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# POTENTIAL FOR POTASH AND RELATED MINERAL RESOURCES

# KHORAT PLATEAU, NORTHEAST THAILAND AND CENTRAL LAOS

by

Robert J. Hite
U. S. Geological Survey

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# CONTENTS

Page

ABSTRACT 1

INTRODUCTION 2

Acknowledgments 4

POTASH 5

General statement 5

STRATIGRAPHY OF EVAPORITES OF THE KHORAT PLATEAU AND VICINITY 14

Paleozoic evaporites 14

Mesozoic evaporites 16

Phu Khadung Formation 17

Sao Khua Formation 19

Maha Sarakam Formation 20

GEOCHEMISTRY OF MAHA SARAKAM HALITE 30

CORRELATION OF EVAPORITE CYCLES 35

STRUCTURE 39

ECONOMIC GEOLOGY 41

Potash 41

Brines 48

Copper and uranium 49

RECOMMENDATIONS 55

REFERENCES 62

## ILLUSTRATIONS

Page

Figure 1. Index map of Khorat Plateau showing boundaries of Plateau (dotted line)........................ 3

2. Models of a barred evaporite basin............... 8

3. Geologic map of northeast Thailand............... 21

4. Comparison of top of massive halite in Maha Sarakam Formation in core hole DH-1 and top as picked on driller's log of water well H2-10.... 25

5. Typical evaporite cycle of Maha Sarakam Formation 27

6. Photographs of drill core from a Maha Sarakam evaporite cycle................................ 29

7. Bromine and $K_2O$ profiles through halite of Maha Sarakam Formation in core hole DH-5............ 31

8. Stratigraphic cross section in western Khorat basin through halite facies of Maha Sarakam Formation.................................... 38

9. Typical topography on the Khorat Plateau......... 43

10. Area of possible sedimentary copper deposits..... 51

11. Map showing tentative recommended locations for potash core holes and the approximate depth of the hole..................................... 58

## TABLES

Page

Table 1. Minerals common in evaporite deposits............ 6

2. Stratigraphy of the Khorat Plateau region........ 15

3. Annual consumption of potash in Asia and the Far East.................................... 44

4. World's potash production in short tons of $K_2O$... 46

# POTENTIAL FOR POTASH AND RELATED MINERAL RESOURCES
# KHORAT PLATEAU, NORTHEAST THAILAND AND CENTRAL LAOS

By Robert J. Hite
U. S. Geological Survey

## ABSTRACT

Thick beds of rock salt have been penetrated by numerous water wells in the Khorat Plateau of northeast Thailand and central Laos. These deposits of Cretaceous age are in the Maha Sarakam Formation of the Mesozoic Khorat Group. Beds of rock salt may also be present in the Sao Khua and Phu Kadung Formations in the Khorat Group and possibly in the Kanchanaburi Group of Paleozoic age.

The salt-bearing Maha Sarakam Formation extends over 21,000 square kilometers in the Sakon Nakhon basin in the northern half of the Plateau. It extends over an additional 36,000 square kilometers to the south in the Khorat basin. The maximum thickness of the halite facies is unknown, but may exceed 1,000 meters. Some individual salt beds are at least 150 meters thick.

Studies of distribution of bromine and potassium in halite from core holes at Chaiyaphum indicate that at least one salt bed may contain potash.

It is possible that potash may be found on the Plateau in almost flat lying deposits at depths of less than 60 meters. These highly favorable conditions, combined with an advantageous location to the growing Asian potash market, justify additional drilling in the area.

Analyses showing anomalously high copper content in ground water from many water wells on the Plateau may indicate the presence of sedimentary copper deposits in the red beds of the Khorat Group. The notable similarity of the Khorat Group to strata hosting copper and/or uranium deposits in other parts of the world suggests that exploration for these resources should be undertaken.

## INTRODUCTION

Thick beds of rock salt and associated gypsum and anhydrite have been penetrated at unusually shallow depths by numerous water wells in the Khorat Plateau of northeast Thailand and central Laos (fig. 1). Although the full extent and character of these evaporites is relatively unknown, there is little doubt that they are among the world's larger deposits. This report is the result of a preliminary investigation, undertaken during the period July 23 to October 20, 1970, to evaluate the potash potential of these evaporites. The investigation was the first step in a two-phase work plan. The principal objectives of this first phase were to review and evaluate all existing geologic data pertaining to the evaporites and then recommend whether a second phase, involving exploratory drilling, was merited. Thus, much of the time was spent examining geologic data from some of the hundreds of water wells drilled on the Plateau. Fieldwork included a one-week visit to Vientiane, Laos, to confer with officials of the Royal Laotian Government and USAID personnel regarding salt deposits in the Vientiane Plain. Another trip was made to the Khorat Plateau to examine outcrops of the Khorat Group, and to study cores and samples stored at Khorat by the Royal Thai Department of Mineral Resources.

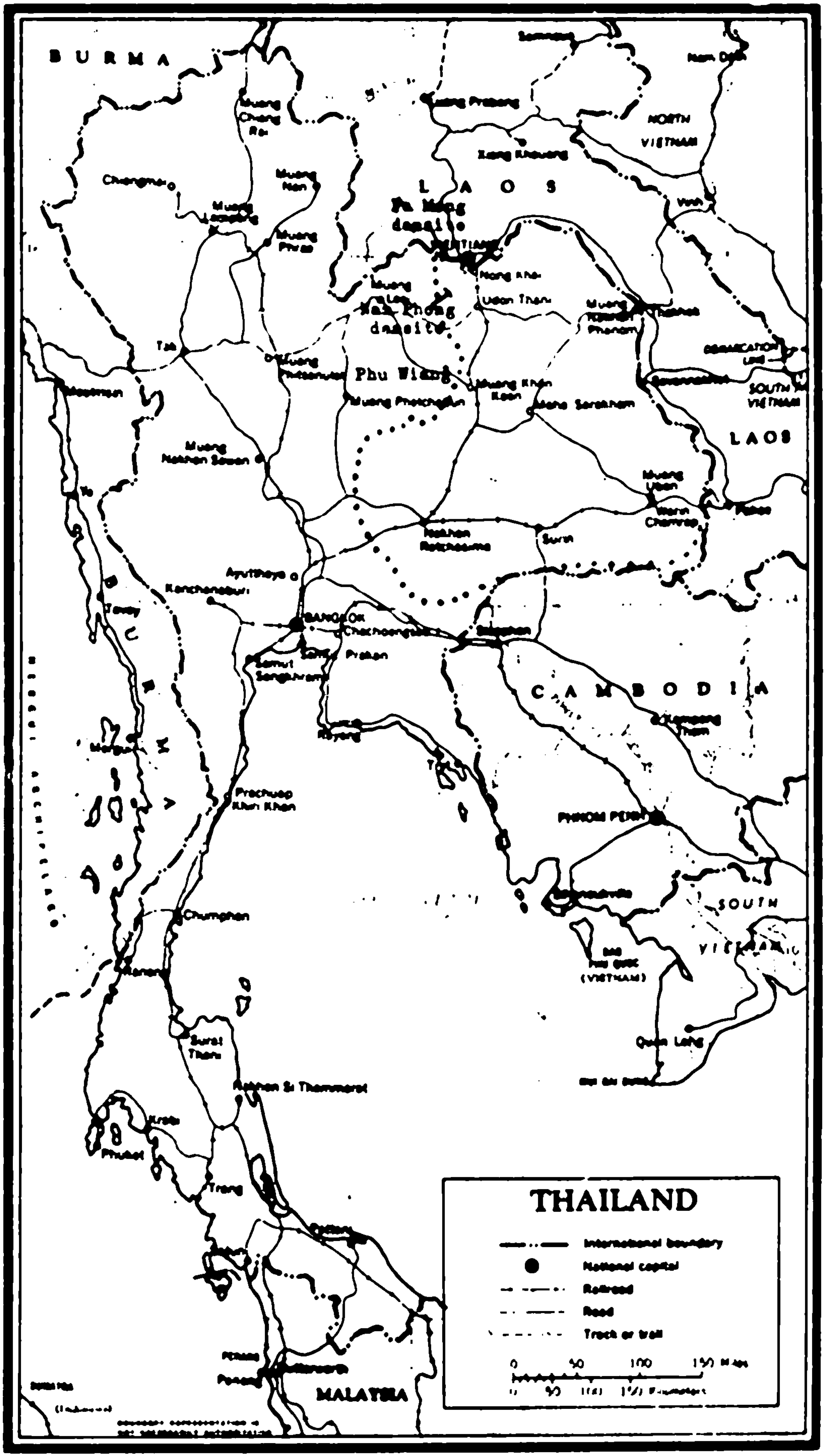

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Figure 1.--Index map of Khorat Plateau. Boundaries of Plateau shown by dotted line.

Soon after the investigation began it became apparent that it would also be necessary to obtain cost estimates on a potash drilling program, and where adequate drilling equipment and services might be obtained. As a result, various drilling contractors, drilling service companies, and representatives from several drill rig manufacturers were consulted. Most of this work was accomplished in Bangkok; however, several inquiries regarding drilling equipment were made after returning to the U.S.A. The results of this work, along with a resume of technical problems involved in drilling evaporites, are covered in a separate supplementary report.

## Acknowledgments

The writer is indebted to a large number of people whose numerous courtesies and freely given assistance made this investigation possible. The Royal Thai Department of Mineral Resources acted as the official host during the writer's stay in Bangkok, and the writer wishes to thank the Director General, Mr. Vija Sethaput, for the excellent support provided by the Department. Special thanks are accorded to the Chief of the Economic Geology Division of the Department, Sangob Kaewbaidhoon, who acted as liaison officer, as well as to Thawat Japakasetr, and the writer's counterpart, Prachon Chareonsri, both of the Economic Geology Division, who were especially helpful in arranging field trips, use of equipment, and transportation in Bangkok. A great debt is owed to Charoen Phiancharoen, Acting Chief of the Ground Water Division, for generously making office space available. The numerous discussions concerning drilling problems with Samrit Lelawongs and Suri Mrigadat of the Engineering Division were extremely helpful. The support lent by M. Hayath of the United Nations Committee for the Coordination of Investigations of the Lower Mekong Basin on numerous occasions

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## POTASH

### General statement

Because many who read this report will be unfamiliar with the occurrence, origin, and use of potash, a brief introduction to these subjects is included here in order to facilitate the reader's understanding of certain technical aspects in the main body of the report.

Potash is a general term used for compounds of potassium. It is one of the three major nutrients required by plants, and thus, its principal use is in agriculture as a fertilizer. Generally most fertilizers are a combination of potash, nitrates, and phosphates.

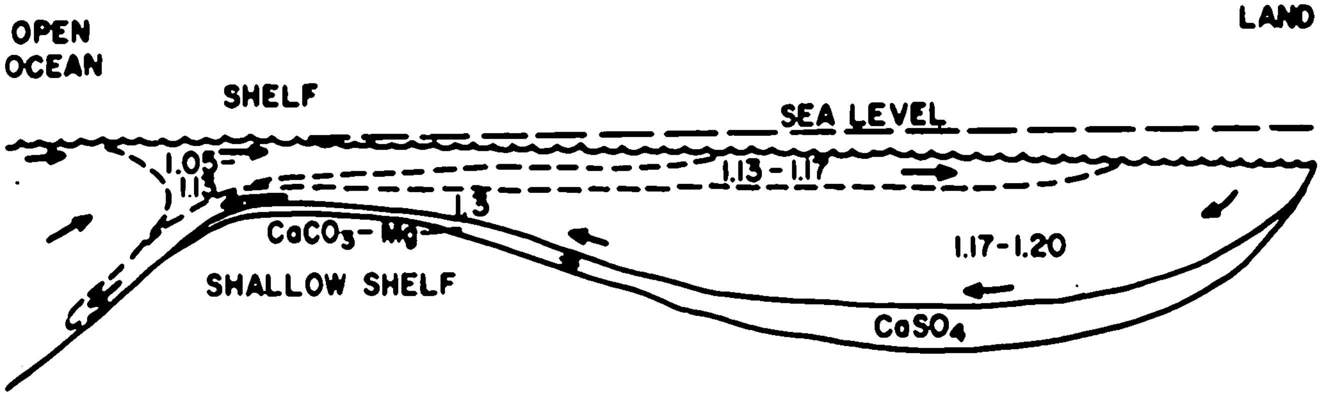
The world's most important sources of potash are deposits associated with marine evaporites. Marine evaporites are chemical rocks precipitated from sea water as the result of concentration by evaporation. Some of the more common potash evaporite minerals are listed in table 1. The potassium content of these minerals is always expressed in terms of equivalent $K_2O$. Sylvite, for example, has an equivalent $K_2O$ content of 63 percent and forms potash deposits of greatest economic value. The value of a potash deposit is dependent not only on its thickness and areal extent but on $K_2O$ content.

Table 1.--Minerals common in evaporite deposits.

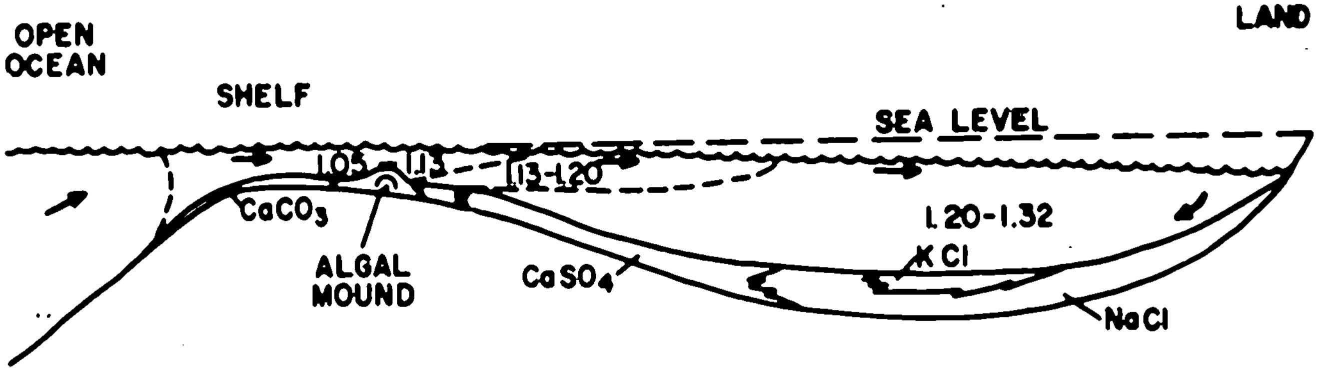
| Potash minerals | | $K_2O$ content in percent |
|---|---|---|
| Sylvite | $KCl$ | 63 |
| Carnallite | $KCl.MgCl_2.6H_2O$ | 17 |
| Langbeinite | $K_2SO_4.2MgSO_4$ | 23 |
| Kainite | $KCl.MgSO_4.3H_2O$ | 13 |
| Leonite | $K_2SO_4.MgSO_4.4H_2O$ | 26 |
| Polyhalite | $K_2SO_4.MgSO_4.2CaSO_4.2H_2O$ | 16 |
| **Other associated minerals** | | |
| Halite | $NaCl$ | |
| Anhydrite | $CaSO_4$ | |
| Gypsum | $CaSO_4 2H_2O$ | |
| Calcite | $CaCO_3$ | |
| Dolomite | $CaCO_3.MgCO_3$ | |
| Kieserite | $4(MgSO_4).(H_2O)$ | |

All potash deposits are mixtures of evaporite minerals. One of the most common ores from these deposits consists of a crystalline intergrowth of halite and sylvite of a tenor that may range from 15-35 percent $K_2O$.

The basic factors involved in the formation of marine evaporites and associated potash deposits are a constant source of sea water, solar energy, and a topographic barrier or sill. In hot, arid climates evaporation concentrates the salt content of the surface layer of the ocean. Under normal circumstances this water of higher salinity and density gradually sinks and remixes with water of open-ocean salinities, but if some type of topographic barrier slows or prevents the return of the water to the open ocean, an increase in salinity of water behind the barrier will result (fig. 2). The accessway of a barred basin may be so constricted that its flow capacity equals only the volume of water lost by evaporation in the basin. Because a constant load of dissolved salts is brought into the basin through the accessway, the water of the basin will eventually become salt-saturated and evaporite deposits will form. If the accessway to the basin is widened or deepened so that its flow capacity is increased beyond the volume needed to balance evaporation, then a return flow (reflux) of brine to open sea can take place. When reflux occurs, equilibrium between inflow salt load and outflow salt load is achieved, and there is no further increase in salinity. If equilibrium is reached during the halite phase of concentration, only halite mixed with the less soluble phases will be deposited and the potash-rich brines will be refluxed to the sea. Any change in the volume of inflow and outflow, caused by raising or lowering of barriers or sea level,



*A*. BASIN-TYPE EVAPORITE MODEL
TRANSGRESSIVE PHASE



*B* BASIN-TYPE EVAPORITE MODEL
REGRESSIVE PHASE

Figure 2.--Models of a barred evaporite basin during (A) the transgressive phase (high sea level), and (B) the regressive phase (low sea level). Numbers representing water densities) are approximate (from Hite, 1970).

will upset this depositional equilibrium and either regressive or transgressive phases will be deposited. Thus, potash deposits should be expected to form only in basins where evaporation rates are high and severe restrictions on circulation minimize or prevent influx.

In the barred basin, the most dense brines are concentrated by gravity into the lowest parts of the depression. For this reason the most soluble evaporites also accumulate in the deepest part of the depression.

Most of the world's important deposits of halite and potash were formed in barred basins. Notable examples include the deposits in the Permian, Paradox, and Michigan Basins of the United States, and the Zechstein Basin of Europe.

Sea water, containing 3.5 percent dissolved solids, is a complex solution of many ions; however, 97.7 percent of the total is made up of only seven ions. These include, in order of abundance, $Cl^-$, $Na^+$, $Mg^{++}$, $SO_4^{--}$, $Ca^{++}$, $K^+$, and $HCO_3^-$. Despite the complexity of the solution, the sequence of salts deposited by its evaporation follows a definite order, at least until the bittern stage of concentration is reached. After that the sequence of salts deposited varies according to changes in physico-chemical factors. The depositional sequence of rock-forming minerals, starting with the least soluble mineral, is 1) calcite or dolomite 2) gypsum or anhydrite, and 3) halite. Only after the original sea water has been reduced by 98.2 percent of its original volume do the highly soluble potash and magnesium salts begin to precipitate.

The depositional sequence in marine evaporite deposits shows that the increase in brine concentration by evaporation is usually interrupted long before salts of potassium or magnesium are precipitated. Often the sequence will be interrupted even before halite has begun to precipitate. These interruptions in salinity increase are generally the result of world-wide changes in sea level. When sea level rises, the circulation between the evaporite basin and the open ocean will be less restricted, and water within the basin will be freshened. Conversely, if sea level falls, circulation becomes more inhibited, resulting in higher salinities within the evaporite basin.

If halite was being precipitated at the time of a sea-level rise, it will now be covered by a layer of the next less soluble salt, either anhydrite or gypsum. If the freshening within the basin is of sufficient magnitude, precipitation will proceed to an even less soluble salt, such as calcite or dolomite. In this manner the repetitive layering of the different mineral facies forming an evaporite cycle is achieved. Sea level may rhythmically rise and fall many times during the depositional history of an evaporite basin, giving rise to a large number of evaporite cycles.

Another characteristic of marine evaporite deposits is the asymmetrical character of individual evaporite cycles. Apparently in the geologic past a sea-level rise always took place more rapidly than a lowering. As a result, in potash-bearing evaporite sequences, a thick layer of halite generally was deposited before the slowly increasing salinity reached a concentration high enough to precipitate potash minerals. Then with a sudden rise in sea level, deposition of potash ceased and the salinity decreased so rapidly that only a thin layer of halite was deposited before deposition of calcium sulfate began. Thus, potash deposits are generally at or near the top of the halite unit of the evaporite cycle, rather than a middle position.

Reconstructing the paleosalinities of evaporite cycles has been greatly facilitated by the use of trace elements present in the evaporite minerals. The most important of these elements is bromine which forms in solid solution in the chlorides. The source of this bromine is the original sea water from which the chlorides were also derived. Theoretically, the first halite to precipitate from sea water should contain 75 ppm bromine (Holser, 1966, p. 253). Experimental evaporation of sea water has shown, however, that the first halite to precipitate contains 38 ppm bromine (Bloch and Scherb, 1953). Similarly it has been shown that the amount of bromine that passes into the solid phase is always directly proportional to the amount in the parent brine (Boeke, 1908).

Because only a small part of the available bromine in solution is incorporated in the solid phase, the concentration of the element in the solution continues to increase, and halite precipitated at a late phase of evaporation will have a much higher bromine content than the first formed crystals. Thus, the bromine content of samples from a halite bed can tell us something about the paleosalinity at the time each layer of halite was precipitated. Ordinarily most halite beds will show a gradual increase in bromine from bottom to top of the bed. This asymmetrical pattern of bromine distribution in the halite units of evaporite cycles is additional evidence supporting a slow lowering of sea level while salinities are increasing, and then a very rapid rise in sea level causing rapid freshening in the evaporite basin.

Because the bromite content of a salt bed tells us the salinity conditions at the time of deposition, it also indicates whether the salt bed might somewhere contain a potash deposit. In using bromine as an exploration tool, it is best to use samples from cores. If no core material is available, cuttings from drill holes can be used, although this is not quite as satisfactory (Raup and others, 1970). Valyaskho has stated (1956, p. 578) that if the bromine content in halite is about 200 ppm, it was crystallized from a brine that was near saturation in respect to potash salts, and suggests the possibility of finding a potash deposit nearby.

From an exploration standpoint the regional distribution of bromine within a salt bed must also be considered. As previously stated, the most concentrated and heavier brines collect in the deepest part of the evaporite basin, and this is where the potash deposits form. The most concentrated brines would also contain the greatest quantities of bromine, and, therefore, a horizontal bromine gradient will exist between the shallow parts (low bromine) and the basin deep (high bromine). Thus, if a halite bed is penetrated by two drill holes located some distance apart, and well A has a higher bromine content at a given stratigraphic interval than well B, a bromine gradient is established, and a potash deposit may be present in the direction of the highest bromine content.

It follows then that, even though the maximum bromine values in drill holes penetrating a salt bed are below 200 ppm, the bed could still contain a potash deposit, depending on the position of the drill holes in relation to the regional paleosalinity gradient. In evaluating the potash potential of any salt bed, the difference between and the lowest and highest bromine values is probably more significant than whether the highest value exceeds 200 ppm. If the bed shows a difference, or an increase of 100 ppm bromine from bottom to top, there is an excellent possibility that somewhere the bed contains a potash deposit.

## STRATIGRAPHY OF EVAPORITES OF THE KHORAT PLATEAU AND VICINITY

Evaporite deposits consisting of gypsum, anhydrite, and halite are found in the general Khorat Plateau region, in rocks ranging from Paleozoic to Mesozoic age (table 2). The deposits of Cretaceous age in the Maha Sarakam Formation are better known and economically the most important and are treated in greatest detail in this report. The older evaporites should not be ignored, however, as they too may some day prove of economic importance.

### Paleozoic evaporites

Thick beds of anhydrite and gypsum have been penetrated in drill holes in the Loei River Valley (Jacobson and others, 1969, p. 18) about 75 kilometers west of the Khorat Plateau (see fig. 1). These deposits are along the west-dipping limb of the Loei anticline in rocks apparently belonging to the Kanchanaburi Group. A similar deposit (Phichit) is about 200 kilometers to the southwest. The latter was assigned to the

| Age | Rock unit | | | Character |
|---|---|---|---|---|
| Quaternary | | | Unnamed | Unconsolidated clay, sand, and gravel; laterite. |
| Tertiary | | | Unnamed | Basalt flows (only overlying Khorat Series on Khorat Plateau). |
| Cretaceous | Khorat Group | Upper | Maha Sarakham Formation*<br>Khok Kruat Formation | Sandstone, siltstone, shale, salt, and anhydrite-gypsum.<br>Sandstone, siltstone, and shale. |
| Jurassic | | Middle | Phu Phan Formation,<br>Sao Khua Formation*<br>Phra Wihan Formation | Massive sandstones with conglomeratic sandstone, siltstone, and shale. |
| Triassic | | Lower | Phu Kradung* Formation<br>Nam Phong Formation | Sandstone, siltstone, and conglomerate (including basal conglomerate). |
| | | | Unnamed | Andesite, rhyolite, tuff, agglomerate. |
| | | | Unnamed | Granodiorite and other intrusive rocks. |
| Permian | Kanchanaburi Group | | Ratburi Limestone | Massive limestone with shale and sandstone. |
| Carboniferous | | | Unnamed* | Sandstone, siltstone, shale, tuff and limestone. |
| Devonian | | | Unnamed | Sandstone, quartzite, phyllitic shale, slate, and limestone. |
| Silurian and older | | | Unnamed | Argillite, quartzite, slate, phyllite, schist. |

Table 2.--Stratigraphy of the Khorat Plateau region (adapted from Jacobson et al, 1969). Formations marked by asterisk are known or thought to be halite-bearing.

Maha Sarakam in the Khorat Group by Gardner (1967, p. 14); however, its similarity to the deposit at Loei plus other geologic relationships suggests that it more likely belongs in the Kanchanaburi Group. The more recently discovered deposit at Nakhan Sawan may also be correlative.

Outcrops of a red bed sequence were discovered by Borax and Stewart (1966, p. 15) between Loei and the escarpment of the Khorat Plateau. On the basis of stratigraphic position of these beds compared to nearby carbonates of the Ratburi Limestone, they felt the beds belong in the Kanchanaburi Group and may be equivalent to the evaporites at Loei.

In summary, all these relationships suggest that the Kanchanaburi Group, in addition to a thick section of marine carbonates, also contains a red bed-evaporite facies. This facies probably extends eastward into the Khorat Plateau. Whether the evaporite facies also contains halite deposits in the subsurface is unknown, but it certainly is a possibility. Thus, these rocks merit some consideration as a future target for potash exploration.

## Mesozoic evaporites

The most extensive evaporites in the Khorat Plateau region are in rocks of Mesozoic age. These rocks belong to the Khorat Group and range in geologic age from Triassic to Cretaceous (table 2). The entire sequence is about 4,000 meters thick, consists of red beds and evaporites, and forms the bedrock of the Khorat Plateau. The Khorat Group has been subdivided by numerous authors largely on the basis of topographic expression. For example, nonresistant siltstones and mudstones of the Sao Khua Formation are overlain and underlain by the resistant ridgeforming sandstones of the Phu Phan and Phra Wihan Formations. This cyclic alternation of resistant and nonresistant is highly significant in terms of prospecting for evaporites. The resistant, cleau, cross-bedded sandstone probably representa, as Borax and Stewart (1965, p. 7) suggest, deposition by an advancing and retreating sea. To the author's knowledge no significant deposits of evaporites are intimately associated with coarse-grained clastics. Evaporites are deposited in low-energy environments where transport of sediment particles larger than clay or siltsize would be highly unusual. Evaporites, then, are most likely to be found in the formations characterized by finer-grained mudstones and siltstones. Formations of this type in the Khorat Group include the Phu Khadung, Sao Khua, and Maha Sarakam. Evaporites are well known in the Maha Sarakam Formation but little data are available on those in the other two formations.

## Phu Khadung Formation

The Phu Khadung Formation, as measured by Ward and Bunnag (1964, p. 12) at the type locality, is more than 1,000 meters thick. Their description of the formation is as follows: "The lower one half of the section is poorly exposed and is mostly soft, micaceous, reddish brown and grayish red siltstone with mottling of greenish gray in some beds. Thick, pale red sandstones that are fine to very fine grained, well cemented, slightly calcareous, micaceous, and partly crossbedded occur above the middle of the section in a zone about 120 meters thick. Interbedded, calcareous, micaceous siltstones and sandstones characterize the upper part of the formation."

The precise age of the Phu Khadung Formation is unknown; however, it has been tentatively assigned to the Triassic by Borax and Stewart (1965) and by Ward and Bunnag (1964). This tentative age determination is based largely on correlation with strata in Laos and Cambodia that contain Triassic fossils.

At present there is no certainty that bedded evaporites are present in the Phu Khadung Formation, but some observations suggest that this is probable. At the northwest corner of the Khorat Plateau, gypsum and halite veins were found in drill core from the outcropping Phu Khadung at the Pa Mong damsite. The Colombo Report (Stapledon and others, 1963, p. 23-25) on the damsite refers to these evaporite-bearing rocks as the Sam Phan Na Formation, which are here correlated with the Phu Khadung Formation. No bedded evaporites were found in any of the drill cores; however, the veins of evaporite minerals are typical of strata from which bedded salt deposits have been removed by solution. The Sam Phan Na Formation at the damsite has been penetrated by only a few shallow core holes. Ground water moving downdip from the upturned edge of the outcrop has probably dissolved any salt beds that were originally present. Drill holes located farther downdip, where this formation would be intersected at depths of 300 meters or greater, might penetrate beds of salt.

Additional evidence of evaporites in the Phu Khadung Formation are some of the unusual synclinal structures along the western edge of the Khorat Plateau. The most striking of these structures is about 18 kilometers southwest of the Nam Phong damsite, near the village of

Phu Wiang. The unusual saucer shape of this depresseion suggests that it may have formed as the result of dissolution of underlying evaporites. These evaporites should most likely be in the Phu Khadung Formation although possibly older evaporites in the Kanchanburi Group are in this area. It should also be noted that groundwater has a higher than average chloride content in the area of this structure (Haworth and others, 1964, pl. 23).

## Sao Khua Formation

The Sao Khua Formation consists primarily of reddish-brown to grayish-red siltstone and minor amounts of yellow-brown and pale-red sandstone. Many of the sandstone units are crossbedded. A few thin lenticular beds of conglomerate consisting of pebbles of calcareous siltstone are present. The formation weathers deeply and forms strike valleys between the more resistant underlying Phra Wihan Formation and the overlying Phu Phan Formation. According to Ward and Bunnag (1964, p. 16), the formation ranges from 400 to 700 meters in thickness. The Sao Khua correlates with the Pla Buk Formation at the Pa Mong damsite. The Pla Buk is also a weak siltstone unit and is about 350 meters thick at the damsite. The Pla Buk also contains some thin calcareous-pebble conglomerates.

Although the Sao Khua Formation is sparsely fossiliferous, a diagnostic fauna has been collected. This includes gastropods, pelecypods, and an icthyosaur tooth, and from this assemblage the formation is dated as Jurassic.

Whether the Sao Khua contains bedded evaporites in the subsurface is not definitely known, as is true also of the Phu Khadung. At the Pa Mong damsite shallow drill holes penetrated siltstone containing traces of halite in this unit (Pla Buk). These holes were located well within the leached zone on the outcrop edge of the formation. Where the Mekong River crosses the Sao Khua outcrop a conspicuous wide pool, called the Pla Buk pool, has formed. The origin of the depression containing the pool is thought by Gardner and others (1967, p. 16) to be the result of collapse following the dissolution of salt. Gardner and others (1967, p. 17) also mention that "brine springs and wells in the mountains of northern Thailand and adjacent parts of Laos suggest that salt is being dissolved from lower strata of the Khorat Group."

All this evidence suggests that if deeper wells are drilled on the Khorat Plateau they may penetrate beds of halite in the Sao Khua Formation.

### Maha Sarakam Formation

The thick sequence of evaporites, nonresistant mudstone, siltstone, and minor sandstone forming the uppermost unit in the Khorat Group was named the Maha Sarakam Formation by Gardner and others (1967, p. 29). This formation is present only on the Khorat Plateau where it forms the bedrock of two large structural basins (fig. 3). Within the smaller and northernmost of these basins, the Sakon Nakhon, the Maha Sarakam Formation covers an area of about 21,000 square kilometers. Most of this area is in Thailand; however, along the Mekong River the formation

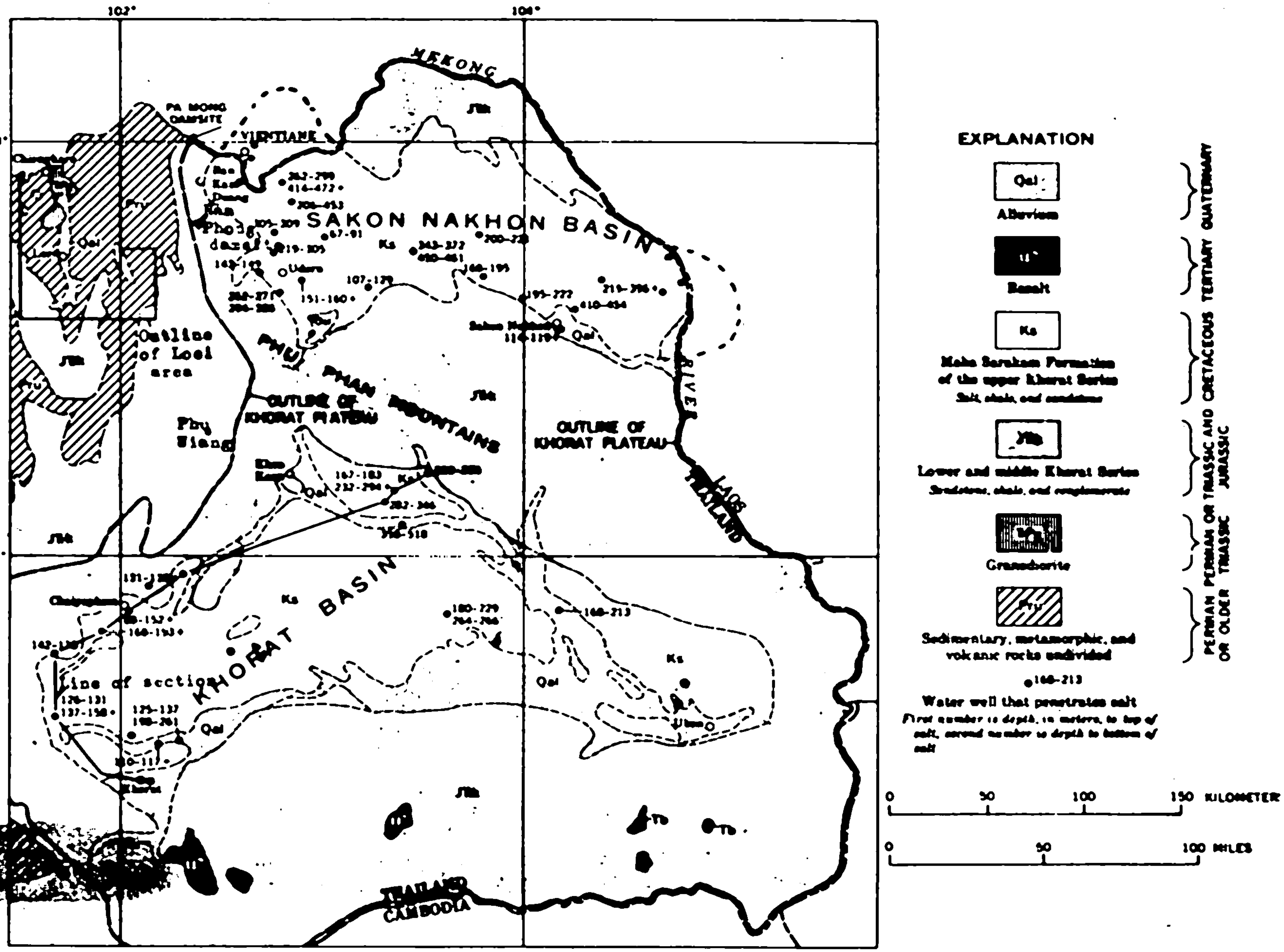


Figure 3.--Geologic map of northeast Thailand (adapted from Jacobson and others, 1969).

crosses into Laos at the Vientiane Plain and the plain near Savannakhet (fig. 1). To the south, the Maha Sarakam Formation covers about 36,000 square kilometers in the Khorat basin (fig. 3). These two basins are separated by the east-trending Phu Phan Mountains.

The maximum thickness of the Maha Sarakam Formation is unknown but Gardner and others (1967, p. 32) believe it may exceed 1,000 meters. In the Khorat basin the deepest drill hole penetrated 610 meters of the formation and was still in the formation at total depth. In the Sakon Nakhon basin several drill holes have penetrated as much as 450 meters without drilling through the formation. Estimates of thickness of the formation from surface exposures are unreliable, not only because of poor exposures but also because great thicknesses of halite have been leached from these outcrops.

There is no direct evidence for determining the age of the Maha Sarakam Formation. Because it is transitional with the underlying Khok Kruat Formation, which has been dated as Early Cretaceous on the basis of a pelecypod fauna, Gardner and others (1967, p. 35) suggest the formation is probably of Late Cretaceous age. The opportunity of determining a precise age seems best afforded by studies of fossil pollen content in the halite beds. This technique of palynological age determination has been described by Klaus (1970).

Although the halite deposits of the Maha Sarakam Formation are still relatively unexplored, there is little doubt that they rank with some of the world's larger deposits. At present, about 46 water wells have penetrated halite deposits in the formation in both the Sakon Nakhon and Khorat basins. Although many of these wells are widely separated, there is little evidence to suggest that the rock salt layers are not continuous between wells except where interrupted by structure. The present-day distribution of the halite deposits suggests that originally they were even more extensive. Several wells located along the margins of the present-day basins show that thick salt beds extend right up to the outcrop edge of the Maha Sarakam Formation (fig. 2). This suggests that originally the depositional edge of halite deposits extended considerably beyond the present limits of the Maha Sarakam Formation. In fact, these deposits may have been continuous between the Khorat and Sakon Nakhon basins and were simply removed by erosion over the Phu Phan uplift.

At least three wells in the Sakon Nakhon basin have penetrated more than 240 meters of massive halite. Another well at Udon Thani penetrated 225 meters and was still drilling in halite when abandoned. It is assumed that these wells penetrated a single vertically continuous bed of salt which may prove to be one of the thickest in the world. In the Khorat basin, the greatest continuous thickness of halite penetrated so far is more than 150 meters.

The total thickness of the halite facies in the Maha Sarakam Formation is unknown; the location of the thickest part of this facies is unknown. Normally the thickest accumulation of evaporites is associated with the lowest depression in the basin at the time of deposition. Well data suggests, however, that the configuration of the present-day structural basins of the Khorat Plateau may not coincide with the configuration of the original basin or basins in which the evaporites were deposited. Thus far the greatest thickness reported for the halite facies in the Sakon Nakhon basin is 344 meters (well No. E4UD1) near Udon Thani. In the Khorat basin an even greater thickness, 423 meters, was penetrated near Maha Sarakam (well No. F34MS2). It should also be noted that both wells were still in the halite facies at total depth.

In addition to massive beds, the halite facies of the Maha Sarakam Formation includes zones described as disseminated salt (Gardner and others, 1967, p. 89). In these zones it has been assumed that the halite is disseminated through a matrix of mudstone and siltstone. In many wells these zones in actuality may be massive salt beds. In fairness to the geologists who logged the cuttings of these wells it should be pointed out that frequently salt beds are drilled for many meters before halite is detected in the well cuttings. Halite is a very soluble mineral and until the drilling mud becomes saturated for sodium chloride it will not be found in the well cuttings. Even then cavings from strata above the salt can so dilute the sample that the well geologist may assume that the halite is interbedded or disseminated in other rock types. A good example of this problem can be seen in a comparison of data from one of the core holes (DH-1) at Chaiyaphum and an adjacent water well (fig. 4). The top of the massive halite layer is firmly established by the core hole at a depth of 58 meters. There is no evidence of faulting or folding between

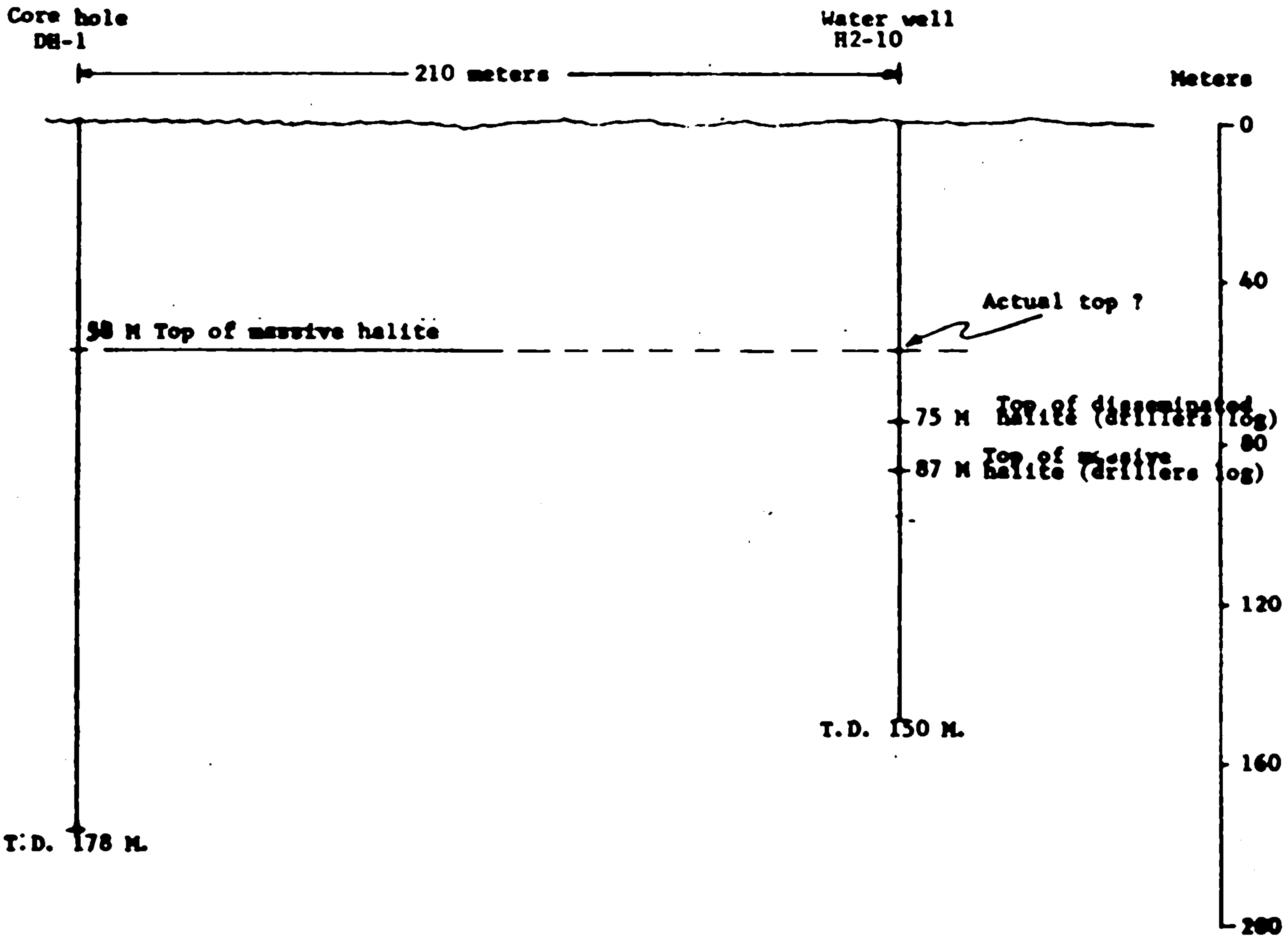


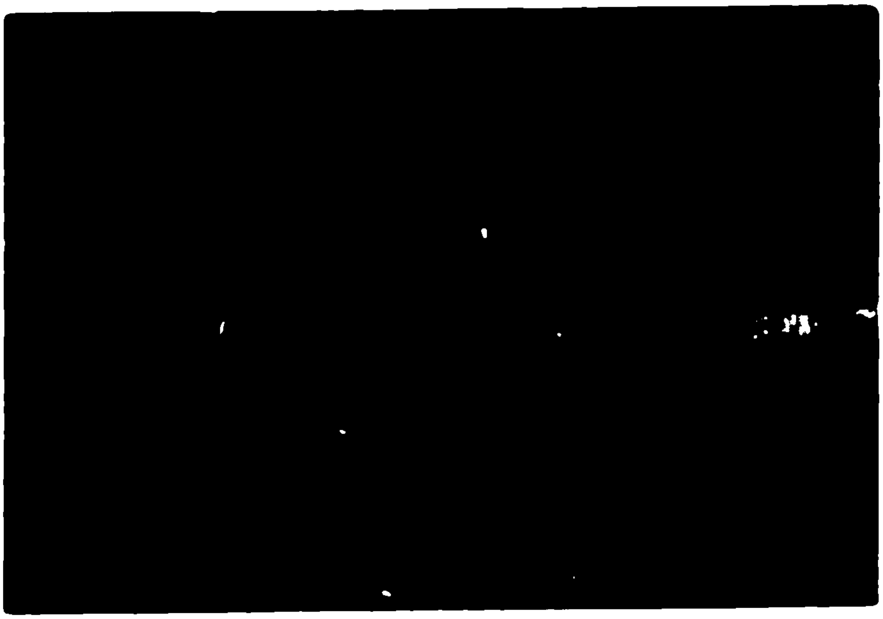
Figure 4.--Comparison of top of massive halite in Maha Sarakam Formation in core hole DH-1 and top picked on driller's log of water well H2-10.

the holes, which are separated by a distance of less than 240 meters. Therefore, it seems reasonable that the top of the massive halite should have been intersected at approximately the same depth in the water well. Note, however, that no indications of halite were logged until the well reached a depth of 75 meters. Massive halite was not reported until the well had reached a depth of 87 meters, or nearly 30 meters deeper than what may be the actual top as projected from core hole DH-1. In consideration of this example, and the history of drilling in many other salt deposits of the world, there is good reason to believe that most if not all the reported depths to massive halite in wells on the Khorat Plateau are deeper than the actual top. In addition, many of the intervals described as disseminated halite may be massive salt. Again, this is the result of drilling with fresh-water mud. Under these conditions the fragments of rock salt were dissolved in the mud column before reaching the surface.

The halite facies of the Maha Sarakam Formation is characterized by depositional cycles similar to those of other marine evaporites. The lithologic detail of a Maha Sarakam cycle has been recorded only at Chaiyaphum in the Khorat basin. In the core from five holes drilled in this area, two evaporite cycles can be observed (Jacobson and others, 1959, pl. 2). Lithologic units in the uppermost cycle consist of A) red claystone and siltstone, B) greenish-gray siltstone and claystone, and C) gypsum with scattered dolomite crystals. In order, the vertical sequence in this cycle is A, B, C, B, and A. The underlying cycle is more complex, consisting of units A and B of the above cycle, unit C which includes an upper gypsum layer and a lower anhydrite layer, and D) halite. The vertical sequence of units in this cycle in order is A, B, C, D, C, B, and A. A detailed description of this cycle is shown in figure 5.

In both cycles the gradual change from the red sediments of unit A to the grayish-green sediments in unit B represents the change from aerobic to the anaerobic conditions of the evaporite environment (fig. 6). In the upper cycle, all the calcium sulfate (unit C) is in the hydrous form (gypsum). In the underlying cycle only the upper C unit is gypsum and the lower is anhydrite. This is probably the result of hydrating the original anhydrite by groundwater. The basal anhydrite has been protected by the overlying impermeable layer of halite and is therefore unaltered. This also suggests that the upper cycle may originally have contained a halite unit but it has been leached out by groundwater. At greater depths halite may be found in this cycle.

Another unusual aspect of both of the evaporite cycles is the small amount of carbonate minerals present. In many evaporite deposits thick beds of limestone and dolomite are present in the vertical sequence of the evaporite cycle. This is expected because, as previously explained, sea water first becomes saturated for the carbonate minerals, and their precipitation must precede that of the more soluble sulfates and chlorides. It is possible that during the deposition of the Maha Sarakam evaporites, the carbonate minerals were deposited within the marine accessway and by the time the evaporite brine moved into the more distant reaches of the basin, it was depleted in these constituents. Thus, if a halite unit within one of the evaporite cycles were traced laterally toward the accessway, it would first grade into a sulfate facies which in turn would grade into a carbonate facies.



A. Halite core showing alternating bands of very pure halite (white) and anhydritic organic-rich layers (dark).

B. Base of evaporite cycle.

C. Top of cycle.

Figure 6.--Photographs showing drill core from Maha Sarakam evaporite cycle. Stratigraphic base of core is at lower left of core trays. Letter A marks contact of anhydrite and siltstone. Halite-anhydrite contact marked by letter H.

## GEOCHEMISTRY OF MAHA SARAKAM HALITE

One of the major objectives of the first-phase investigation of the Khorat Plateau salt deposits was to test the possibilities of using bromide geochemistry as a potash exploration tool. The author was hopeful that, in addition to the halite cores from the five holes at Chaiyaphum, cuttings from water wells which penetrated halite would provide material suitable for bromine analyses. Unfortunately, because of the ravages of insects, high humidity, and floods, the well cuttings could not be used. Despite this limitation in sample material, some very valuable data were obtained on bromine content of halite in the Maha Sarakam Formation.

Because the core holes at Chaiyaphum are located in a relatively small area, only samples from one core hole (DH-5) were chosen for analysis. One hundred sixty four samples composited from intervals approximately 0.6 meter thick were taken. These and halite picked from the cuttings from two wells drilled near Vientiane, Laos, were analyzed for bromine and $K_2O$ content. Analyses were made by X-ray fluorescence spectrometer in the U. S. Geological Survey laboratories in Denver, Colorado.

The bromine content of the halite at Chaiyaphum ranged from 30 to 150 ppm and the $K_2O$ from 20 to 160 ppm. When these values were plotted as statistically smoothed profiles (5-point moving averages) several significant relationships were observed (fig. 7). The lower three-fourths of the bromine profile shows a slow but continuous increase in bromine content from the base toward the top of the salt bed. Through an interval of nearly 85 meters the bromine content increases only by about 20 ppm.

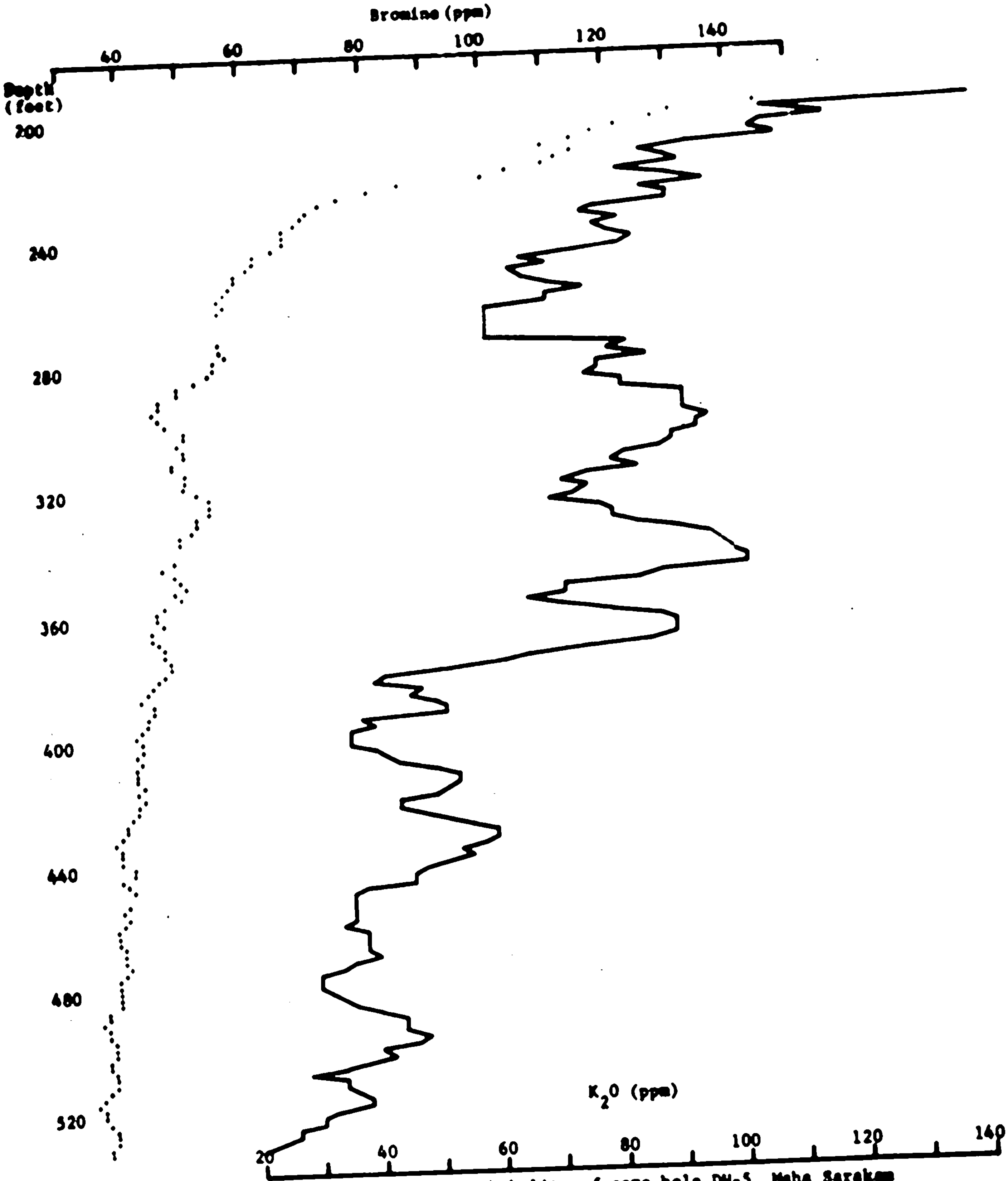


Figure 7.--Bromine and $K_2O$ distribution through halite of core hole DH-5, Maha Sarakam Formation, Chaiyaphum, Thailand. Analyses by X-ray fluorescence spectrometer.

This means that near equilibrium conditions between influx salt and reflux existed in the evaporite basin during this period, and salinity was increasing at a very slow rate. Above this point the bromine content in the halite increases rapidly from about 55 to 150 ppm. This suggests that during the deposition of the last 18 meters of halite, circulation between the evaporite basin and the open ocean was severely restricted, perhaps completely cut off. As a result, salinities within the basin began to increase very rapidly and may have become high enough to precipitate potash. The general shape of this profile is very similar to bromine profiles of potash-bearing evaporite cycles in the Zechstein Formation of Europe and the Paradox Formation of the U. S. A.

The two halite samples from Laos were picked from the cuttings of two water wells drilled on the Vientiane Plain near Vientiane. One sample as marked came from a depth of 253 meters and contained 127 ppm bromine. The other sample which was a composite from a different well from the interval 283-380 meters, contained 172 ppm bromine. The salt bed from which these samples were obtained may correlate with the bed at Chaiyaphum; however, at present there is insufficient data to demonstrate this. The stratigraphic position of these samples in the salt bed at Vientiane is also unknown. The average depth to the top of the salt in this area is probably about 60 meters. Thus, these samples were probably collected from somewhere in the upper third of the bed. These samples represent a mixture of halite fragments that came from different depths in the hole and perhaps span a stratigraphic interval of 10 meters or more. Therefore, the sample that contained 172 ppm bromine may have been a mixture of halite fragments containing less than 172 ppm and some containing more than that amount. This factor, coupled with the problem that this well probably penetrated 10 meters or more halite before the drilling fluid became salt saturated and halite fragments were preserved, strongly suggests that the halite at the top of the bed at Vientiane may contain well over 200 ppm bromine.

The analyses for trace amounts of $K_2O$ in closely spaced sample intervals in the halite bed at Chaiyaphum may be the first time a complete picture of potassium distribution through an evaporite cycle has been obtained. Ordinarily halite rock is not analyzed for $K_2O$ unless potash minerals are known to be present and the $K_2O$ content is generally above 1 percent. Many complete chemical analyses of halite rock giving $K_2O$ content are published (see Jacobson and others, 1969, p. 90-91); however, these analyses are seldom carried out to the third decimal place, and generally are from random, stratigraphically unoriented samples. The manner in which trace amounts of $K_2O$ forms in halite is unknown. It is unlikely that it is in solid solution with NaCl. It may be in submicroscopic crystals of potash minerals; however, even the formation of those tiny crystals is governed by the established phase-equilibria of the sea-water system, which shows that potash minerals are not precipitated until a large amount of halite has already crystallized from the solution. Therefore, the basal halite of any evaporite cycle should not be expected to contain potash minerals, and the trace amounts of potash present must be in some other form. The most likely form is in solution in the tiny fluid inclusions disseminated through all salt beds. These inclusions represent the mother brine from which the enclosing halite crystals grew.

The brine was trapped in the halite as the crystalline mass grew and was compacted. The brine from which the first crystals of halite grew should contain about 3,125 ppm K or 3,764 ppm $K_2O$. Assuming that the brine inclusions in the basal layer of halite at Chaiyaphum would contain a similar amount of $K_2O$, the 20 ppm reported in the analyses of this material would require that 0.53 weight percent of the sample consist of brine inclusions. This figure compares reasonably well with visual estimates of brine inclusions in halite of other evaporite deposits. The evidence cited here suggests that brine inclusions are the major source of trace $K_2O$ in the halite.

As more halite was deposited, the concentration of $K_2O$ in the parent brine would have increased, resulting in a corresponding increase in the trace amount of $K_2O$ in the solid phase. Thus, the trace $K_2O$ content would be a measure of paleosalinity of the brine. Note that on figure 7 increasing $K_2O$ content corresponds closely to the bromine profile. The numbers of brine inclusions in a salt bed will probably vary somewhat from one layer to the next; however, the average amount should be relatively consistent. The somewhat ragged nature of the $K_2O$ profile (fig. 7), with numerous spikes showing amplitudes of about 25 ppm, is probably the result of vertical variations in numbers of brine inclusions. The highest $K_2O$ value on the profile was 160 ppm. If the amount of brine inclusions in the upper part of the halite is about the same as the base, then the $K_2O$ content represents a concentration factor of X 8. On this basis the parent brine, at the time the uppermost halite was deposited, would have contained about 25,000 ppm $K_2O$. Evaporation of modern-day sea water shows that brines containing this much $K_2O$ are nearly saturated for potash and magnesium salt. This suggests that the brine which deposited the uppermost halite at Chaiyaphum may have been saturated for potash and magnesium salts at some deeper point in the basin. On this note it should be mentioned that Jacobson and others (1969, p. 71) noticed an easterly increase in the average $K_2O$ content in halite at Chaiyaphum.

In summary, the geochemistry of bromine and potassium in the rock salt of the Maha Sarakam Formation strongly suggests that potash deposits are present in the Khorat or Sakon Nakhon basins. Studies of the distribution of these elements in the halite from future core hole samples will be of great assistance in a potash exploration program.

## CORRELATION OF EVAPORITE CYCLES

Some investigators have suggested that some halite in the Maha Sarakam Formation is restricted to small local basins (Jacobson and others, 1969, p. 70). If this is true then exploration for potash deposits will be very difficult. Each small basin would have its own particular history of deposition. Some basins might contain potash and others would not, and a much greater density of drill holes would be required than if only one large basin were involved. It is the author's belief, however, that a halite bed such as penetrated at Chaiyaphum is continuous throughout both the Khorat and Sakon Nakhon basins and perhaps originally was continuous between the two basins. Evaporite basins of small extent show the influence of runoff from surrounding land areas. Evaporites deposited in these basins generally have a high clay content and are poorly bedded. Periods of runoff causing repeated dilution of basin brine and re-solution of salt are common and result in many intraformational disconformities. In addition, the bromine content in halite deposited in a small basin will show a much more erratic pattern of distribution. The salt at Chaiyaphum shows none of these characteristics. It contains very little if any clay, is uniformly bedded (fig. 6a), and as previously shown (fig. 7), it has a bromine profile characteristic of a marine evaporite basin that was too large to be freshened by minor periods of runoff. Understandably, a case for discontinuity of beds can be made if lithologic logs from water wells penetrating the Maha Sarakam Formation are taken at face value. However, as discussed in a previous section, the problems of accurately portraying the lithology of an evaporite sequence from well cuttings make it necessary to do some interpretation where regional correlation is involved.

One of the characteristics of marine evaporite deposits is the presence of lithologic units, sometimes only a few meters thick, consisting of anhydrite, dolomite, or shale that can be traced and correlated over thousands of square kilometers. Geophysical well logs, such as the gamma ray-neutron log, are particularly useful in correlating such units. These logs record slight lithologic changes in the bore hole that even a careful visual examination of core may miss. As a result, many of these correlative units or marker beds have a definitive character or "fingerprint" on the log which can be recognized throughout the evaporite basin. Unfortunately only a few electric logs were run in water wells on the Khorat Plateau, and this type of log is almost useless when one is working in an evaporite sequence.

Despite the lack of good geophysical logs, it is possible to make some regional stratigraphic correlations for the Maha Sarakam Formation by using only lithologic logs. By using lithologic units firmly established on data from the core holes at Chaiyaphum, several stratigraphic cross sections were drawn through the Khorat basin. In these sections the anhydrite of the upper evaporite cycle was used as a datum plane. This anhydrite bed (locally altered to gypsum) may be continuous over much of the Khorat basin, and if so it will make an excellent stratigraphic marker. As shown on figure 8, there are local variations in the thickness of this unit and in some wells it was not observed at all. Again, this is probably due to the inaccuracy of lithologic logs prepared from well cuttings rather than to a discontinuous and erratic distribution of the unit.

Correlation of the halite unit in the lower evaporite cycle at Chaiyaphum can be attempted in two ways. It can be assumed that the top of this unit correlates with the first massive salt recorded on driller's logs (solid or dashed line) or it can be correlated with the first material described as disseminated halite (dotted line). For reasons previously described, the latter is probably the best interpretation. The cross section (fig. 8) shows a definite thickening of the halite facies right up to the northern limits of the Maha Sarakam Formation in the Khorat basin. This suggests that originally the facies was continuous across the present Phu Phan uplift into the Sakon Nakhon basin. Cross sections in the Sakon Nakhon basin by Gardner and others (1967), and Watthanachan (1964) show a gypsum bed above the halite facies which, because of its similar stratigraphic position, may correlate with the anhydrite of the upper evaporite cycle in the Khorat basin.

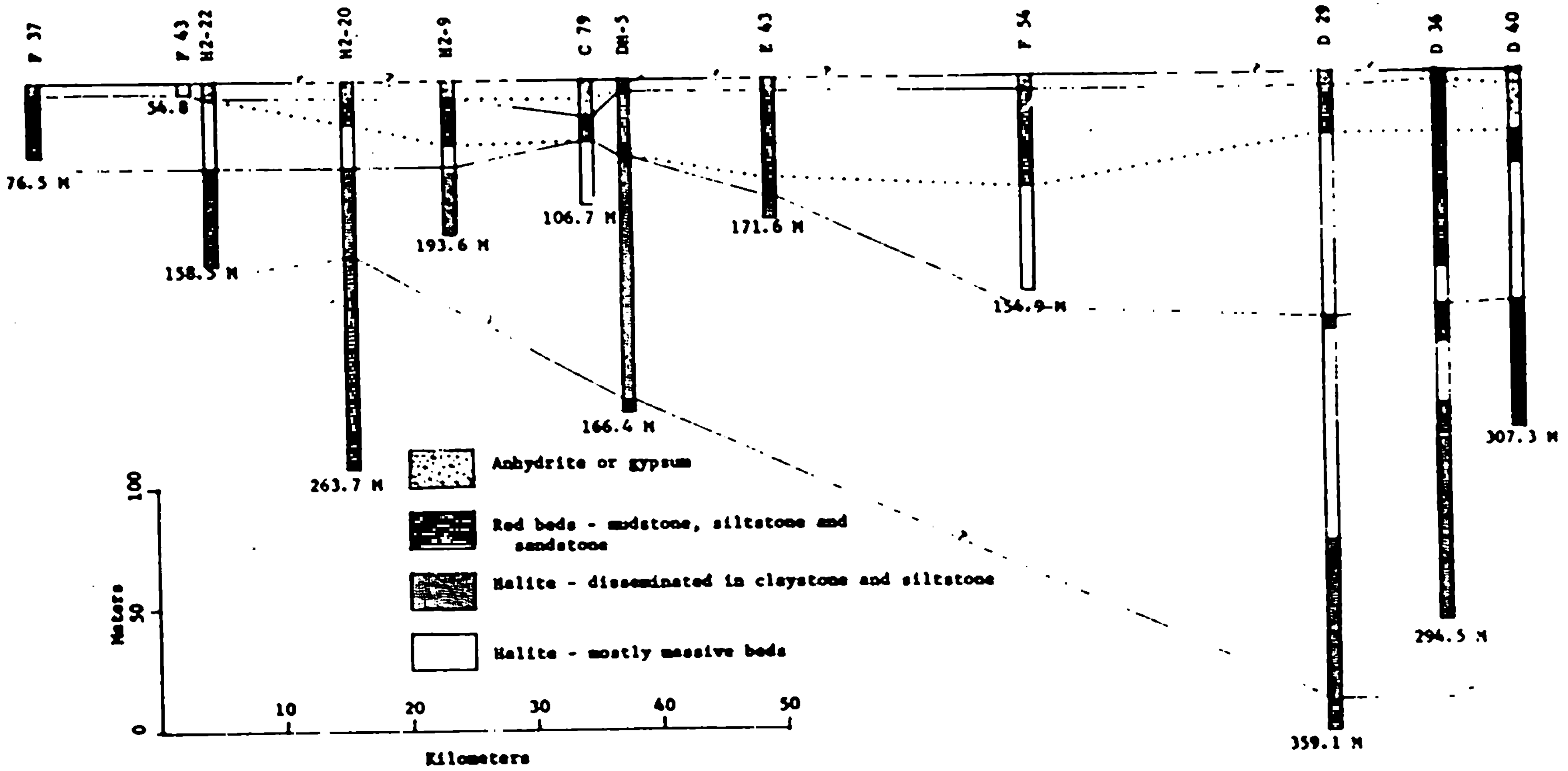


Figure 8.--Stratigraphic cross section through halite facies of Maha Sarakam Formation, in western half of Khorat basin. Datum is upper anhydrite cycle. Solid and dashed lines show boundaries interpreted from driller's logs. Dotted line represents alternate interpretation. Line of section shown on figure 2.

To summarize, this preliminary investigation suggests that with better data stratigraphic correlation in the Maha Sarakam Formation in both basins may not be a problem. It is possible that the upper anhydrite at Chaiyaphum is continuous over both the Khorat and Sakon Nakhon basins. If so, this bed can be used to guide future drilling for potash. As shown on figure 8 the thickness of the interval between the anhydrite marker and the top of the halite is relatively consistent. The geologist in charge of a drilling well should watch closely for evidence of penetration of this key bed. Once penetrated he will know approximately at what depth to expect the first halite. This will allow time to set surface casing, get the appropriate drilling mud in the hole, and switch over to coring equipment before the first halite is penetrated. This is extremely important because most potash deposits are at or near the top of the halite unit of the evaporite cycle. If the proper mud is not in the hole and the switch from drilling to coring has not been made before the top of the halite unit is penetrated, core of any potash deposit present will not be obtained.

## STRUCTURE

The Khorat Plateau forms a large (155,000 Km$^2$) block-like stable platform between two structurally complex orogenic belts that trend north along the Plateau's east and west boundaries. With the exception of the gentle open folds of Phu Phan uplift, which divides the Plateau into the Khorat and Sakon Nakhon basins (fig. 2), the Mesozoic rocks of the plateau are essentially undeformed. In size and structural configuration it is strikingly similar to the Colorado Plateau of the western U.S.A.

Within the Khorat and Sakon Nakhon basins regional dips probably average less than 2°. According to the geologic map of Haworth and others (1966, pl. 2), some large but gentle folds bring rocks of the Phu Phan Formation to the surface near Chaiyaphum. Practically no faults have been observed; however, this may be due in part to lack of outcrops.

The relatively undisturbed nature of the rocks on the Plateau is of great importance when considering the economic value of any potash deposits that may be found here. If potash deposits are broken by faulting or steep folds, the cost of mining may exceed the value of the ore even if it is in a high-grade deposit. All evidence at hand indicates that if potash deposits are found in the Maha Sarakam Formation they will be nearly flat-lying and unfaulted. Thick deposits of halite when deeply buried have a tendency to deform by plastic flow. The undisturbed anhydrite laminae in the halite cores at Chaiyaphum indicate that there has been no deformation of this type (see fig. 6a). In regard to depths, the halite in the Maha Sarakam Formation is unusually shallow. Around the margins of the Khorat and Sakon Nakhon basins the halite facies has been penetrated at depths of less than 60 meters. The shallowest depth reported is at Sakon Nakhon, where well FIOSN4 penetrated halite at a depth of 15 meters. Considering the amount of rainfall in this region, it is truly remarkable that deposits of highly soluble halite exist at such shallow depths. Near the structural axes of the two basins, maximum depths to the halite facies may be about 300 meters; however, compared to other salt deposits even this is a shallow depth.

# ECONOMIC GEOLOGY

The major emphasis of this investigation is placed on finding potash deposits in the evaporites of the Khorat Plateau. However, many other mineral resources are directly or indirectly associated with evaporites. A few of these resources for which the promise of discovery is excellent are discussed here in addition to potash.

## Potash

Prospecting for potash deposits is no different than prospecting for any mineral deposit in that there is no guarantee of success. There are few exploration targets, however, that have more favorable odds than the evaporites of the Khorat Plateau. Geochemical data has shown that at least one salt bed in the Khorat basin is an excellent prospect. Limited geochemical data from the Sakon Nakhon basin are also favorable. Many other deeper salt beds, any of which might contain potash, are probably present in both basins. Potash deposits, if present, will probably be flat lying and at shallow depths. It is possible that potash could be found here at depths of less than 60 meters, which would be one of the shallowest deposits of potash in the world. Rocks above the salt deposits have low permeabilities, and, therefore, no water problems should be encountered in sinking mine shafts. These aspects suggest that potash produced on the Khorat Plateau could favorably compete with the world's largest potash deposit in Saskatchewan, Canada. In that deposit most mine shafts are more than 1,000 meters deep, and a high-pressure aquifer above the salt deposits makes shaft sinking extremely hazardous and expensive. The initial investment to open a mine in the

Canadian deposits requires about 70-80 million dollars. Another favorable aspect of the Khorat Plateau is its accessibility. Most of the area is flat and many of the coreholes for a drilling project could be located near all-weather roads (fig. 9). In addition the area is serviced by railroad from Bangkok. This should substantially reduce exploration costs.

The economic value of a potash deposit on the Khorat Plateau will depend on the supply and demand in Asia. Annual consumption in Thailand is estimated at only 13,240 tons of $K_2O$ (United Nations, 1969, p. 7) which would probably not justify the expenditure necessary to bring a mine into production. However, total consumption for the region is expected to reach over 2 million tons of $K_2O$ by 1970-71 (op. cit., p. 6). A breakdown of consumption on an individual country basis is shown on table 3. In addition, it has been estimated that mainland China will soon be using 500,000 tons of $K_2O$ per year (Industrial Minerals, 1971, p. 10). Producers in the Canadian field are thought to be attempting to acquire this market. At present there is no production of potash in the Asiatic region although some production is expected late this year as a byproduct from sodium chloride brines at Lake McLeod in western Australia. This production may eventually satisfy all the Australian demand but little will be left for export. Therefore, there is a potential market for about 2-1/4 million tons of $K_2O$ that potash producers from the Khorat Plateau could compete for. At present the Canadian producers control most of this market, and they will offer the strongest competition for years to come.

Figure 9.--Photograph of typical Khorat Plateau topography. Rice paddies in foreground.

Table 3.--Annual consumption of potash in Asia and the Far East (Report prepared by Minerals Advisor, Mekong Secretariat, 1969).

| | Annual consumption 1965-66 (tons of $K_2O$) | Estimated domestic requirement 1965-66 | Projected annual consumption 1970-71 (tons of $K_2O$) |
|---|---|---|---|
| Austraila........ | 64,000 | n.e. | 166,400 |
| Cambodia......... | 300 | n.e. | 2,000 |
| Ceylon........... | 34,400 | 18,000 | 30,000 |
| China (Taiwan)... | 45,400 | 42,000 | 45,200 |
| India............ | 89,600 | 200,000 | 320,000 |
| Indonesia........ | 11,000 | 10,000 | 24,500 |
| Japan............ | 607,000 | 595,000 | 700,000 |
| Korea, Rep. of... | 40,100 | 55,200 | 269,000 |
| Laos............. | Nil | n.e. | n.e. |
| Malaysia......... | 15,300 | n.e. | 32,400 |
| New Zealand...... | 108,600 | n.e. | 309,000 |
| Pakistan......... | 2,300 | 18,000 | 50,000 |
| Philippines...... | 50,000 | 50,000 | 101,000 |
| Thailand......... | 5,000 | 4,000 | 13,240 |
| Viet-Nam......... | 11,100 | 15,400 | 39,700 |
| | | | 2,101,460 |
| | | [Corrected total, | 2,102,440] |

n.e., not estimated.

The Canadian potash field in the short time of 7 years became the world's leading producer (table 4). This field contains huge reserves of very rich sylvite ore and it will no doubt continue to dominate the industry for many years. A too-rapid expansion of Canadian production created an oversupply of potash, and during 1969 the price dropped to an all-time low of $11 per ton of muriate (KCl averaging 60-62 percent $K_2O$). To correct the problem of oversupply and price cutting, the Canadian government is now prorating production and setting minimum prices. For the year 1970 allowable production was set at 3-1/2 million tons $K_2O$. This was divided into separate quotas for nine operators.

To successfully compete with Canadian potash a producer should have a transportation advantage or a deposit which can be mined more economically. If potash deposits are discovered on the Khorat Plateau, they may have an advantage in both categories. The following comparison shows the advantage a Khorat deposit would have in terms of transportation costs to Manila:

| | |
|---|---|
| Canadian potash | |
| Rail freight (Regina to Vancouver) 1600 km | |
| 1600 x 5 mills/ton-km = | $ 8.00 |
| Ocean freight (Vancouver to Manila) 11,000 km | 11.00 |
| Total cost per ton | $ 19.00 |
| Khorat potash | |
| Rail freight (Udon to Bangkok) 460 km | |
| 460 x 5 mills/ton-km = | $ 2.30 |
| Ocean freight (Bangkok to Manila) 2,400 km | |
| 2400 x 1 mill/ton-km = | 2.40 |
| Total cost per ton | $4.70 |

Table 4.--World's potash production in thousands of tons $K_2O$

(Industrial Minerals, 1971, no. 42, p. 10).

|  | 1968 | 1969 | Rated capacity |
|---|---|---|---|
| Canada | 2,700 | 3,400 | 7,890 |
| USSR | 3,120 | 3,200 | 4,500 |
| USA | 2,469 | 2,544 | 3,500 |
| East Germany | 2,293 | 2,400 | 2,500+ |
| West Germany | 2,220 | 2,260 | 2,500 |
| France | 1,719 | 1,800 | 1,800 |
| Spain | 592 | 633 | 700+ |
| Israel | 366 | 400 | 600 |
| Italy | 266 | 259 | 300+ |
| Congo | -- | 50 | 500 |
| Total | 15,745 | 16,946 | 24,790 |

The above figures are based on estimated transportation rates in Canada and from Vancouver. No figures were available on rail freight charges in Thailand or ocean freight charter between Bangkok and Manila. It is possible that the actual rates are much lower. Although the total transportation costs used here are subject to correction, the comparative costs showing that a Khorat Plateau deposit would have a $10-$15 advantage in the Asian market are reasonably accurate.

If potash deposits are found in the Khorat Plateau it is possible that they might be mined more cheaply than the Canadian deposits. A comparison of factors influencing mining costs in both areas is made below:

| <u>Canadian</u> | <u>Khorat</u> |
|---|---|
| 1. Mining depths 1,000-900 M | 50 ?-300 M |
| 2. Difficult shaft sinking conditions | None |
| 3. Flat beds | Flat beds |
| 4. Rich ore | ? |
| 5. Good roof conditions | ? |
| 6. Low extraction ratio due to depths | High extraction ratio |
| 7. Expensive labor | Cheap labor |

In summary, a preliminary appraisal suggests that if potash deposits of sufficient thickness and $K_2O$ content are found in the Khorat Plateau, they should be able to compete economically for a share of the Asian market.

## Brines

Brines associated with evaporite deposits are often important sources of common salt, potash, bromine, boron, lithium, iodine, magnesium and sodium carbonate. These brines may be generated as the result of groundwater leaching of salt deposits or they may be fossil brines which were trapped in the sediment during deposition. The chemical composition of fossil brines is often altered from its original form by reactions between the brine and the enclosing rock.

Well-known localities of brine production in the U.S.A. include Searles Lake, California, Wendover, Utah, and the Michigan basin. Major brining industries using the many chemical compounds in these brines have been in existence for many years. The prospects for finding brines in the Khorat Plateau similar to those in the Michigan basin appear excellent.

The Michigan brines have been exploited for many years by Dow Chemical Company as a source of magnesium, bromine, and potash. In Michigan the brine aquifers crop out around the margins of the large saucer-shaped basin. Within the basin proper the brine-bearing horizons are underlain and overlain by evaporites. The densest and most valuable brines are found in the deepest part of the basin. The geologic conditions in the Khorat and Sakon Nakhon basins are very similar. Some brines of intermediate concentration have already been found in the Maha Sarakam Formation at shallow depths. Similar to the Michigan basin, the more highly concentrated brines should be found in the deepest parts of the two basins. The best brine aquifers in the Khorat Group will probably be found in coarse-grained sandstones and conglomerates of the Nam Phong, Phra Wihan, and Phu Phan Formations. These units, which alternate with the evaporite-bearing formations, should have much more favorable permeabilities than the latter.

The most valuable product from any brining industry on the Khorat Plateau would probably be magnesium chloride. This compound is the basic ingredient in the production of magnesium metal. Basically the process of refining the metal is by electrolysis of magnesium chloride, and a large source of cheap electrical power is required. With the eventual availability of large amounts of hydroelectric power from the Pa Mong dam, the development of a magnesium metal industry on the Khorat Plateau has considerable appeal. Magnesium, like potash, is subject to periods of oversupply; however, the market shows a steady pattern of growth. The growing use of magnesium in the automotive industry will probably be one of the most important influences on increasing consumption. Considering Japan's booming business in light-weight automobiles and motorcycles, a potential market for Khorat Plateau magnesium may already exist.

### Copper and uranium

The Khorat Plateau apparently has never produced copper or uranium and has never been regarded as a particularly favorable area to prospect for these commodities. If the geologic character of this vast area (155,000 $Km^2$) is examined closely, however, it becomes apparent that a potentially important mineral province may have been overlooked. From the hundreds of water wells drilled in this region, a large number of water analyses contained significant traces of copper (see tables in Jacobson and others, 1969). Of nearly 1,600 analyses, almost one-third contained Cu in values ranging from 0.10 to 5 ppm. These values are significantly above the normal background suggested by Hem (1970, p. 202) and probably indicate the presence of copper deposits in the

Khorat Group. When the location of wells containing 0.5 ppm or more Cu were plotted on a map of the Khorat Plateau, most fell within a large linear area that trends northwest across the Khorat basin (fig. 10). Within this anomaly it may be possible to find economically valuable sedimentary copper deposits. The geology of this type of deposit is discussed in the following paragraphs.

Sedimentary copper deposits associated with red beds and evaporites ranging from Precambrian to Tertiary in age are distributed throughout the world. Their association with red sediments has caused them to be commonly referred to as red bed coppers. These deposits are stratiform and are in both sandstone and shale layers. Sulfide minerals such as chalcocite and covellite are common in the unoxidized deposits, and the carbonates azurite and malachite are found in oxidized deposits. Although these deposits are associated with red beds, the mineralized zone is always a contrasting green to gray color. Not all of the lighter colored strata in a red-bed sequence will contain copper; however, much unnecessary sampling in any exploration program can be eliminated by concentrating only on the "gray-green" zones.

Another characteristic of sedimentary copper deposits is the presence of carbonaceous material or, in places, hydrocarbons. Most deposits in sandstone are lenticular and many are confined to old stream channels. The development of ore bodies in sandstones is apparently controlled by variations in permeability. Those deposits in sandstone are considered epigenetic. Some deposits in shale beds such as the recently discovered deposit near Creta, Oklahoma, may be syngenetic (Ham and Johnson, 1964).

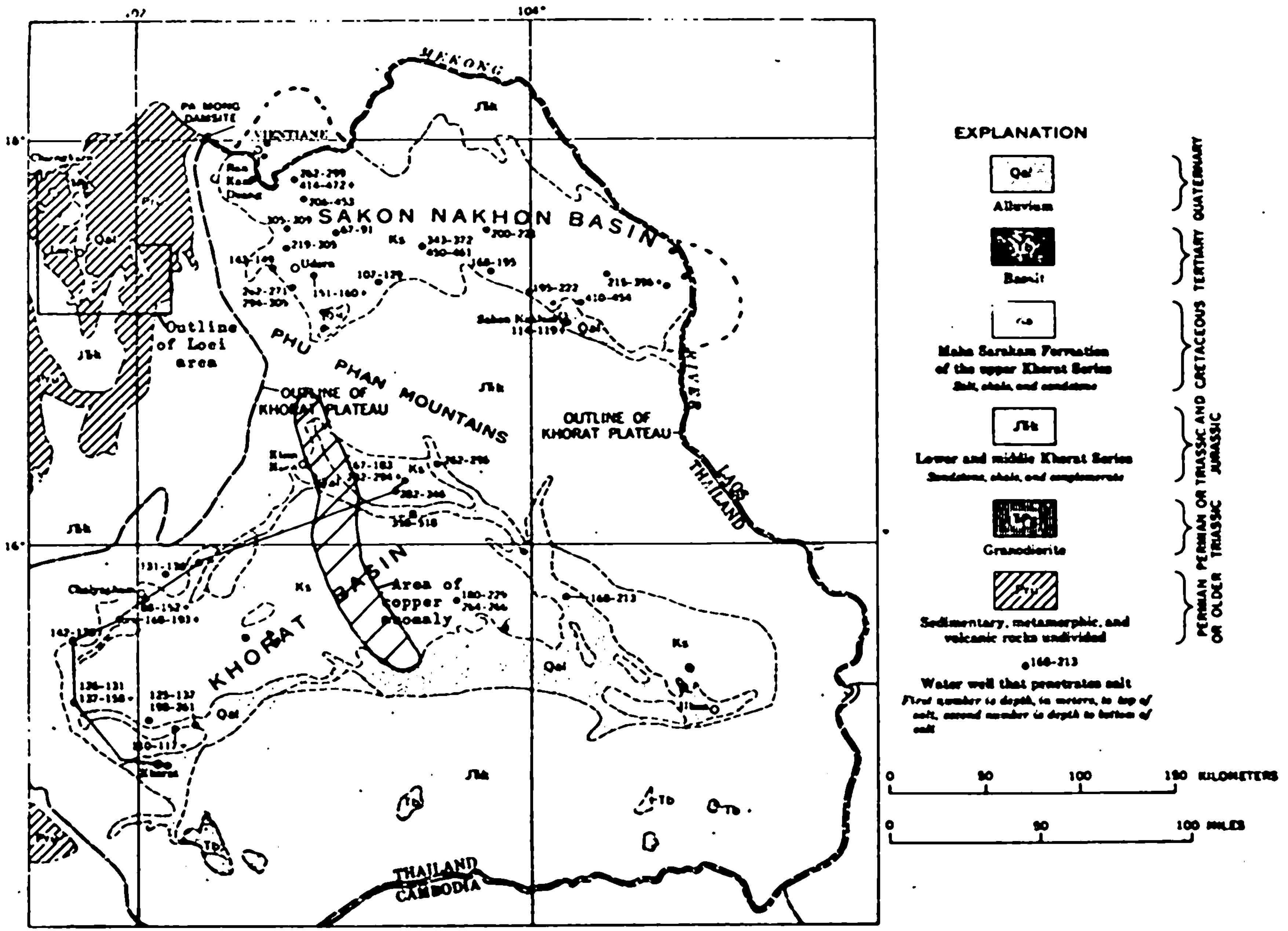


Figure 10.--Area of possible sedimentary copper deposits as suggested by geochemical anomaly in ground water.

There are many theories on the origin of sedimentary copper deposits; however, in the last decade most theories invoke evaporitic-type brines as the mineralizing solution (Davidson, 1965). These brines, which can either be fossil brines buried in the red bed-evaporite sequence or brines resulting from dissolution of salt beds, are highly active chemical agents. Detrital minerals soaking in these brines are decomposed and stripped of their trace metal content. The copper in the brine can be held in solution as a chloride or sulfate. These copper-rich brines moving through permeable zones in the red bed sequence would also solubilize and remove most of the hematite, leaving behind iron-depleted gray-green-colored strata. Where the brines come in contact with abundant organic remains or where they migrate in structural traps along with hydrocarbons, sulfate in the brine will be reduced by micro-organisms, producing $H_2S$. This biogenic $H_2S$ will react with copper in solution and sulfides will precipitate.

The migration of copper-rich brines through relatively impervious shale layers seems unlikely, so deposits formed in shale are probably syngenetic. In this type of deposit, reducing conditions on the bottom of an evaporite basin could bring about a constant precipitation of copper sulfides as long as a supply of organic matter was available. Under these conditions the source of copper in the brine could be reaction of brine with sediment around the shallow margins of the evaporite pan or highly saline streams draining into the pan.

The volume of copper in all the red bed deposits of the world must be enormous; however, individual deposits are commonly small. In western U.S.A. hundreds of localities have been noted in red beds of Permian, Triassic, and Jurassic age. Total production from New Mexico and Colorado has been estimated by Soulé (1956, p. 4) at about 21,000,000 pounds of copper. Some of the more important individual deposits, such as the Stauber mine in New Mexico, are known to have produced in excess of 5 million pounds of copper (Harley, 1940, p. 96). Favorable copper prices have recently revived interest in these types of deposits, resulting in several new discoveries and the reopening of old mines. The newly discovered deposit at Creta, Oklahoma, contains ore averaging 3.8 percent copper. Inferred reserves in this deposit total 137 million pounds of copper which can be removed by open-pit mining (Ham and Johnson, 1964, p. 27). In another new deposit near Cuba, New Mexico, a company has reportedly blocked out 15-20 million tons of strippable ore averaging 0.7 percent copper. Compared to some of the huge "porphry copper" deposits the typical red bed deposit appears quite small; however, if mining conditions are favorable and labor costs are low, these deposits offer an excellent profit margin to the medium-size mine operator.

Commercial deposits of uranium are commonly associated with copper in sandstones of the Colorado Plateau, U.S.A. (Gott and Erickson, 1952). By analogy, considering the many striking similarities between the geology of the Colorado and Khorat Plateaus, uranium deposits may be found in the latter. The Mesozoic rocks of the Khorat Plateau have all the characteristics of the host rocks of the Colorado Plateau deposits. This includes locally abundant organic matter, channel-type sandstones, and associated evaporites. To the author's knowledge no uranium minerals have been identified in the Khorat Plateau. Unfortunately no gamma-ray logs were run in the hundreds of water wells drilled in this area. Some of these wells may have penetrated uranium deposits. Without some direct evidence of uranium minerals, exploration by drilling is unwarranted. Future drilling in the area for water, potash, and copper may indirectly lead to the discovery of uranium if gamma-ray logs are routinely run in all drill holes.

In summary, the prospects of finding economically valuable deposits of copper in the Khorat Plateau appear excellent. The most favorable areas to explore are localities where the groundwater contains anomalous amounts of copper. Although the deposits may be relatively small, the cheap labor in the region would allow profitable small-scale mining operations. Because this region is also considered a favorable site for uranium deposits, gamma-ray logs should in the future be run in all drill holes.

# RECOMMENDATIONS

This preliminary investigation of the evaporites of the Khorat Plateau has shown that the possibilities of finding potash deposits and other related mineral commodities are excellent, and a follow-up program is justified. The recommended course of action for this program is outlined in the following paragraphs.

In regard to potash, the immediate exploration target should be the Maha Sarakam Formation in both the Khorat and Sakon Nakhon basins. Exploration of the older evaporites can be postponed until the Maha Sarakam has been thoroughly tested. At present so little is known about the regional geochemistry of the Maha Sarakam Formation that it is impossible to pinpoint favorable areas for drilling. Accordingly, the exploration program recommended here consists of two phases of work. The objectives of Phase I will be to provide the necessary data on regional distribution, stratigraphy, and geochemistry of the halite deposits which will isolate the area or areas most likely to contain potash. It is possible that a potash discovery could be made during this phase. Phase II will consist of close-spaced drilling within the specific target area outlined by Phase I. The objectives here will be to find potash and to determine the character and extent of the deposit.

## Phase I

The work in this phase should be performed in the following steps:

A. As soon as possible a cooperative program should be worked out with the Royal Thai Department of Mineral Resources for re-entering and running geophysical logs in all the water wells that penetrated the halite facies of the Maha Sarakam Formation. This would total nearly 15,000 meters of hole. Considering what it would cost to drill this much new hole, and the value of these logs to the entire program, the relatively small expense involved is more than justified. There is a good possibility that some of these old holes penetrated potash deposits. Thus, this first step of the program might result in a potash discovery. This work would involve drilling out cement plugs and putting the holes in proper condition for running logs. It is suggested that the Royal Thai Department of Mineral Resources could handle this part of the work. Ordinarily a logging service company could be called in to log these holes; however, because none of the companies are located in Thailand the expense would be prohibitive. Therefore, it is recommended that a U. S. Geological Survey specialist with the necessary expertise be assigned to the project. Both Geologic and Water Resources Divisions in Denver have the personnel and the type of equipment to do the job. New equipment would probably have to be purchased for the Thailand work. It would be advisable to have at least two trainees from the Department of Mineral Resources assigned to the logging team.

People with ability to operate and repair geophysical logging equipment are badly needed in both the Water Resources and Economic Geology Divisions of the Royal Thai Department of Mineral Resources and this would be an excellent training opportunity. As these logs are run they will be interpreted by the geologist in charge.

B. This step will entail drilling of four holes in the Khorat basin and four in the Sakon Nakon basin. It will not be necessary to complete step A prior to the start of drilling. The locations and approximate depths of these holes are shown on figure 11; however, as data from step A becomes available changes in plan may be necessary. Locations were picked that give maximum regional control and yet are close to the railroad or good roads. It should be possible to easily move a drill rig and supplies to these locations even during the rainy season. All of these holes will be cored continuously through the halite facies of the Maha Sarakam Formation. Unless depths are prohibitive, coring should be continued as long as the hole is still in halite. If brine zones are penetrated during drilling, samples should be collected for analysis. After the completion of each hole an appropriate set of geophysical logs will be run. Arrangements should be made for storing core where it can be protected from moisture during examination and sampling. Ultimately, it may be practical to store all cores at the Department of Mineral Resources facilities in Khorat. An estimated 15,000 feet of core will be needed to complete Phase I. All this drilling, with the exception of one hole near Vientiane, Laos, should be done through

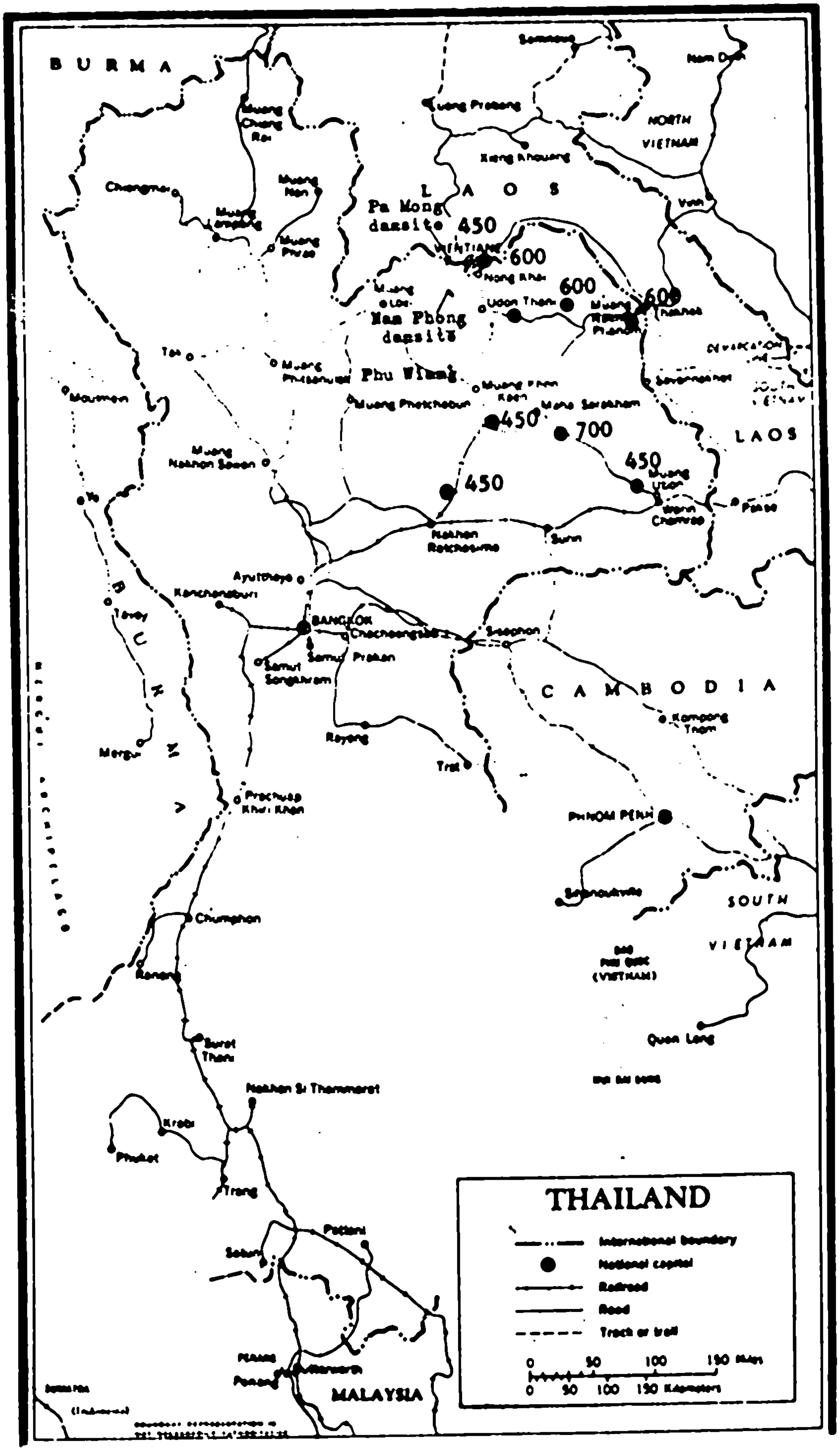


Figure 11.--Map showing tentative recommended potash core holes and approximate depth of the hole in meters.

a contractor. The Laos location could be drilled by the USAID Failing 1500 drill rig if a few minor items of equipment are purchased. A more detailed account of drilling techniques in salt deposits, equipment needs, availability of contractors and drilling services, and estimated costs of the Phase I program are included in a supplement to this report.

C. All halite cores will be sampled by slabbing the core with a diamond blade rock saw. These samples, which will amount to about 30 kilograms per hole, can be air freighted to U.S. Geological Survey laboratories at Denver, Colo., for bromine and $K_2O$ analyses. Results, which may influence the location of future drill holes, can be obtained and mailed to the geologist in charge in Thailand in a matter of days.

### Phase II

After completing Phase I and evaluating the data, the decision can be made on whether further drilling in the Maha Sarakam Formation is merited. Should it be decided to continue testing this formation, the pattern of exploration will be somewhat different than the preceding phase. The data from Phase I will allow drilling to be performed in a more selective manner. Drilling will be confined to a specific target area or areas. The size of these areas will dictate the spacing and number of drill holes needed. In addition, a specific stratigraphic horizon in the Maha Sarakam Formation will have been selected for testing. This will eliminate the need for continuous coring and might conceivably reduce the total depth of each hole by 50 percent. It may even be practical to completely eliminate coring, drill each hole using standard rock bits, and rely on geophysical logs to indicate the presence of potash minerals. This type of exploration could be done very cheaply. Once a potash deposit is discovered in this matter it then would be necessary to return to coring procedures in the follow-up drilling, at least through the mineralized interval.

If data from Phase I suggest that further prospecting of the Maha Sarakam Formation would not be rewarding, then attention should be focused on the older salt-bearing formations of the Khorat Group. The most logical place to drill these formations (Phu Khadung and Sao Khua) would be on one or more of the anticlinal structures of the Phu Phan uplift or possibly along the western edge of the Khorat basin. Elsewhere in both the Khorat and Sakon Nakhon basins the greater depths to these formations would put them out of reach of available drilling equipment. The Phu Khadung Formation is exposed in the cores of some of the large anticlines along the Phu Phan uplift. Therefore, by drilling on the crest of the structure and at two or three more locations, each a greater distance down dip, it would be possible to test both the Phu Khadung and Sao Khua Formations even with drill rigs of limited capacity. This drilling would also provide data of great value to future petroleum exploration in this area.

Prospecting for sedimentary copper deposits in the Khorat Plateau should involve a program similar to the investigations of Jacobson and others (1969) in the Loei region. Geochemical surveys including stream-sediment sampling and possible additional ground-water analyses would be useful. Electrical surveys should be attempted; however, they may be ineffective due to deeply oxidized sulfides and near-surface salt water. Targets for diamond drilling in the Maha Sarakam Formation would probably average less than 150 meters in depth. Copper deposits may also be present in some of the other formations of the Khorat Group. Drilling in these formations might be somewhat deeper.

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