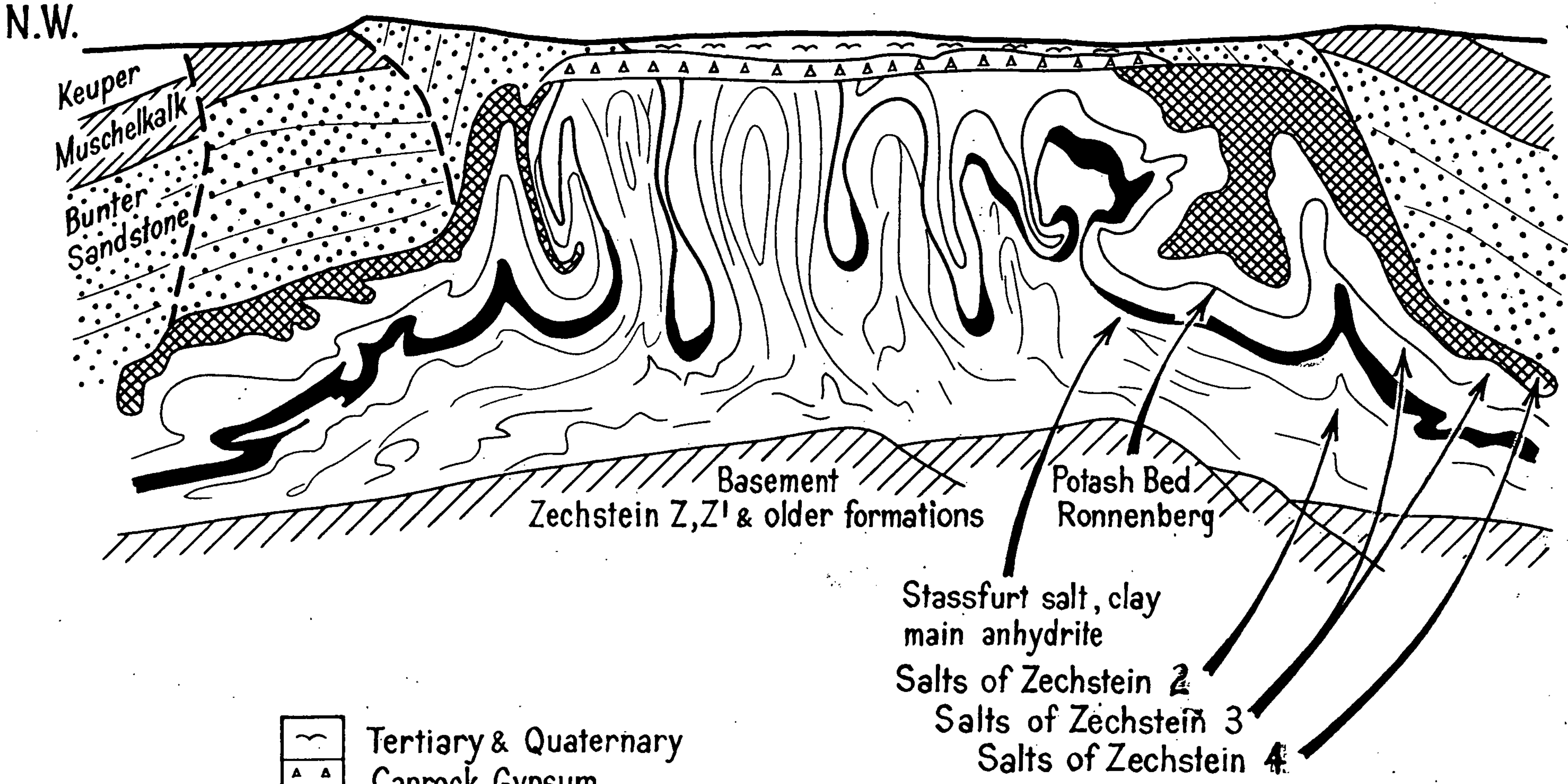


- ⌒ Tertiary & Quaternary
- △ Caprock Gypsum
- ▨ Bunter Sandstone (collapsed)
- ☐ Keuper } Triassic
- ▨ Muschelkalk } Triassic
- ⁘ Bunter S.S. } Triassic

FIG. 14

CROSS SECTION THROUGH THE BENTHE SALT DOME
After O. Ahlborn & G. Richter - Bernburg 1955 & C. Dietz, 1959

(c) **Field Excursion.** During a trip conducted by Drs. Hofrichter and Hermann to the Harz Mountains and the East German border exposures of classical Zechstein shoreline stratigraphy were inspected - between Seessen and Osterode, at Latzenstein, Sachsenstein and Walkenried - anhydrite, gypsum, dolomite and limestones and the Kupferschiefer, (see Fig. 7 for locations).

2. England

Billingham, Anhydrite, Co. Durham, I.C.I. Ltd.

11th June, 1964 to 12th June, 1964.

G.E. Pearse, Mine Manager, I.C.I. Ltd., Norton Hall.
T.P. Gregson, Deputy Manager, I.C.I. Ltd. Billingham.
Malcolm Harmer, Mining Engineer, I.C.I. Ltd. Billingham.

Factories of I.C.I. Ltd. occupy an area of some 1100 acres on the north bank of the River Tees between Stockton and Port Clarence where the principal products include fertilizers and heavy chemicals based on ammonia, brine and oil. Anhydrite, used in the manufacture of sulphate of ammonia, sulphuric acid and cement is mined from deposits lying directly beneath the factory site.

Permian Evaporites

In northeastern England the Permian potassic evaporite section was first intersected by D'Arcy Exploration Co. during oil search operations in 1939. Coring with brine fluids has been undertaken since that time by I.C.I. Ltd., Fissons Fertilizers Ltd. and Armour & Co., in search of workable deposits of potassium salts in the Eskdale-Whitby-Scarborough-Darlington-Fordon area of north Yorkshire. The succession includes three cycles of evaporites with potash zones in the "upper evaporites" and "middle evaporites", the most promising being a bed of sylvinite 14 to 28ft. in thickness and containing 10 to 20% KCl at a depth of about 3,800ft. near Eskdale. I.C.I. Ltd. are continuing investigations and are closely following solution mining developments in Canada.

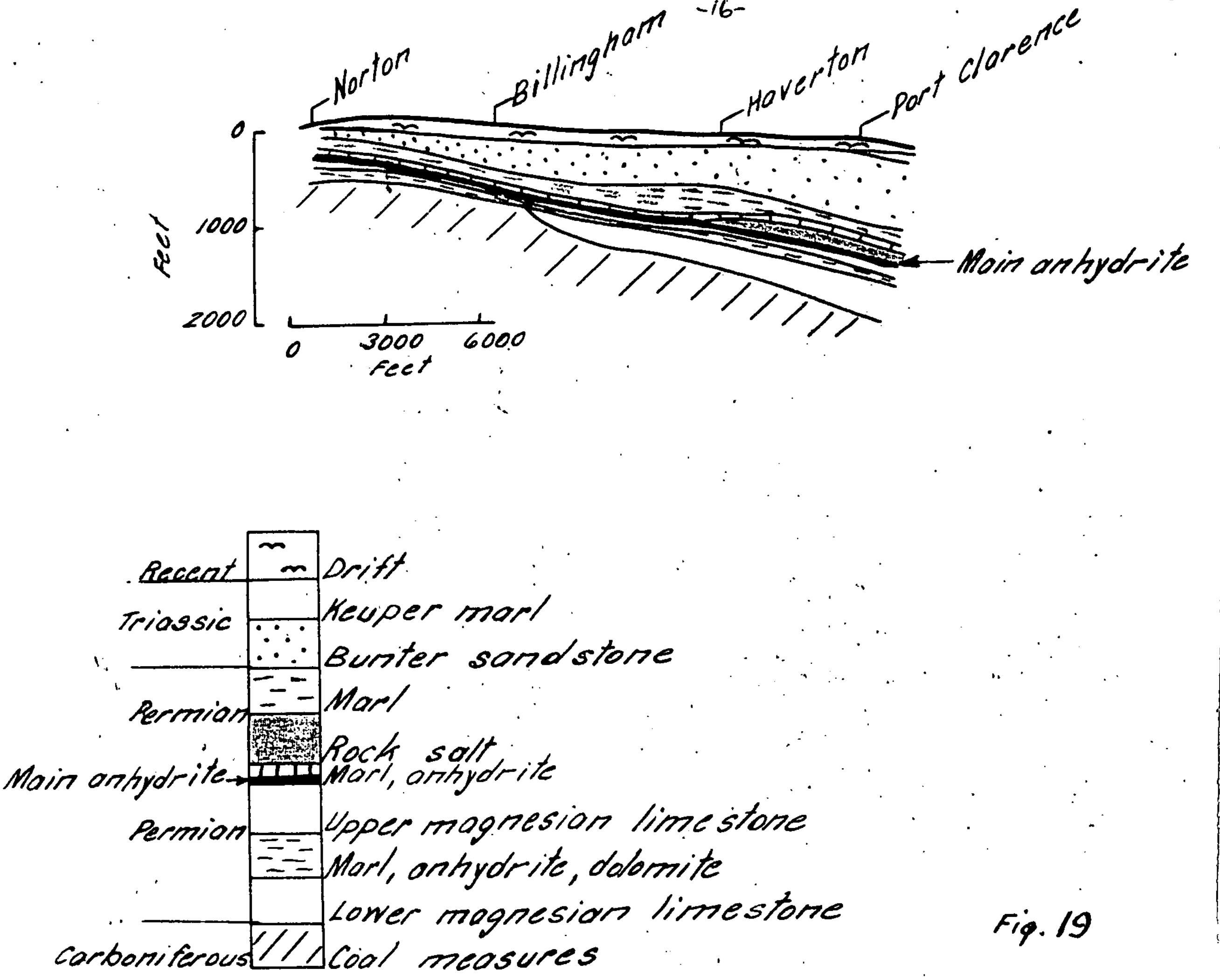


Fig. 19 Cross section - Billingham area.

Almost 2,500ft. of Permian sediments have been intersected in the Scarborough locality while the total thickness near Billingham is less than 300ft. It is inferred that southward from the Billingham locality the Permian Basin deepened rapidly and that continued subsidence throughout Permian time allowed development of a substantial thickness of evaporites (Fig. 19).

A correlation of the English and German Zechstein evaporites is shown in Table 2.

Anhydrite, Billingham

At Billingham the "main anhydrite" has been exploited by I.C.I. Ltd., Agricultural Division, since World War I from two 13ft. diameter shafts, 800ft. in depth. Below the surface clays are some 300ft. of Bunter sandstone and 200ft. of upper Permian marls followed by 300ft. of evaporites in which anhydrite and rock salt deposits occur. The ore bed ranges up to 25ft. The minimum working face is 13ft. and most openings seen ranged from 15 to 25ft. in height. Workings extend over an area of some 2 miles by $1\frac{1}{2}$ miles, mining operations being confined to areas where the bed is at least 13ft. thick, not faulted, and where NaCl content is less than 0.1%. The bed dips at an angle of 3°. A room and pillar system of mining is employed with

TABLE 2

EVAPORITE SUCCESSIONS IN THE GERMAN AND ENGLISH ZECHSTEIN (PROBABLE EQUIVALENTS)

ES	HANOVER SUCCESSION	THICKNESS	NORTHWESTERN ENGLAND	WHITBY (YORKS) THICKNESS (FT.)	BILLINGHAM THICKNESS (FT.)
Series	marl	16	upper Permian marl	up to 600	200
tein)	top anhydrite Aller halite Pegmatitic anhydrite	30 350 4	top anhydrite	2 to 4	
	red pelite	50	salt clay	7 to 12	
Series tein	halite Riedel potash Leine halite Ronnenberg potash halite Main anhydrite	20 to 50 15 to 30 230 to 500 15 to 30 130 to 150 115	Upper Evaporites (upper halite (potash zone (lower halite (anhydrite (carbonate	50 to 90 0 to 28 41 to 64 17 to 28 2 to 4	upper anhydrite 10
	grey pelite, dolomite	25	Carnallitic marl	31 to 61	red,greymarls 10-20
urt s tein	Top anhydrite Stassfurt potash Stassfurt halite basal anhydrite	3 to 10 20 to 65 130 to2300 6	Middle Evaporites (upper halite (potash zone (lower halite (halite-anhydrite) (anhydrite)	0 to 17 11 to 13 92 to 277 50 to 92	Main halite 0 to 100 Main anhydrite 0 to 25 (avge. 18)
	Stinkscheifer	30	upper magnesian limestone	117 to 183	70 to 100
es stein	anhydrite Werra halite anhydrite	70 20 100	lower evaporites (upper halite-anhydrite (upper anhydrite (lower halite-anhydrite (lower anhydrite	40 to 117 40 to 670 46 to 142 151 to 309	30 to 80
	Zechstein chalk Kupperschiefer Conglomerate	13 1 6	lower magnesian limestone basal sands, breccia,marls	365 ±	750

rooms 25ft. in width; 51% extraction of the bed is maintained. Trackless mining equipment is used throughout. Anhydrite is blasted from the face, loaded by gathering-arm loaders on to dumper trucks and transported to underground crushers. Minus 1 inch rock is delivered to the plant.

The anhydrite bed is underlain by gypsiferous anhydrite and is overlain by grey marl. The 'ore' is generally dark grey and massive and in parts is buff to light grey, translucent and massive. The lower portion of the bed generally shows fine bedding laminations and has a shaley appearance though the average product has the following composition:

$CaSo_4$.	90%	
$(Ca,Mg)\ Co_3$	5%	
SiO_2	3%	
Other Insolubles	2%	(mica, felspar, clay, hornblende, iron oxide)
NaCl $<$ 0.1%		

Production averages 1¼ million tons per year, 2/3 of this being consumed for ammonium sulphate fertilizer production and the remainder for sulphuric acid.

REFERENCES

Napier, E (1948) The lower anhydrite seams of the Tees area. Proc. Yorks.Geol.Soc. 27 (3).

and in Stewart, F.H. (1963) The 'Permian lower evaporites of Fordon in Yorkshire. Proc.~~Yorks~~.Geol.Soc. 34 (1) No. 1.

3. France - Alsace

30th June, 1964 to 3rd July, 1964

Etienne Gannat - Geologist
M. Courtot - Chef du Service Géologique
M.H. Hardy - Chief Engineer
} - Mines Domaniales Potasse d'Alsace, Mulhouse.

M.D.P.A. operate six miles (Theodore, Marie Louise, Rudolphe Joseph Else, Amélie, Anna and Ferdinand) in the Haut Rhin of Alsace for the production of potash; annual output now totals 1,900,000 tons/yr. K_2O, which is 18% of world potash production. Daily ore production (20% K_2O) ranges from 8,000 - 10,000 tons. The company has sunk 18 shafts and operate seven plants for the production of KCl. Output has increased steadily since

1910 except for drastic curtailment during the Wars.

Operations are centred between Mulhouse and Colmar townships situated on an extensive flat plain of the Haut Rhin bounded by the Vosges Mountains on the west and the River Rhine on the east. Beyond the River Rhine in Germany rise mountains of the Black Forest and the Kaiserstuhl. The potassium salts were discovered in 1904 during petroleum investigations at depths of 2,069ft. Intensive drilling then defined the limits of the deposit.

Inspections were undertaken of the Marie Louise mill (with M. Gannat), of the Amélie-Anna Mines (with Messrs. Courtot and Hardy) and a drive taken through the Vosges and to the River Rhine (with M. Gannat).

31115

Fig. 22 Alsace Plains, looking towards Colmar and the River Rhine, from The Vosges.

A fine museum is maintained by M.D.P.A. where plans and sections of the mine are housed and cores and suites of samples of the relevant ore beds from the major potash deposits of the world are displayed - these include those of Germany, Carlsbad and Moab (U.S.A.), Saskatchewan (Canada), Spain, Morocco, the Congo, Poland, U.S.S.R., and Sicily.

The Alsace potash deposits

(a) Stratigraphy

The two potash beds being exploited by M.D.P.A. are part of a Tertiary (Oligocene) evaporite sequence preserved in a basin some 85 square miles in area, lying between Mulhouse and Colmar and extending in a northeastern direction to the Rhine (Fig. 20); one German mine operates on a deep section of the basin which extends across the River Rhine, see locality plan (Fig. 20). The deposits are reputed to contain 1,800 million tonnes of potash salts with an estimated content of 300 million tonnes K_2O.

The stratigraphic sequence of the Alsace basin is as shown in Tables 3 and 4.

The lowermost Tertiaries (Eocene) comprise continental conglomerates with clay which rest disconformably on Jurassic "basement". These are succeeded by the Oligocene (Sannoisien) salt sequence some 4,500 feet in thickness. Shale partings and clay beds occur throughout, being most strongly developed in the Middle Salt and Top Salt; little anhydrite and dolomite is present. This sequence shows occasional fossils particularly in the lower beds where airborne spiders, flies and mosquitoes have been preserved in shale.

Within the Top Salt are two mineable beds of sylvinite, the bottom potash bed 12 - 18 feet in thickness (with 15 - 20% content K_2O) being separated by about 60 feet of salt and shale and containing three very thin beds of sylvinite from the upper potash bed 4½ to 6ft. in thickness (with 22-25% K_2O content). The current output originates exclusively from the lower bed.

(b) Structure

The structure of the potash and confining beds has been controlled by flowage and deformation imposed by rise of salt of the basal evaporite section - the structure is illustrated in Fig.21. In the northeastern sector of the basin low angle faulting related to diapirs has either eliminated the potash beds by creating large barren areas or raised these horizons to erodable levels.

In the Zechstein Basin of Germany the potash beds have been

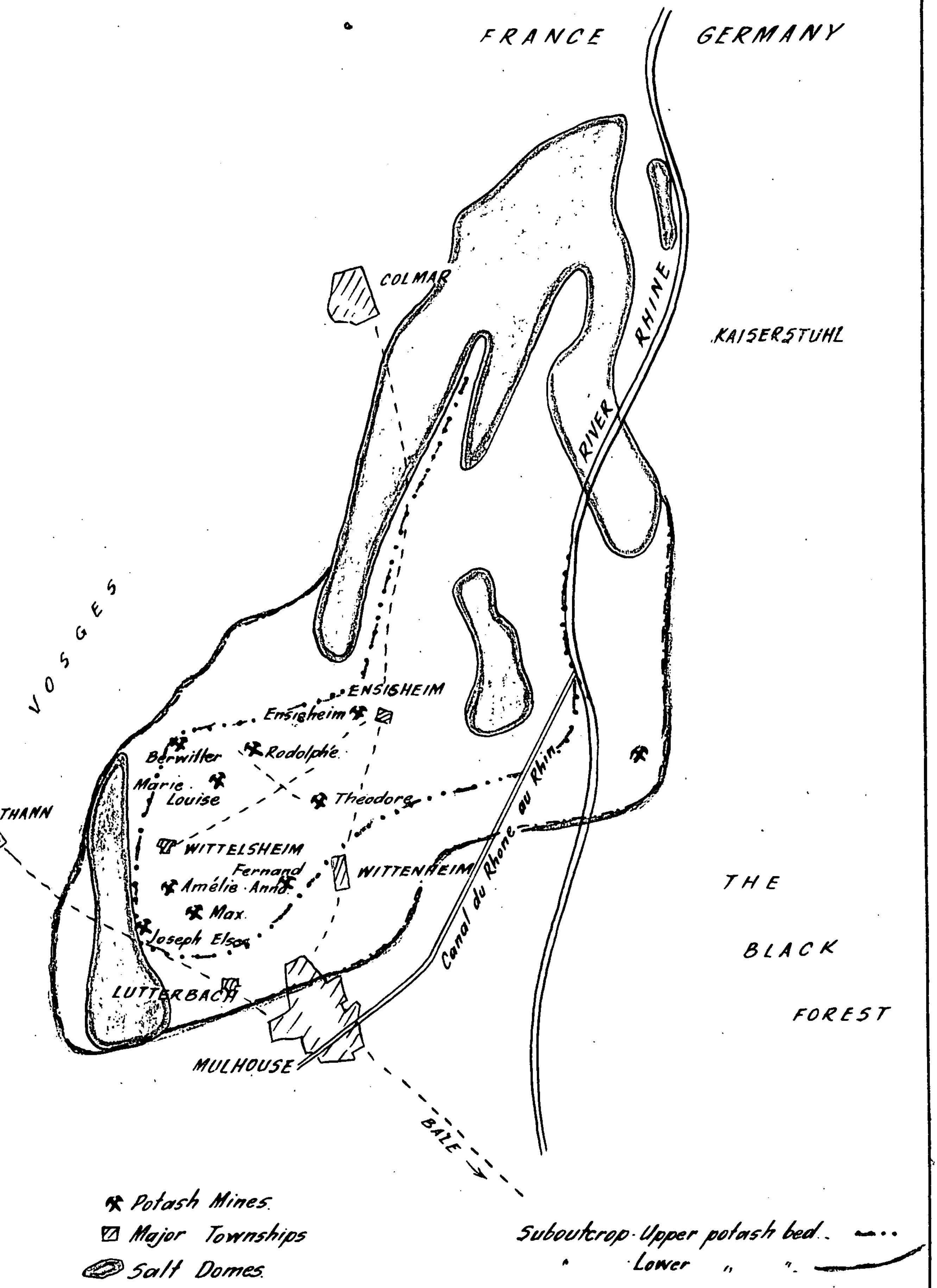


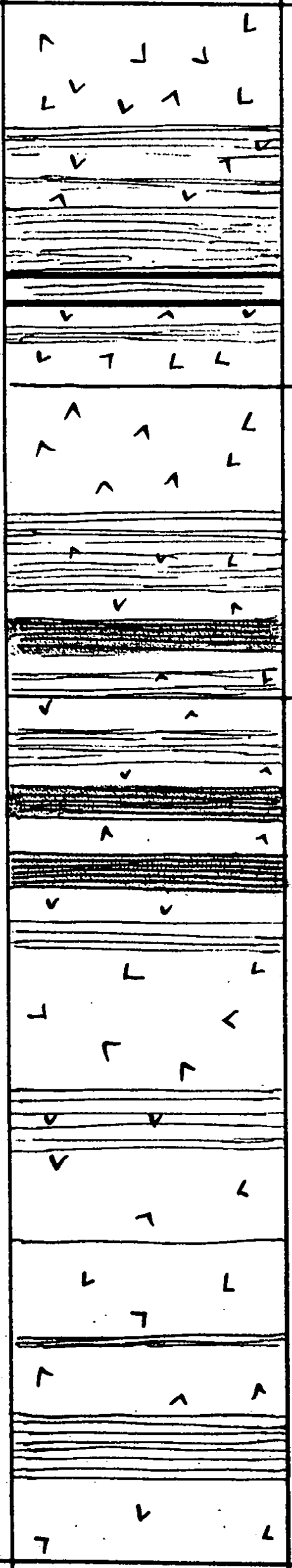
Fig. 20

S.A. DEPARTMENT OF MINES

Approved	Passed	Drn.	SKETCH MAP OF THE ALSACE POTASH MINES	D.M.	Scale
		Tcd.		Req.	S 4109
		Ckd.			944
Director		Exd.			Date

400— 6.63 1423

TABLE 2 · STRATIGRAPHIC SEQUENCE - ALSACE BASIN

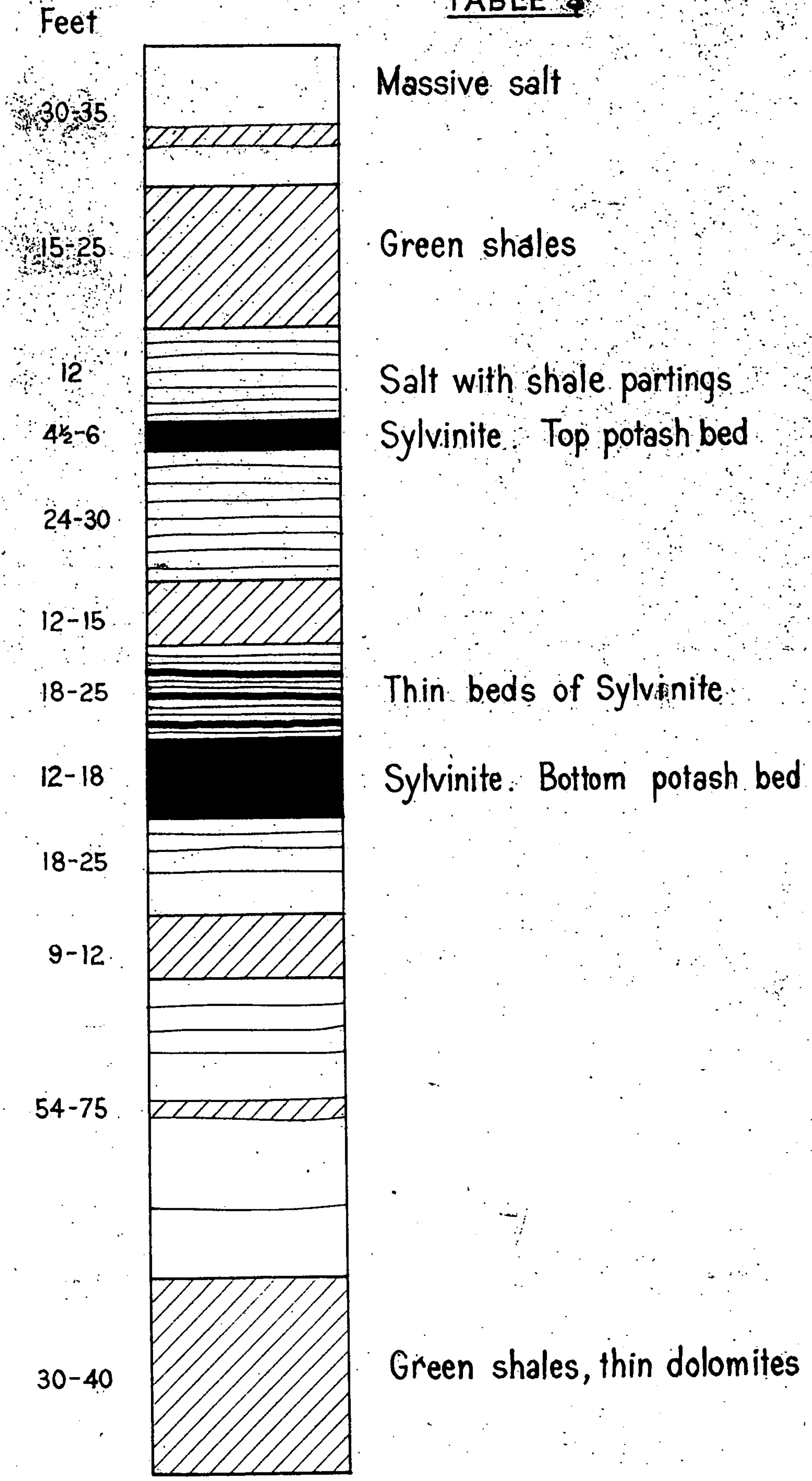
UATERNARY			~	Alluvium - 150 ft.
OLIGOCENE	Chattien		Continental	Lacustrine shales, sandstone gypsum (with continental snails) 300 ft.
	STAMPIEN	Upper	Marine	Richly fossiliferous shales (oysters, gastropods) - 240 ft.
		Middle	brackish	Shales, silstones, sandstones - 900 ft. - Carbonaceous (fish, crabs, leaves)
		Lower	Marine	Shales (with fish, lammelibranchs, foraminifera) 90'
	SANNOISIEN			SALT BEDS WITH CLAY SEAMS & BEDS - LITTLE ANHYDRITE DOLOMITE occasional fossils throughout (Note fossil insects, spiders, flies, mosquitoes in lower beds) Top salt -1200 ft. shale partings Bed, top potash Bed, bottom potash Middle Salt 900 ft. shale shale shale Bottom Salt 2400 ft Some continental beds near base with freshwater gastropods.
EOCENE			Continental	Conglomerate with clay - 150 ft.
IURASSIC			Marine	Limestone, dolomite oolites Bathonian. - Oxfordian shales (oil)

944. S. 4101.

ALSACE BASIN

DETAILED SECTION-PART OF TOP SALT

TABLE 4



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DETAILED SECTION
PART OF TOP SALT
Table 4

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DIAGRAMMATIC CROSS SECTION
ALSACE BASIN

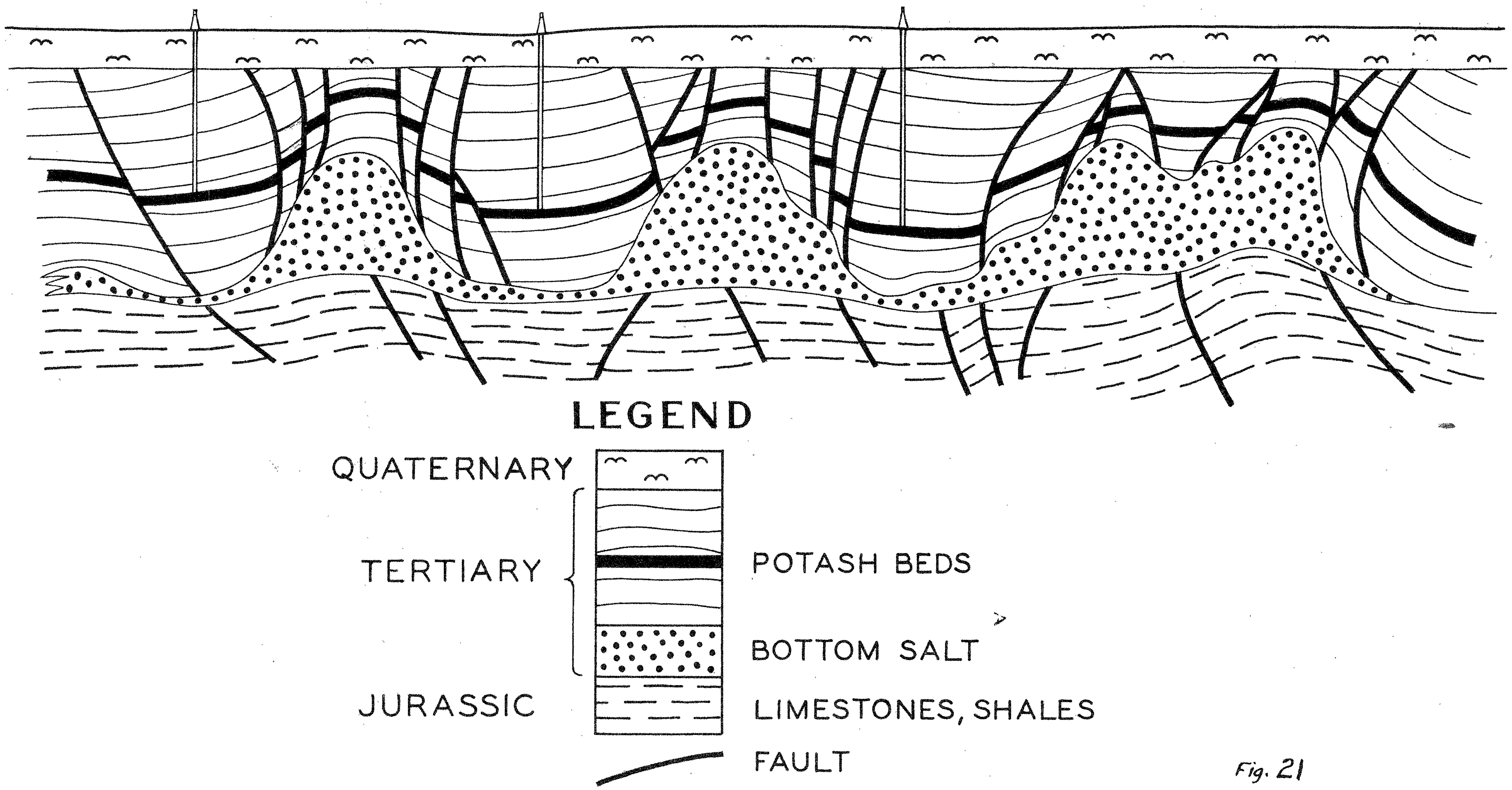

Fig. 21

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Diagrammatic Cross Section
Alsace Basin

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involved in folding within salt domes resulting in structural deformation and great thickening. It will be noted that in Alsace, however, the potash beds are not part of the diapiric salt body. Though the potash beds are disrupted by the flowage of underlying salt the mined beds are sensibly flat and thinning of these beds is related to primary deposition and not to folding processes.

(c) Amélie-Anna Mine

The lower potash ore bed (at a depth of 1,500 feet) was inspected at the Amélie-Anna Mine where descent was achieved via the main shaft and a long incline. Diesel electric trains haul ore from the working faces some 3 miles distant. Natural gas creates a fire hazard and strict precautions to obviate fires are taken. Most of the mines operate at levels of 1,200 - 3,000 feet; oppresively high temperatures (115°F) discount mining to greater depths.

The lower bed is subdivided into units (from the base) A, B^1, B^2, C and D with shale partings separating them. The ore is finely bedded and is characteristically yellow-brown to red in colour with alternating light (almost white) bands $\frac{1}{8}$ inch to one inch in thickness (Fig. 23). The strata are gently warped with prominent rolls in the beds and small scale faulting throughout. Ripple marks are evident in the potash and shale beds. The bedding is varve-like and constant and even the thinnest beds are traceable throughout the mine workings. The potash beds characteristically show crenulations extending downwards with truncations at the top - explained as a feature of seasonal solution at the top of the preceding bed.

The strongly rhythmic (cyclic) banding of the ore (see Fig. 23) contrasts with say Esterhazy (Canada) ore which is more coarsely crystalline, homogeneous in colour and grain size and is quite massive.

A room and pillar "advance-retreat" system of mining is practised. Beds A and B are mined first and, in retreat, beds C and D. The pillars are robbed and finally blown up to allow collapse of the roof behind the workings. Subsidence is gradual and extends to the surface. The ore is broken with integral cutters and Joy-miners and transported with Joy loaders to bunkers. The mine cars are loaded from this storage by automatic photoelectric control. The cars are hauled by train to the shaft where they are weighed and automatically emptied into a hopper from which the skips are filled.

Separation of sylvite (KCl) (25 to 35%) and halite (NaCl) (55 to 65%) from the sylvinite ore is effected by:-

(a) Thermal separation which takes advantage of the fact that NaCl is slightly less soluble in hot aqueous solution than cold whereas KCl is markedly more soluble in hot solution. Fractional crystallization of the chlorides is achieved under close temperature - pressure control.

(b) Flotation in a brine solution using suitable frothing agents (amines) - Theodore mill (Fig. 24). Three to four tons of crude ore are treated for the recovery of 1 ton of product.

Byproduct salt from this separation is channelled to the River Rhine!!! Mine output is governed by a limitation on the resulting salinity of Rhine water and is at its peak during periods of high river level.

M.D.P.A. Museum

Among exhibits in the museum are cores from the Moroccan (Triassic) potash bearing sequence. These feature an evaporite cycle comprising salt with thin potash beds and including a basalt 80 metres in thickness which flowed over the floor of the evaporating basin. It directly overlies a thin (1 cm) bed of anhydrite and is succeeded by further salt deposition. In the German (Kaiserstuhl) section Quaternary basalts intrude the salt formation.

Gamma-ray and neutron logging of boreholes in the Alsace Basin allow ready detection of shale partings within the salt sequence and aid correlations.

3116

Fig. 23 Sylvinite ore bed, Museum M.D.P.A., Mulhouse.

31117

Fig. 24 Theodore mine, main shaft and mill, M.D.P.A. Alsace.

4. U.S.A.

Carlsbad

7th May, 1964 to 9th May, 1964

L. Jordan, General Manager, National Potash Co. of America, Carlsbad

Bob Fulton, U.S.G.S., 504½ N. Canal St., Carlsbad (Mining Engineer, Division of Mineral Classification).

Bruno Alto, U.S.G.S. Geologist, Carlsbad.

Jim Fassitt, U.S.G.S. Geologist, Farmington.

Historical - search for sources of supply of potash

Discovery of potash in commercial quantity in southeastern New Mexico and its development successfully culminated the efforts initiated over 50 years ago by the U.S. Government to free that country from dependence on a foreign course of supply. Up to the time of World War I, Germany, as the World's largest producer of potash, dominated the industry, making it necessary for American agriculture to depend entirely on imports controlled by a foreign monopoly. A number of sources of potash were sought, among them being vegetable and animal materials, cement dust, deposits of dry lake beds, brine deposits, distillery waste, leucite (Wyomingite), alunite, felspars (from 11 to 16% K_2O), muscovite and from porphyry copper tailings of the Utah Copper Company (5 - 10% K_2O). Of all these sources only the American Potash and Chemical Co. operating on the brines of Searle's Lake were later successful in developing into a producer of any magnitude.

Discovery at Carlsbad

In 1912 potash brines and their salts, principally polyhalite ($K_2SO_4.2CaSO_4.3H_2O$) were discovered in well drilling operations in the Permian Basin in western Texas. Sylvite was recognised in oil well cuttings near Carlsbad in 1925 and this led to further private and Government core drilling and to the establishment of the industry. The first shaft was sunk by the U.S. Potash Co. (now U.S. Borax) in 1929 and the first ore was shipped in 1931. Most of the land is Federal Government-or State-owned.

In 1933 the Potash Co. of America sunk its first shaft (1,085 feet) after drilling 20 exploratory holes; the first ore was shipped by this company in 1934. A recrystallization process as used by U.S. Borax was not utilized and sylvite was concentrated by means of flotation in a brine solution with suitable frothing agents.

Regional Geology

The closing epoch in Permian time is significant for the extensive evaporite deposits that fill the Delaware Basin and extend across a reef zone for considerable distances over the shelf area in southeastern New Mexico and southwest Texas (see locality plan in Fig. 25). This epoch is represented by the strata of the Ochoa Series, which include the following formations:

Dewey Lake red beds - protective cover, no evaporites
Rustler formation)
Salado formation) include extensive deposits of halite and anhydrite with economic potash
Castile formation) deposits.

(a) Castile Formation - a lower salt series composed mainly of layered anhydrite with occasional beds of halite - it is barren of potash salts. The marginal Capitan limestone reef (in which the famous Carlsbad Caverns are developed) formed concurrently with basin deposition and attained a thickness of 2,000 feet prior to the re-establishment of a connection with the ocean to the south.

The formation is divisible into a lower unit, composed of alternating laminae of grey anhydrite and limestone, and an upper unit comprising massive white anhydrite.

(b) Salado Formation - marks a change from anhydrite to halite with lateral transitions from anhydrite of the Castile to halite of the Salado accomplished by means of depositional pinchouts of anhydrite tongues extending reefward from the core of massive anhydrite (See cross section, Fig. 26).

Beds of halite exceed 100 feet in thickness in this zone while the intercalations of anhydrite and polyhalite are from a few inches to a few feet in thickness. The maximum known thickness of the formation is 1,600 feet. There are about 45 persistent sulphate and as many halite beds and some 40 beds showing enrichment in potash. Due to their continuity these beds have been recognized in most of the test wells drilled within

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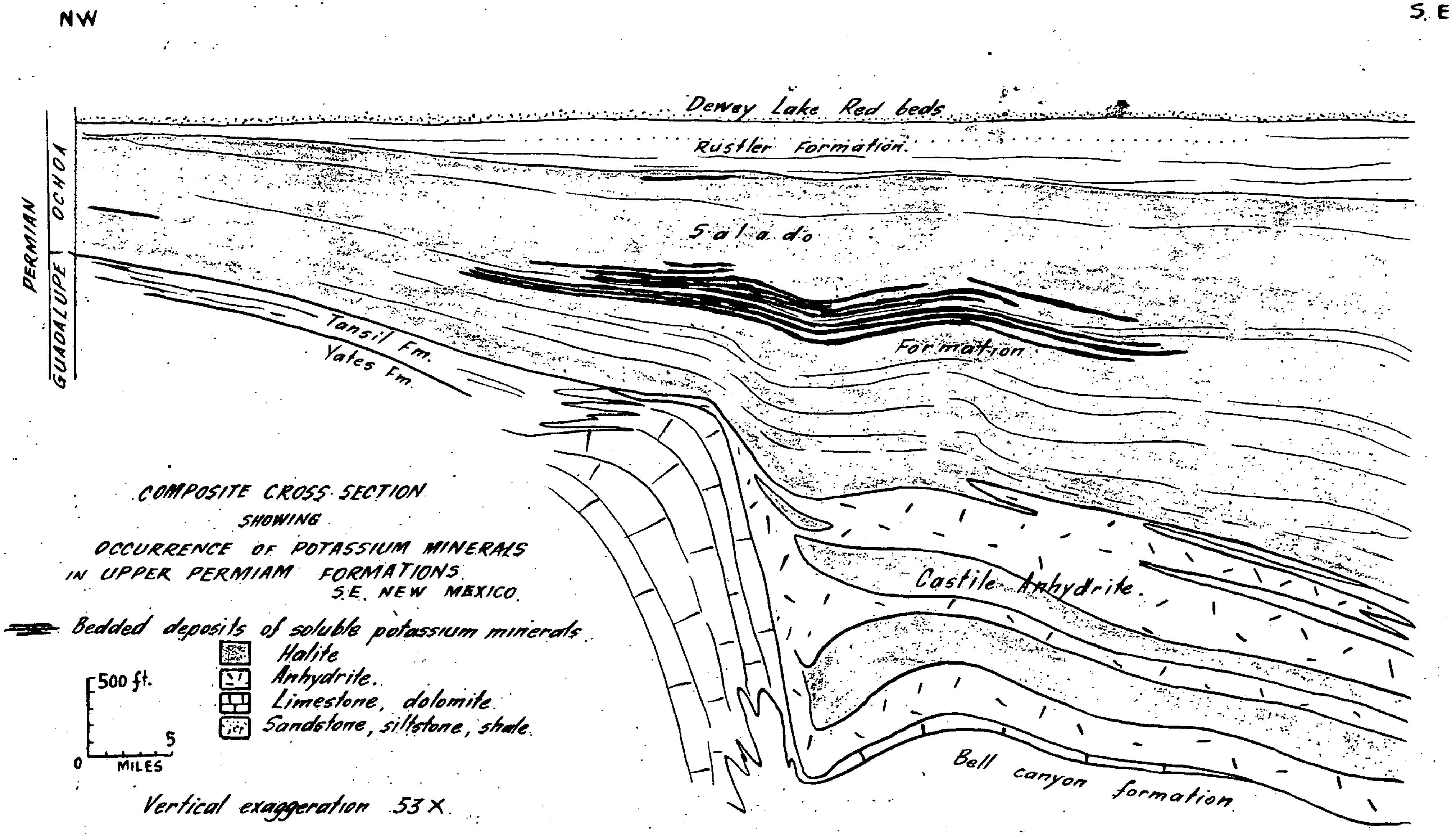

COMPOSITE CROSS SECTION
SHOWING
OCCURRENCE OF POTASSIUM MINERALS
IN UPPER PERMIAM FORMATIONS
S.E. NEW MEXICO

Vertical exaggeration 53 X

Fig. 26

the confines of the Delawere Basin and by correlation they have been successfully used as a guide in the search for sylvite as they represent marker beds outlining the depositional cycles which were repeated in periodical sequence throughout the salt building epoch. The various marker beds are designated in Fig. 25.

Halite occurs in two very distinct forms - as clean massive rock salt or as a mixture of halite and clastics (principally clays and silt sized particles of quartz).

Sulphate (calcium and magnesium) beds show characteristic changes in mineralogy laterally from the Delawere Basin into the Shelf area - anhydrite ($CaSO_4$) to polyhalite ($2 CaSO_4 \cdot MgSO_4 \cdot K_2SO_4 \cdot 2H_2O$) to kieserite ($MgSO_4 \cdot H_2O$) or elsewhere anhydrite to glauberite ($CaSO_4 \cdot Na_2SO_4$) and then to polyhalite and kieserite.

Thin shale seams are normally present at the base of each sulphate stratum while siltstones and fine grained sandstones are occasionally present.

Throughout, the above lithologies are repeatedly associated in a rhythmic depositional cycle that comprises clastics, sulphates, halite and a mixed halite - clastic stratum in ascending order. Gradational contacts are characteristic of the change from one lithology to another in the cycle. There is no evidence forthcoming of an interruption within the sequence or between the sedimentary sequences, each of which range from about 2ft. to 30ft. in thickness.

The areas in which sylvite and associated potash salts are found occupy only a small part of the Delawere Basin. These beds occur in a zone (the "Sylvite Zone") restricted to a vertical section some 250 feet in thickness near the middle of the Upper Permian Salado salt. Each of the anhydrite - polyhalite - halite intervals in this part of the sequence represents a depositional cycle or successive period in which sylvite was deposited.

One main sylvite bed (First OreZone) is exploited by the principal operating companies while two mines operate on the Tenth Ore Zone. Two beds (Fourth and Fifth Ore Zones) which carry langbeinite and are respectively 40 feet and 100 feet above the "First Ore Zone" are also being exploited. The other potash bearing beds (except for the Seventh and Eighth Ore Zones which are potential sources) are too thin, not sufficiently rich, or are too small in areal extent for exploitation at present. Along the western and southern borders of the Reserve the upper part of the formation has been so deeply eroded that all potash deposits have been removed.

A major difference between U.S. and the Stassfurt deposits is the presence of great developments of dolomite with salt in the great salt basins of the United States.

(c) Rustler Formation of late Permian age lies unconformably upon the Salado formation in the mines area. It is some 425 feet in thickness and consists of "red beds" - anhydrite, halite and dolomite with several persistent marker beds of sandstone and siltstone.

Some of the dolomite beds are porous and contain useful stock water.

(d) Dewey Lake red beds composed entirely of red sandstone, siltstone and minor shales form a protective cover that serves to retard the dissolution and removal of the underlying soluble salts.

Sedimentary rocks of Quaternary and Triassic age vary from nil to 1,800 feet in thickness and include surficial playa deposits, gypsite, caliche, sand, alluvium and sandstones.

The Potash Ore

Sylvite has been deposited over an area some 20 miles square in a number of beds along with halite in the Salado Formation in amounts sufficient to constitute ore. In most parts of the deposit the changes from ore to barren salt above and below is fairly abrupt, but the lateral transitions at the margins of the beds are gradual. Barren masses of halite (salt horses) are scattered irregularly throughout the ore body and probably result from differential solution of the potash bed after deposition and burial and squeezed into cavities by solid flow.

The sylvinite ore is an intimate intergrowth of crystalline halite and sylvite in varying proportions and most of the ore contains about one half as much sylvite as halite. Carnallite, polyhalite and langbeinite occur and in some beds constitute the main potash minerals. Langbeinite is mined from two beds for production of sulphate of potash (for use as a tobacco fertilizer).

The crystals of the ore beds range from specks to masses six inches across; however, most of them are only $\frac{1}{4}$ to $\frac{3}{4}$ inch in diameter. Stringers and disseminations of clay are found in the ore and ranges from about 1% in the main area to 5 to 10% at National Potash Co. mine and up to 25% in some sections.

Sylvite commonly is milky or faintly blue-grey but is generally stained red by iron oxide. It is waxy in texture and highly soluble in water. The halite may be clear, greyish, buff or orange-yellow, but it also may be stained red by iron oxide; blue halite sometimes is found in association with the sylvite.

The mineable beds are four to 14 feet in thickness and dip at a barely perceptible angle to the east so that the deposits of past and present economic importance are mined at depths of from 750ft. to 1,700ft. from the surface. No faulting of the beds is evident though occasional rolls with amplitudes of less than 15 feet in the strata are encountered. There is a regional dip of 100ft. per mile. The ore contains 12% to 25% K_2O equivalent and approximates 40% KCl, 60% NaCl.

Reference to Fig. 25 will illustrate use to which gamma ray and neutron logs may be put for correlation purposes. Gamma ray logs record variations in the distribution of radioactive material while neutron logs record variations in distribution of hydrogenous material - each of the potash ore zones become immediately evident.

Mining Operations

The U.S. Potash Reserve is situated on the high semi-arid rolling planes of southeastern New Mexico at elevations of 3,270 to 3,380 feet above sea level, five to 50 miles east of Carlsbad. The country is covered with range grasses, scattered mesquite, greasewood and occasional cacti.

Rainfall approximates 13 inches.

In 1963 Carlsbad production totalled 2.6 million tons K_2O equivalent.

(a) U.S. Borax (formerly U.S. Potash Co.). This was the first company to operate in the area from the main ore zone at 986 feet and to develop a separation process based on fractional crystallization (still in vogue) after sylvite was dissolved in a brine solution. An ample water supply was necessary so the refinery was located near the Pecos River, about 13 miles southwest of the mine. Production amounts to 12,000 tons/day.

(b) Potash Co. of America (several miles north of above). Twenty prospecting drill holes were completed before the main shaft was sunk. As water was short the company developed a process of separation of sylvite by means of flotation in a brine solution. Production is about 8,000 tons/day.

(c) I.M.C. (International Minerals and Chemical Corporation) - formerly Union Potash and Chemical Co. which originated in 1936 and came into production in 1940. Holdings are situated a few miles south of (a) above. This plant also used a flotation process with a brine solution but unlike (b) above where the halite is floated the I.M.C. refinery floated the sylvite. Production (including some glauberite) from three levels (800ft., 850ft. and 900ft.) approximates 1,000 tons/day. Sixty million tons have been extracted to date from beds ranging from 54 inches to 10 feet in thickness.

(d) Duval Sulphur and Potash Co. production 12,000 tons/day.

(e) South West Potash Corporation. production about 6,000 tons/day; production since 1946.

(f) National Potash Co. (1,750ft. shaft). Production since 1956 - now at 3,000 tons/day.

(g) Eddy Shaft (of National Potash Co.)

(h) Kermac Potash Co. - Reserves of 90 million tons of 17% K_2O equivalent are reported. Production of 1,500 tons of ore per day is planned.

) shaft sinking in progress.

The National Potash Co. is mining ore of low grade; to maintain grade of the product 3,000 tons of ore per year are being bought from S.W. Potash Corp.

The company has almost completed sinking the Eddy Shaft some 750ft. deep from which high grade potash ore will be mined.

National Potash Co. and Kermac are located near the margins of the deposit and are operating on the Tenth Ore Zone which is higher in clay content than the main bed worked elsewhere (I.M.C., U.S. Borax Co etc.) but it is fast being exhausted.

Methods of Prospecting and Exploration

The limits and grade of the various ore beds has been now well established so that very little exploration is in progress, and the following notes refer to activities of the period to 1946. Cable tools were utilized to penetrate 25ft. below the top of the halite formation with 10in., 8in., and 6in., bits - the character of the rock and water horizons were noted. Casing (5½ inch) was seated at this level. The seal in salt eliminates the possibility of water entering the hole while diamond drilling in the halite and to prevent the loss of drilling fluid through the overburden during the process of forcing the salt cuttings to the surface where they are settled out before recirculation of the brine. To core salt, N rods and special 21ft. double tube core barrels were utilized.

The drilling fluid used at first was a saturated solution of NaCl, $MgCl_2$ and KCl. Later, when it became available, carnallite or sylvinite was substituted for the salts. With a saturated solution no leaching of the cores takes place so that an accurate determination of the mineralization can be made.

A double core barrel 16ft. long (at first and later 21ft.) and cutting a 2½ inch core effectively lifted full runs of core. The cutting bit was slightly different from the one ordinarily used where the drilling fluid passes over the core and inner portion of the bit before returning across the face. With a salt bit the walls are double and the solution, instead of washing the core, is forced out through the face of the bit which eliminates all contact between the solution and core while cutting. Erosion was also eliminated thus. Diamonds are used for cutting and in most cases the recovery of full sized cores was 100%.

Spacing

Holes were drilled on co-ordinates of a regular grid system initially at $\frac{1}{2}$ mile intervals by the Bureau of Mines but later at 1 mile centres to depths well below the prospective bed. Thus continuity and thickness were established in advance of mining operations. Laterally, potash values seldom remain uniform for any great distance or area thus drilling in this regard is not really illuminating. Irregular barren salt horses are unpredictable in occurrence and could not be outlined in advance with any certainty.

Aquagel was mixed with water and placed between the top strings of casing to make them easier to remove when coring in the salt had been completed.

Mining Methods

Seepage from beds in the upper portions of the shafts has coated all mine timbers with gypsum though limestone beds which carried large flows of water were sealed off during shaft sinking.

The tabular gently rolling potash deposit is similar in many respects to relatively flat coal deposits and therefore coal mining methods and equipment were tried and have since proved adaptable to potash ore. The mines are fully mechanized, electricity being used for powering the trailing-cable undercutters and loaders, conveyors and crushers.

Lateral development consists of a 3 or 5 entry system for haulage and ventilation. Haulage entries are 6ft. x 20ft. in cross section and driven on the ore horizon. Some regrading is required on haulage entries to maintain easily negotiable grades. On each side of the main entries 250ft. barrier pillars are left for protection. Smaller pillars are provided between cross entries and panels.

The operating cycle consists of undercutting to a depth of nine feet, drilling to the same depth, blasting and loading of broken ore to 10-ton mine cars and thence by 48-inch belt conveyors to the crushers. Ore is crushed underground to six inch size, hoisted to the surface and crushed to 14 mesh. Loading machines and cutters are caterpillar mounted while shuttle cars are rubber tyred. Identical machines are used in development and extraction.

Room and pillar mining methods have proved successful. Pillars are left to provide support for the roof as subsidence might conceivably create fractures extending upward into overlying water bearing strata. Extraction of 40% is achieved during the first phase of development while up to 85% is finally recoverable, widths of rooms and breakthroughs range from 24ft. to 30ft.

Following single rolls crushing (- 5 inch) the ore falls to the skip loading station (a 300 ton pocket) to be drawn and measured automatically into the skips by a double rotary skips loader located 80ft. below the mine level. The loader is operated by the skips as they come into and leave the loading position.

No explosive gases have been met during mining operations but petroleum oil and natural gas are recovered marginal to and under the salt (at depths of 200ft. to 1,000ft.) in these and underlying structures at depths of up to 10,000ft. Provision for adequate ventilation of the mine openings is therefore made.

Oil and gas producers have a prior right to land tenure and a proportion of ore is made unavailable to extraction through the provision of adequate pillars about production wells in the mine area.

Ore Treatment

The refinery of the Potash Co. of America constituted the first commercial plant to concentrate a soluble salt by flotation in a saturated brine; there is a difference in S.G. of only 0.16; both are easily ground and yield a small percentage of fines. Clean sylvite can be obtained as a float at 2.02 while halite can be obtained as a sink in 2.14.

In the <u>refinery</u> are four tube mills with classifiers in closed circuit as the grinding units. The classifier overflows are pumped to thickeners to produce a pulp of the right density for flotation, the thickener overflows going to form the tailings.

In the <u>flotation section</u> are a number of rougher cells which at Potash Co. of America lift the NaCl and clayey slimes by mechanical entrainment leaving behind the KCl; at other plants KCl is floated using amino-acetate and starch as a depressant after separation of clays through thickeners.

The froth is taken to "cleaners". Potash left from the flotation operation is pulp-thickened in Dorr thickeners. This pulp goes to filters where the solids after being washed by immersion of the filter leaves in a tank of salt brine are discharged, repulped and pumped to the tailings dam. The warm brine of the overflow of the thickeners is cooled in agitators which effect a crystallization of the potassium chloride that is recovered in subsequent filtration.

The high grade concentrates go to the same cooling agitators as the warm brine so that they are mixed with the crystallized potash. Cooled pulp is pumped from the cooling agitators to classifiers to separate fine concentrates from coarse concentrates.

31118

Fig. 27 Mine, Mill and potash storehouse, National Potash Co. of America, Carlsbad.

Centrifuges remove moisture to 4%. The product is gas fired and taken to **beehive type** storehouses (Fig. 27). The fine concentrates are compacted in rolls (250,000 p.s.i.) thence granulated and screened to produce three marketable grades (fine, standard, coarse).

The beehive storehouses are half elliptic in cross section with no interior supports, columns or trusses.

The KCl product is a reddish brown coloured salt whose colour is due to minute iron oxide content.

Langbeinite as a fertilizer source

Langbeinite is of particular interest as K is in the form of SO_4 - the basis is the demand that fertilizers designed for certain crops, notably tobacco, shall be largely Cl'free. It is this fact that assigned a value of $ 42/ton for 90% K_2SO_4 as compared with $ 34/ton for 80% KCl.

Langbeinite ($K_2SO_4 \cdot 2MgSO_4$) contains the equivalent of 22.7% K_2O; it is white to pale pink and tasteless; it has conchoidal fracture and therefore is readily distinguished from halite from which it is separated by flotation. The ore is mined by I.M.C. at Carlsbad while at least one company produces K_2SO_4 from KCl by sulphuric acid treatment.

Solution Mining

Solution mining experiments have been conducted at the National Potash Co. property. Bores were drilled and brines circulated to selectively dissolve the main ore bed while opportunity was taken to observe results in subsequent mining operations. Circulation was difficult to maintain and the results were considered disappointing; U.S.G.S. Mining engineers at Carlsbad were sceptical of whether solution mining could be satisfactorily controlled. This, however, might be more easily achieved with coarser grained ores as occur in Canada.

Reserves

Reserves in beds equal to or greater than 4ft. in thickness with a minimum 14% K_2O equivalent are estimated at 50 to 80 million tons of potash. The reserves would be doubled by lowering the grade to 10%.

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Moab, Utah

3rd May, 1964 to 6th May, 1964

Frank E. Tippie, General Manager. Jim H. Ogg - Supervisor of Special Projects Frank Kennedy - Mill Supt.	Texas Gulf Sulphur Co., Moab.
Bob Norman	- Minerals Exploration Supervisor, Delhi Taylor Oil Corp. Moab.
Larry Norman	- Assistant

Regional Geology

A large area of southeastern Utah and western Colorado is underlain by Middle Permian (Pennsylvanian) evaporites of the Paradox Formation which include beds of potash in the northern Paradox Basin. These are capped by limestones and dolomites of the Cutler Group (Permian) and younger Mesozoic rocks (mostly sandstones) in the Colorado Plateau region. Approximately 16,000 feet of Pennsylvanian, Permian, Triassic, Jurassic and Jurassic beds are preserved - the generalized geologic section is shown in Fig. 28.

The "Paradox fold and fault belt" is a tectonic division of the Colorado Plateau in the "Four Corners" area where a series of anticlines and synclines with north west - south east trends, due largely to salt flowage, are spread over an area of some 10,000 square miles (Fig. 29). This is an arid region with a predominantly spectacular red landscape in which are featured extensive areas of relatively horizontal strata, long lines of cliffs, canyons, erosional remnants, natural arches, balanced rocks etc. The geological structure is dominated by salt anticlines with which are associated monoclinal folds with large offsets, long normal faults and domal mountains.

The salt structures have been the subject of intensive investigations since the 1920's in the exploration for oil. The principal structures are a series of N.W. trending faulted folds having cores of thickened salt at depth. They are localized in the deep part of the basin. The growth of the cores began in pre-Triassic time and continued into Jurassic time with a complex pattern of stratigraphic thinning and pinchout of formations across the axial parts of the salt structures. Ultimately broad anticlines were formed over the salt cores. Topographically the axes of the anticlines are marked by elliptical valleys due partly to the removal of resistant beds above and exposure of the weaker beds beneath and partly to collapse follow-

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Showing
GENERALIZED GEOLOGIC SECTION
Southeastern Utah

VERTICAL SCALE RELATIVE

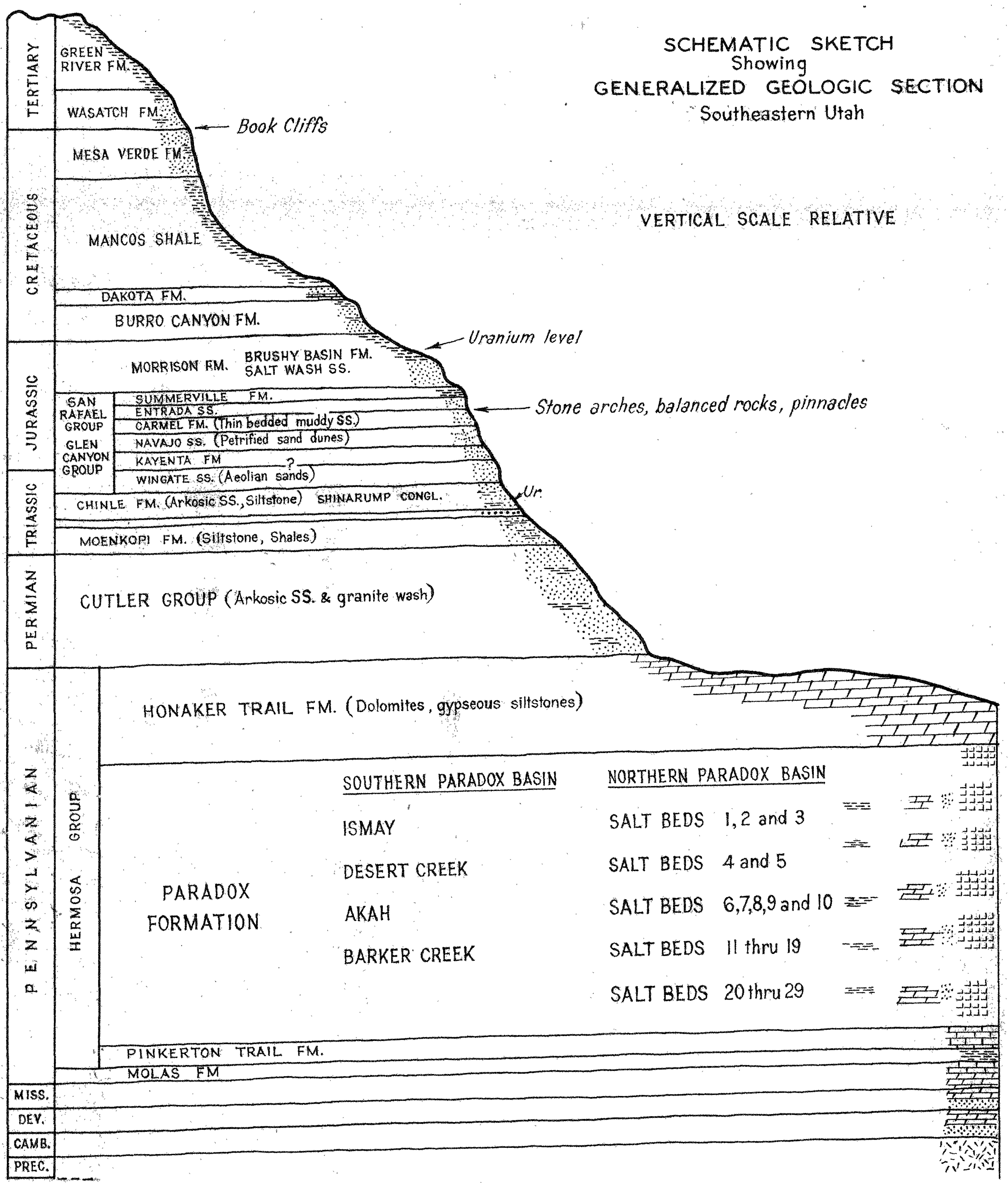

Fig. 28

S.A. DEPARTMENT OF MINES

SCHEMATIC SKETCH
Showing
GENERALIZED GEOLOGIC SECTION
South Eastern Utah

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ing solution and removal of the salt (Figs. 31,32, and 33).

One of the most spectacular structures is Upheaval Dome, a steeply dipping conical structural dome with an associated rim syncline, circular in groundplan, resulting from diapiric movement of salt to moderate levels and perhaps igneous intrusion at deeper levels. The diameter of the affected area is three miles. Erosion has carved a crater-like canyon some 1,600 feet deep and 4,500 feet wide into the apex of the dome exposing bright coloured contorted sediments of the Hermosa Group which pierce upturned (30° to 90°) Wingate sandstone and succeeding formations (Fig. 34).

The La Sal (Fig. 35) mountains rise in three groups of peaks to elevations of over 12,000 feet and comprise intrusive diorite porphyry stocks whose form were influenced by fold structures; they intrude sediments of the Paradox Basin.

The Uncompahgre Plateau lying along the eastern margins of the basin is the only highland in this province comprised largely of crystalline rocks.

Economic Geology

The area is of great economic interest to both mining and petroleum geologists but importance was not attained until a few years after World War II when large reserves of uranium ore were discovered in Mesozoic sandstones of the Colorado Plateau.

The hypersaline environment of the Paradox salt basin was highly conducive to the preservation of organic matter and there are numerous black carbonaceous shale beds and black shale laminations in the salt. Much of the original organic debris has been converted to hydrocarbons and few wells have drilled through this facies without finding some oil and gas. Numerous spectacular but short lived "blowouts" of oil and gas have been discovered in both the salt and clastic sulphate beds.

The Pure Oil Co. in 1959 established commercial production on the Lisbon Valley anticline (from Mississippian and Devonian Carbonates) and raised the salt anticline country to the rank of major petroleum production. Strangely enough this important discovery was made scarcely a stone's throw from one of the largest uranium mines on the Colorado Plateau while its operator (Charlie Stein) was seeking oil in Nevada!!! Since that time there has

31119

Fig. 31 Gypsum Valley, an elongate elliptical anticline, Utah.

31120

Fig. 32 Collapsed salt anticline, Colorado River Canyon, near Moab.

31121.

Fig. 33 Jointing in Navajo sandstone, Moab anticline top left.

31122

Fig. 34 Upheaval Dome, Utah.

31123

Fig. 35 La Sal Mountains, from The Arches National Monument, near Moab.

been great activity by oil companies.

Potash Deposits

Potash deposits were discovered in 1924 during petroleum exploration activities by Crescent Eagle Oil Co. when analyses showed the presence of KCl and carnallite in the Paradox formation of the Hermosa Group of Middle Permian (Pennsylvanian) age. The discovery generated considerable interest and exploration effort by a number of companies.

(a) Paradox Formation

Deposition of potassium salts was confined to the deepest parts of the Paradox Basin (see Fig. 29). The Paradox formation up to 7,000ft. thick consists of a series of evaporite cyclothems composed of alternating clastic, carbonate and evaporite deposition. A typical cyclothem in ascending order consists of black shale, carbonate rocks (predominantly dolomitic), anhydrite, halite and K-Mg-salts, halite and anhydrite. The complete sequence follows a pattern of gradually increasing and then decreasing salinity though the order within a cyclothem may be interrupted and incomplete; there are similar lateral transitions. Contacts may be sharp or gradational. Each cyclothem has its own particular areal extent due to differing salinity gradients and changes in the configuration of the basin floor.

Minor micro-cycles occur at regular intervals throughout each cyclothem - these may consist of alternating thin laminae of dolomite and shale, dolomite and anhydrite, anhydrite and halite, shale and halite or other combinations and represent seasonal fluctuations in salinity, temperature and clastic supply. The laminations range from $\frac{1}{4}$ inch to 18 inches, but average two to three inches.

This deposit of maringe evaporites probably contains the greatest aggregate thickness of rock salt in any single formation on the North American continent - the saline facies covers an area exceeding 10,000 square miles and contains 29 beds of halite separated by clastic and penesaline interbeds (see Fig. 30). The salt beds are numbered in sequence from youngest to oldest and range from 15ft. to 990ft. in thickness. In 18 of the 29 salt beds concentration of the brine is known to have reached the stage of potash salt precipitation. As a rule, the limestone and dolomite facies is not part of the cyclothem in the deeper part of the salt basin; the operation of a strong horizontal salinity gradient within the evaporite basin brought about peripheral precipitation of the less soluble carbonate salts. By the time each surge of fresher water initiating a new cycle had reached the deeper part of the basin they were depleted in nearly all salts but the chlorides and sulphates.

Correlation of the stratigraphic units of the saline facies is aided by the recognition of several significant marker beds titled A, B, C and D. These consist of interbedded black to dark grey carbonaceous shales, mudstones, siltstones minor sandstone and laminated and blebby anhydrite which are markedly higher in radioactivity. In general, salt beds can be correlated with a high degree of reliability from well to well even where some may be entirely missing.

Potash beds occur at 18 levels ranging from several inches up to almost 25ft. - possibly 10 of these levels have potential for commercial production though only three are at present under test. Thickening of potash beds in some sections is related to flowage, elsewhere it is a primary depositional feature. Grade is variable from 12% K_2O to 25% K_2O equivalent.

(b) Potash

Unlike the complex mineral suites of southeastern New Mexico, Stassfurt etc. the Paradox Basin deposits exhibit a comparatively simple mineralogy and only sylvite and carnallite have been identified, though analyses of brine from several wells have been found to be high in boron, bromine and lithium suggesting that other saline minerals may be found. High density Mg-rich brines, oil and gas zones are commonly found in these beds.

Sylvite here is milky white or grey to colourless, light orange, salmon pink or blood red in colour and occurs as a crystalline intergrowth with halite (sylvinite). Fine grained anhydrite, clay and carnallite may be present as impurities.

The richest sylvite concentrations appear in the upper halite units. Almost everywhere the sylvite is restricted to a specific position in the cyclothem, which is near the top of the halite unit. Beds show a downward decrease in potash content while they pass abruptly up into barren halite.

Carnallite zones, although of minor economic significance, are very rich and occasionally of remarkable thickness. One bore penetrated 227ft. - this anomalous thickness is almost certainly due to salt flow adjacent to the Moab fault.

(c) Well Logging

The presence of the radioactive potassium isotope K40 has made the radioactivity log a valuable tool in detecting potash. As depicted in Fig. 30, a high grade zone of sylvite creates considerable response on the gamma ray curve from which good qualitative correlations can be made. Carnallite with a lower potash content (17% K_2O equivalent) is not as easily detected because of the subdued response. Many factors including diameter of borehole, logging speed and contamination may interfere with the quantitative evaluation of potash content. Despite this some fairly reliable estimates of potash grade can be made. Radioactivity, electric, sonic and lithologic logs facilitate correlation of wells. Isopachous maps have been constructed for each salt bed and for a number of the intervening shale-anhydrite marker beds.

(d) Exploitation

The Paradox Basin is a potential future source of potash;

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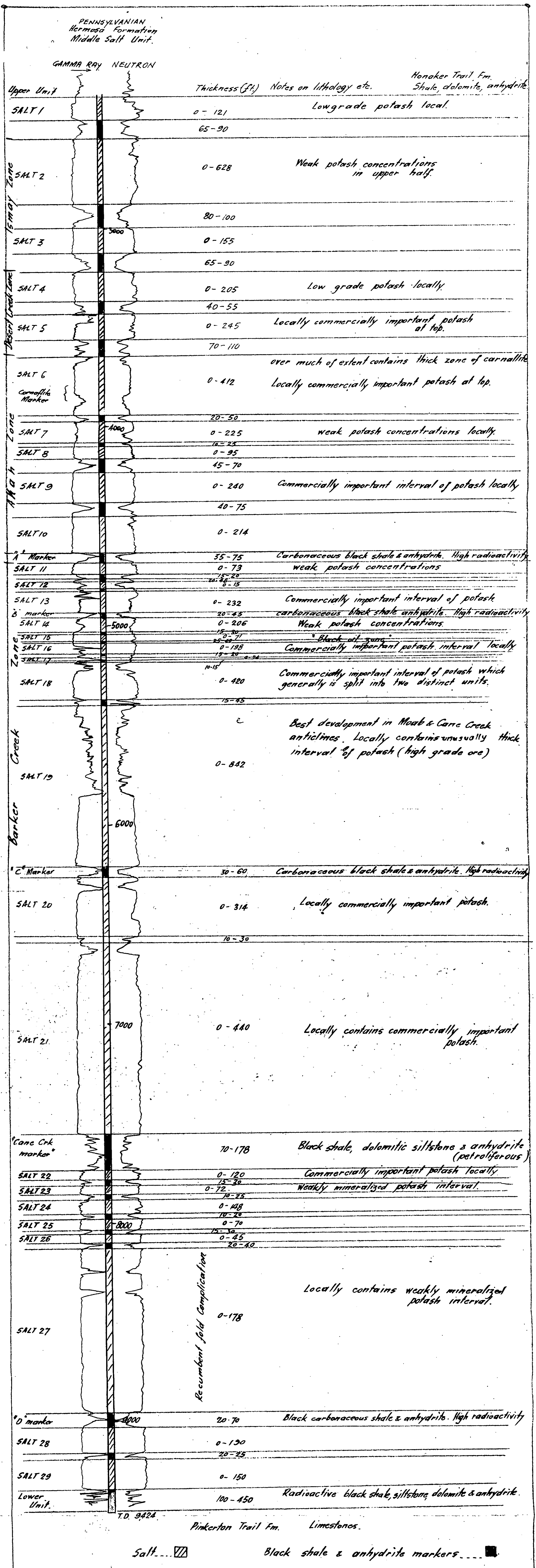

GAMMA RAY & NEUTRON LOGS OF
SALINE FACIES, PARADOX MEMBER

SEVEN MILE STRUCTURE - DELHI TAYLOR OIL CORP., WELL 2, UTAH.

Fig. 30

After Robert J. Hite, 1960.

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the grade compares favourably with that of Carlsbad.

The depth of the zones and the structural deformation are handicaps that must be overcome in any exploitation of the deposits. A number of companies are engaged in potash exploration though only one (Texas Gulf Sulphur Co.) has progressed to the mining stage.

(1) Texas Gulf Sulphur Co.

The Cane Creek potash mine of T.G.S. is situated near the Colorado River 12 miles south west of Moab on Cane Creek anticline (Figs. 36 and 37) - an elongate structure with more than 400ft. of local defined surface closure. Delhi Taylor Oil Corp. proved this area by drilling seven bores at varying intervals from $\frac{1}{4}$ mile to one mile apart on this structure and then sold out to T.G.S.

In 1960 construction of a mine shaft began and by mid 1963 this had reached 2,600 feet; railway connection to Green River was established and a potash mill to process 4,000 tons of ore per day was completed ready to receive ore. The shaft has a concrete 187-feet high head frame and was completed in Upper Pennsylvanian Honaker Trail formation (dolomites) in preference to sinking into salt. The shaft makes connection to the potash zone by way of an inclined drive. This course was adopted because of doubt as to how the salt would behave during shaft sinking operations. Experience suggests that the shaft would now have been completed to the potash level.

The bed which is to be exploited is 20ft. thick and has a 24% K_2O content.

On August 27th, 1963, when salt was intersected a disastrous methane gas explosion underground claimed the lives of 18 men. Since that time modifications to the shaft and more stringent ventilation procedures have been stipulated following an enquiry by the U.S. Bureau of Mines. Contractors are still constructing drifts and as yet no production has been achieved - this is now scheduled for "the fall" of this year. Mining methods to be employed will be similar to those employed at Esterhazy. The ore here is finer grained and has a lower iron oxide and clay content. (< 1%).

31124

Fig. 36 Cane Creek Anticline, Utah. Mine and mill of Texas Gulf Sulphur Co. located to left of Colorado River.

31125

Fig. 37 Mill and potash storehouses, T.G.S. Cane Creek Mine.

(2) Other activity

A number of other (oil) companies are actively engaged in potash exploration. Because of the depth of the ore, the fire hazard occasioned by the presence of inflammable gas and the setback experienced by T.G.S. solution mining may prove the answer to economic recovery. Companies engaged here include Delhi Taylor Oil Corp., Tenneco Oil Co., Midwest Oil Corp., Continental Oil Co. and Richfield Oil Corp.

In coring the soluble beds of the Paradox formation various methods are used to prevent solution including dry drilling with saturated brine or with diesel oil. Delhi Taylor Oil Corp. are currently investigating the 7-mile Anticline area. This company drills to the top of the salt using conventional techniques and cases off the little water held in the overlying sediments. As the salt section is usually dry this is rotary drilled using air to return cuttings. A saturated brine fluid is utilized if this section is not dry.

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5. Canada, Saskatchewan

Esterhazy Mine

(International Minerals and Chemical Corp.(Canada) Ltd.)

15th April, 1964 to 17th April, 1964.

Cliff Haryatt (Chemical Engineer), Esterhazy.

Tim Edwards (Plant Engineer) "

Harly D. Strain (Geologist) "

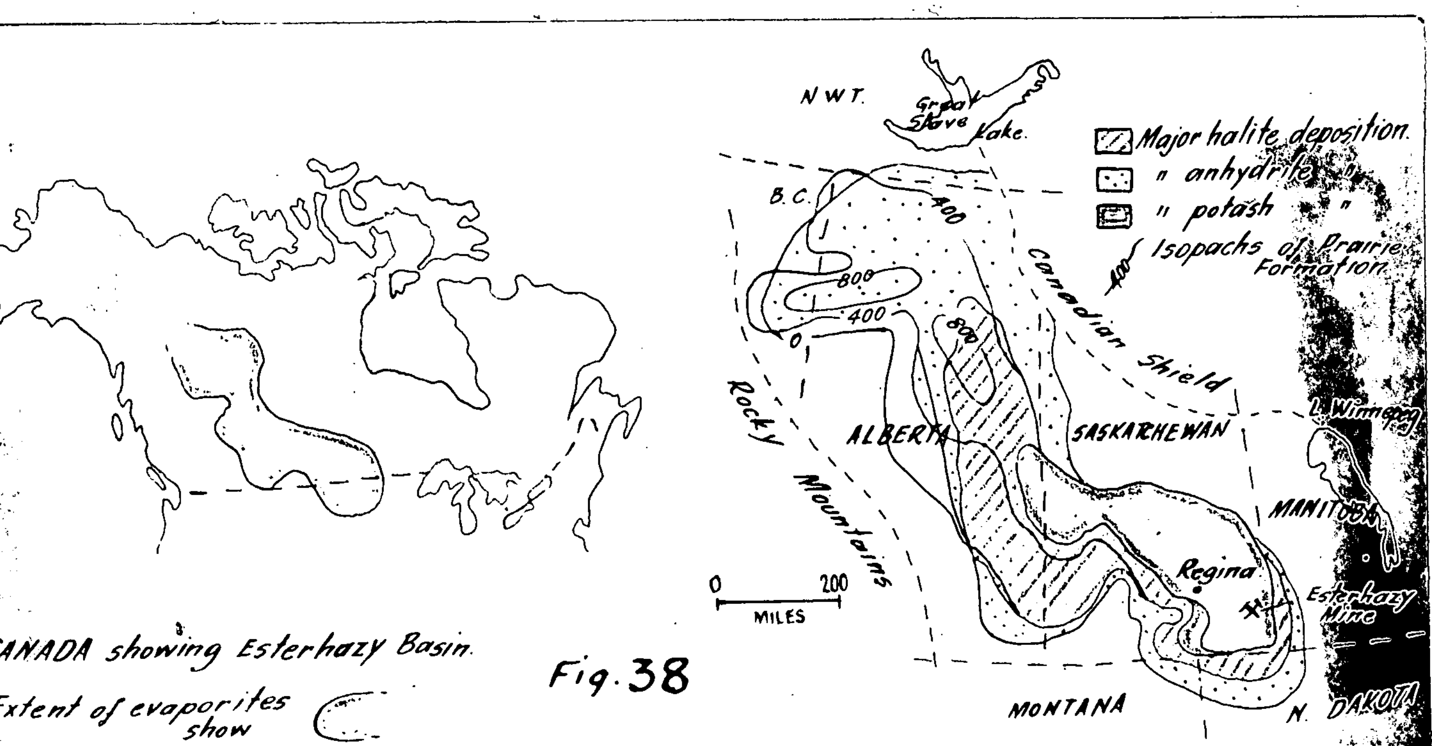
R. (Bob) D. Lindbergh (Operations Manager) Esterhazy

Merv. Upham (General Manager), Esterhazy.
"Fitz" Prugger (Mining Engineer), "
Ted Ellingham (Geologist) - Dept. of Mineral
Resources, Regina.
Art Morris (Industrial Minerals Section) " "
Resources, Regina.

Potash was first recognised at a depth of some 7,000 feet in the Esterhazey (Williston) Basin during oil-well drilling operations in 1943. Subsequent operations proved the occurrence over an area ranging from 15 to 50 miles in width and some 450 miles in length. Over 200 deep boreholes have now been completed and disclose potash beds 2½ft. to 15ft. (average 10ft.) in thickness at depths below 2,800 feet containing 25-35% (average 30%) K_2O equivalent. These are the largest known deposits in the world having reserves estimated at 17.7 billion tons.

Regional Geology

The Middle Devonian Elk Point Group which extend some 1,200 miles from northern Montana and North Dakota to Canada's Northwest Territories (see Fig. 38) include the Prairie Evaporite formation. It is best known and developed under the Prairies of Saskatchewan where it consists largely of salt and lesser anhydrite beds and contains extensive potash ores now being developed. The formation reaches a maximum thickness of 670 feet in Saskatchewan and approximately 450 feet in the Esterhazy locality and includes a depositional sequence of shales and carbonates, followed by evaporites,



ANADA showing Esterhazy Basin.
xtent of evaporites show

Fig. 38

climaxing in potash salts and capped by red beds (Figs. 39, 40). This sequence is overlain by similar depositional units in which evaporites are less well developed.

These sediments rest on Siluro-Ordovician limestones and dolomites (600ft.), Cambrian Sandstones (800ft.) andthese, on a vast gently dipping shelf area bordering the Canadian Shield; they have undergone only mild epeirogenic movements. The northern end of the basin was open to the sea but restricted by carbonate reefs while the southern part contained the most concentrated brines. The evaporites of the Prairie Formation represent the final stage of a major depositional cycle. At the onset of this cycle, the sea spread over the eroded pre-Devonian surface, depositing a thin basal shale. This was followed by fairly clean shelf-type carbonates, presumably deposited under comparatively stable tectonic conditions. Subsequently, a central basin developed and extensive reef banks formed along the margins of the subsiding trough, and isolated pinnacle reefs grew up to heights of 400 feet from the basin deep. These died as a result of increasing salinity in this inland sea and were covered by evaporites, anhydrite, thick sequences of halite and finally sylvite.

The evaporites are now buried under a cover of younger rocks ranging up to 8,000 feet thick in North Dakota.

The regional structure of this large area is simple. The evaporites and enclosing beds are tilted gently to the south and west with an average dip of 30 to 40 feet per mile; they are relatively undisturbed and folding and faulting are almost non-existent.

Over large areas the salt deposits have been affected by underground solution and in parts have been completely removed by leaching (Fig. 41).

Potash ore

Sylvite occurs with halite (sylvinite) in three principal zones separated by halite near the top of the Prairie Evaporites Formation. Red carnallite occurs mainly as irregular vertical veins within the halite zone. Numerous clay seams occur in the upper part of the formation but in the ore zones varies from 1.0 to 1.5%.

The ore is coarsely crystalline and massive with crystals commonly

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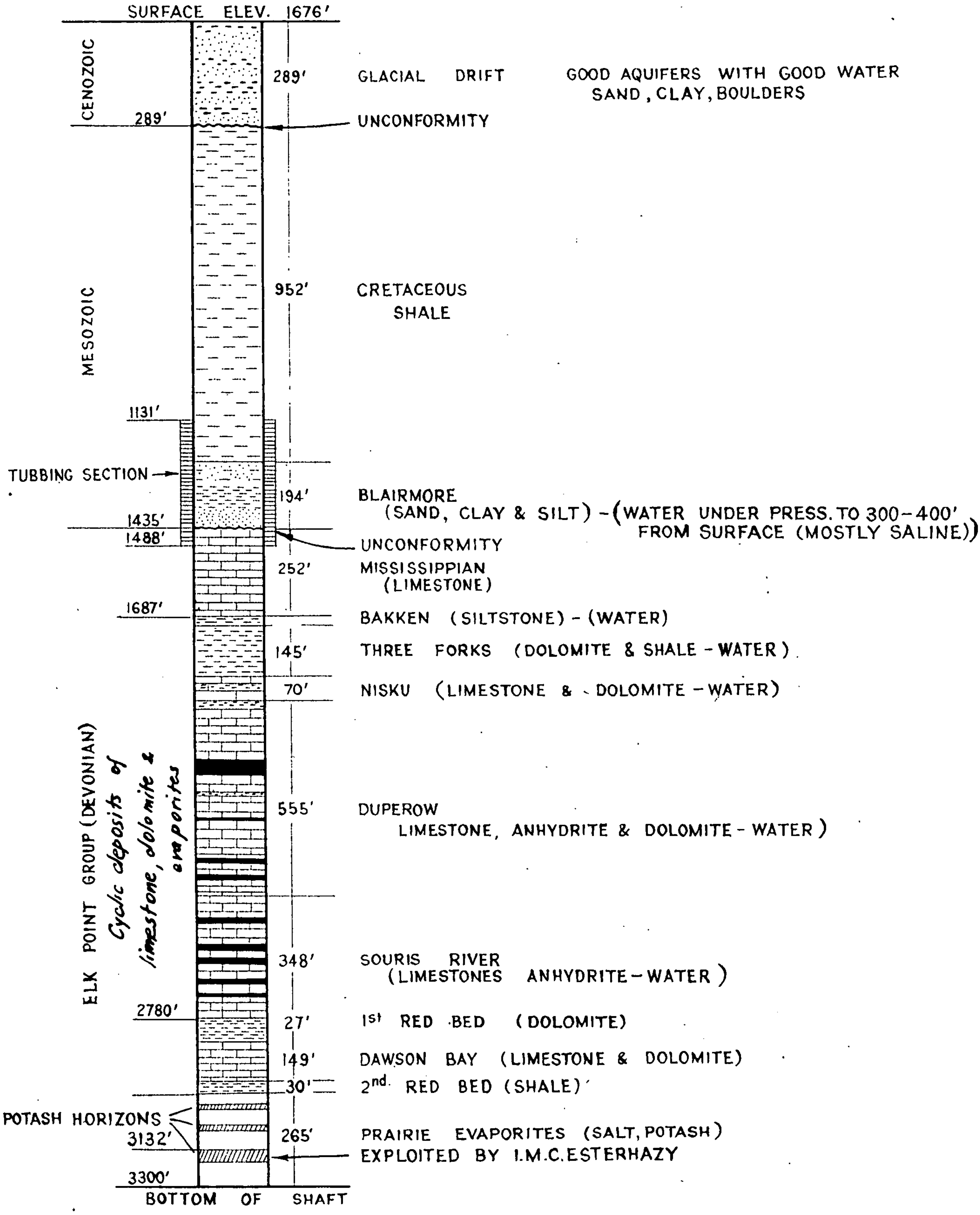

Fig. 39.

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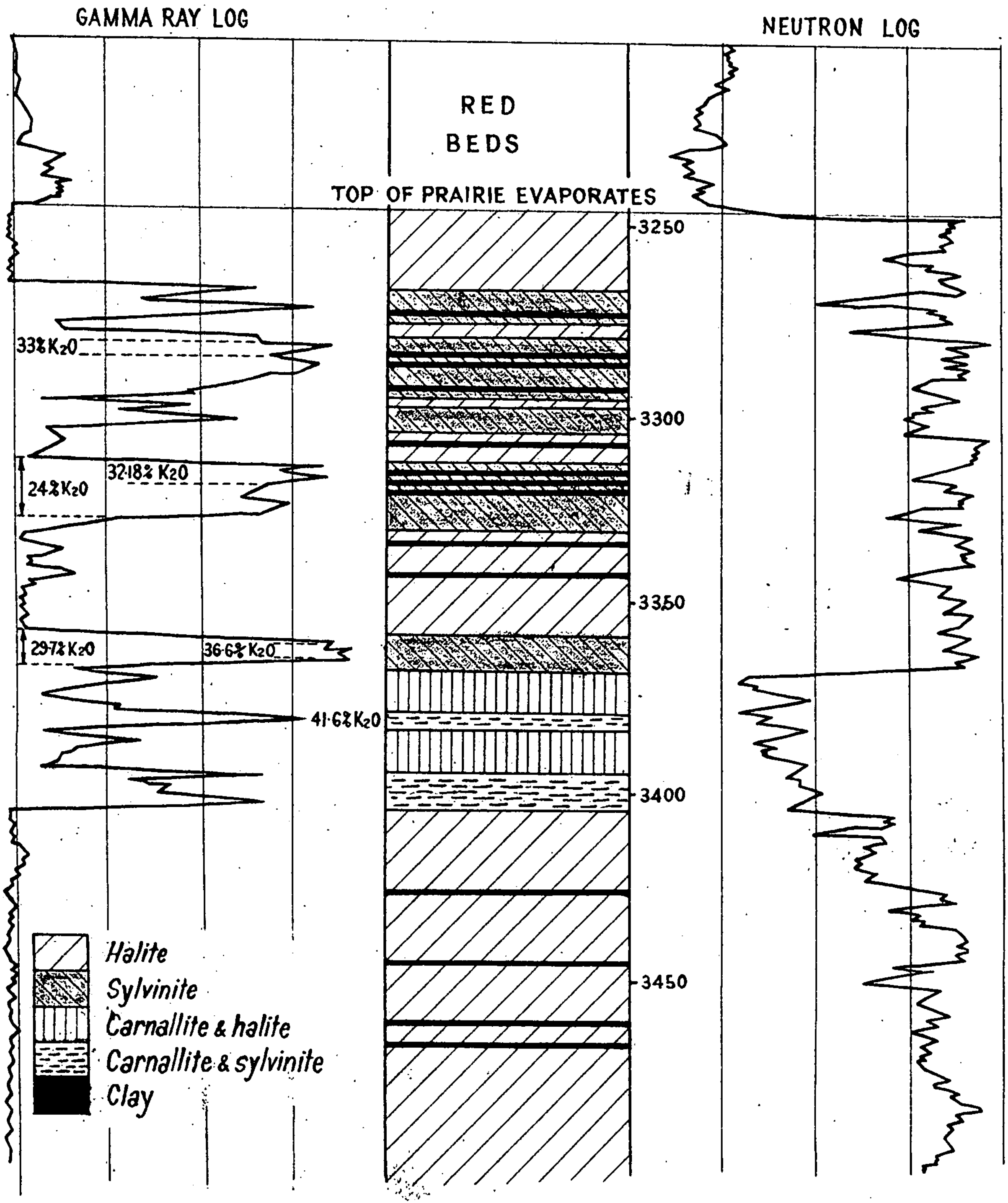

CORRELATION OF GAMMA RAY AND NEUTRON LOGS WITH THE MINERALOGY AND LITHOLOGY OF THE UPPER PART OF THE PRAIRIE EVAPORITES

Fig. 40

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of one inch. It is waxy in appearance with contained iron oxides and clay giving a pink colour. At Esterhazy the ore zone (the lowest of three) is 8½ feet thick. The top 4½ft. of the ore zone is clean high grade ore; the next bed below is the mining control or marker bed and contains coarser crystals with a minor amount of disseminated grey and green clay; below this is a bed of good grade ore. The sylvinite contains 40 - 45% sylvite with 25 - 35% K_2O equivalent.

Exploitation

Solution recovery attempts were made at Unity in 1951 but it was not until 1953 that mineable deposits were indicated. The Blairmore Formation, a layer of sand, clay and silt having the consistency of quicksand and containing salt water under pressures of up to 1,100 lbs/square inch has presented problems in shaft sinking to the potash beds. Seventeen companies hold two million acres under lease but to date only three companies have collared shafts in the potash district. The first company started in 1958 but never reached the ore. Potash Co. of America completed a shaft to the topmost potash bed at Saskatoon but had to stop production (geared to 4,000 tons of ore per day) the next year because of water leaks in the shaft; this is expected to be rectified for renewed production inlate 1964. International Minerals and Chemical Corp. (Canada) Ltd. succeeded in sinking a shaft (Yarbo No. 1 Shaft) to a depth of 3,378 feet but it was the most costly for its size and depth yet sunk and took five years, $10 million and a combination of freezing, tubbing and extensive grouting to complete. Their Esterhazy plant, located close to the Manitoba border 110 miles east of Regina, cost $40 million before production on a continuous and commercial basis was achieved in August, 1962.

Conventional mining methods are limited to a depth of 3,500 feet because of the strength characteristics of salt-potash beds and the danger of uncontrollable flows of water should strain occur. Increasing attention is being given, therefore to solution mining which will make available, if successful, vast reserves of potash in Saskatchewan that are beyond the reach of practical shaft mining techniques.

31126

Fig. 42 Esterhazy Mine, I.M.C. (Canada) Ltd.

31127

Fig. 43 Yarbo No. 1 Shaft, mill and potash storehouses, Esterhazy Mine.

To date two underground mines are in operation and two refineries have been built with combined capacity of $1\frac{1}{2}$ million tons potash equivalent. Annual production by I.M.C. Co. at Esterhazy will be stepped up from 1.2 to 1.6 million tons when a second shaft is completed. Solution-mined salines are expected to come "on stream" in late 1964 at the refinery of Kalium Chemicals Ltd. near Regina. This will be the world's first commercial solution mining project and will have a rated capacity of 600,000 tons per year of product.

Raw potash ore is valued at the mine at about $10 per ton and, when refined and sized, at $21.60 ton - freight to the east coast adds a further $20 to the cost.

(a) I.M.C. Co., Esterhazy

A descent to the working level at a depth of 3,132 feet and an inspection of underground operations and of the surface plant was arranged (Figs. 42, 43). The company has 250,000 acres of land under tenure.

Drilling at approximate one mile centres preceded mining operations to confirm continuity of the ore bed and of structure. Yarbo No. 1 shaft is an 18ft. diameter circular shaft with three compartments taking a $5\frac{1}{2}$ft. aluminium ventilation pipe, skips, cage, ladderway, and electrical and communication systems. In sinking, ten water bearing zones were penetrated. To control any intake of water into the shaft pump stations are maintained at the 600ft., 1,800ft., 2,400ft., and 2,900ft. levels. There are 100ft. of salt directly above the potash.

A second shaft is being sunk some six miles away to the north to connect with the underground workings.

There are 90-miles of 21ft. wide openings to date and the inspection of the working faces involved a four mile drive underground in a diesel-engine Landrover. Mining is dry, clean, and highly mechanized. Rock temperatures approximate 78°F. Trackless mining is practiced throughout, ore being excavated by Goodman rotary cutters, Joy Loaders, Joy Shuttle cars and belt conveyors in the material handling systems. There are eight mining units in operation or on standy-by. The continuous boring machines have a 7½ft. cutting height and 13 feet width; they advance about six inches per minute and cut uniform, smooth openings which greatly assist in stabilizing the salt beds. A seven entry system is practiced; panel mining is carried out by a modified room and pillar method with development drives being 21ft. wide and remnant pillars 150ft. x 50ft. - this allows for 35% recovery in rooms and 19% recovery in the main drives. Ore is taken to the shaft, currently at the rate of 9,000 tons per day, by 42-inch fire-resistant belts up to 4,000ft. in length, and suspended from hangers lag-bolted to the roof. To date 4.5 million tons or ore have been extracted.

At the surface the ore is crushed to ½ inch in rolls and leached with a saturated salt solution to allow disocciation of carnallite. Clay is removed in cyclones, hydroseparators and thickeners; sylvite is floated, using amino acetate as an agent and starch as a depressant of halite, dewatered in centrifuges, dried and sized in three fractions whose K_2O content exceeds 62%. In 1963 this mine produced one million tons of potash valued at $25 million.

(b) Solution Mining

More than 50 years ago attempts at solution mining of potash were made in Germany. During the late 1940's test projects were operated in Carlsbad as well as in England. In Saskatchewan at least two companies attempted recovery before Kalium Chemicals Ltd. started and there are now four solution mining pilot plants. These prior tests were unsuccessful but Kalium Chemicals Ltd. have announced firm plans for commercial production in late 1964.

This method obviates the necessity for shaft sinking through the Blairmore formation and would also allow for fuller extraction of the ore at depths below 3,500 feet which is considered to be the limiting depth for conventional underground mining; at this depth openings would be difficult to maintain and resulting failure could admit water.

In solution mining the entire opening can be supported by fluid pressure and since depth of the salines is not an overriding consideration the plant can be located more advantageously with regard to transport, fuel sources, population centres etc.

Kalium Chemical Co. at Belle Plain, 25 miles west of Regina, has three clusters of wells which tap salt beds at a depth of 5,000ft. It is not known whether injection and recovery will take place through the same well. The use of natural gas or petroleum or other fluid immiscible with water will establish a thin layer at the roof of a cavity to cause expansion of the cavity laterally. For most purposes it is desirable to extract both NaCl and KCl from the deposit in the proportions in which these two minerals exist in the deposit. Later, KCl may be preferentially extracted from the 100ft. thick ore zone by feeding aqueous solution which is saturated as to NaCl into the cavity.

Initial connection of wells is achieved by the hydraulic fracturing or bed splitting method whereby target wells can be reached exactly on line many hundreds of feet away after pumping comparatively small amounts of brine into an injection well. Once the fracture is made controlled solution of a cavern can be initiated.

Brines pumped from recovery holes will be piped to a refinery for fractional crystallization of the solutes. To meet the production goal of 600,000 tons of potash per year it will be necessary for Kalium to dissolve 2,400,000 tons of ore.

Other companies operating pilot plants include Duval Corp., Southwest Potash Corp., and Imperial Oil Ltd. European potash mining companies (Mines Domaniales de Potasse d'Alsace (France) and Wintershall and Salzdetfurth (Germany) have combined to form Alwinsall Potash and are engaged in this area.

Many are sceptical of solution recovery and claim that it will not be competitive because of:

(a) the number of wells required for sizeable output

(b) plugging of openings and coating of crystal grains by released clay.

(c) higher cost of crystallization as opposed to flotation.

(d) non-selectivity of the method.

(e) likelihood of collapse of wells and cavities.

If this does prove to be a successful method of recovery, however, it will make available enormous reserves of potash not only in Canada but in the United States, England, continental Europe and elsewhere.

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(c) Borates

The world's largest known reserves of boron bearing minerals are found in south eastern California and these supply almost 95% of the world's requirements; in 1962 borates from California sources were valued at over $46 million. Borax which is the most important borate mineral occurs as glassy, clean to translucent, crystals which on exposure turn white by dehydration to tincalconite, a dull white powdery mineral. It is very soluble in water. The chief uses for borax are in glass making, in ceramics, fibre glass (for viscosity control), detergents, the nuclear energy field, fuels etc. and production is now in excess of one million tons per year.

Production in California was initiated in Death Valley (some 276 feet below sea level) where rainfall is about 2 inches per year (Fig. 44). Cotton-ball ulexite was scraped from the surface of the playa which occupies the near-lowest depression in the 140 miles long and four to 16 miles wide valley, refined at the Harmony Borax Works (Fig. 45) and transported 165 miles to the railway across the Mojave Desert in the now famous 20-mule team wagons (Fig. 46). Borax recovered from the Searle's Lake brines since 1914 then became the main source of supply until the Kramer deposits were discovered and exploited. There has been small sporadic production of borate minerals from bedded deposits located to the east of Death Valley, near Ryan. Visits to all of these deposits were made.

Listed below are borate minerals found at Boron and elsewhere.

Borax (tincal)	$Na_2O.2B_2O_3.10H_2O$
Tincalconite	$Na_2O.2B_2O_3.5H_2O$
Kernite (rasorite)	$Na_2O.2B_2O_3.4H_2O$
Inyoite	$2CaO.3B_2O_3.13H_2O$
Meyerhofferite	$2CaO.3B_2O_3.7H_2O$
Colemanite	$2CaO.3B_2O_3.5H_2O$
Ulexite	$Na_2O.2CaO.5B_2O_3.16H_2O$
Probertite	$Na_2O.2CaO.5B_2O_3.10H_2O$
Kurnakovite	$2MgO.3B_2O_3.13H_2O$
Inderite	$2MgO.3B_2O_3.13H_2O$
Hydroboracite	$CaO.MgO.3B_2O_3.6H_2O$
Tunellite	$SrO.3B_2O_3.4H_2O$
Searlesite	$Na_2O.B_2O_3.4SiO_2.2H_2O$
Howlite	$Ca_2SiB_5O_9(OH)_5$
Sassolite	$B(OH)_3$

Boron products normally sold in bulk sell for prices ranging from about $45 per ton for granular borax (99.5% pure) to $200 per ton for high purity boric acid.

<u>Kramer pit, Boron, Calif.</u> (U.S. Borax & Chemical Corp.)

8th April, 1964.

Ralph Barnard, Senior Mine Geologist, U.S. Borax, Boron.

Bob Kistler, Geologist, " " "

31128

Fig. 44 Death Valley. Note extensive outwash alluvial fans and their truncation on a recent fault scarp marginal to the Valley.

31129

Fig. 45 Harmony Borax works, Death Valley.

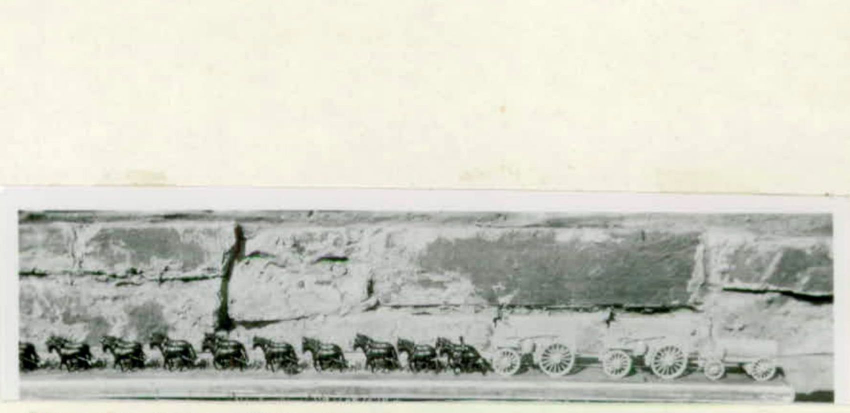


Fig. 46 20-mule team, U.S. Borax.

31130

Colemanite was first discovered at a depth of 370 feet in water drilling operations in 1913 in the arid western part of the Mojave Desert where there are no surface indications of a borate deposit. During the next 12 years, the deposit was explored by further drilling, shafts were sunk, and some commercial production developed. The value of this find was abruptly eclipsed in 1925 when a near-by drill hole encountered thick beds of borax and kernite. These crystalline beds were outlined by drilling at 200ft. centres (utilising diesel oil as a drilling fluid). They were reached by a shaft in 1926 and since then they have developed into the world's leading source of borates. In 1956 the company converted this into an open pit which is now some 325 feet deep and covers an area of 4,000ft. x 3,000ft. (Fig.47). The deposit is situated three miles north of Boron and eight miles north east of Edwards Air Force Base.

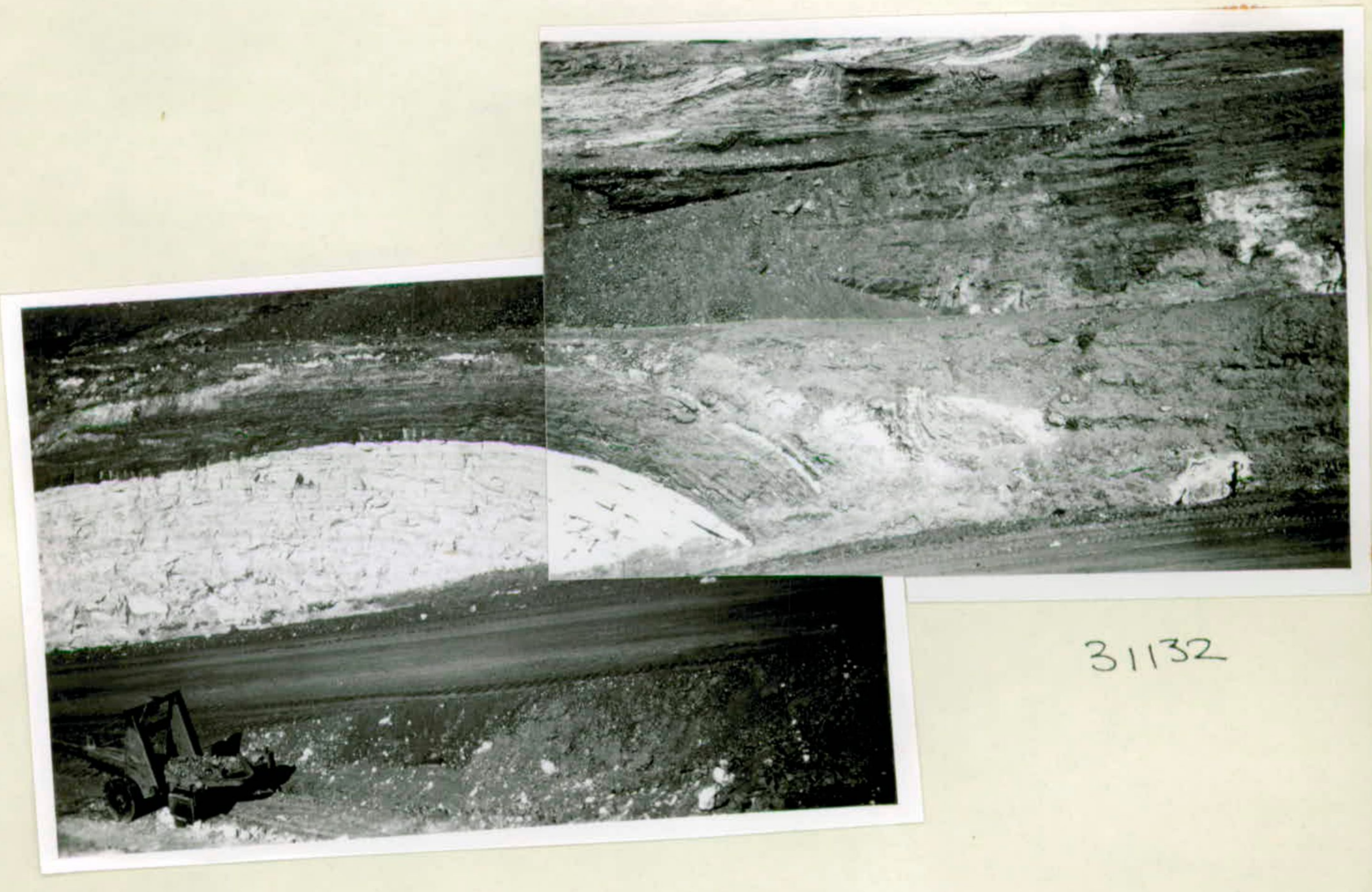
The borates were ultimately derived from volcanic gases or waters and concentrated in an upper Miocene playa some four miles in length and one mile in width (Fig. 49). Impervious clays protect the borate minerals from groundwater solution and the whole section has been preserved from erosion by downwarping; the principal borates range in depth from 300ft. to 1,000ft. below the surface. The section exposed in the Kramer pit is as follows:-

Quaternary	40ft.	Alluvium, sand - - - -unconformity
Upper Miocene	100ft.	Tuffaceous arkose, fanglomerate, stream bed deposits (mammalian remains have been found in the arkose). Perched water table.
(Ricardo formation)	20ft.	Brown claystone.
	- 60ft.	Upper shale member - laminated green claystone. Lower beds contain thin (1ft.) bands of ulexite and colemanite.
(Kramer Beds)	0-270ft.	"Borax" - bedded crystalline borax (primary) and Kernite (secondary), with ulexite, colemanite etc.
	40-60ft.	Lower shale member - green claystone with ulexite.
	1,000ft.	Saddleback Basalt
Lower Miocene (Rosamund Formation)	500ft.	Arkose, tuff, shale, cherty limestone.
Cretaceous-Jurassic	Granite	

The borate beds range up to 270ft. in thickness and it is estimated

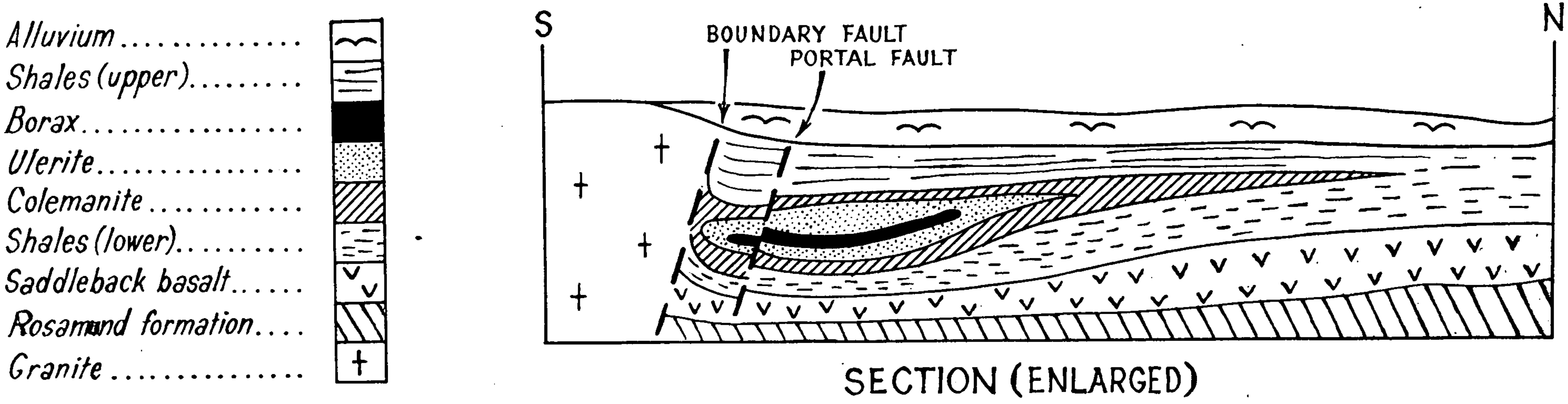
31131

Fig. 47 Kramer Pit, U.S. Borax & Chemical Corp., Boron. West Baker mine shaft at extreme right. Old underground workings (sand filled) are discernible in the bed of borax.



31132

Fig. 48 Boundary Fault which truncates the Kramer beds, Kramer Pit. Thin white beds are ulexite which serve as markers.



KRAMER BORATE DEPOSIT, BORON (U.S.BORAX)

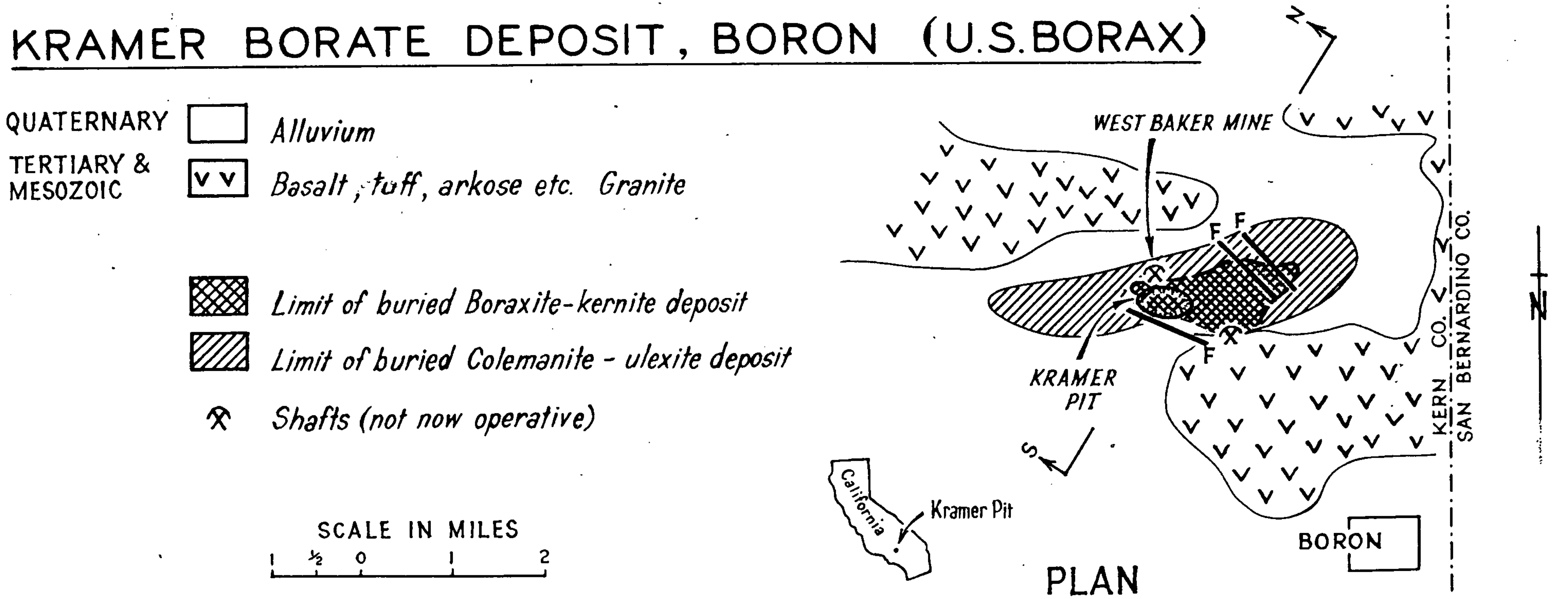


Fig. 49

S.A. DEPARTMENT OF MINES

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Passed
Drn.
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Ckd.
Exd.
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Scale 1in. = 1.8m. app.
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that they contain 100 million tons of ore with 25% B_2O_3. The crystalline borax when freshly broken is clear and glassy and contains an admixture of green tuffaceous and montmorillinotic clays - the mined material being about 75% borax and 25% clay. On exposure to the air for two or three days the borax dehydrates to white opaque tincalconite. The beds are buckled into low open folds with dips of $10^\circ - 15^\circ$ being common, and are cut by minor N.W. trending faults. The deposits are truncated on the southern margin by a major fault dislocation (Fig. 48). Fig. 49 illustrates the concentrically zoned nature of the ore body with the core of borax being successively enclosed by a layer of ulexite and then colemanite. There are two beds of tuff within the orebody which serve as markers. Occasional clay lenses also occur.

Dolomite and calcium carbonate occur in the shales but sulphates and chlorides are absent. The deposit has yielded over 15 million tons of sodium borate ore since 1927 from the open pit and underground workings.

Traces of realgar (sulphide of arsenic) occur in amounts from 1,200 up to 3,500 p.p.m. as red ink-like spots in the kernite crystals.

To expose the orebody some 15 million tons of overburden have been removed. Ore is mined utilizing a shovel-truck system and is dumped into a belt conveyor for haulage to a refinery built at the top of the pit. Borax is separated after 3-stage crushing from the associated clays by solution in hot water, filtration and crystallization.

Ryan Mine, Furnace Creek (Kern County Land Co.)

10th April, 1964.

Ken Reim, District Mining Engineer, K.C.L. Co., Bakersfield.

Colemanite deposits have been sporadically mined by the Kern County Land Co. since the 1920's from a shaft connecting levels at 60ft. and 125ft. in a bed dipping at about 45° (Fig. 50). The deposits are in folded and faulted Tertiary strata which outcrop in Inyo County to the east of Death Valley. The colemanite occurs in a bed 20ft. in thickness in the 2,500 feet thick upper Miocene Furnace Creek Formation, a highly variable formation that includes basaltic lavas, pyroclastics, conglomerate, bentonitic clays, sandstone and shale. Colemanite occurs as white cleavable crystalline lenses and irregular masses in grey bentonitic shale in the upper levels of the mine.

Ulexite, derived from colemanite through circulation of groundwaters which percolate along a strike fault in this locality, is mined in the bottom level. The ore mined carries 10 - 30% B_2O_3 equivalent (12% being considered the lower economic limit).

The company has done considerable prospecting in the area, by drilling and by bulldozing and has proved reserves of 20 million tons of 20% B_2O_3 ore. U.S. Borax also have holdings in this region.

31133

Fig. 50 Ryan Mine, Furnace Creek, Kern County Land Co. In foreground are colemanite bearing beds of Furnace Creek Fm; in background, Cambrian limestones.

BRINES

borates, potash, bromine etc.

1. Searles Lake, California (American Potash & Chemical Corporation)

8th April, 1964 to 9th April, 1964.

Dr. George I.Smith (Geologist), U.S.G.S., Menlo Park.

David Holmes (Geologist), American Potash, Trona.

D. Dickenson (Vice-President), " " , Los Angeles.

Dr. Capper (Chemical Engineer)" " , " "

P. Peterson (" ")" " , " "

Searles Lake is one of a number of playa lakes that now occupy undrained depressions in the Mojave Desert, in the southwestern corner of the Basin and Range physiographic province, and constitutes one of the largest bodies of exposed evaporite salts in the U.S. Other lakes in the region are, or have been, commercial sources of salines but Searles Lake is by far the most important - it produces the largest variety of salts, has the greatest tonnage and is the only one from which potash is recovered.

The basin in which Searles Lake is situated is a broad depression some eight to 10 miles from east to west and 25 miles from north to south, and bordered by abruptly rising slopes of the surrounding mountain ranges (Figs.53, 54, 55).

Geological Setting

The Basin and Range province comprises 'strings' of oriented north-south, fault-bound, high, mountain ranges, separating and partly enclosing elongate undrained basins. Mountain building took place in the late Tertiary and the subsequent history of these basins may be summarised as one of extensive alluviation by which the valleys have been largely filled with outwash derived from the uplifted mountain areas. Faulting is still taking place and a number of fault scarps in Recent alluvial outwash fans are observable in this region (compare Fig. 44).

During the early Pleistocene a topography essentially like that of the present day was developed and in the alluviated basins glacial lakes expanded. Searles Lake comprised one of a string of lakes immediately east of the glaciated Sierra Nevadas (Fig. 51); each basin in the chain lies in turn at a lower elevation than the one above it and the lowest divides connected one basin with the next. Waters formerly filled Owens Valley until they overflowed into China Lake. Overflow from this basin found its way through a narrow channel over the divide into Searles Basin; successively lower basins were flooded and overflowed into Panamint Valley, and finally into Death Valley. The supply of water wasn't sufficient during any of the glacial stages to fill all of the intermontane valleys completely and a permanent drainage course was never established to the sea. Numerous lakes were in existence and these served as settling ponds for the rock debris allowing salt-laden waters to flow down to lower basins more or less free of detritus. Some of these became sumps which accumulated salts on evaporation

Searles Lake

The last vestiges of a saline lake occupy about 12 square miles

31134

Fig. 53 Western side of Searles Lake, separation plant of American Potash & Chemical Corp. in middle distance.

31135

Fig. 54 Crustal Salt, Searles Lake.

31136

Fig. 55 Brine wells and pipelines, Searles Lake. Note fossil strand line on flanks of Slate Range.

PLAYAS OF THE MOJAVE DESERT
REMNANTS OF A CHAIN OF PLEISTOCENE LAKES

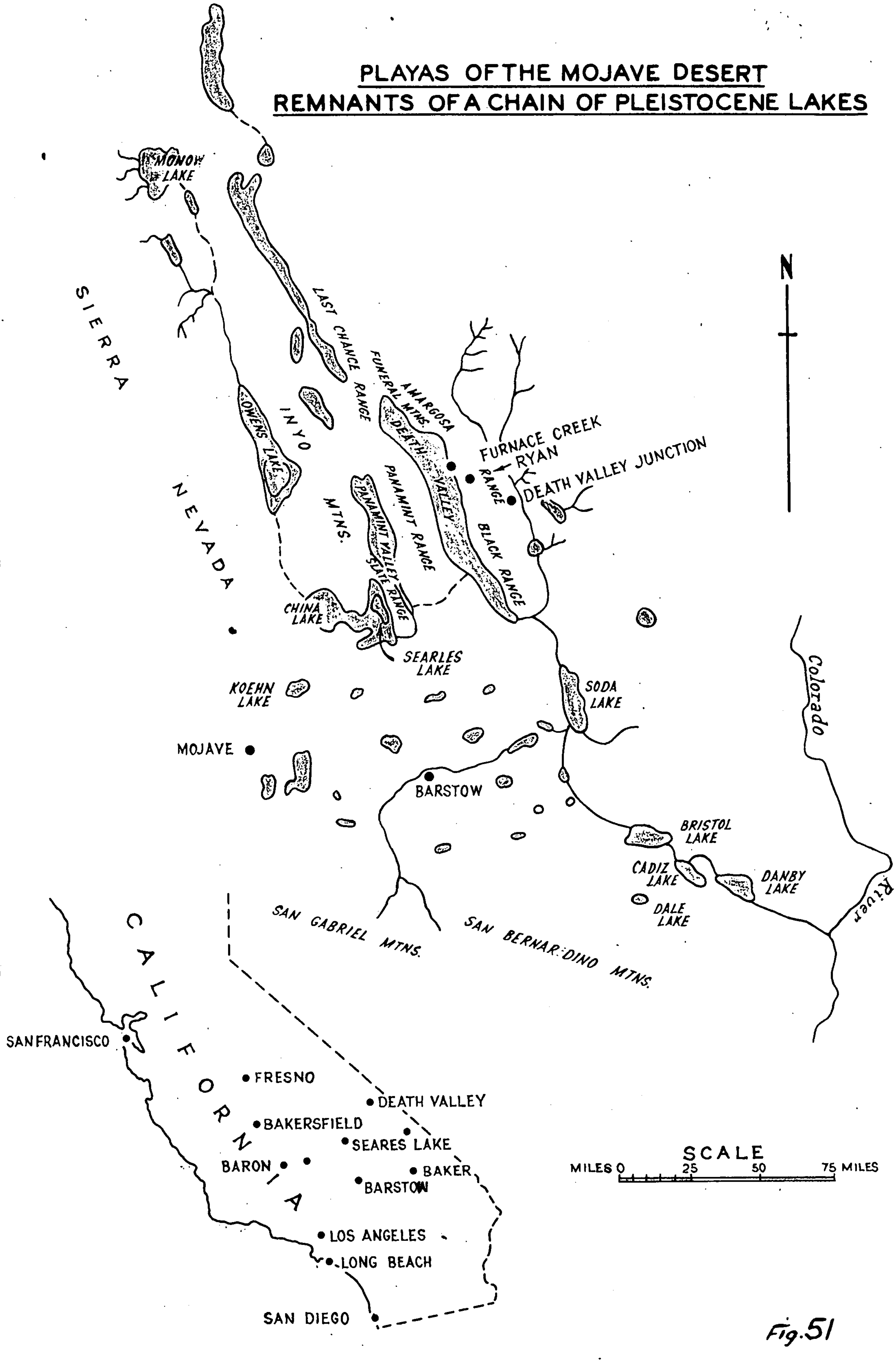

Fig. 51

S.A. DEPARTMENT OF MINES					
Approved	Passed	Drn.	PLAYAS OF THE MOJAVE DESERT	D.M.	Scale 45m. to 1m.
		Tcd. F.B.	REMNANTS OF A CHAIN	Req.	S 4115
		Ckd.	OF PLEISTOCENE LAKES		973
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BRINE OPERATIONS SEARLES LAKE

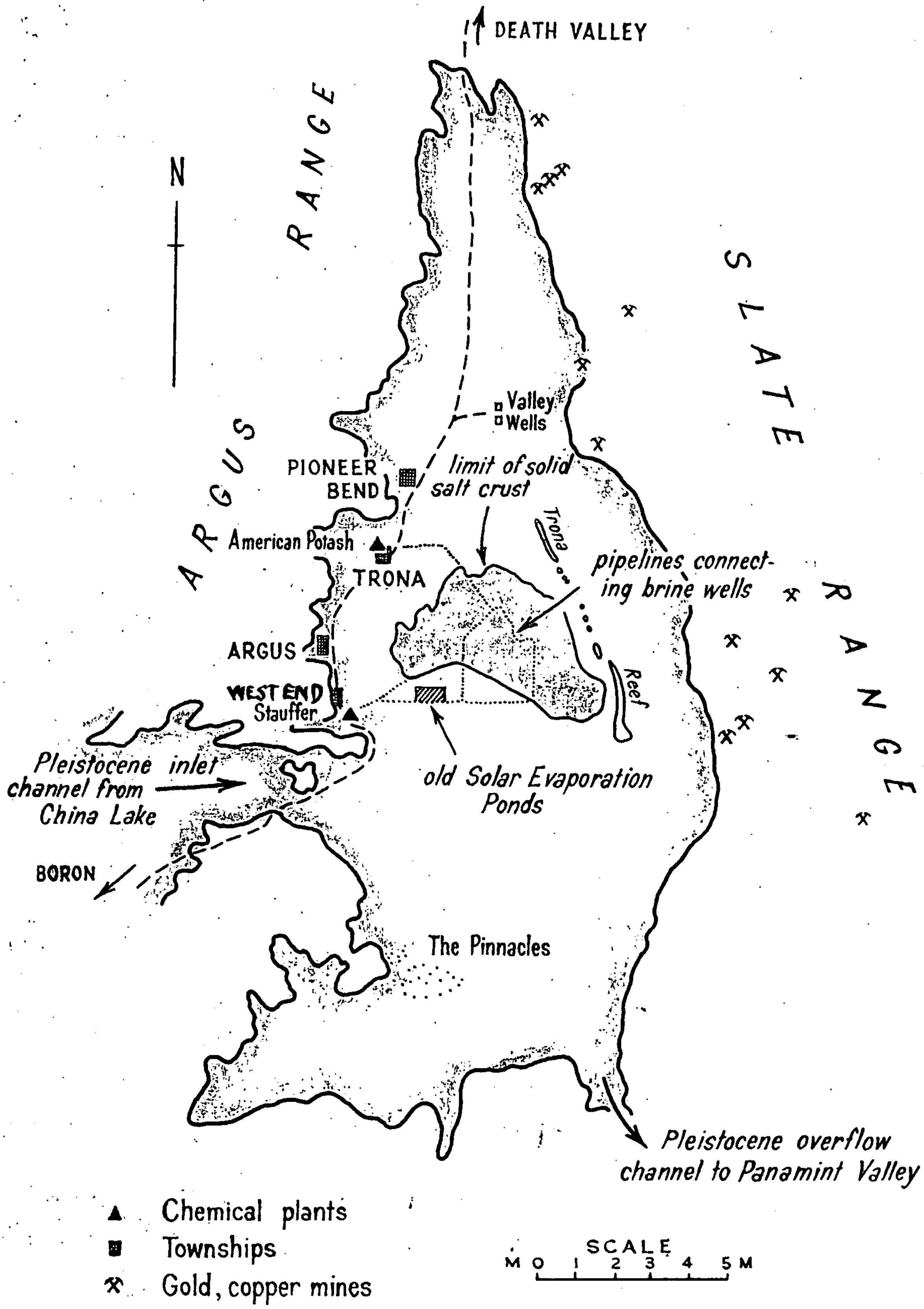

Fig. 52

S.A. DEPARTMENT OF MINES

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		Ckd.			973
Director		Exd.			Date

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near the centre of the Searles Basin (Fig. 52). It is normally dry but after heavy rains there may be one or two inches of water on the lake. The static water level is usually less than 1ft. below the surface.

Searle's Lake was, except for the surrounding mountains, reminiscent of Lake Eyre - it is generally flat and smooth, it has a central salt crust margined by mud, and it shows patches broken by polygonal cracks and upturned edges of salt (Fig. 54) similar to that seen at Kunoth Shoal on Lake Eyre North.

The lake is underlain by two superimposed crystal bodies of mixed salts that are permeated with concentrated brines (Fig. 56). The crystal bodies are extremely porous and have from 30% - 45% pore space. These result from the crystallization of salts from evaporated waters which were ponded in this basin. Searle's Lake is one of a System of mostly larger lakes of the Great Basin that occupied large areas of Southeastern California, Nevada and Utah.

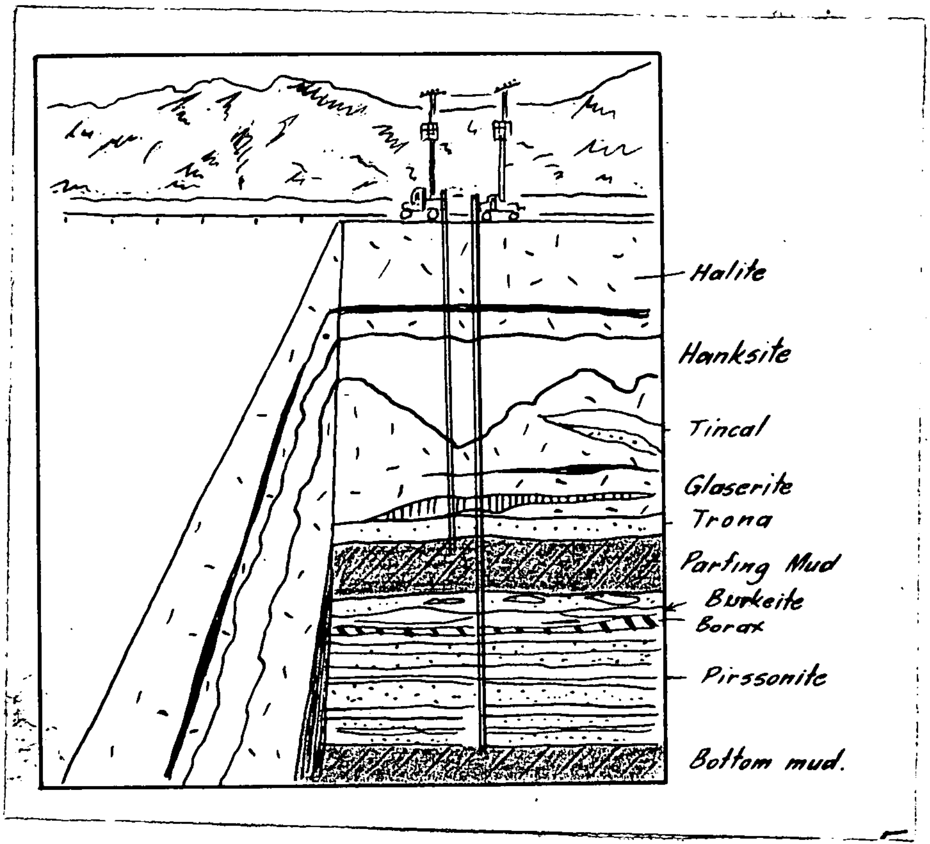

Fig. 56 Cutaway of Searle's Lake Salt Structure.

The playa surface has an elevation of 1,620 feet; it gives way abruptly to the mountains which surround it. A succession of strand-line terraces, wave cut benches, sand and gravel bars and tufa remnants are preserved at the basin margins - the highest ancient shore line terrace being 640 feet above the level of the present lake surface. The thickness of Quaternary lake sediments has not been determined but from geophysical (gravity) survey it has been estimated that these approach 2,000 feet. At its greatest expansion Searles Lake must have been almost 400 square miles in area before it overflowed into Panamint Valley.

Lake deposits, chiefly gravels and sands outcrop at the basin margins. At the southern end of the basin are a number of 100 to 150 feet high pinnacles of algal limestone which apparently grew by lime accretion as sedimentation proceeded. The shore lines and outcropping lake sediments have been but slightly modified by erosion since the waters disappeared from the basin.

The upper salt body underlying Searles Lake was discovered in 1862 and first exploited in 1873. It covers an area of 40 square miles and ranges in thickness from nil to 95ft. (and averages 70ft.); It contains 100 million tons of salts per square mile. About 12 square miles of the upper body are exposed in the centre of the normally dry lake while the remaining 28 square miles are covered by as much as 40ft. of mud.

The lower salt body which was discovered in 1946 is as much as 54ft. thick but averages about 35ft. It lies 10ft. to 15ft. below the upper body from which it is separated by impervious muds, and extends over about the same area.

The Trona Reef marks the trace of a fault along which groundwaters escape and on evaporation deposit a saline efflorescence; the "reef" rises several feet above the level of the playa.

Stratigraphy

The late Quaternary sediments beneath the lake surface consist of interbedded crystalline salts and mud layers that are very gently folded. Knowledge of the basin-fill from cores extends to only 875 feet and to date no Government or private drilling has penetrated beyond that depth. The major stratigraphic units are shown in Fig. 57.

The stratigraphic subdivisions of the Lower Salt are discrete beds of muds and salines that can be recognised throughout most of the deposit, except toward the edges where the saline beds pinch out. The several mud beds are similar in composition while the saline beds change in composition laterally.

The muds in this deposit are dark green to brown, soft and impervious; they are chiefly combinations of Ca, Na and Mg with CO_3, precipitated

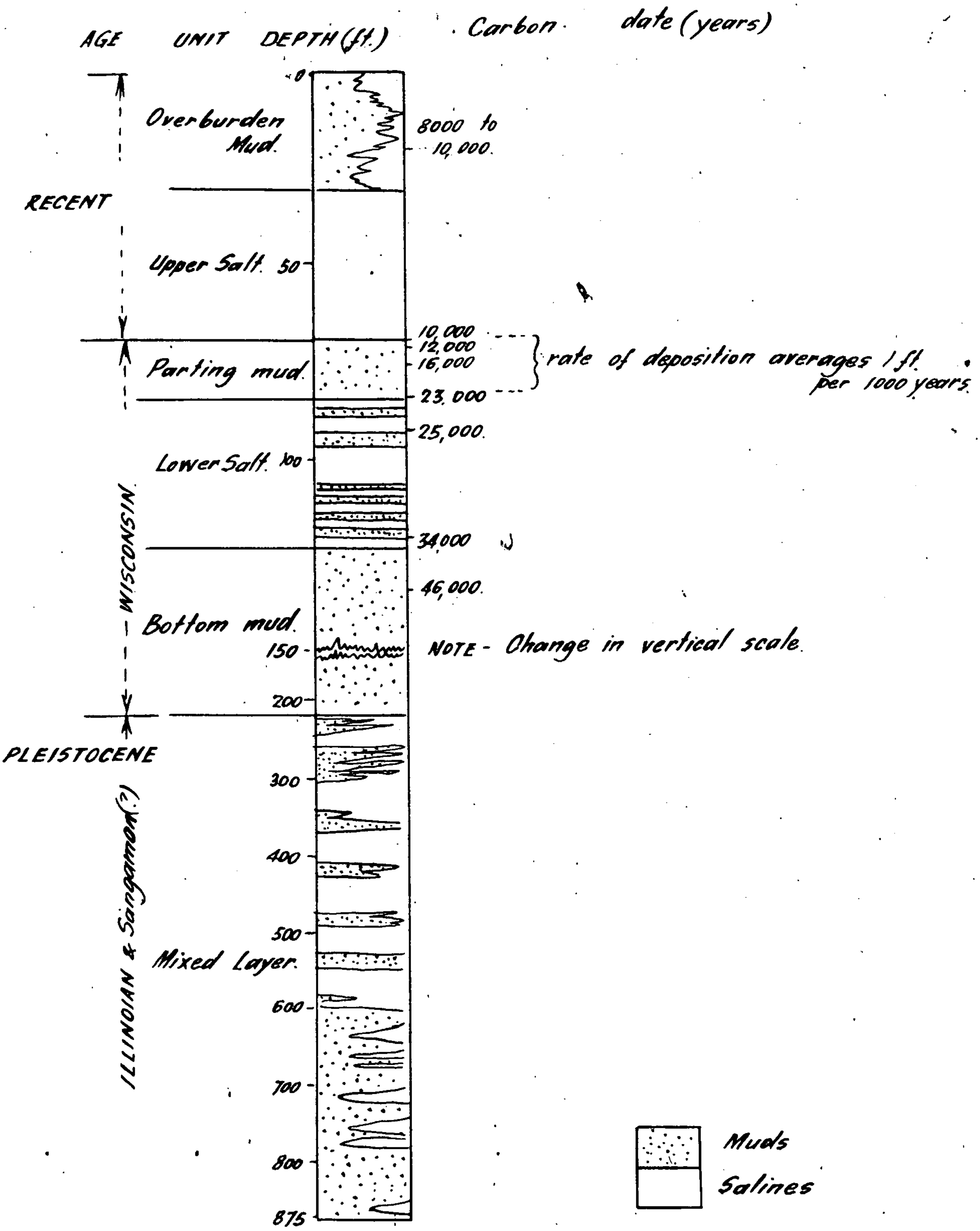

Fig. 57

S.A. DEPARTMENT OF MINES					
Approved	Passed	Drn.	DIAGRAMMATIC SECTION SEARLES LAKE EVAPORITES SHOWING STRATIGRAPHIC UNITS	D.M.	Scale
		Tcd.		Req.	S. 4118. 973
		Ckd.			
Director		Exd.			Date

300—6.60 0049

as fine grained aragonite and dolomite with Na -, Ca - carbonates. Halite or borax may occur in fine crystals while clastic silt and clay are generally subordinate. A species of fossil fish has been recovered from the lake muds.

The salines are mostly white to grey, hard, and porous. They consist chiefly of combinations of Na, K and Mg with CO_3, HCO_3, SO_4, Cl or B_4O_7, precipitated as coarse-grained halite (NaCl) and hanksite ($9\ Na_2SO_4 . {}_2Na_2CO_3 . KCl$), and both coarse - and fine-grained trona ($Na_2CO_3 . NaHCO_3 . {}_2H_2O$), nahcolite ($NaHCO_3$), burkeite (${}_2Na_2SO_4 . Na_2CO_3$), borax, mirabilite ($Na_2SO_4 . 10H_2O$), thenardite ($Na_2SO_4$), northrupite ($MgCO_3 . Na_2CO_3 . NaCl$) and aphthitalite (glaserite) ($K_3Na(SO_4)_2$). The average evaporite-mineral composition of each unit has beendetermined; altogether, some 30 minerals have been identified in this deposit.

Brines

Though the brines in the basins of this region generally contain, NaCl, $CaCl_2$, Na_2SO_4, Na_2CO_3 and borax they vary in type and in concentration from lake to lake. The dissolved salts are derived by leaching of the rocks exposed over the large area of the drainage system; the assemblage of saline minerals deposited on final desiccation being controlled by the types of rocks exposed, by the chemical nature of the drainage water, and by the elements supplied to the system from hot springs. Minerals rich in Na and K were pro derived from weathering of granitic rocks: CO_2 from the atmosphere was fixed as carbonates; metallic sulphides yielded sulphate minerals; boron, fluorine and lithium were introduced by volcanic hot spring waters.

At Searles Lake the salt bodies contain layers, lenses or irregular masses made up entirely of one of the evaporite minerals listed above. Pore spaces in the salt bodies amount to 30 to 45% of their volume and these are filled with saturated brines that are in chemical equilibrium with the soluble salts. The lower brine differs slightly from the upper brine mainly in that it contains less potash and more borax and Na_2CO_3.

The brines have a S.G. of 1.3 and have a salt content about 10 times that of seawater - the average composition is as follows:-

Constituent	Upper Brine (%)	Lower Brine (%)
KCl	5.08	2.94
Na_2CO_3	4.80	6.78
$Na_2B_4O_7$	1.63	1.96
Na_2SO_4	6.75	6.56
NaCl	16.06	15.51
Na_2S	0.08	0.38
Li_2O	0.015	0.006
KBr	0.120	0.080
WO_3	0.007	0.004
I_2	0.003	0.002
P_2O_5	0.070	0.044
F	0.002	0.002
Total dissolved salts	34.617	34.268

Exploitation

The total production of chemicals extracted to date exceeds 15 million tons valued at almost $1 billion. Daily production from current operations exceeds 3,000 tons of the various chemicals.

The Searles Lake deposits yield about 30% of the annual production of borates in California and they yield 7% of the U.S. potash production.

Reserves of B_2O_3 were estimated in 1926 to be over 17 million tons in the upper brine and salts. Since then the lower body has been discovered and the upper body has been found to be more extensive than believed at that time.

Three companies currently mine and market products from Searles Lake.

(a) Pacific Salt & Chemical Co.

Salt recovery by scraping the lake surface.

(b) West End plant of Stauffer Chemical Co. -

production of Na_2CO_3, Na_2SO_4 and borax from lake brines.

(c) American Potash & Chemical Corp.

This company operates a $40 million per annum project based on the Searles Lake brines at Trona. The plant, built in the 1920's, was designed to recover soda carb (soda ash), salt cake (Na_2SO_4), KCl, borax, lithium carbonate, bromine and phosphoric acid from both crystal bodies. Tungsten is not yet being produced commercially but is beingreturned to the lake with NaCl and 10% of the KCl content; this may yet become the largest single source of tungsten in the U.S. The upper brine contains only 0.007% WO_3 but this amounts to 170 million pounds of WO_3 in the lake.

The Company have drilled numerous production and observation wells, mostly about 150 feet in depth and at ¼ to ½ mile intervals, as part of an intensive, carefully planned brine recovery programme. Brine samples are taken at regular intervals from various depths to obtain information on the character of the brine, rate and direction of its flow and the influence of sustained pumping on its composition. Movement of the brine is detected by fluorescent - dye tests. The brine wells are drilled to the separating mud seam and cased to within 16ft. of the bottom. Brine is drawn horizontally from the bottom of the crystal structure. Bores are drilled at 9 inch diameter with calyx drills - full cores being taken throughout each hole. Electric logs are run to confirm brine salinites.

The company pump 10 million gallons of brine per day to the plant from 62 wells. The temperature of the brine at recovery is 76° and this temperature is maintained to the plant by enclosing the stainless steel pipelines in fibre glass and aluminium foil.

Sodium sulphate is recovered on the lake bed by spray-pumping brine into the air. The air temperature at Searles Lake ranges from 8° to 130°F and when the desired temperature for optimum recovery of the salt is attained pumps are cut in and out automatically and these spray the brine into the air; the salt cake crystallizes, separates, and falls in a heap for easy recovery.

In the Trona plant the upper and the lower brines are treated separately. The brines are put through a complex cycle process which involves fractional crystallization of the various salts by evaporation and cooling under rigid pressure - temperature control. Most of the NaCl is first removed from the brine and returned to the lake; soda ash, salt cake and Li_2CO_3 are then extracted, leaving a liquor rich in KCl and borax. The KCl separates when the liquor is chilled and this is removed by filtration.

The bulk of the production consists of agricultural grade KCl (90% recovery attained), anhydrous Na_2SO_4 and Na_2CO_3. The upper brine is second only to the Carlsbad district as a domestic source of potash, is the only source of lithium salts in the U.S. other than pegmatite minerals, and is the country's major source of sodium sulphate.

The main plant cycle has been reported by Leonardi (1954) and is shown schematically in Fig. 58. Details of the processing plant were not disclosed and the company personnel generally showed a reluctance to discuss the operations. Photography was limited to only certain areas on the lake.

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SEARLES LAKE - AMERICAN POTASH & CHEMICAL CORPN

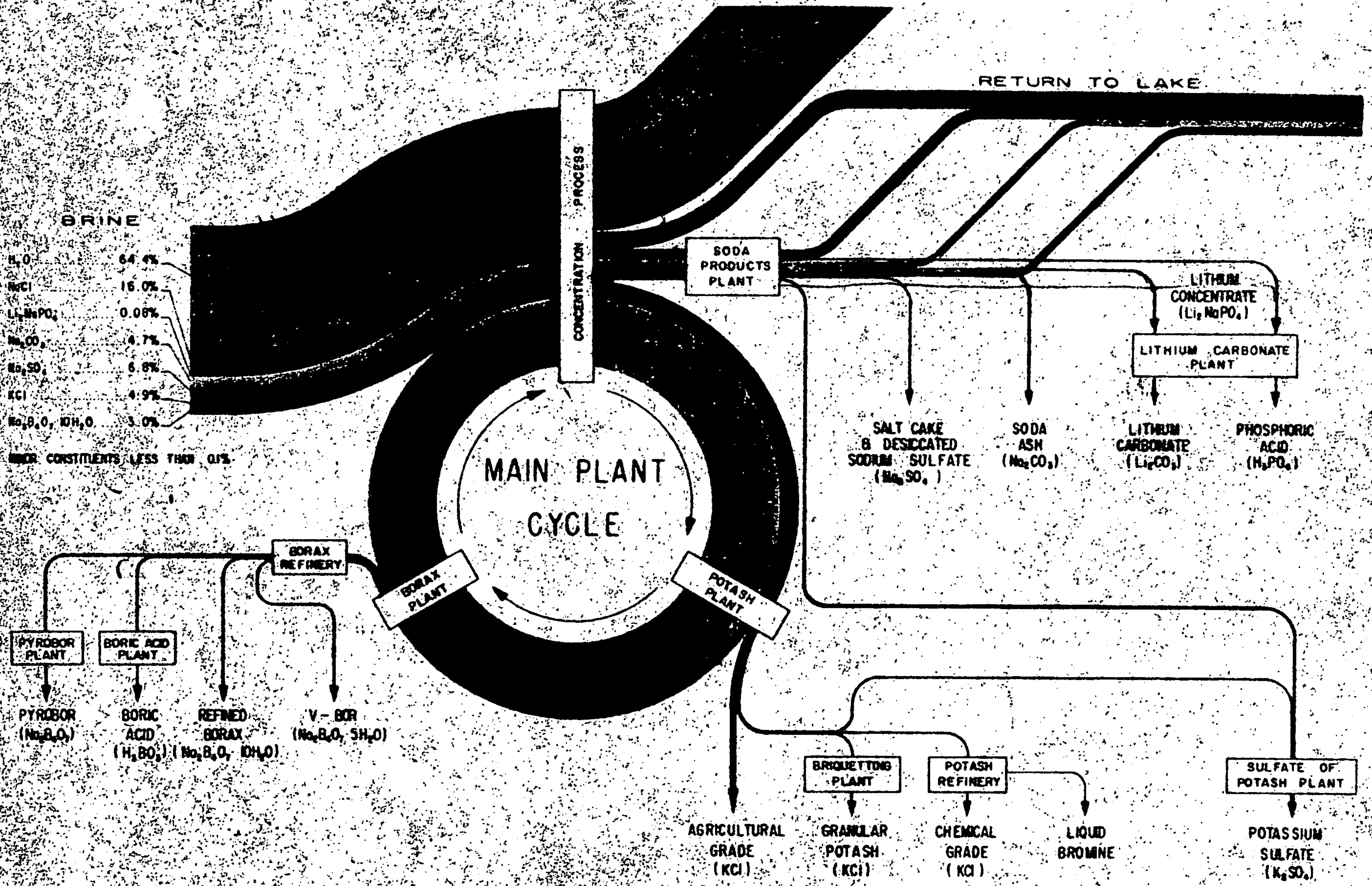

Fig. 58

S. 4119/3
973

2. Lake Bonneville, Great Salt Lake, Utah.

Bonneville Ltd. Potash.

24th April, 1964 to 25th April, 1964.

Lowell, S. Hilpert, Geologist-in-Charge, Geologic Div., U.S.G.S. Salt Lake City, Utah.

Rands Wiley, plant foreman, Bonneville Ltd. Potash, Wendover (Nevada).

The Great Basin of northwestern Utah lies within the Basin and Range province characterized by isolated narrow mountain ranges separated by desert basins and marked by interior drainage. The fossil shorelines of the Pleistocene glacial-fed Lake Bonneville of which Great Salt Lake is a shrunken remnant are marked by beach deposits with bars, spits and wave cut terraces onthe flanks of the mountain ranges and on the islands which stood above the surface of the ancient lake (Figs. 59, 60, 61). The lake at its maximum was some 325 miles long, 125 miles wide and had surface area of about 20,000 square miles. Its maximum depth was a little more than 1,100 feet nea the western edge of the present Great Salt Lake. To the south the lake extended through passes between the ranges where its average depth was about 500ft. The lake overflowed to the north through Red Rock Pass and discharged into the Snake River by way of the Portneuf River.

Domical upwarping as an isostatic readjustment of the area formerly occupied by the lake has been established and westward tilting resulted in the closure of the Bonneville Salt Flats near Wendover, adjacent to the Nevada state border.

Great Salt Lake

When the pioneers settled this region the elevation of the surface of Great Salt Lake was 4,200 feet above sea level. It rose almost 12 feet in the years 1862 - 1868 and it then fell with oscillations to its present 4,191 feet above sea level. Construction of reservoirs on rivers which discharge into the basinhas resulted in the fall in lake level and it is still receding. A resort at Saltair, formerly built at the lake edge is now a ruined group of jetties and kiosks on stilts several miles from water! The lake now covers an area of 950 sq. miles and is shallow, being less than 30 feet at the deepest part.

31137

Fig. 60 Great Salt Lake near Saltair, Utah. Wave cut terrace marking limit of Lake Bonneville discernible at extreme left and on Antelope Island.

31138

Fig. 61 Northern shore of Great Salt Lake. Strand lines of former Lake Bonneville.

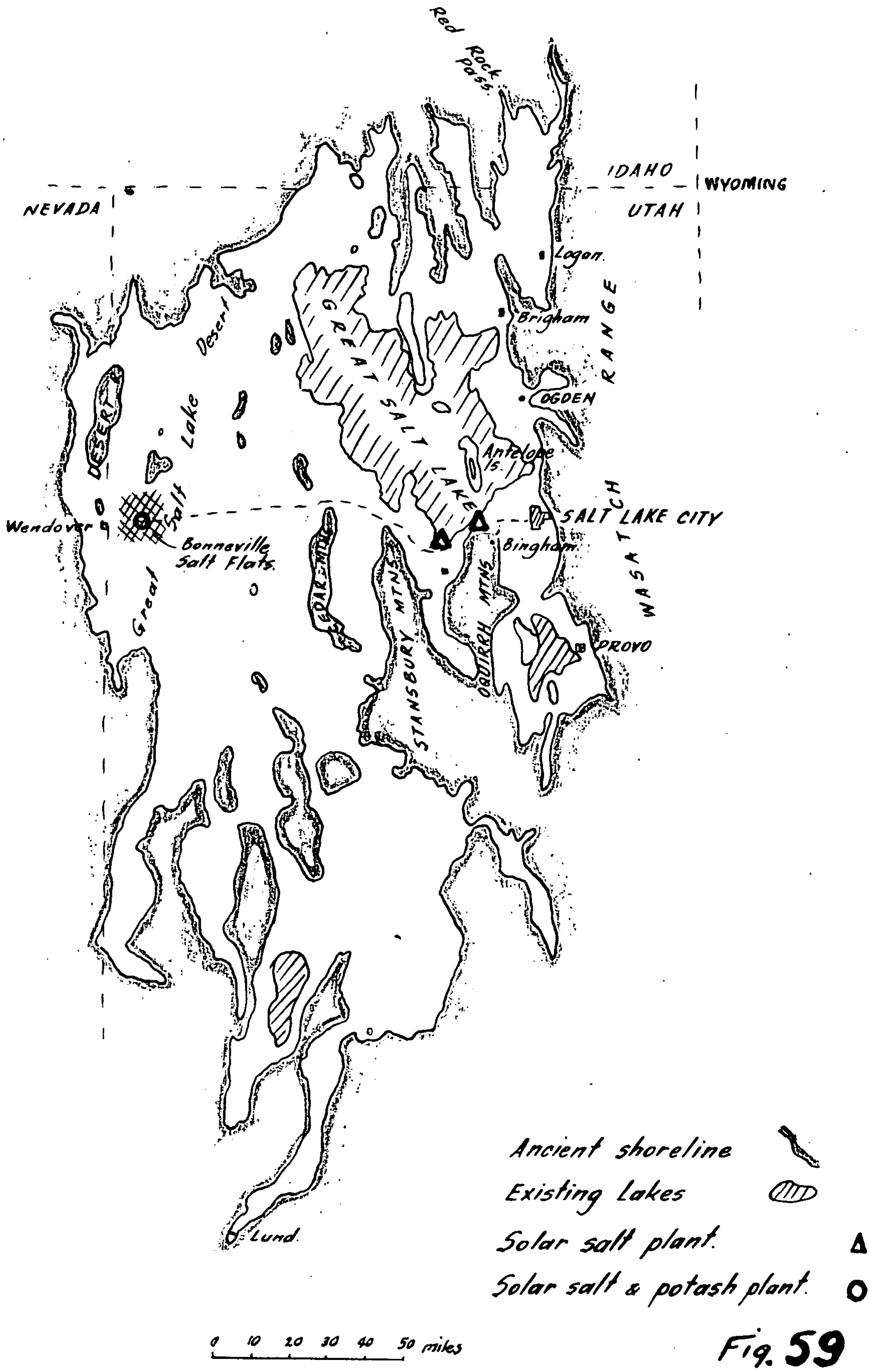

Fig. 59

S.A. DEPARTMENT OF MINES

Approved	Passed	Drn.	LAKE BONNEVILLE	D.M.	Scale
		Tcd.	Limits of Pleistocene lake, Utah.	Req.	S 4120 973
		Ckd.			
Director		Exd.			Date

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Early developments of the U.S. saline mineral industry were concentrated round Great Salt Lake. Sodium chloride was extracted from the lake brine by artificial and solar evaporation in pans constructed on saline mud flats which surround the lake.

The brine of Great Salt Lake contains about 26.6% by weight of dissolved solids comprising as under:-

	Concentration (p.p.m.)
Ca	319
Mg	8,050
Na	85,700
K	4,550
Li	40
HCO_3	327
SO_4	17,400
Cl	147,000
F	6.0
I	0.4
B	30
Total	263,000 ppm (S.G. 1.208)

This is the largest existing body of concentrated brine in the U.S. The composition of the brine is generally similar to seawater (except that salinity is much higher) - Na and Mg ratios are similar, Li is about six times as abundant while K and B are deficient. The deficiency of K and B are attributed to the scarcity of igneous rocks underlying the drainage basin.

There are no crystalline bodies of salt under the mud flats of the lake though the brine is saturated with respect to Na_2SO_4 and this precipitates during the summer. Thus there is a body of Na_2SO_4 (mirabilite) as a comparatively recent deposit in the bed of Great Salt Lake.

The production of potash in Utah began in 1916 with the extraction by several solar salt plants utilizing brines of Great Salt Lake. At the present time only common salt is being produced at the rate of about 200,000 tons per year by Morton Salt Co. though plans have been announced for the extraction of Li, Na_2SO_4 and Mg.

Bonneville Salt Flats (Tooele County)

In 1917 potash production began at Salduro Station utilizing brines from theSalduro Marsh (now known as theBonneville Salt Flats) in an area of 4.68 average annual rainfall. By 1920 this was the largest producer of potash inthe U.S. but in 1921 the plant was shut down and brine operations were idle until 1938, Bonneville Ltd. Potash then resumed operations at a new plant and output has continued since without interruption.

Lake Bonneville, 120 miles west of Salt Lake City, is perhaps most widely known as the site for numerous attempts on the world's land speed record (Fig. 62). Surface crusts and layers of saline minerals resulting from the desiccation of ancient Lake Bonneville are numerous in western Utah but the most extensive cover an area of about 150 sq. miles around Salduro Station - the Salt Flats proper are 10 miles wide east-west and 15 miles long north-south. The deposit reaches a maximum thickness of about five feet and is a white, porous, coarsely crystalline mesh of halite crystals. A chemical analysis of the soluble portion of the bed is as follows:-

	%
K	0.07
Na	36.85
Ca	1.20
Mg	0.10
SO_4	2.88
Cl	58.98
CO_3	nil

Brines occur in the salt beds and in underlying lake sediments. The chemical composition of the brines in the salt beds is relatively uniform while those of the clay-beds are variable - as under.

	brine of salt beds (p.p.m.)	brine of clay beds (composite of 126 separate samples) (p.p.m.)
Cl	192,000	96,150
K	10,600	2,940
Na	100,000	57,300
Mg	6,300	1,910
SO_4	5,200	4

Brines from which potash is being recovered are drawn from the lake surface from open trenches 20ft. deep and these are augmented as required by 12 flowing bores 300ft. deep and six bores 1,200ft. deep. The brines are channelled into evaporating ponds which extend over a semicircular area of some 20 sq. miles. When salt has accumulated to a thickness of about 4ft. in one system this is abandoned and a further system is developed.

Only five square miles are utilized for concentrating pans at any one time and the company are now using the fourth system. The feed water, containing 22% NaCl and 1% KCl is evaporated until a concentration of 5% KCl is achieved. The brines are then pumped to harvesting ponds (Fig. 63) which cover an area of 400 acres. In a season 4" to 6" of salts containing 30% KCl are precipitated; the bitterns containing Mg salts are returned to the main lake although some are being stored for possible lithia recovery. The effluent contains a high concentration of $MgCl_2$ that has been discarded but plans for recovery of 33,000 tons of $MgCl_2$ per year have been announced. The precipitated salts are scraped into rows with graders and picked up by scrapers fitted with elevators (Fig. 64); the salts are harvested on a floor of precipitated salt as the muds below these ponds are extremely soft.

The fine grained sylvinite is carried to a nearby plant, crushed in rolls (+ 14, - 25 mesh), and the KCl separated by flotation using amines and fatty acids as agents; no depressant is added. The separated halite is returned to the lake.

The process achieves 86% recovery of the potash which is marketed as + 95% KCl. The annual production now amounts to 100,000 tons KCl. In 1961 production was valued at $2 million and amounted to 2% of U.S. output. To this time Utah had accounted for the production of 1.3 million tons of crude potash salts, containing 770,000 tons K_2O equivalent and valued at $26 million.

The crystal salt body has been excavated over an area of 12 miles by 9 miles located to the east and adjacent to the salt flats, but there is no current production.

31139

Fig. 62 Bonneville Salt Flats, Lake Bonneville, Utah.

31140

Fig. 63 Potash crystallizer. Plant of Bonneville Potash Ltd. in background.

31141

Fig. 64 Harvesting potash, Lake Bonneville.

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3. Midland, Michigan (Dow Chemical Co.)

1st June, 1964 to 2nd June, 1964.

Max Key - General Manager, Midland Division, Midland.
R.E.(Trent)Peterson - Dow International.
Doug. Lake - Chemicals Department Corporation.
Louie Carmouche - Midland Division Management.
Charles Querio - Suptd. of Wells, Midland Division.
Ralph Hultin - Section Manager, wells, Midland Division.
George Meier - Bromine section manager, " "

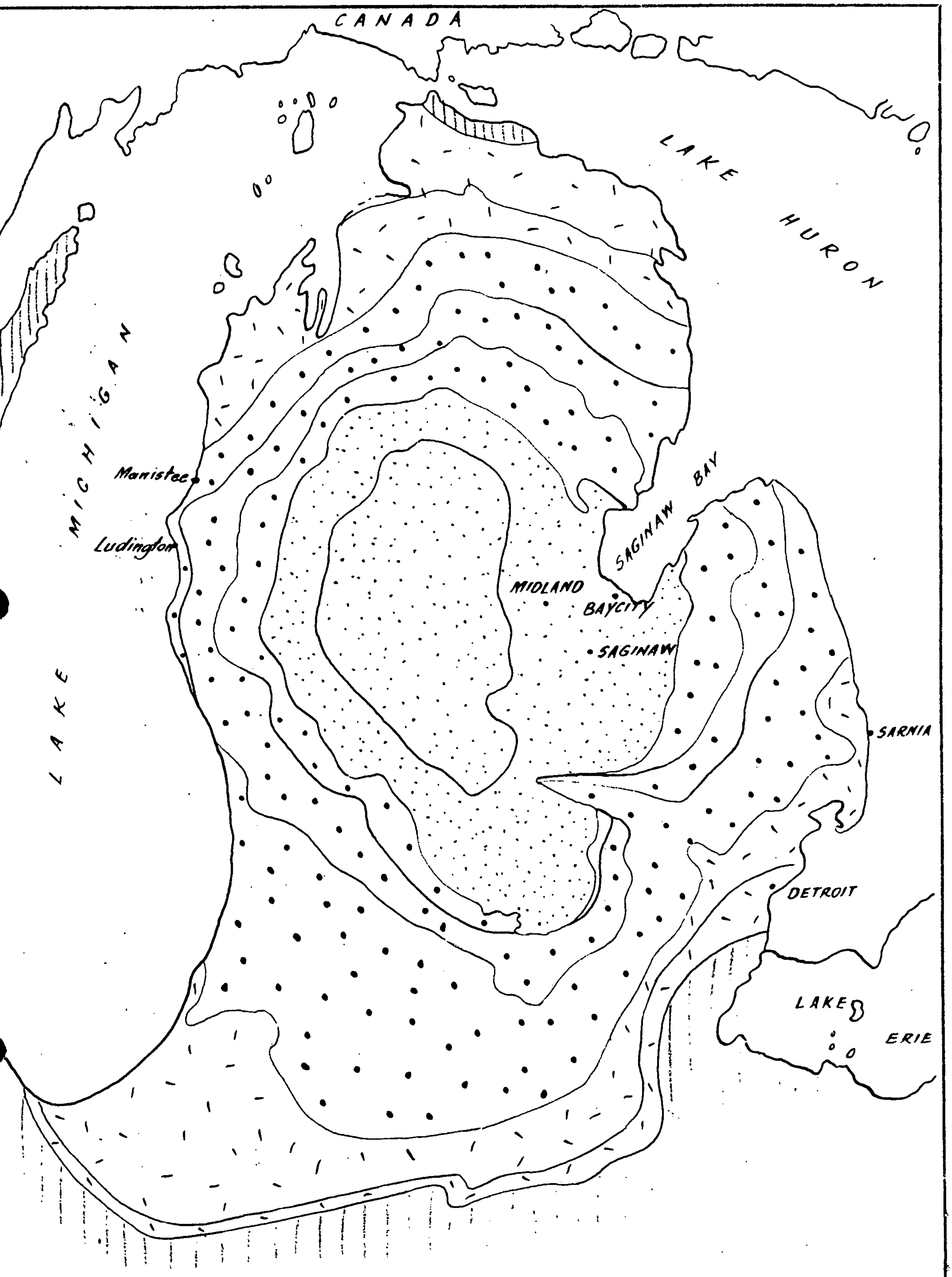
The Dow Chemical Co. works covering an area of some 1,000 acres at Midland is an extensive integrated chemical complex based on unique natural brines which are recovered from a depth of some 5,000 feet. Dow is reputed to be the largest producer in the U.S. of $CaCl_2$, $Mg(OH)_2$, epsom salts bromine and iodine; NaCl and KCl are also produced. The company also manufactures a diversified line of organic and inorganic chemicals, plastics, bioproducts and metals.

A typical analysis of the Midland brine follows:-

	%
$CaCl_2$	19.03
$MgCl_2$	3.65
NaCl	5.20
KCl	1.68
Br_2	0.26
I_2	38 ppm.

Regional Geology

Peninsular Michigan is underlain by Archaean igneous rocks and metasediments and, above these, a more or less continuous sedimentary succession to the Permo-Carboniferous. The sediments comprise Cambrian sandstones and younger rocks (largely carbonates) which occupy a gentle closed basin structure (see Figs. 65, 66). Of great economic importance is the rock salt



⁘	PENNSYLVANIAN (400'-700')	Grand River sandstone, Saginaw formation (coal measures) Parma sandstone (sulphate water & brine.
●	MISSISSIPPIAN (1800'-2500')	Grand Rapids Series - Bayport limestone (sulphate water), Michigan formation (limestones) red shales, gypsum. Marshall Series, Marshall Sandstone (brominiferous brine, CaCl$_2$ brine) Lower Marshall sandstone, Coldwater shale, Berea S/S (brine)
⁄	DEVONIAN (1100'-2000')	Traverse formation (limestone shales) Dundee L/S (brine)
⦀	SILURIAN	Monroe series (dolomite, anhydrite) Sylvania sandstones (brines) (dolomite, rock salt, anhydrite, shale. Guelph Series (dolomites) Rochester shale.

Fig 65

S.A. DEPARTMENT OF MINES

Approved	Passed	Drn.	GEOLOGY OF PENINSULAR MICHIGAN	D.M.	Scale
		Tcd.		Req.	S 4121
		Ckd.			973
Director		Exd.			Date

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of the Salina formation (upper Silurian) which underlies peninsular Michigan and extends into Ohio, New York, Pennsylvania and Canada (Ontario). An aggregate salt thickness of at least 1,800 feet has been penetrated in oil test well in central Michigan where the top of the Salina is some 8,000 feet below the surface. This is mined in the Detroit (and in other) areas and is also recovered in artificial brine operations.

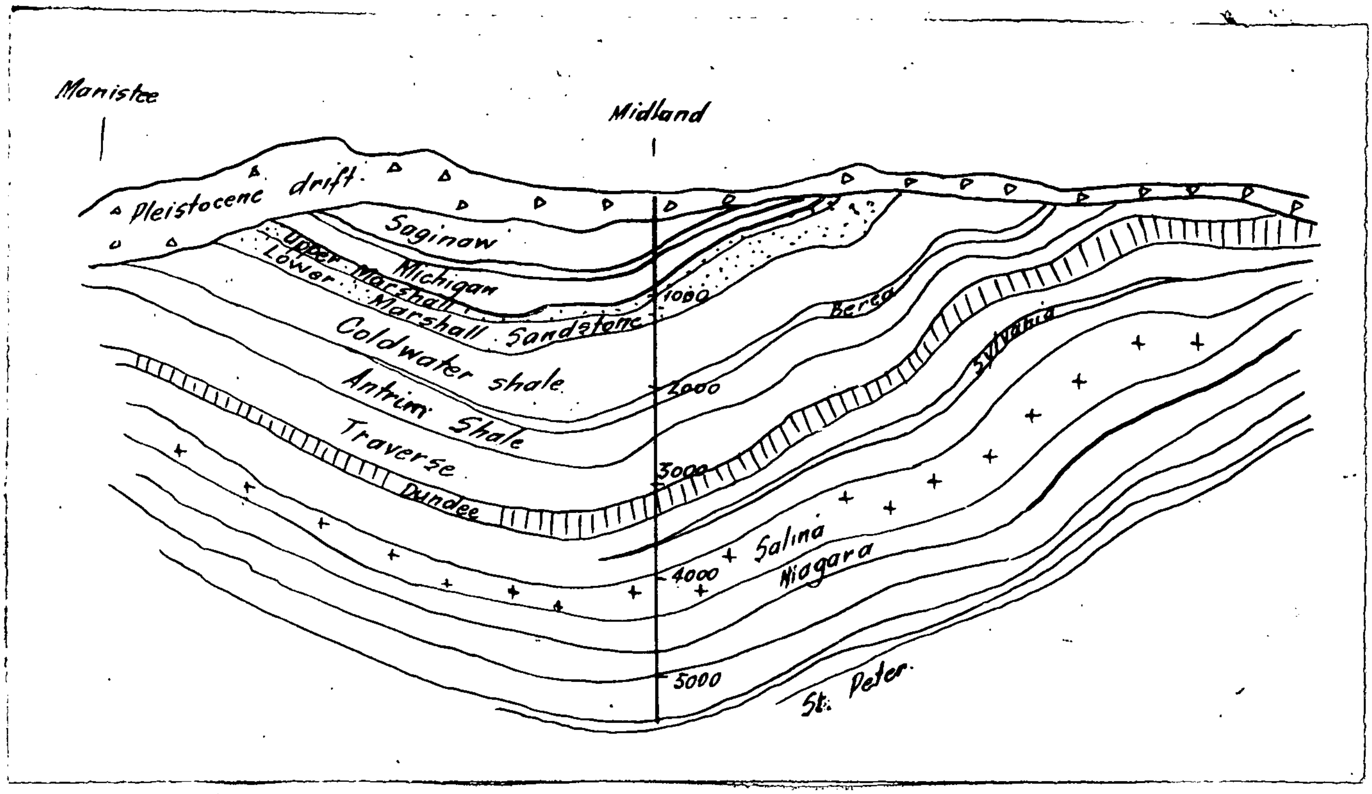

Fig. 66 Section across the Midland Basin.

Natural supersaline brines support sizable chemical industries in central and western Michigan and in adjacent Ontario.

At Midland brines are obtained from three zones:-

a. the Mississippian Marshal sandstone.

b. the Middle Devonian Dundee limestone.

and c. the Lower Devonian Sylvania sandstone.

There is a second natural brine district which borders Lake Michigan on the western edge of the state with plants at Ludington and Manistee producing NaCl, $MgCl_2$ and Br from sandstones 60 - 100 feet thick at a depth of 2,500 feet.

A generalized columnar section of Michigan geology is tabled below:-

System, series	Formation, group	Lithology	Thickness (ft.)	Economic Products
Pleistocene	glacial drift	sand, clay, gravel marl.	0:251	Freshwater
Permo-Carboniferous	"Red beds"	Shale, sandy shale, gypsum		
Pennsylvanian	Grand River	sandstone	90	Freshwater
	Saginaw	shale, sandstone coal measures	20-500	Brine, coal, gas
Mississippian	Bay Port	Limestone, (sandy)	0-100	Freshwater
	Michigan	shale, gypsum, anhydrite	0-500	gypsum
	"Michigan stray"	sandstone	0-80	gas
	Marshall	sandstone (fine grained)	100-400	Original source of brine
	Coldwater	blue shale, sandstone, limestone	500-1100	Freshwater
	Sunbury	shale	0-140	
	Berea-Bedford	shale, limestone, grit	0-325	oil, gas
	Ellsworth-Antrim	shale, limestone	100-1000	gas
Devonian	Traverse	limestone, shale	100-800	oil, gas freshwater
	Bell	shale	0-80	
	Dundee	limestone, cherty, porous	0-475	Brine, oil, gas, freshwater
	Detroit River	dolomite, salt, anhydrite	150-1400	oil, gas, salt, brine, freshwater
	Sylvania	sandstone, sandy dolomite	0-550	Brine
	Bois Blanc	dolomite	0-1000	
Silurian	Bass Island	dolomite	50-550	freshwater
	Salina	salt, dolomite, shale, anhydrite	50-4000	salt, oil, gas
	Niagaran (Guelph, Lockport, Cataract)	dolomite, limestone shale	150-800	oil, gas, freshwater

System, series	Formation, group	lithology	Thickness (ft.)	Economic Products
Ordovician	Cincinnatian	shale, limestone	250-800	
	Trenton-Black River	limestone, dolomite	200-1000	oil, gas
	St.Peter	sandstone	0-150	
Ozarkian (Canadian)	Prairie du Chien. Hermansville	dolomite	0-900	
Cambrian	Lake Superior	sandstone	500-2000	freshwater
Algonkian	Keweenaw	lavas, conglomerate, shale, sandstone	9800-35000	Copper formations
	Killarney granite	granite		
	Huronian	slates, haematite	2000 +	iron formations. graphite.
Archaean	Laurentian	schist, gneiss, granite		
	Keewatin	schist, greenstone		

Two modes of origin of the natural brines are considered possible:

(a) they are meteoric or surface waters that have acquired concentrations of salts in their migration into and through the underground strata e.g. from the Salina formation.

(b) they are connate water, i.e. fossil seawater trapped during deposition of the enclosing sediments and more or less modified by migration, temperature and pressure changes and mixing with meteoric waters.

The latter concept is reputed to be more widely accepted despite the proximity of the Salina evaporites which would appear to be the logical source.

Brine Operations

Dow recover brines from some 100 bores ($8\frac{5}{8}$" O.D.) drilled at intervals of $\frac{1}{4}$ to one mile and delivering 10 million gallons per day to the plant. The bores have an average depth of 5,000 feet and each has an output of 50 to 100 gallons/minute. Initially, operations of Herbert Dow were based

SCHEMATIC OF DOW'S BRINE PROCESSING

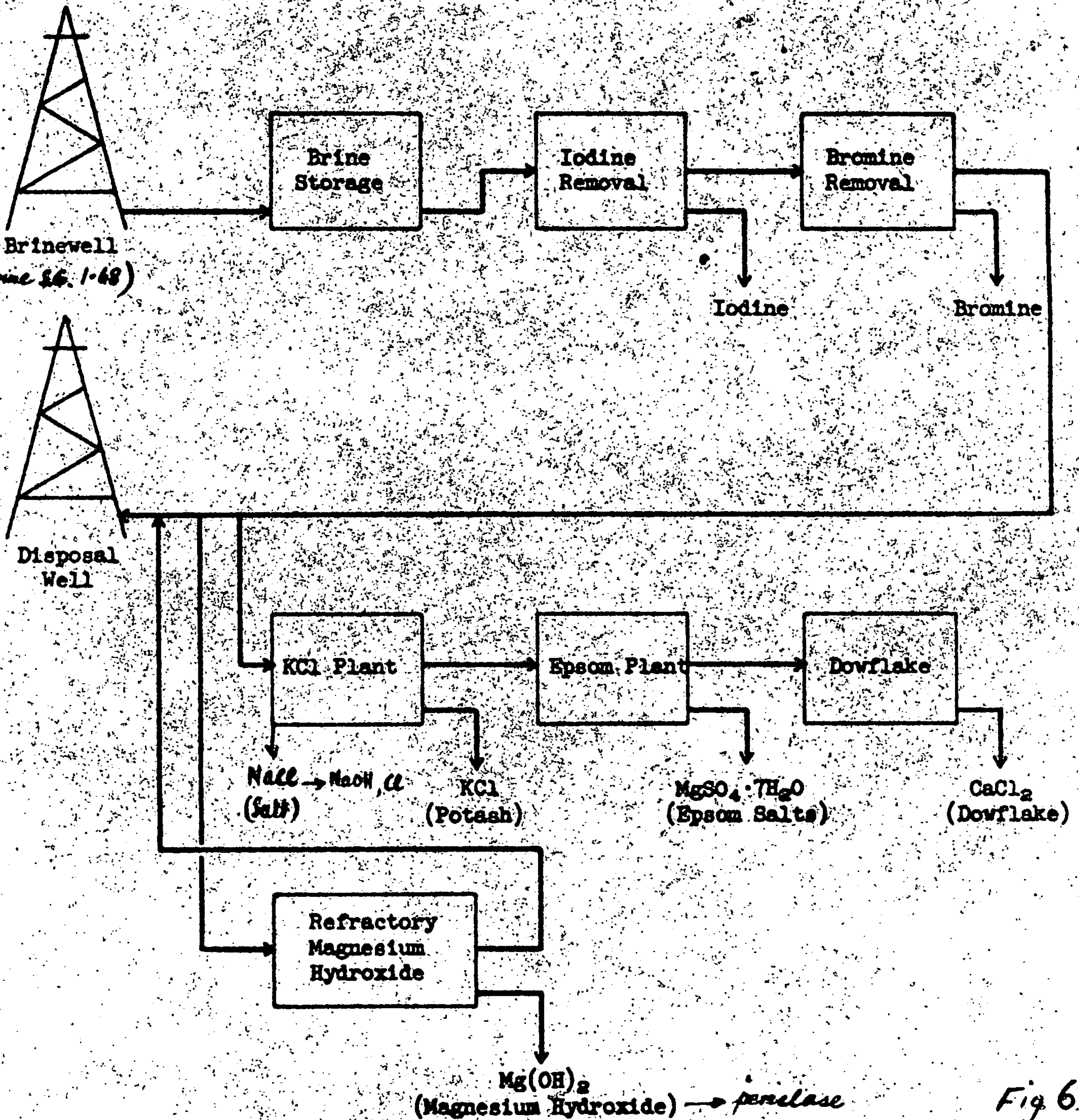

Fig 6.7

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on recovery of bromine from the brines of the Marshall sandstone which had been discovered in oil and gas well drilling. Now there are three horizons utilized - the Marshall sandstone, Dundee limestone and Sylvania sandstone. A number of bores have been drilled to intersect the underlying Salina formation; freshwater is pumped down and NaCl brine is withdrawn for chlorine production.

The company have closely studied the porosity and permeability of the various aquifers and can now predict very accurately the output of production wells. A model of the wells layout was demonstrated on a sheet of agar $\frac{1}{8}$ inch thick impregnated with a copper electrolyte. To simulate brine flow an electric current was passed in at points scaled to represent well locations. A colour change consequent on current movement demonstrated interference and cones of influence between "wells"; at various stages the system was "frozen" and photographed as a permanent record of the developments.

In drilling operations both cable tools and rotary drills (mud and/or air system) are utilized. Depending on the ground conditions and on fresh waters encountered the holes may be left open, cased and perforated or be lined with tubing and packers. In development of an aquifer the company employ mechanical scraping, acidizing, explosion and implosion.

A schematic representation of Dow's brine process is shown in Fig. 67. Iodine is first recovered from the Monroe Brine (inconcentration of 38 ppm) by displacement by chlorine after acidification with HCl. The iodine tower effluent is sent for bromine recovery and then are removed in order NaCl, KCl, epsom salts, "Dowflake" ($CaCl_2$) and $Mg(OH)_2$ by fractional crystallization.

4. Israel, Dead Sea Brines

9th July, 1964

Dr. Yaacov K. Bentor, Director, Geological Survey of Israel, Jerusalem

Jakob Nir, Geologist, " " " "

Dr. David Neev, Geologist, " " " "

M. Shvueli, Liaison Officer, Dead Sea Works, Sdom.

The Dead Sea, the surface of which lies almost 1,300 feet below Mediterranean Sea level, is confined to the most depressed part of the Jordan - Arava Graben which is part of the African Rift System. The Sea lies in an extremely arid area and has an extremely high salinity, the chemical composition of the brines being unique. From these, potash and bromine are recovered at the Dead Sea Works located at Sdom. (Fig. 69).

The Dead Sea covers at the present time an area of 2,560 sq. m.: it is 127 miles long and has a maximum width of 28 miles. It is composed of two parts, very different in character and almost separated by the Lisan Peninsula. The southern part covers an area of 625 sq. m. and is very shallow, rarely exceeding 30 feet in depth while the northern part covers an area of 1,935 sq. m. and has a maximum depth of 1,303 feet. The total volume of brine held is 575 cubic miles, nine times that of Great Salt Lake, Utah.

The drainage basin of 102,400 square miles is underlain by Precambrian granites and acid volcanics, Mesozoic (Nubian) sandstone, Mesozoic to Eocene limestones and dolomites, lacustrine and continental shales and sandstones of Tertiary age, Tertiary to Pleistocene basalts and the clayey, silty, calcareous and gypsiferous sediments of the Pleistocene Lisan Lake which formerly filled the Jordan graben southward from the Sea of Galilee (see Fig. 68).

The Dead Sea is not a relict body of seawater - its salt assemblage results from accumulation in a closed inland basin under arid conditions. The salts are considered to originate from the River Jordan and from highly saline springs which discharge into the Dead Sea. The Jordan - Arava graben came into existence during the early Tertiary (Oligocene). The sea gained access to the region for a time and the bromine content of the present Dead Sea probably owes its origin to concentration in fossil residual brines.

In late Pliocene or early Pleistocene times the depression was occupied by a great freshwater lake which was later reduced to the brackish Lisan Lake. The Lisan sediments comprise seasonally varved clays, limestone, gypsum, silts and occasional coarse clastics 600 - 5,000 feet in thickness. The present Dead Sea became established in late Pleistocene times with a renewal of fault movements which uplifted the block of Mt. Sdom with its cover of Lisan sediments and young fluviatile scree. At least 17 regressive shore terraces were developed on both the steep eastern and western shores - the highest being some 660ft. above the present level of the Dead Sea. Mt.Sdom is a diapiric salt anticline (Lot's wife) in which Pleistocene salt beds intrusive into Quaternary sediments are vertical and even overturned (Figs. 70, 71). They have a caprock of anhydrite and gypsum.

Calcium carbonate is precipitating at the present time in the Dead Sea though the waters are not saturated with respect to NaCl. However, salt (over 3,000ft. thick beds) has been precipitated at the southern end of the basin under what are now saline marshes adjoining the Dead Sea in sub Recent time consequent on a temporary lowering of water level which effectively separated this sector from the deep northern part of the basin. In historical times the Dead Sea has been confined to the region north of Lisan Peninsula while on the southeastern shores drowned tamarisk trees (Fig. 71) point to a comparatively recent rise in water level.

31142

Fig. 69 Dead Sea Works, Sdom. Separation plant.

31143

Fig. 70 Dead Sea rift valley, looking across Arava Valley to hills of Moab. Lisan sediments in graben; Cretaceous limestones in immediate foreground.

31144

Fig. 71 Dead Sea, Mt. Sdom inleft background. Tamarisk trees have been drowned by a comparatively recent rise inlake level.

Dead Sea Brines

The average salinity of Dead Sea water (31.5%) is exceptionally high, the concentration of sulphates is very low, while the concentration of bromine (5,920 mg/litre) is probably the highest recorded for any surface water. There are changes of salt content with depth in the deep northern lobe - these are fossil lake brines which do not mix with the less concentrated waters above.

The chemical composition of the water is tabled below (mg/litre)

	Average Dead Sea		Great Salt Lake, Utah (mg/litre)	Average ocean (mg/litre)
	Mg/litre	% total solids		
Na	34,940	11.1	64,498	10,561
K	7,560	2.4	3,378	380
Ca	15,800	5.0	326	400
Mg	41,960	13.3	5,616	1,272
Cl	208,020	66.1	112,896	18,980
Br	5,920	1.88		65
SO_4	540	0.17	13,593	2,649
HCO_3	240	0.05	183	140
Rb		0.02		
Total	315,040		203,490	34,446

The total salt content of the Dead Sea (millions tons) is as

over:-

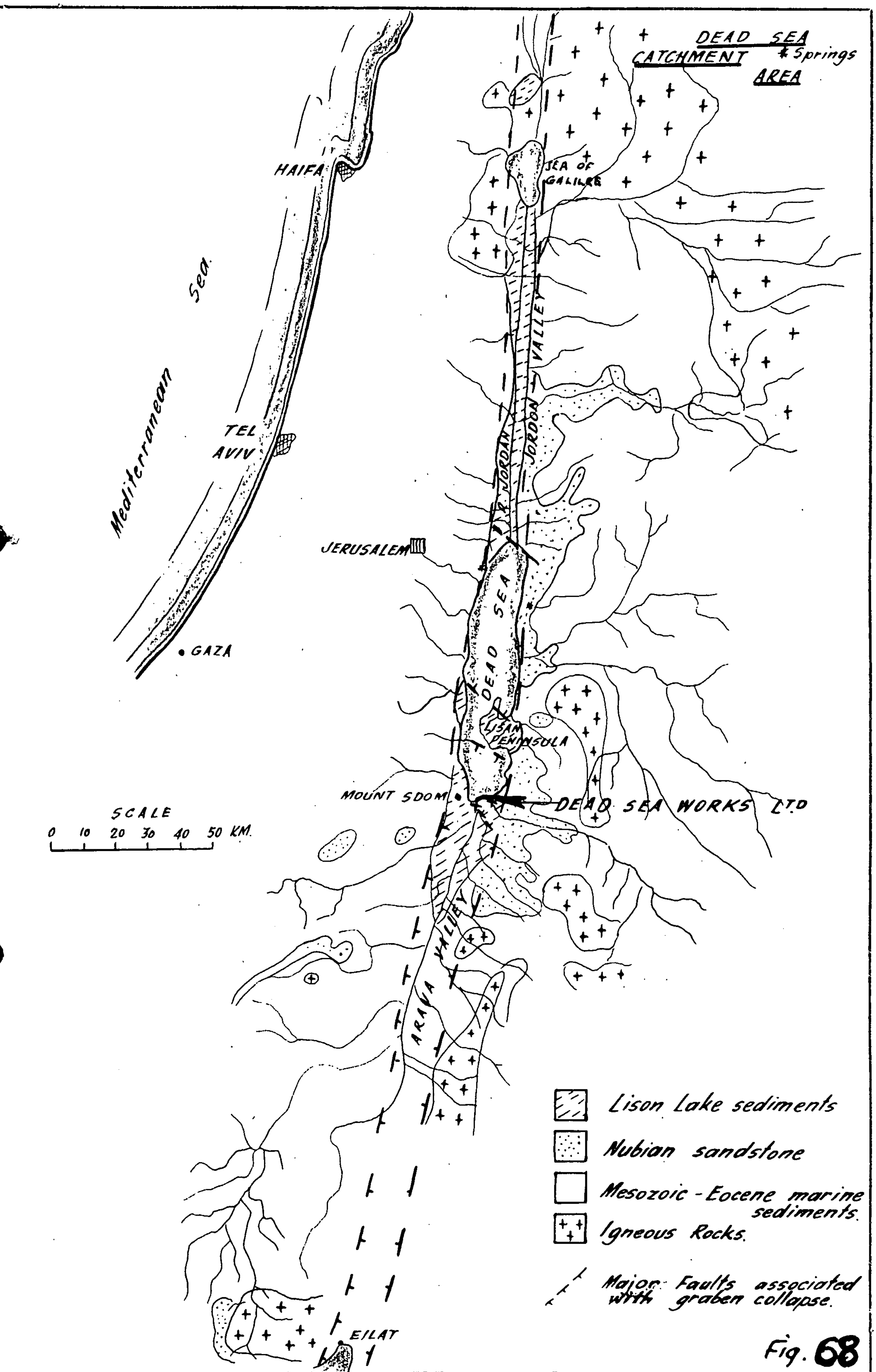

Fig. 68

S.A. DEPARTMENT OF MINES

Approved	Passed	Drn.	GEOLOGY OF DEAD SEA CATCHMENT	D.M.	Scale
		Tcd.		Req.	S 4126
		Ckd.			915-694
Director		Exd.			Date

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$MgCl_2$	23,000	
$NaCl$	12,650	
$CaCl_2$	6,150	
KCl	2,050	
$MgBr_2$	975	
$CaSO_4$	105	
$RbCl$	12	
Total	44,942	million tons

Exploitation

Economic exploitation of the brines on the north shore of the Dead Sea was achieved in 1930 after preliminary investigations which date fro 1911. At first, KCl was receoverd and in1932, bromine. In 1935 a plant was erected at the southern extremity at Sdom which in 1953 became the Dead Sea Works Ltd. with a capacity of 180,000 tons KCl/year. Further expansion, started in 1962 and due for completion in 1965 will raise the output by 1967 to 600,000 tons of potash annually and by 1972 to 880,000 tons. The output of bromine will be increased at the same time from the present 10,000 tons/year (7% of world production). The Israelis plan to build an industrial chemical complex in this region to utilise natural gas, the Negev phosphates and Dead Sea salts for a wide range of industrial and agricultural products.

Table salt production amounts to 30,000 tons annually, but its recovery meets with strong competition from easily exploitable crystalline salt bodies which outcrop at Mt. Sdom. The recovery of magnesia after carnallite precipitation is also planned. "Frigor", a concentrated solution of calcium chloride is very hygroscopic and serves as an antidust coating on unsealed roads in the Negev. Because of its low freezing point it also finds use in industry in refrigeration.

The lower ⅓ of the Dead Sea will be transformed into a 36 sq. mile evaporation area (the Sea here is only 15ft. deep) by the erection of some 28 miles of dykes. The sea floor has been test-drilled and sand banks, with a clay core and protected from wave action by gravel, are under construction. The salts will be harvested under water.

At present, Dead Sea water (S.G. 1.192) is pumped into a channel where it flows to evaporating pans which cover an area of 8 sq. miles on an adjacent playa some 10ft. above the level of the Dead Sea. Solar evaporation is accelerated by the introduction of a synthetic green dye. Salt is precipitated until saturation with respectto carnallite is reached when the brines are transferred to the "Carnallite pans". This stage is determined by measurement of S.G. Carnallite and NaCl are precipitated together and the residual brines, which contain mainly $MgCl_2$ and $CaCl_2$, are sent back to the Dead Sea.

The mixture of carnallite (containing 23% KCl) and halite is transported as a slurry into large tanks at the plant for recrystallization of KCl which is then separated from halite by flotation; the end product contains 96% KCl. In the expanded plant sylvite will be separated by fractional crystallization from halite.

Brines recently discovered in oil drilling operations near Sdom contain five times as much K per volume as the Dead Sea and the K:Na ratio is much more favourable; in fact, this is the only water known in the region in which K exceeds Na by weight. Insufficient supplies of this brine have yet been found for exploitation and exploration is continuing.

Bromine has been recovered at Sdom since 1958 from concentrated brines from the potash evaporation pans by oxidation with chlorine gas in counter current. Dead Sea water contains 4,000 ppm. bromine while the residual brine, (S.G. 1.341) resulting from precipitation of halite and carnallite contains 8,750 ppm. bromine. Two processes are in use for the separation of bromine. The first is the classical method of Kubierschky which uses steam. Bromine charged steam leaves the columns which are built of inert basalt and covered by perforated tiles near their upper end; the bromine gas is condensed in water-cooled stoneware spirals and is purified from the excess chlorine. In the second process bromine is separated from the solution by air and from the air-bromine mixture by contact with sodium bromide solution which dissolves bromine readily at low temperatures and gives it off again on heating; the bromine thus obtained is free from any admixture of chlorine. In Beersheba are produced ethylene dibromide and dichloro-bromo-propane, and methyl bromide for use in petrol, agricultural pesticides etc.

Production

	Tons		
	K_2O	NaCl	Br
1956-7	41,000	5,900	-
1957-58	89,000	9,300	917
1958-59	105,000	18,600	1,584
1959-60	115,000	13,400	1,885
1960-61	135,000	13,900	2,870

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SOLAR SALT OPERATIONS, CALIFORNIA

1. Newark, SanFrancisco Bay (Leslie Salt Co.)

3rd April, 1964

Hal. B. Goldman, Geologist - California Bureau of Mines, San Francisco.

Guy Wilkins, Manager, Crude Salt production, Leslie Salt Co., Newark.

Alan Woodhill, Vice President & General Manager, Salt and Chemical Division, Leslie Salt Co., Newark.

Don Linton, Manager, Westvaco Chemical Division of F.M.C. Corp., Newark.

During the visit to the solar salt operations of Leslie Salt Co. located at the southern end of San Francisco Bay the writer met Alan Woodhill who had just returned from a visit to South Australia in connection with development of the salt industry at Pt. Paterson. Claire Lopez, who was resident for some time at Pt. Augusta, retired from the company's employ at the end of March but is still retained as a consultant.

Leslie Salt Co. is the largest solar salt producer in the United States and, before a Mexican field located in the Gulf of California recently came into production, was the largest in the World. Other small California operators based at Moss Landing and San Diego include Western Salt Co. and

Morton Salt Co.

Leslie Salt Co. own 50,000 acres of land on the Bay shore which are in production (see Figs. 72, 73). Facilities include five crude salt producing units, a dredged deep-water terminal for the bulk loading of ships at the port of Redwood City, an undried crude salt processing plant at Newark, and a refinery at Newark that produces both kiln dried and vacuum refined salt.

Each of the crude salt plants is complete in itself with its own crystallizing ponds, harvesting equipment and washer. Each is normally operated independently of the others, although provision has been made for the transfer of brine between plants to afford greater flexibility of operations.

San Francisco Bay water is influenced by the Sacramento River and other smaller freshets draining the surrounding high ground so that its salinity is slightly lower than normal open seawater. Rainfall in the area varies from 13ins. to 22 inches per year. The net evaporation ranges from 31ins. to 49ins. of freshwater per year - an important contributing factor is the prevailing northwest wind which blows during the summer.

The present company has resulted from the consolidation (since 1908) of numerous small plants, some of which had been in production since 1862.

Water is pumped at an annual rate of 30,600,000 tons (10°sal. = 2.24 lbs. of salt/gallon) into the evaporating ponds and circulated by gravity and pump movement in three lifts to the crystallizing ponds, it taking five years for movement of water from the point of intake to crystallizer. The ratio of evaporating pond area to crystallizing pond area is 15:1. No artificial dyes are added as it is considered that this has no beneficial effect on evaporation; the water in the ponds has a natural red hue. Permeability losses from the ponds is not known but is under study; the muds of San Francisco Bay are underlain in places by permeable sand lenses.

The production at Newark averages ½ million tons annually (with record production in 1963 totalling 557,000 tons). The overall output for al plants is in excess of one million tons, thus the output amounts to approximately 20 tons/acre. At Newark plant there are 830 acres of crystallizers which develop five to six inches of salt in a season amounting to 600 tons of

LESLIE SALT CO.-CRUDE SALT PLANTS
SAN FRANCISCO BAY

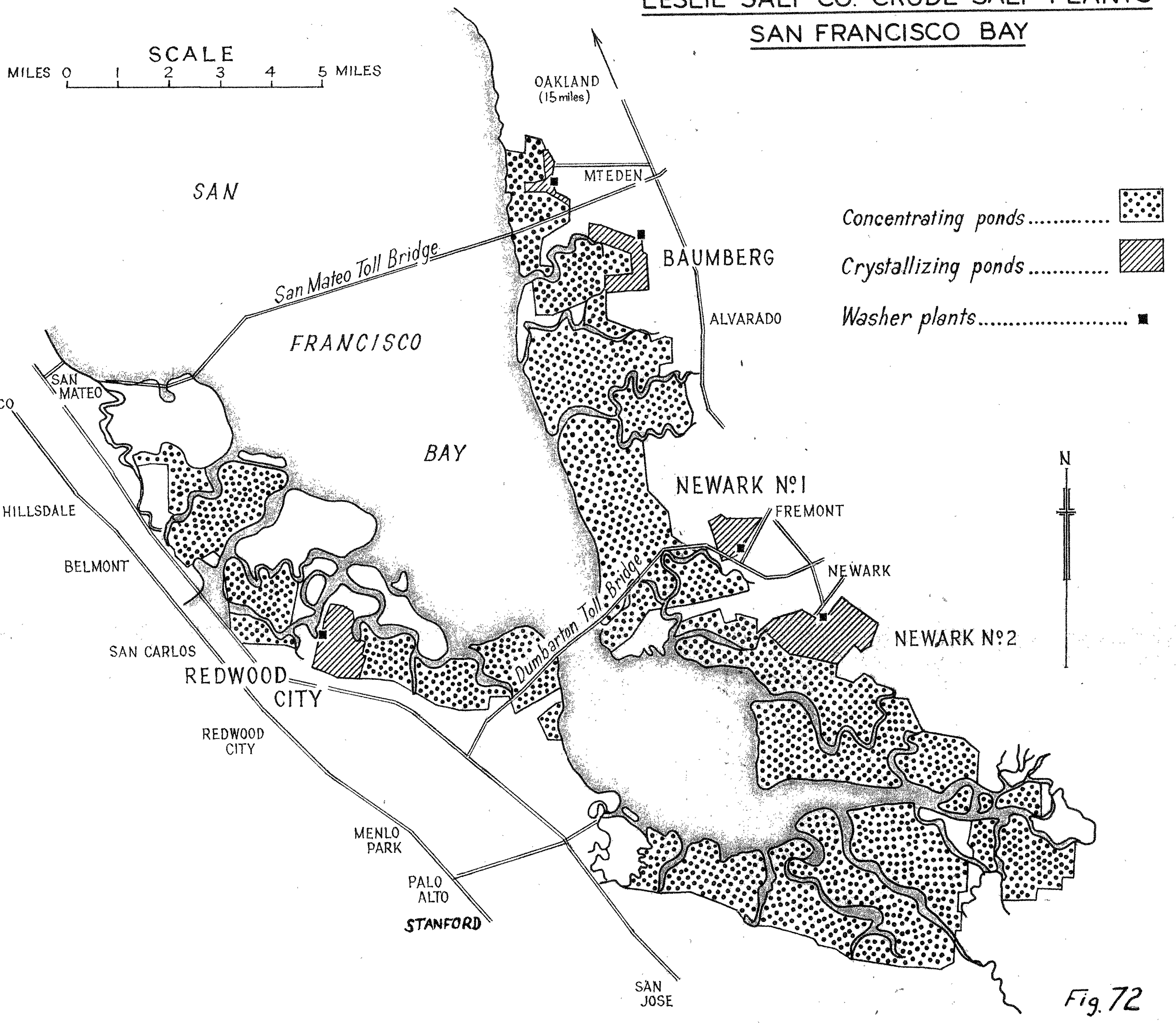

Fig. 72

S.A. DEPARTMENT OF MINES

No.	Amendment	Exd.	Date

LESLIE SALT CO. CRUDE SALT
PLANTS ON SAN FRANCISCO BAY

Approved
Director
Passed
Drn.
Tcd.
Ckd.
Exd.
Scale: 2m. to 1in.
65-89
973
Date 11·1·65

200—8.63 1429

salt per acre of crystallizer. Harvesting of salt during the period September - December is accomplished by means of several caterpillar-type tractor-drawn 14ft. wide scarifiers, each at a rate of 150 tons/hour. The salt is elevated and dumped into rail trucks, the temporary rails being moved by tractor as harvesting progresses. The company have at present under study the use of trackless haulage to the refinery site where the harvest is stockpiled in two $\frac{1}{4}$-million ton stacks after washing with brine and rinsing with freshwater.

Crude, unrefined, kiln-dried salt is used for domestic purposes, chemical use, water softening, meat preservation, stock etc. while 40% of the output is being exported from Redwood City to Japan - this is valued at$5 per ton.

A proportion of the output is refined in the company's refinery (Fig. 74). Some of this is washed further, dried in rotary kilns and screened into five grades of coarse crude salt and bagged - the dust from this operation is pressed by a 600 ton press into blocks for stock licks ("stoc bloc"), each of 50lbs. with additives including 3% sulphur, potassium iodide, vegetable oil, phosphates, trace elements etc.

Vacuum salt for domestic use is valued at $20/ton. Crude salt is dissolved and treated with soda ash and lime to remove the gypsum and evaporated in a series of closed stainless steel vessels by boiling with steam under vacuum. Salt of high purity (99.95% NaCl) and of constant particle size continuously crystallizes and is withdrawn for packaging into cartons, bags etc. The packaging of salt is a highly mechanized operation with cylindrical and rectangular cartons being manufactured at the site from water-proofed cardboard and filled with measured quantitites of salt, capped, labelled and packed.

Utilization of Bitterns - Westvaco Chemical Div. (F.M.C. Corp).

Bitterns produced by Leslie Salt Co. are purchased by the Westvaco Chemical Division of Food Machinery and Chemical Corp. and treated in an adjoining plant (Figs. 73, 75), for the recovery of bromine, magnesia and gypsum.

The plant is rather antiquated and no photography was permitted. It came into being in 1924 for the recovery of bromine and in 1937 for magnesia recovery, gypsum being a by-product of the latter. Potassium chloride (about 6% in the residual bitterns) was recovered during the period 1917-1927, the final product containing 12 to 45% K_2O equivalent but there has been no production of potassium salts since that time because economic recovery could not be achived in the face of competition from Searles Lake etc.

31145

Fig. 73 Solar Salt ponds, San Francisco Bay. Salt stack and refinery of Leslie Salt Co., Newark to left of wing tip and Westvaco plant of F.M.C. Corp. to right.

31146

Fig. 74 Crystallizer, $\frac{1}{4}$ million ton salt stack and refinery, Leslie Salt Co., Newark.

31147

Fig. 75 Westvaco Chemical Div. (F.M.C. Corp.), Newark. Bromine recovery plant at left, magnesia plant at right.

About 400 gallons of bitterns are obtained for each ton of salt produced. An analysis of a typical seawater bittern of 30° Baumé gravity follows.

Constituent	%	Tons per million gallons
NaCl	12.5	656
$MgCl_2$	8.7	457
$MgSO_4$	6.1	320
KCl	1.9	100
$MgBr_2$	0.18	9.2

The bitterns are drained from the salt crystallizing ponds and pumped in open trenches to bittern ponds which cover more than 80 acres near Newark and have a capacity of about 200 million gallons. A certain amount of NaCl that crystallizes in these ponds during the storage period is flushed out with seawater when they are emptied and before the new supply of bittern is received in the period September to October each year.

(a) Bromine recovery

Bromine is first recovered from the bitterns by the use of a battery of four Kubierschky towers, slate lined and held together by an iron frame, in which chlorine displaces bromine after acidification and addition of $MgCO_3$ (for close pH control). The bitterns are pumped to an overhead supply tank and flow through a feed-regulating, constant-level float box and heat exchangers to the top of the bromine-separation towers. Steam is introduced at the bottom of the tower and chlorine gas (purchased from a Dow plant located at Pittsburgh, Calif.) at an intermediate point. Proportioned quantities of these result in the displacement of bromine which separates as a vapour and escapes to a stone condenser near the top of the tower. A gravity separation of the condensed water and liquid bromine is effected and excess chlorine is removed in a series of glass towers packed with porcelain rings. The chlorine is removed by distillation and returned to the tower for re-use. Each of the towers can handle 2,000 gallons of bitterns per hour and effect a 95% bromine recovery.

Recovered bromine reacts in further porcelain packed glass towers with ethylene to form ethylene dibromide which is a non inflammable liquid with a characteristic odour; it is slightly corrosive to steel and is therefore stored in open lead-lined vats. The bulk of the bromine production is used in insecticides.

As the supply of bromine from bittern sources is strictly limited and insufficient for the production of ethylene dibromide adequate for U.S. needs Dow Chemical Co. at Freeport, Texas, turned to seawater as a bromine source but utilizing the same procedures as outlined above.

(b) Magnesia recovery

The bromine-free liquid escaping from the bottom of the Kubierschky towers is treated for the recovery of magnesia according to the following equations:-

(a) $\underset{\text{(of bittern)}}{MgCl_2 + MgSO_4} + CaCl_2 \xrightarrow{H_2O} 2MgCl_2 + CaSO_4 \cdot 2H_2O$

The gypsum is filtered off in vacuum cloth filters and stockpiled - it is marketed for use in agriculture, plaster and cement. Plant capacity is 150 tons per day.

(b) $\underset{\text{from (a) above)}}{MgCl_2} + \underset{\text{(dolime)}}{CaO.MgO} \xrightarrow{H_2O} 2Mg(OH)_2 + \underset{\text{(returned to (a) above)}}{CaCl_2}$

Dolomite for this reaction is quarried and railed from Hollister, some 75 miles to the south east and adjacent to Kaiser Steel's iron ore pit, and contains $< 0.5\%$ SiO_2 and $< 0.4\%$ Al_2O_3, Fe_2O_3. The dead-white, medium grained, crystalline dolomite is calcined in a 350ft. long, rotary, oil-fired kiln at Newark. Formerly, oyster shells, dredged from San Francisco Bay under 10 to 15ft. of water and often under muds, was used to provide a source of lime.

The magnesium hydroxide after Dorr 4-cell counter-current separation is converted to magnesia in a rotary kiln lined with alumina bricks. A proportion of the output is converted to periclase by fusion with silica (beach sand) in a furnace lined with chromium firebricks.

Magnesia is valued at $60/ton while high grade periclase is sold for $200/ton. Some 120 tons of magnesia products are produced daily.

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Ver Planck, W.E. (1958) Salt in California. Calif.Div.of Mines Bull. 175.

1. Chula Vista, San Diego Bay (Western Salt Co.)

14th April, 1964.

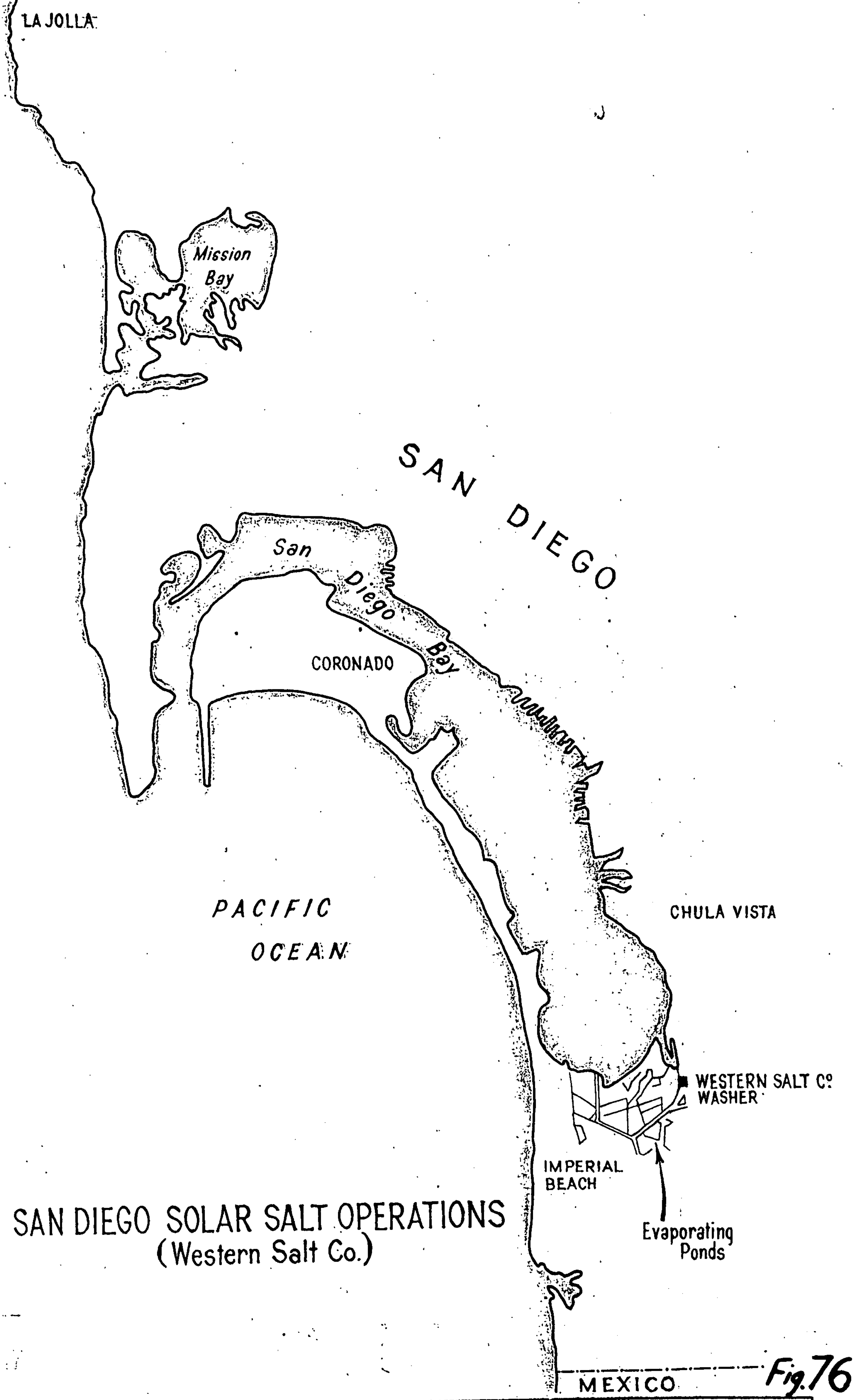
Art Babbitt, Engineer, Western Salt Co., San Diego.

D.M. Miller, Vice President and General Manager.

Admiral T.N. Hunt, Vice President.

Western Salt Co. have operated a small plant near Chula Vista on the southern end of San Diego Bay since 1869 with an annual output ranging from 70,000 to 120,000 tons (Fig. 76). There are approximately 1,600 acres of marshlands covered by evaporating ponds and some 100 acres of crystallizers. The operation is similar to that at Newark except for its smaller scale. The rainfall averages nine inches per year while evaporation ranges to 55 inches per year. The water of San Diego Bay is but little affected by stormwater dilution.

Harvesting normally begins early in June and is completed by



SAN DIEGO SOLAR SALT OPERATIONS
(Western Salt Co.)

Fig. 76

S.A. DEPARTMENT OF MINES					
Approved	Passed	Drn.	SAN DIEGO SOLAR SALT OPERATIONS (Western Salt Co.)	D.M.	Scale
		Tcd. F.B.		Req.	5 4125 973
		Ckd.			
Director		Exd.			Date 5·1·65

mid-November. The salt is broken with scarifiers, loaded into dump cars with a $\frac{3}{4}$ cub. yd. dragline and is transported by rail to the plant, washed and placed in an outdoor storage pile. The salt, valued at $9.50 per ton contains 99.7% NaCl and is used in bulk in chemical industry while the remainder is bagged for domestic purposes, preservation of meat, fish, hides, water softening etc. The bitterns are taken by F.M.C. Corp. for recovery of magnesium chloride for use in sorrel cement. No bromine has been produced at Chula Vista since 1945.

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4. ROCK SALT

1. Bedded Halite deposits

Winsford, Cheshire (Meadow Bank mine, I.C.I. Ltd.)

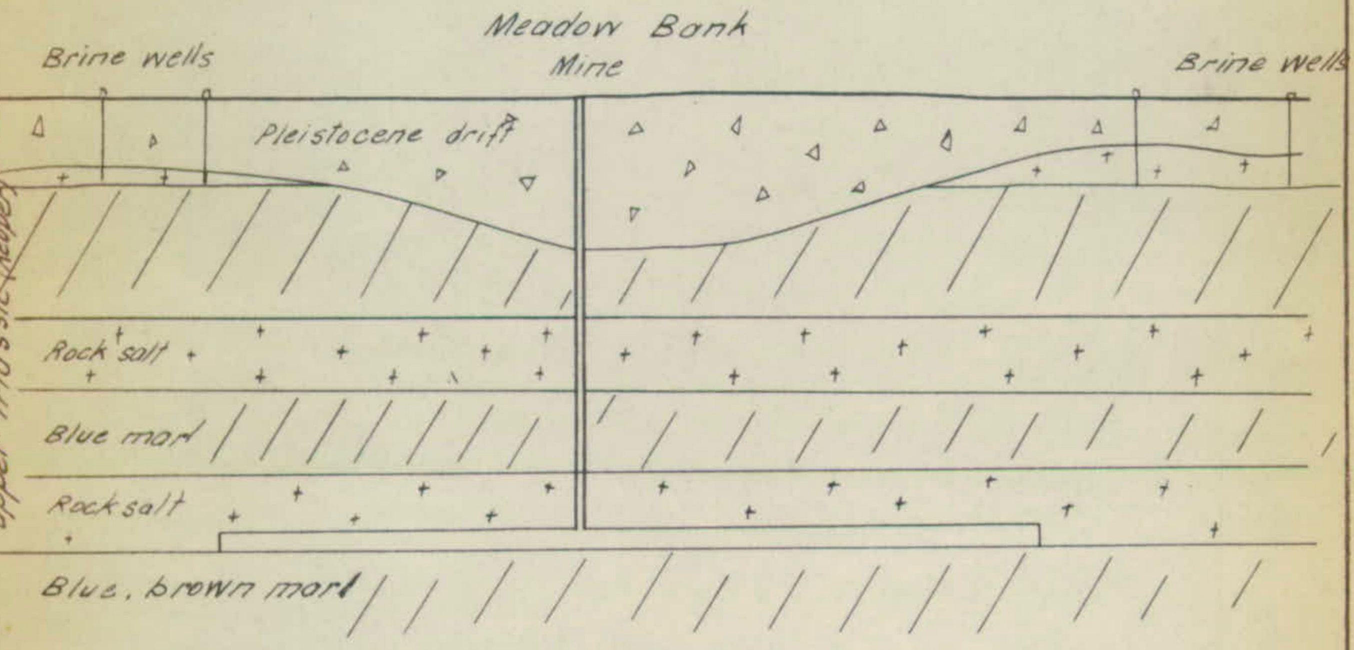
16th June, 1964 to 17th June, 1964

Alan [illegible], Works Manager, I.C.I. Ltd., Winsford.
Alan Jones, Underground Manager, " " "
Peter MacFarlane, Geophysicist, " " "
Jim Newman, Mining Engineer " " "
Jim Strachan, " " "

Salt recovery from natural brines in Cheshire dates from the time of the Roman occupation of Britain. With the discovery of rock salt in 1670 at Northwich, mining was introduced and for 200 years both rock salt and brine salt were produced. Inadequate roof support was provided and the mines collapsed in rapid succession from about the middle of the 19th Century as freshwater broke into the now-abandoned workings and resulted in extensive subsidence and damage in the salt district.

The Meadow Bank rock salt mine was opened in 1928 and this is now the only rock salt mine in the U.K. (Fig. 77). "Wild" Brines are also recovered by I.C.I. for chemical use and are refined for vacuum-salt production.

90A



Vertical Scale 1" = 200 ft

MEADOW BANK MINE - CROSS SECTION

31148

I.C.I. WORKS, Winnington Hall, Winsford, Cheshire

Fig. 77

S.A. DEPARTMENT OF MINES

Approved	Passed	Drn.		D.M.	Scale 1 inch to 200'
		Tcd. B.S.		Req.	S 4126
		Ckd.			420
Director		Exd.			Date 29-1-64

There are two 80ft. thick beds of salt present (230ft. to 310ft. and 370ft. to 450ft.) separated by marl, comprising part of the upper Triassic (Keuper) which at the mine dips at 3° with some dislocation by faulting. Mining operations are confined to the lowermost 20ft. of the lower halite bed. The workings covering an area of over 1 square mile, are connected to the surface by a 450ft. shaft. In the old workings (prior to 1892) 95% recovery was achieved from the upper bed of halite without regard for the inevitable consequences. Present practice allows 75% recovery by leaving 50ft. pillars with 50ft. wide rooms. The operation is highly mechanised and compares favourably with that seen elsewhere.

The rock salt mined varies in colour from amber to dark brown due to presence of up to 5% marl - a typical analysis follows:-

NaCl -	95.00%
$CaSO_4$ -	1.29
$CaCl_2$ -	0.03
$MgCl_2$ -	0.08
Insolubles	3.60

The salt shows prominent bedding planes which in section show a series of shallow saucer-like depressions separated by marly partings at intervals of about 6ft. In plan, these breaks trace out hexagonal equidimensional areas; they appear to be desication features in which saliniferous marl has been deposited in "mud cracks". Present production totals $\frac{3}{4}$ million tons of rock salt per year. Its main use is for clearing roads of ice and snow.

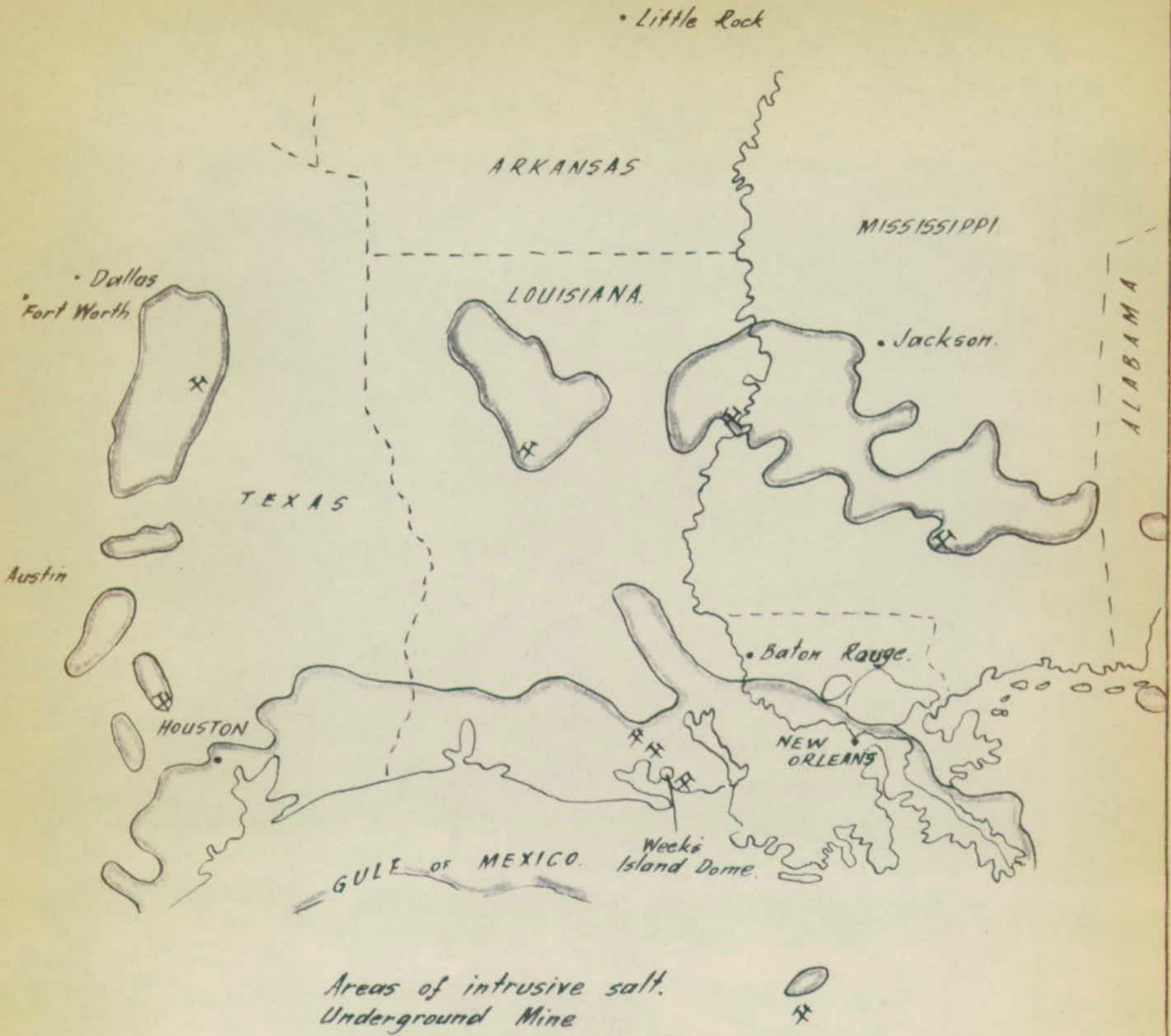
2. Salt in Domes

13th May, 1964

Charles Jeanfreau, Geologist, Freeport Sulphur Co., New Orleans.
Ralph West, Manager, Morton Salt Co., Weeks Island.
Milton Joliet, Engineer, " " " " "

General

About 30% of U.S. salt output is produced from the Gulf Coast region, chiefly in Louisiana and Texas from salt domes. More than 300 salt domes are known; six have subsurface salt mines, while others are being developed (see Fig. 78).



SALT INTRUDED REGIONS of GULF COAST

WEEKS DOME

31149

Fig. 78

S.A.

Approved	Passed	Drn.		Scale
		Tcd.	Req.	S. 4127
		Ckd.		973
Director		Exd.		Date

400— 6.63 1423

Diapiric (piercement) salt domes are produced by the breaking out of incompetent rock salt from its confining environment and its intrusion by plastic flowage into overlying sedimentary cover - the mobilizing force being tectonic, isostatic or both. The parent bedded salt in the Gulf Coast area is the (?) Jurassic Louann salt which lies at variable depths from 10,000 to 40,000 feet below the flat coastal plain and is as much as 5,000 feet thick. The domes were emplaced before the Pleistocene.

Lying directly on the salt at the top of most domes is a "caprock" consisting of residual granular anhydrite, altered in places to gypsum and grading through a transition zone into cavernous limestone, at times with sulphur. The thickness of the caprock may range from a few feet to 1,000 feet or more.

Salt domes which have mostly been located by geophysics are of great importance as commercial sources of:-

(a) Oil and gas which are associated with them in porous strata about their flanks, in cavernous caprock limestone, or in domed overlying strata.

(b) Sulphur.

(c) Rock salt.

(d) Gypsum and limestone occasionally.

(e) Large internal openings created by solution which are used for storage of petroleum, chemicals etc.

Weeks Mine, Weeks Island Dome (Morton Salt Co.,), Louisiana

Weeks Island dome, an almost cylindrical mass of salt standing vertically and some two miles in diameter, appears at the surface as a gentle rise with elevation of 90 feet on the shores of Vermillion Bay in the Gulf of Mexico, some 90 miles east of New Orleans. It has an unconsolidated sand cover 90 feet in thickness. The waters of the bay lap on one edge of the dome and, as Morton Salt Co. mine salt from two levels 700 - 800 feet below sea level and also recover salt from two artificial brine wells, it is imperative that these operations are kept well inside the salt stock.

The salt dome has been proved to exceed 20,000 feet in depth. There is small oil production about the flanks of the structure.

The Morton Salt Co. produce one million tons of salt per year as:-

(a) mined salt for industrial, stock etc.

(b) solution-mined salt for domestic usage after vacuum pan processing.

The main shaft, 800 feet in depth connects two levels 25 feet apart. The workings range from 60 - 100 feet in height and are mined on a room and pillar system. The rooms and pillars are generally 50 feet wide. Exfoliation, spalling of openings and flowage of the salt inward is evident but these show a decreased intensity with time and present no hazard in mining.

The salt shows a distinctive layered structure with layers from one inch to several feet consisting of interbedded white and darker bands in shades of white, light grey, light tan, dark grey and locally even black The colouration is due to the presence of anhydrite and also to internal reflection in translucent halite crystals. The layers represent original bedding which has been folded, stretched, recrystallized and distorted but everywhere they preserve their sedimentary character. The layers in the salt all stand essentially vertical and are isoclinally folded around vertical axes so that the ceilings show transverse cross sections of the folds and show great complexity (see plans in Kupfer, 1962 etc.) whereas the vertical walls, like longitudinal sections, show little else than a series of vertical bands (Fig. 78).

The salt itself comprises white or pale grey to blue compact equidimensional aggregates of halite crystals $\frac{1}{4}$ inch to $\frac{1}{2}$ inch diameter. The sole impurity is anhydrite ranging in the darker bands from 1 - 10% though a grade of + 99% NaCl can be maintained in mining operations.

In mining of rock salt the faces are undercut to a depth of 12 feet and auger drilling of holes for blasting vertically and horizontally, undertaken by use of "jumbos". Two holes are drilled at a time, $1\frac{1}{2}$ inches diameter. The salt, after blasting, is taken by self-loading rubber-wheeled cars to a belt conveyor 600 feet in length, thence crushed (- 6 inch) and hauled by skips to the surface for crushing, screening and a proportion for refining. The refined salt is packaged in cartons etc. in a plant similar to that operated by Leslie Salt Co. at Newark. The bulk salt being loaded in barges which ply on the intracontinental canal was sprayed with a blue chemical dye to deter pilferers.

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SULPHUR

General

The first commercial sulphur (brimstone) was produced in Sicily and from 1735, when a process was developed for the manufacture of sulphuric acid from sulphur, this was the world's monopolistic source. Other nations were driven to develop alternative sources and competition was met in England and the United States by the roasting of pyrites.

In 1891 Dr. Herman Frasch developed a process of recovery of sulphur which had been discovered in 1867 in the caprock of salt domes of the Gulf Coast. The Frasch process is based on the low melting point of sulphur (235°F); superheated water is pumped underground ("steaming") and the molten sulphur is pumped by compressed air to the surface. Fewer than 10% of the Gulf Coast domes have commercial deposits of sulphur in the caprock and since 1894 some 33 "mines" in Louisiana, Texas and Mexico (see Fig. 79) have produced (to January, 1st, 1964) 165,822,846 long tons of elemental sulphur. The U.S. thus emerged as the world's largest brimstone producer, U.S. Frasch output in 1963 being 4,900,000 tons.

Since the mid 1950's, with the discovery of extensive deposits of sour natural gas in France (Lacq) and Canada (Alberta) and the production of "recovered sulphur" from their contained hydrogen sulphide, there have been major increases in world sulphur output which in 1963 totalled 19,900,000 tons, of which recovered sulphur accounted for four million tons.

U.S. Frasch sulphur is valued at $25 per ton f.a.s. gulf ports for bright sulphur with discounts of $1.00 per ton for off-colour sulphur.

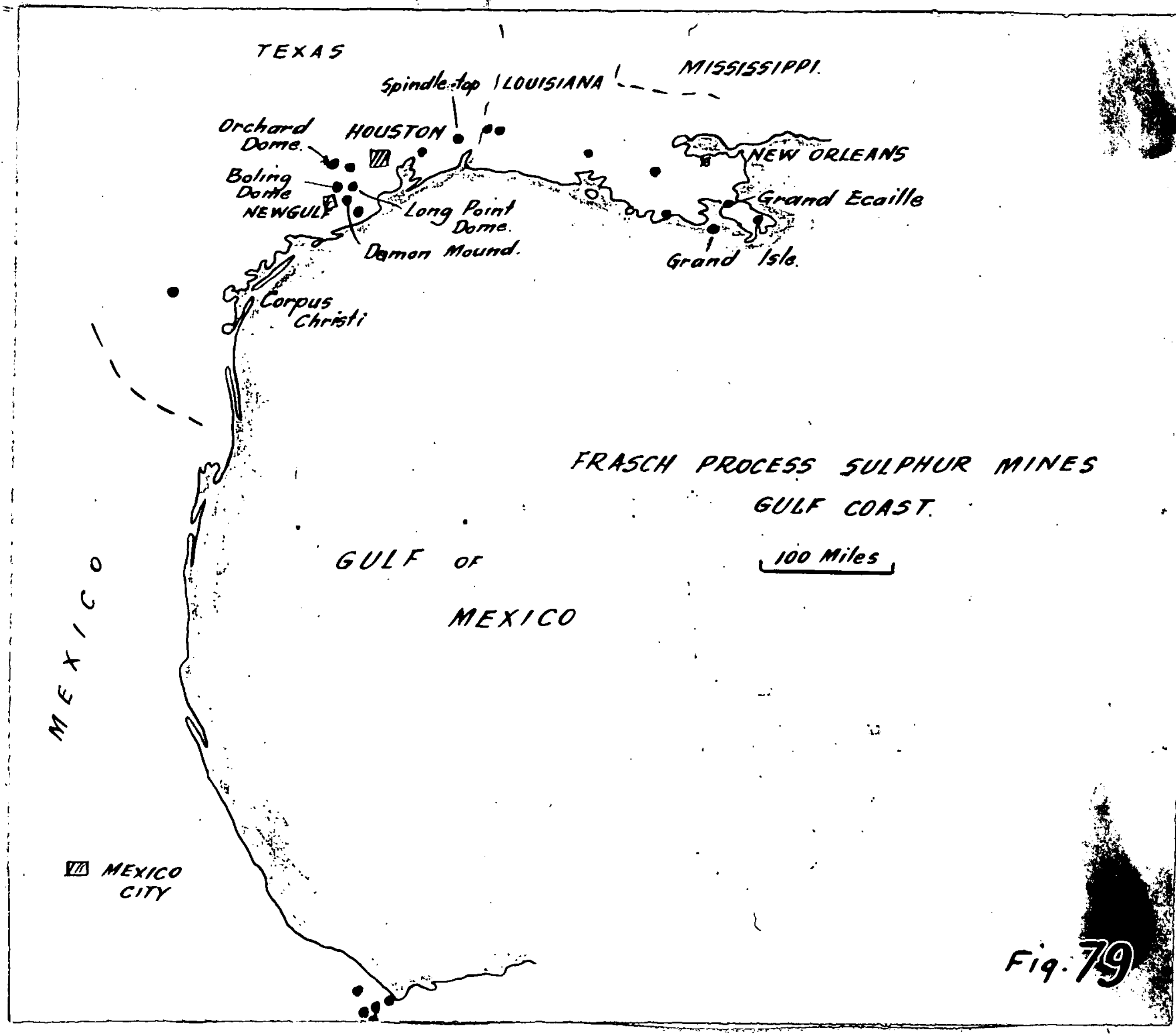


Fig. 79

1. <u>Frasch Process Sulphur</u>

11th May, 1965 to 15th May, 1964

H. Van W. Donohoo, Chief Geophysicist, Texas Gulf Sulphur Co., Houston.

Frank Moultin, Geophysicist " " " "

Ira E. (Mac) McKeever, General Manager of Mines, T.G.S., Newgulf.

Clinton White)
G. Mason) T.G.S., Newgulf.
"Junior" O'Neill)

Harvey A. Wilson, General Manager, Jefferson Lake Sulphur Co., Long Point.

Les Trahane, Assistant Manager, " " " "

Les MacFarlane, General Manager, Duval Sulphur & Potash Co., Orchard Dome.

Delos Flint, Chief Geologist, Freeport Sulphur Co., Gravier St., New Orleans.

"Hank" Agnew, Chief Engineer, Freeport Sulphur Co., Grand Isle.

Caprock, Origin of Sulphur

The caprock of Gulf Coast salt domes generally comprises a lower layer of granular anhydrite which grades up through a transitional zone into cavernous, vughy, grey, finely crystalline limestone. The anhydrite is a cemented insoluble residual of the salt stock derived by leaching of halite by circulating groundwaters; the base of the anhydrite is generally flat and truncates bedding structures within the salt. Sulphur mostly occurs within the transition zone as fine to coarse bright yellow rhombic crystals in vughs, in disconnected seams, as disseminations or irregular pockets in association with sulphide waters, hydrogen sulphide and polysulphides. Oil and gas are common associates, occurring within the caprock or on its margins. Sulphur occurs in the caprock of most salt domes but in only a few in commercial quantities. The caprock is of variable thickness, from a few feet to over 1,000 feet while the sulphur-bearing part of the formation in commercially exploited domes may range from 25 feet to over 300 feet and contain 15 to 25% sulphur.

The salt dome sulphur originated through reduction of anhydrite of the caprock through the agency of sulphate reducing bacteria (Desulfovibrio) to H_2S and subsequent oxidation to native sulphur. The following sequence of events in the formation of a typical sulphur-bearing Gulf Coast salt dome have been outlined by Feely and Kulp (1957). Anhydrite began to accumulate at the top of the rising salt plug when this entered the zone of groundwater circulation (perhaps within 10,000 feet of the surface). Thickness of the cap depended on the rate of upward movement of the salt, the anhydrite content of the salt column and the rate of dissolution. At a depth of 5,000 feet (or less) sulphate-reducing bacteria would become established, growing with petroleum hydrocarbons as their source of energy, reducing the anhydrite, and liberating CO_2 and H_2S. The CO_2 was largely incorporated into calcite and the limestone part of the caprock began to form, replacing anhydrite along its upper surface. Most of the H_2S produced would escape through fractures in the limestone and overlying formations produced by continued upward salt movement. By the time the salt had risen to within 500 - 1,500 feet of the surface stability would have been achieved, the overlying strata domed and deposition of calcite and pyrite along fractures would have largely sealed fractures by which H_2S had been escaping. Oxidation of trapped, stagnant, sulphide gases yielded elemental sulphur.

Since large quantities of petroleum must be used up during the formation of calcite and sulphur, the domes showing thick source beds of petroleum in their flanking sediments merit careful exploration of their caprock.

The amount of sulphur present is not a function of the size of the dome but of a number of variables including length of time that the salt had been in the zone of circulating groundwaters, the permeability of the cover and the availability of petroleum.

The Frasch process, recovery, storage.

In the Frasch process of mining, water at 320°F to 340°F is injected into the base of the sulphur-bearing caprock through rotary-drilled eight or ten inch diameter wells (Fig. 80). The sulphur which melts at 235°F separates from the rock and accumulates at the bottom of the well. Molten sulphur rises under hydrostatic pressure several hundred feet up the four inch casing which extends to near the bottom of the well inside the water-injection casing. The sulphur, 99.5% pure, is lifted to the surface, by compressed air introduced through a 1½ inch pipe within the sulphur line, where it is collected at relay stations as a dark brown pulsating liquid stream and piped to storage (Figs. 81, 82, 83). The process is a continuous one and hot water and air must flow for 24 hours a day for the life of the mine. All sulphur lines are insulated and carry within them steam lines to inhibit freezing of the product. Input of hot water and air and output of sulphur are registered on individual gauges for each production well on every field.

Fig. 80 Boling Dome (T.G.S. Co.), Texas. Note subsidence beyond production wells. 31150

31151

Fig. 81 Hot-water and molten sulphur lines, Newgulf.

31152.

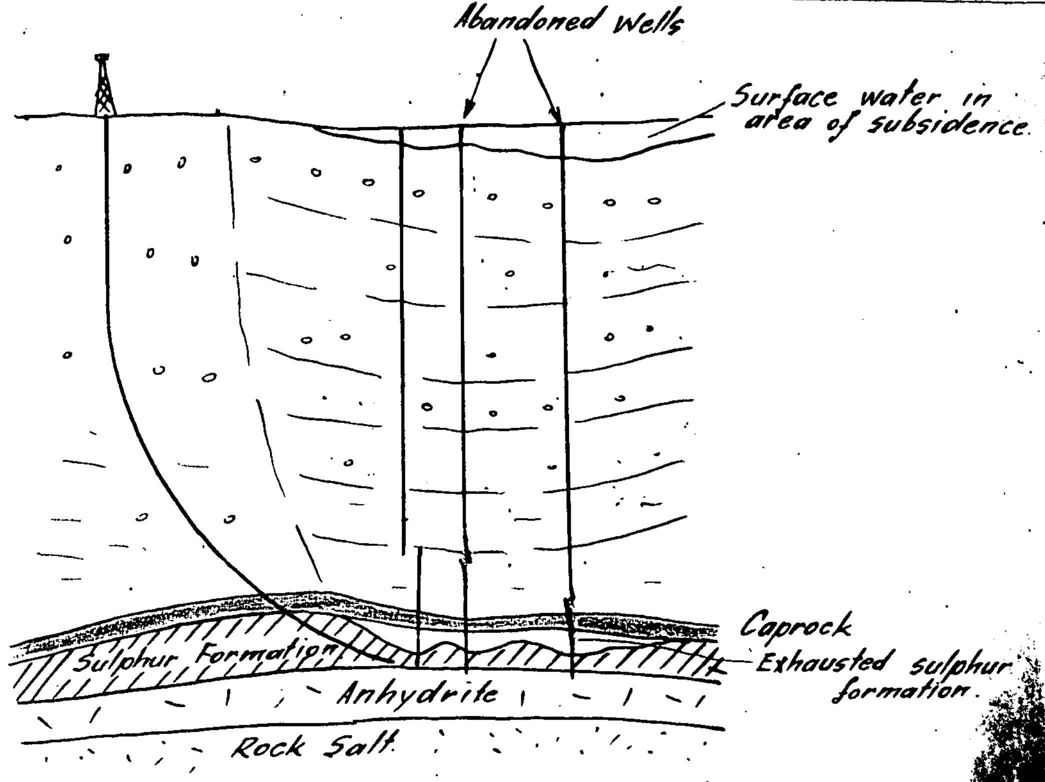
Fig. 82 Molten Sulphur collecting station. Long Point Dome, Texas (Jefferson Lake Sulphur Co.). Oil production well in right Background.

Increasingly the trend is to transport and market sulphur in liquid form. The molten liquid is piped to heated storage tanks and thence to heated rail tankers, barges or ocean going tankers (Fig. 88).

Alternatively the molten sulphur is sprayed out on to the surface of gigantic rectangular vats to cool and solidify into bright yellow brimstone (if free of hydrocarbons but of grey-brown hue if the content of hydrocarbon exceeds 0.2%). The vats at Newgulf (typical of operations inspected) are 1,500 feet long x 180 feet wide and provide a surface for cooling 4,000 to 5,000 tons of production daily. Such a vat when complete will be 50 feet in height and contain ½ million tons of sulphur (Figs.84,85).

Molten sulphur is retained at the top of the vats by aluminium panels which are held in position on raiseable posts set in the already solidified previous production and are raised as the height of the vat increases. The solid sulphur is broken by power shovels as required and transported by belt conveyors to road or rail trucks, barges etc.

The ideal sulphur production well has caprock formation characteristics which permit circulation of the superheated water from the well in all directions and the return flow of molten sulphur. Recent developments include directional drilling techniques (Fig. 89), which has led to better utilization of heating water, to longer well life and has permitted the efficient reworking of areas exhausted to vertical mining techniques. It is impossible to predict where the injected hot water will flow and in some areas mud is pumped underground to plug cavities which would otherwise drain off hot water and molten sulphur; at Grand Ecaille $2\frac{1}{4}$ million cub. yds. of mud were injected into a well before production was maintained.



MODIFIED METHOD OF EXTRACTING SULPHUR FROM SUBSIDENCE AREAS.

Fig. 89

One well can draw sulphur from only about $\frac{1}{2}$ acre of dome area so that new wells are being continually drilled and the necessary water, air and sulphur lines laid. Wells favourably located may produce continuously for more than a year, while others may be abandoned within a few weeks because of impermeability of strata etc. The deposits may be very irregular

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Fig. 83 Sulphur lines and vats, Port Sulphur (Freeport Sulphur Co.)

31154

Fig. 84 Molten Sulphur being sprayed on vat, Port Sulphur.

31155

Fig. 85 Completed sulphur vats, Orchard Dome (Duval Sulphur Co.)

and it is always difficult to accurately assess reserves.

Withdrawal of sulphur is always accompanied by subsidence at the surface and for this reason permanent buildings etc. are located "off structure". Subsidence, though it often terminates productivity of a well, is a desirable feature in mining as the volume of exhausted formation through which hot water can circulate is thereby reduced. Cool "spent" water is withdrawn from near the margins of the dome through "bleed" wells.

A critical factor in Frasch mining is an adequate supply of water and this may total 10 million gallons per day at a large plant. To produce one ton of sulphur the amount of hot water required varies widely from 1,000 gallons to 12,000 gallons. To ensure continuous supplies at plant sites reservoirs are built to store water pumped from rivers or canal systems. These are supplemented at Newgulf from underground sources. Water used in operations is first softened by hot lime or soda ash treatment and filtration, or with zeolites (ion exchange) to remove corrosive and scale forming solutes. After the water has been softened it is superheated to about 330°F by direct contact with steam under pressure. Boilers, fired by readily available natural gas or oil, produce the steam which is used to heat the water for mining as well as to operate mechanical drives on air compressors etc. and to maintain the sulphur in a molten condition during pumping and/or storage. It is apparent that great boiler capacity is required at each "mine."

Operations

Geophysical prospecting for oil has been the means of locating most of the Gulf Coast salt domes. After discovery, detailed gravimetric surveys yield information on the size, thickness and configuration of the caprock, but evaluation depends on diamond drilling and full recovery of the core in the sulphur formation.

From the foregoing it is apparent that enormous costs are involved in Frasch mining of sulphur, drilling and equipping wells, power and boiler plants, water supply systems, heating and pumping machinery, transport and in housing. When a new deposit is developed, a large and expensive plant must be built adjacent to the dome wherever this may be and all commercial operations are located within 50 miles of the coast of the Gulf of Mexico.

Sulphur mines are located mostly at sites difficult of access - under the wide open spaces of Texas, the flat coastal plain of the Gulf, the jungle of bottleneck-cyprus festooned with Spanish moss, amid a desolate maze of Louisiana bayous, the floating swamps of the Mississippi delta, and in the Gulf of Mexico.

Production of sulphur is considered to be economic only where deposits are within 2,500 feet of the surface. The reserves are not unlimited and, except offshore, there is little prospect of finding important domes. However, large stockpiles are on hand and reserves for the near future are considered to be ample.

There are at present five companies engaged in sulphur recovery from U.S. Gulf Coast domes, these include:-

(a) Texas Gulf Sulphur Co. operating at Newgulf, Wharton Co., on Boling Dome, and at Spindletop, Fannet and Moss Bluff domes in Texas.

(b) Freeport Sulphur Co. at Garden Island, Lake Pelto, Grand Ecaille and Grand Isle domes in Louisiana.

(c) Jefferson Lake Sulphur Co. at Long Point dome in Texas.

(d) Duval Sulphur and Potash Co. at Orchard dome, Texas.

(e) U.S. Sulphur Corp. at the High Island Dome, Texas.

Below are tabulated the history of Frasch production to January, 1964.

TABLE

Frasch Sulphur production to January, 1st, 1964

Started	Property	Producer (Sulphur Co.)	Closed	Total Tons
27.12.1894	Sulphur Mine	Union	23.12.1924	9,412,165
12.11.1912	Bryan Mound	Freeport	30.9.1935	5,001,068
19.3.19	Gulf Hill	T.G.S.	10.8.1936	11,804,648
31.3.23	Hoskins Mound	Freeport	26.5.55	10,895,090
6.3.25	Big Creek	Union	30.8.29	8,009
27.10.28	Palangana	Duval	10.3.35	236,662
14.11.28	Boling Dome	Union	30.8.29	8,009
19.3.29	*Boling Dome	T.G.S.	OPERATING	57,279,327
19.3.30	Long Point	T.G.S.	19.10.38	402,105
20.10.32	Jefferson Island	Jefferson Lake	7.6.36	430,811
8.12.33	*Grand Ecaille	Freeport	OPERATING	27,085,690
23.3.35	Boling Dome	Duval	25.4.40	571,123

Started	Property	Producer (Sulphur Co.)	Closed	Total Tons
2.6.35	Boling Dome	Baker-Williams	18.12.35	1,435
3.5.37	Clemens Dome	Jefferson Lake	14.12.60	2,987,204
29.1.38	*Orchard Dome	Duval	OPERATING	4,759,970
7.6.46	*Long Point	Jefferson Lake	OPERATING	5,723,882
24.6.48	Moss Bluff	T.G.S.	OPERATING	4, 388,032
15.6.51	Starks	Jefferson Lake	13.12.60	840,250
12.5.52	Spindletop	T.G.S.	OPERATING	4,629,968
19.11.52	Bay Ste Elaine	Freeport	29.12.59	1,131,204
11.11.53	*Damon Mound	Standard	20.4.57	139,618
19.11.53	Garden Island Bay	Freeport	OPERATING	5,045,391
7.12.53	San Cristobal (Mexico)	Mexican Gulf	5.5.57	152,167
3.2.54	Nash Dome	Freeport	23.11.56	153,115
26.9.54	Jaltipan (Mex.)	Pan American	OPERATING	7,495,941
25.2.55	Chacahoula	Freeport	28.9.62	1,199,114
3.5.56	Salinas (Mex.)	Gulf	OPERATING	2,032,800
8.2.57	Nopalapa (Mex.)	T.G.S.	27.2.60	322,243
16.5.58	Fannett	T.G.S.	OPERATING	1,349,607
12.6.59	Texistepel (Mex.)	Texas International	1.10.61	9,210
25.3.60	High Island	United States	8.2.62	37,753
17.4.60	*Grand Isle	Freeport	OPERATING	1,338,869
26.11.60	Lake Pelto	Freeport	OPERATING	956,665
	*Mines visited.			

Boling Dome (Texas Gulf Sulphur Co.), situated at Newgulf, 47 miles south west of Houston and 40 miles from Gulf of Mexico in semitropical jungle (Fig. 80).

This dome, five miles x 3½ miles in extent on the 1,500ft. contour, is the largest shallow salt structure on the Gulf Coast and boasts the greatest production of brimstone. The sulphur formation occupies an area of some 1,500 acres as a crescent round the eastern and southern slopes of the dome and ranges in grade from traces to as high as 50% and varying in thickness to 250 feet.

The dome is surrounded by upwarped Jurassic sands and is overlain by unconsolidated Quaternary and Tertiary sediments. Oil and gas wells produce from shallow pools (about 500 feet) peripheral to the dome. At the surface subsidence due to mining is up to 40 feet while, beyond the affected area, the dome is expressed as a rise of about five feet above the general ground level.

For efficient operation production wells are grouped together, starting at the top of the sulphur bearing area and working down the side of the dome so that collapse closes in the area from which sulphur has been extracted. Five water heaters at Newgulf deliver nine million gallons of water per day to the field.

Present production approaches 1¼ million tons per year. Reserves of some 40 million tons are reported.

Orchard Dome (Duval Sulphur and Potash Co.)

This deposit is unusual in that the top of the dome has a thin, almost barren, caprock and all exploitable sulphur occurs along the flanks beneath overhanging caprock and in pockets in step faults in limestone as well as in salt (Fig. 90). Sulphur is recovered from depths to 3,000 feet.

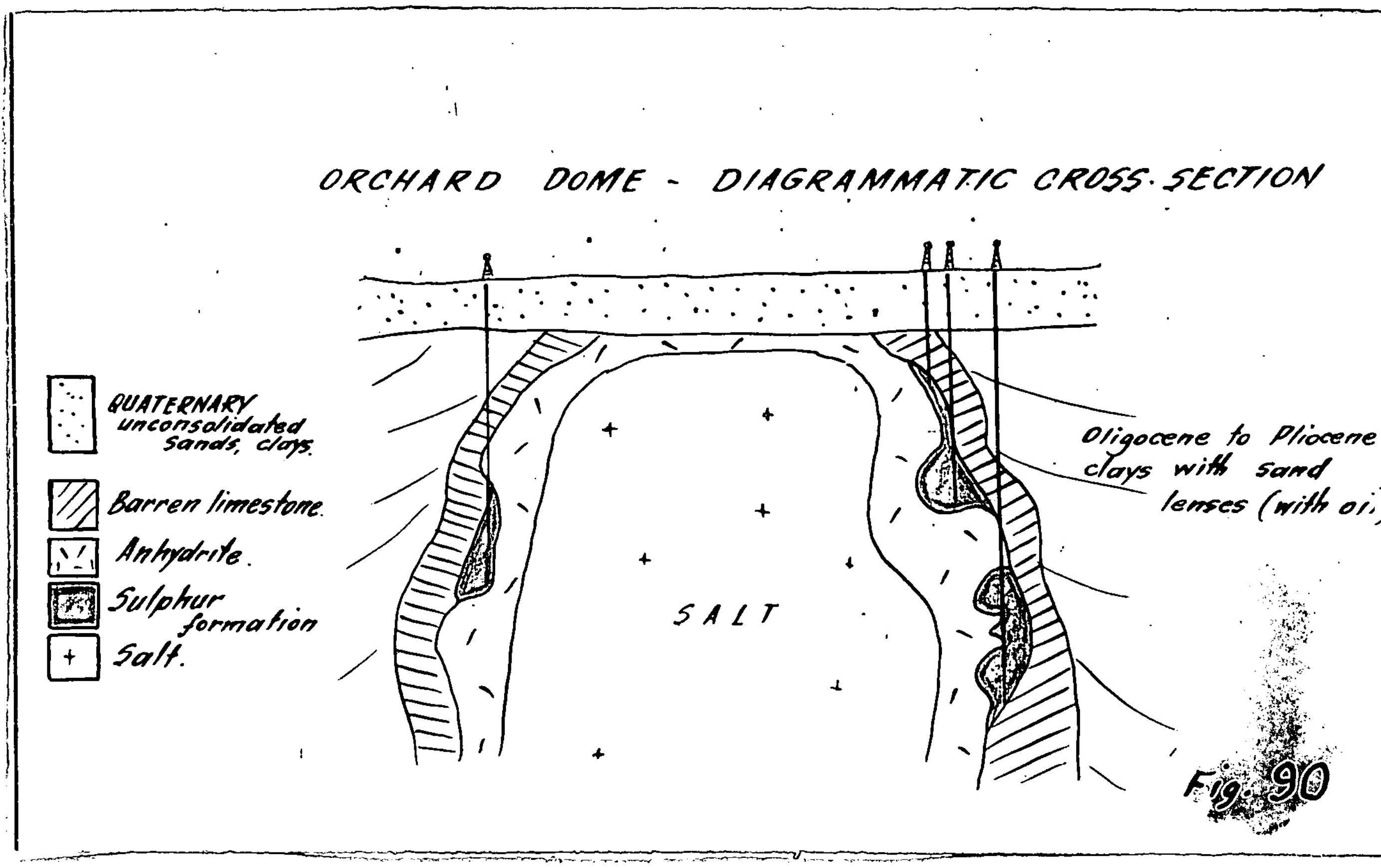


Fig. 90

Long Point Dome (Jefferson Lake Sulphur Co.)

Sulphur is recovered from an area of 500 acres at a depth of 700 to 1,000 feet below the surface at Long Point Dome, 12 miles northeast of Boling Dome. The mine has a water capacity of 3,380,000 galls/day. Production of 20 tons of sulphur per hour from some wells is recorded.

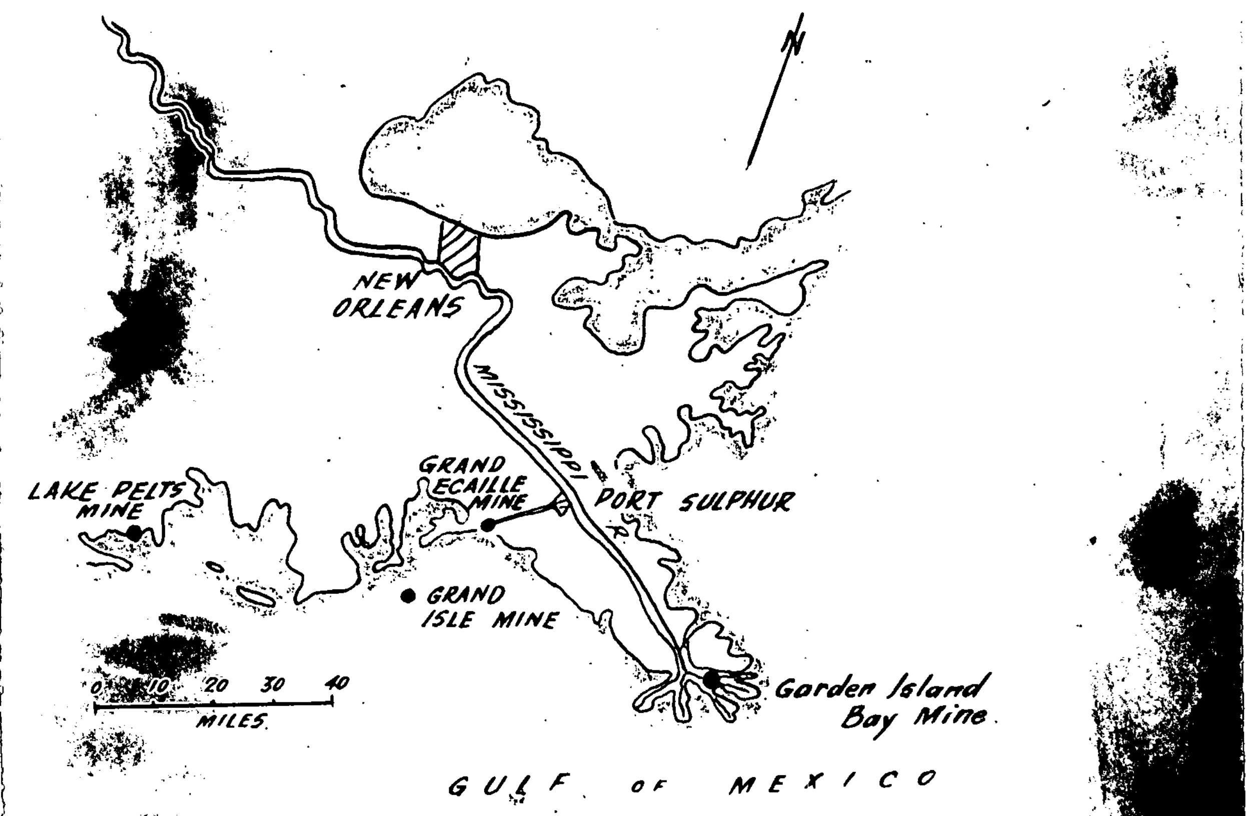
Damon Mound (Union Sulphur Co., abandoned).

An oil field, located on the flanks of Damon Mound is the site of now-abandoned sulphur mining operations. The dome rises to almost 100 feet above the general surface level.

Sulphur occurrence is reported to have been "spotty" and was restricted to an area of 120 acres on the north side of the dome.

Grand Ecaille (Freeport Sulphur Co.)

This comprises one of four mines operated by Freeport on or near the Mississippi River delta in Louisiana (Fig. 91), and is almost 50 miles below New Orleans, 10 miles southwest of the company's terminal at Port Sulphur, and within four miles of the Gulf on a tidal marsh (Figs. 86, 87). Construction operations faced difficulties at this site where what appears to be land is actually a matting of decayed salt grasses floating on ooze. The entire plant has been built on reclaimed marsh and this is connected by a ten mile long dredged canal to Port Sulphur.



Some Marshland, shallow water & offshore Sulphur Mines of Freeport Sulphur Co

Fig. 91

The sulphur-bearing caprock occupies an area of 1,100 acres and lies at 1,250 feet below the surface; it averages 250 feet in thickness.

Hydraulic dredges are used to restore the surface to an operating level above sea level as subsidence due to mining takes place.

Water requirements of two million gallons per day are piped from the Mississippi and stored in reservoirs at Grand Ecaille. As new brimstone sources were located in tide-water areas and in the Gulf of Mexico, Freeport turned to seawater as a mine water. The Company developed a process to eliminate scaling

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Fig. 86 Port Sulphur, storage, refinery and loading installations on the River Mississippi (Freeport Sulphur Co.)

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Fig. 87 Mississippi River delta. Barge on Port Sulphur- Grand Ecaille canal.

31158

Fig. 88 Sulphur barge, Port Sulphur canal (Freeport Sulphur Co.)

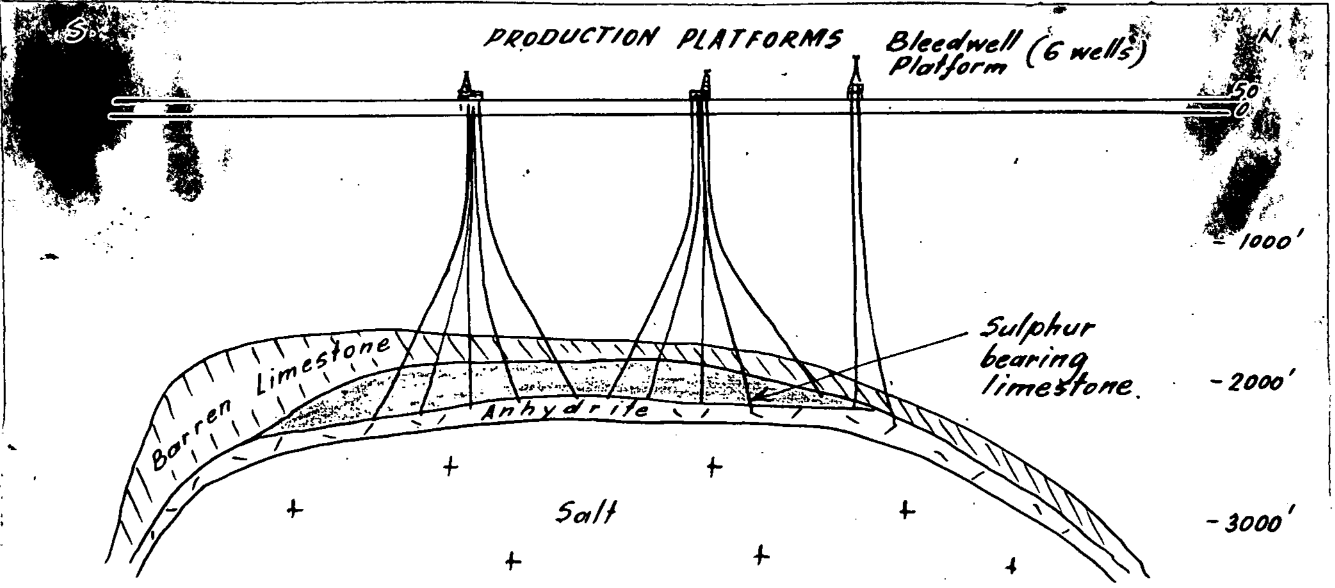
and corrosive problems which are ordinarily expected due to precipitation of $Ca(HCO_3)_2$, $Mg(HCO_3)_2$ and $CaSO_4$.

The sulphur recovered from this deposit is contaminated with a small percentage of petroleum residues. The discolouration is readily removed at other plants, Orchard Dome etc., by filtration using adsorptive clays, but here by distillation. The contained NaCl from use of seawater for steaming is then separated by filtration.

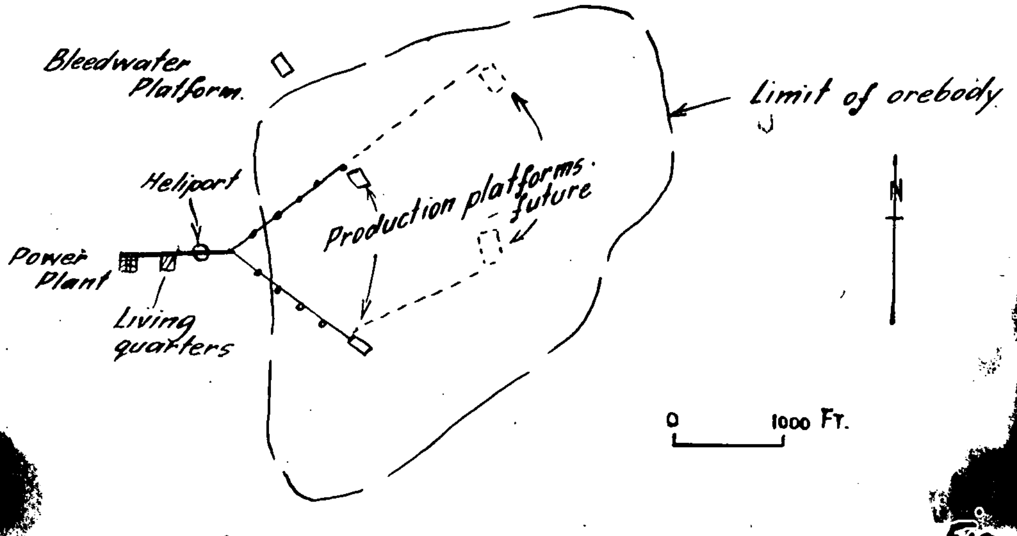
Grand Isle (Freeport Sulphur Co.)

In 1949 Humble Oil and Refining Co. discovered, seven miles off the Louisiana coast and 1,800 - 2,500 feet below the floor of the Gulf, a dome several hundred acres in area (Fig. 94). The reserves of sulphur were estimated to be 30 to 40 million tons in a formation varying from 200 - 600ft. in thickness. Sulphur content averages 25%. Over 125 domes have now been located in the Gulf of Mexico but the number bearing exploitable sulphur is not disclosed.

The development of the $30 million Grand Isle Mine involved problems of design and construction imposed by 50ft. water depth at the mine location and the extremes of weather of the Gulf. Historically, the Frasch



GRAND ISLE DOME · CROSS SECTION



PLAN OF MINING FACILITIES

Fig. 94

industry has been dependent on freshwater in large quantities and since the nearest unlimited source of freshwater was the Mississippi River, some 30 miles away, it became necessary to evolve a method of using Gulf water. A further unique problem was posed by the necessity for a safe, reliable, all-weather system of sulphur storage and transport.

The visit to the offshore installation involved a 30 mile flight in an amphibian Grumman Mallard from Port Sulphur to Grand Isle Base and thence seven miles by Sikorsky S-55 helicopter to the Grand Isle heliport. The Gulf of Mexico is dotted with oil and gas wells and drilling platforms.

The Grand Isle operation is supported on a Y-shaped structure almost one mile long, 75ft. above sea level with drilling rigs, production wells, a seawater heating plant, a heliport and living quarters for 250 men (Figs. 92, 93). The main plant is located off-structure beyond the sphere of influence of subsidence. Drilling activities are concentrated on two

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Fig. 92 Grand Isle Mine (Freeport Sulphur Co.). Power Station, living quarters and heliport on distant arm. Production wells and drilling platform at left and right. Bleed Well at distant right.

31160

Fig. 93 Grand Isle Mine (Freeport Sulphur Co.)

platforms at each arm of the Y with wells drilled directionally to achieve the desired dispersal of bottom hole locations almost 1,000 feet laterally from the well heads. Subsidence is taking place as mining proceeds and the company is resigned to future reconstruction and extensions. At present compensation for subsidence is achieved by adjusting the platform supports. Bleed wells are based on a satellite platform and these are operated from the main installation by remote control.

The plant uses 13 million cub.ft. of gas per day to heat five million gallons of seawater to 325°, to compress air and for power to operate drill rigs etc.

The sulphur is landed through a 7-mile steam-heated pipeline laid beneath the floor of the gulf to Grand Isle Base from where tank barges carry the still-liquid sulphur 30 miles to the Port Sulphur storage, refinery and shipping point (Fig. 88).

2. Recovered Sulphur

20th April, 1964 to 21st April, 1964

Dr. R.T.D.Wickenden, Geologist-in-charge, Western Plains office, Geological Survey of Canada, Calgary.

Elgin D. Bell, Assistant Manager of exploration, Texas Gulf Sulphur Co., Calgary.

Fred Ronicker, Manager of plant T.G.S. Okotoks.

John MacDougall, Geologist, T.G.S. Calgary.

Sulphur is recovered by oxidation of hydrogen sulphide contained in sour natural gases at 20 plants in Alberta, one in Saskatchewan and one in British Columbia, the plant visited being that of Texas Gulf Sulphur Co. at Okotoks, Alberta, 25 miles S.E. of Calgary (Figs. 95, 96). In 1963 Texas Gulf Sulphur Co. accounted for 317,000 tons of Canadian production which amounted to 1,300,000 tons (valued at $12,232,000). Production dates from 1960.

At Okotoks the sour natural gas is drawn from six bores at the rate of 30 million cub. ft. per day from Devonian sediments at a depth of about 8,000 feet. The gas containing 34% H_2S and 11% CO_2 is first separated from liquid hydrocarbon condensate which is co-produced at the rate of 120 barrels per day. The H_2S and CO_2 are then removed in scrubbers with monoethanolamine (M.E.A.) from the residual sweet gas which is piped to consumers.

Fig. 95 Okotoks plant, Texas Gulf Sulphur Co., Alberta. Condensate separator at left, scrubbers in central building. 31161

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Fig. 96 Waste gas stack, Okotoks (Texas Gulf Sulphur Co.)

The acid gas is stripped from the amine with steam and is now composed of 75% H_2S, 22% CO_2 and 3% water to which is added a controlled amount of air. Partial combustion of the mixture yields recoverable heat and sulphur in the presence of a catalyst (bauxite) as under:-

$$2H_2S + O_2 \dashrightarrow 2H_2O + 2S$$

Daily production amounts to 370 tons. The molten sulphur is pumped through heated lines to storage vats or for transport in rail tankers to the U.S.

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CONCLUSIONS

Potash, salt, gypsum, anhydrite and occasionally limestone which comprise extensive evaporite sequences resulting from the evaporation of seawater are being exploited in many areas in the Northern Hemisphere. These deposits are widely distributed in rocks ranging in age from Cambrian to Tertiary.

The salt beds may be undeformed throughout their extent, elsewhere they have been mobilised to accumulate in broad anticlines while often they have forcibly intruded the overlying sediments (salt domes).

Salt and petroleum are often closely connected stratigraphically and the history of exploitation of evaporite salt deposits shows that their discovery has largely resulted from the search for petroleum. In Australia, in the accelerated search for oil and gas, drilling operations have recently led to the discovery of hitherto unknown evaporite sequences in widely separated basins in Western Australia. (Canning Basin, Permian, Frome Rocks etc.), Queensland (near Tambo, Devonian, Bores No. 1) and the Northern Territory (Amadeus Basin, Proterozoic, Alice No. 1; Cambrian, Mt. Charlotte; and at Ooraminna in Ordovician Stokes Fm. and in Proterozoic Bitter Springs limestone).

The Minlation bore penetrated a gypsiferous and shaley red bed sequence within the Cambrian strata at 724ft; this marks the closest approach in South Australia to a marine evaporite succession though H.G. Thode in 1958 determined from sulphur isotope ratios that the "gypsum is either of non marine origin or if it is.......was introduced in rather recent times". Further investigation of this section is warranted.

A number of structures in the Amadeus Basin and in the Canning Basin appear to result from diapiric intrusion of salt; the best known is Gosse's Bluff, a circular wall of faulted sandstone closely resembling Confusion Dome of the Paradox Basin, Utah. From Mt. Toondina I.B. Freytag (1964, unpublished report, S.A. Department of Mines) has described an "unusual structural situation" wherein strongly deformed outcropping Permian sediments are confined to a small area within a region of subhorizontal Cretaceous strata; it is suggested that this may be a piercement structure possibly "motivated by low-density evaporite material". His recommendations for a stratigraphic test drilling are endorsed.

In search of potash in the dry lakes of the desert basins the Department has recently directed attention to natural accumulations, including brines under the floors of Lake Eyre and Lake Torrens. Concentrations of potash in saline desert basins depend on evaporation of large bodies of saline waters without outlets to the ocean but large or persistent bodies of water of this type are of rare occurrence and the existence of a concentrating reservoir through a long period of time does not guarantee the accumulation of a large mass of salts. Commercially valuable concentrations of water-soluble potash in part depend on the freeing of the lake waters of their admixture of clays and other clastics. At Lakes Eyre and Torrens any potash which may have accumulated has probably been selectively adsorbed by clays or is so intimately mixed with muds as to apparently disappear.

South Australia is climatically and geographically well favoured for the recovery of salt by solar evaporation of seawater and the expansion of its already important solar salt industry could be readily achieved; the bitterns which are now returned to the sea could, however, be treated for the recovery of bromine, magnesia and possibly, potash. All Australian bromine requirements are imported - in 1963 these totalled 178,834 lbs. of bromine salts valued at £30,000. High grade calcined magnesia imports in 1963 totalled 31,720 tons valued at £826,400.

ACKNOWLEDGMENTS

I wish to record my thanks and appreciation to the Director of Mines for making possible this interesting, stimulating and rewarding visit to study a number of overseas non-metallic mineral deposits. The kind help and hospitality afforded by overseas geological survey personnel and by the various mining companies in arrangement of visits to their operations in the countries visited is appreciated and acknowledged. Personal messages of thanks have been sent to individuals and to the companies concerned.

RKJ:AGK:AVR

R.K. JOHNS
SENIOR GEOLOGIST
NON-METALLICS SECTION