

INTERPRETATION OF THE CHEMICAL ANALYSES OF  
THE GROUND WATER OF THE KHORAT  
PLATEAU, THAILAND

by

Charoen Phiancharoen

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SIGNED: C. Phiancharoen

## APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

John W. Harshbarger June 23, 1962  
JOHN W. HARSHBARGER Date  
Professor of Geology

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ABSTRACT

The Khorat Plateau of Northeastern Thailand is a shallow saucer-shaped basin tilted slightly to the southeast. It is divided into three structural provinces with the Phu Phan folds at the center and the Sakon Nakhon and Khorat Basins on the two flanks of the folds.

The plateau is mainly underlain by Triassic sandstone and shale of the Khorat Series, Permian limestone of the Rat Buri Series, and pre-Permian shale, sandstone, phyllite, slate, and quartzite of the Kanchana Buri Series. It is also overlain by shale and siltstone, with interbedded rock salt and gypsum of Jurassic and younger age. Alluvium and terrace deposits occur mainly along the courses of the Mun, Chi, and Mae Khong Rivers and in limestone terrane.

Ground water occurs within five aquifers: alluvium, upper shale and siltstone, Phu Phan sandstone, Phra Wihan and Phu Kadung

sandstones, and limestone. The ground-water system is recharged by the tropical monsoon rainfall with an annual average of about 1,330 millimeters.

The chemical quality of the ground water varies considerably. The major constituents in water of the alluvial aquifer are calcium, sodium, iron, chloride, and bicarbonate, which give hardness properties to water. The water has no salinity or alkali hazard for agriculture, however. The sources of chemical constituents are mainly from clay minerals in the aquifer and contamination with mineralized water from both the lower aquifer and leached zones.

The shale and siltstone aquifer produces water of most inferior character, among which sodium chloride, calcium sulfate, and calcium bicarbonate types are common. The principal sources of these chemical constituents are rock salts and gypsum layers existing within the aquifer. Percolating water carrying salts which have been laid down on the ground surface through capillary action and evaporation is also considered as another source.

Water in the Phu Phan sandstone and Phra Wihan and Phu Kadung sandstones is generally similar in properties and character. The major dissociated ions are iron, calcium, and bicarbonate, with sodium, chloride, and sulfate in places. The principal sources are impurities of cementing materials of sandstone, residual salts in

interbedded shale, and contamination by mineralized waters from overlying aquifers and leached zones. The property and character of water are satisfactory for most purposes.

The limestone aquifer is free from sodium and chloride, but contains high concentrations of calcium, magnesium, sulfate, and bicarbonate, of which the sources are dolomitic limestone and gypsum. These chemical constituents are usually responsible for carbonate hardness at shallow depths and noncarbonate hardness at greater depths. The water also has salinity hazards for agricultural uses.

For ground-water development, depths of wells within the shale and siltstone aquifer should be limited to not more than 300 feet, because the salty water mostly occurs in the deeper zones. In limestone, the well should not be more than 200 feet deep, due to the occurrence of highly saline water beyond the specified depth. In other aquifers the location and depth of wells are not critical.

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## INTRODUCTION

### Purpose and Scope

Many water wells in the Khorat Plateau, Northeast Thailand, have been abandoned because of inferior water quality. Waters from several wells contain high concentrations of elements such as iron, carbonate, chloride, or sulfate, whereas other wells nearby yield sweet water. The water quality in the area varies from place to place and vertically. Although more than 550 exploratory wells have been drilled and considerable data, including the chemical analyses of water, have been collected by the Thai Geological Survey, the special variations in water quality have not been scientifically studied. This report of interpretive study of the chemical analyses of the ground water in the area has three purposes: (1) to describe the chemical character of waters of good quality and of inferior quality existing under natural conditions, (2) to describe the sources of the chemical constituents in waters insofar as they can be identified and related to geology and hydrology, and (3) to determine the present extent of the water quality of all water-bearing zones of the area, including the contamination, pollution, or the chemical modification within the aquifers.

Included in this report are a discussion of the geology and a

geologic map of the area. The geologic map was prepared by the compilation of many data from surface and subsurface geology based on sample logs and electric logs, on a topographic map made by the U. S. Army Map Service, Corps of Engineers. The differentiation of the aquifers is made on the basis of stratigraphy, lithology, and water-bearing characteristics of the formations. General hydrology and ground-water hydrology affecting the water quality will be briefly discussed.

As an important part of this report, water-quality maps show the concentration and distribution of individual constituents over the area. The sources of each constituent with relation to the geology and hydrology of the area, as well as general considerations of the chemistry of those constituents in natural water, will be discussed.

The interpretive studies will be made by various comprehensive techniques such as the use of ratios, diagrams, graphs, or maps. The data used will be grouped as cations, anions, and others, including calculated values. The theoretical basis of interpretation will be included for the benefit of those who may be interested and cannot find the references in Thailand.

With proper studies of the chemical analyses, the general and critical water-quality problems of the area will be understandable. The knowledge thus gained will lead to recommendations for uses of ground water for domestic purposes, livestock, irrigation, and industry within

each political division of the area. Recommendation will also be made for the development of ground water with respect to the water quality over the plateau. This report is hoped to be beneficial for the recently established Ground Water Development Project of Northeast Thailand in guiding the selections of appropriate drilling sites.

### Location and Political Division

The Khorat Plateau is in the northeastern part of Thailand, between  $14^{\circ}$  and  $18^{\circ}$  latitude north and  $101^{\circ}$  and  $105.5^{\circ}$  longitude east. It is bounded on the north and the east by the Mae Khong River, separating Laos from Thailand, on the southeast and south by the outward-facing escarpment called Phanom Dong Rek, standing 200 meters to 500 meters above the Cambodian plain to the south, and on the southwest and west by Dong Phrayayen cuesta and the Petchabun Mountains, rising 800 to 1,000 meters above the Chao Phraya Plain to the west (fig. 1).

The Khorat Plateau, comprising an area of about 155,000 square kilometers, is politically divided into 15 counties, or "changwats" as they are called in Thai, on the basis of differences in population, topography, and areas. The names of these changwats are listed in table 1, as they will be referred to many times in this report.



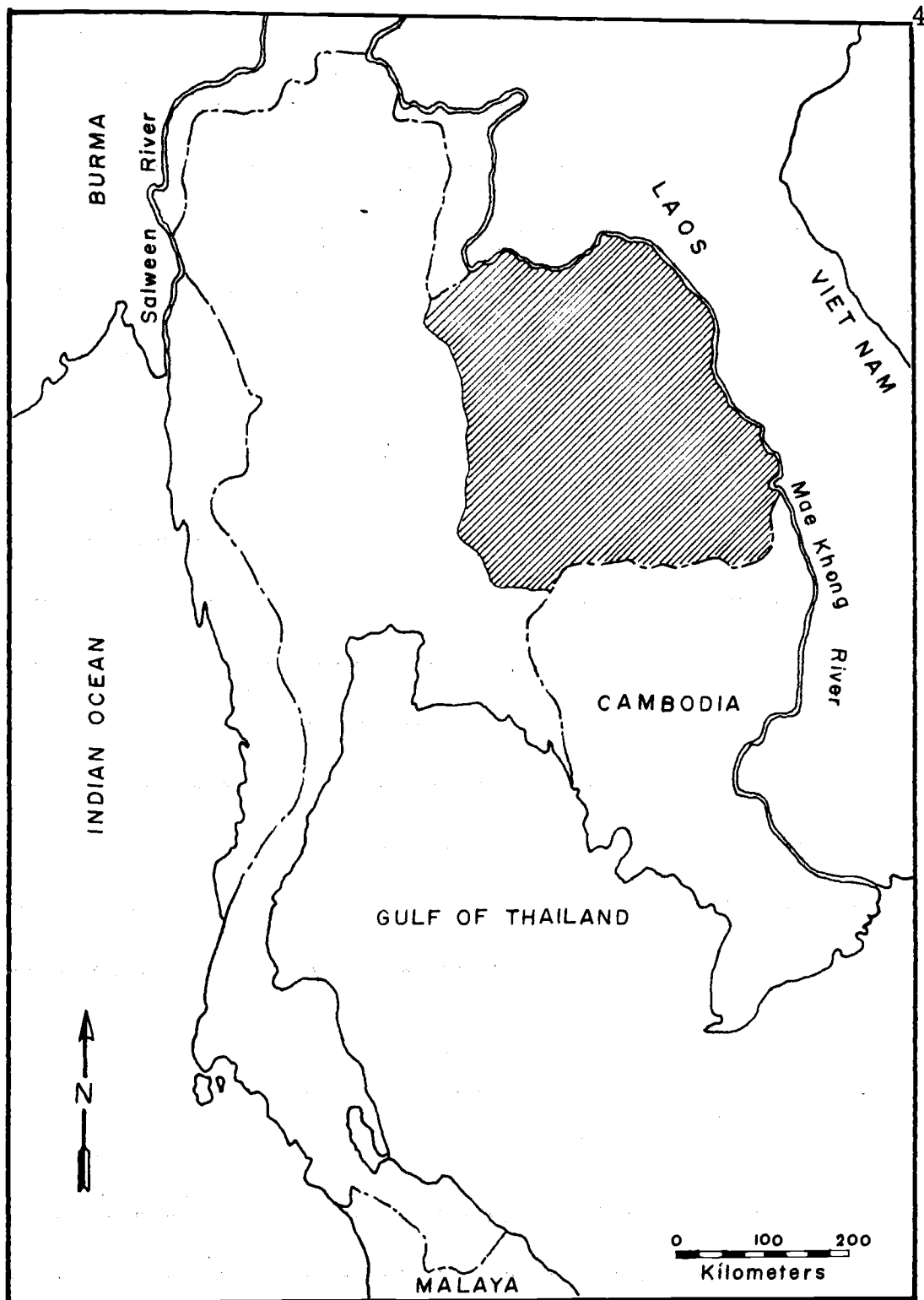


Figure 1 - Location map of Thailand. Shaded area is covered in this report.

TABLE 1  
LIST AND IDENTIFYING LETTERS OF THE  
POLITICAL DIVISIONS IN THE  
KHORAT PLATEAU

Number	Changwat (county)	Identifying letters
1	Buriram	B
2	Chaiyaphum	C
3	Kalasin	K
4	Khon Kaen	KK
5	Loei	L
6	Mahasarakham	Ms
7	Nakhon Phanom	NP
8	Nakhon Ratchasima	NR
9	Nong Khai	NK
10	Roi-et	R
11	Sakon Nakhon	SN
12	Sisaket	SK
13	Surin	S
14	Ubon Ratchathani	Ub
15	Udon Thani	Ud

## Ground-Water Investigations

A well-drilling program in the Khorat Plateau was initiated by the Royal Department of Health under the Economic Commission for Asia and the Far East (ECAFE) aid in 1952. Data and information from 374 shallow wells drilled under this program prior to 1955 will not be treated in this report, as the unreliability of poorly collected data and poor distribution of wells does not permit a valid analysis.

In 1955, the Ground Water Exploration Project was established by the coordination of the Royal Department of Mines, the Royal Department of Health, the Royal Irrigation Department, and the United States Operation Mission (USOM) for Thailand. This project as submitted was based on recommendations of P. E. LaMoreaux, U. S. Geological Survey, and geologist of the Thai Geological Survey. By 1956 this program completed 83 wells with depths ranging from 40 to 1,290 feet. Several complete chemical analyses of waters from these wells are available.

In 1958 the project was turned over to the Royal Department of Mines with continuing USOM aid. A 3-year contract was awarded to the firm of Daniel, Mann, Johnson, and Mendenhall, Inc., Los Angeles, California, for an accelerated ground-water investigation. By the expiration of the contract in 1961 the contractor, with the cooperation of geologists and engineers of the Thai Geological Survey, completed 411

wells including most geologic and hydrologic data.

After the contract expired, the project was again turned over to the Royal Department of Mines who are carrying on the exploration and development of ground water over the entire area of Thailand at the present time.

### Sources of Data

From the wells drilled by the contractor, 297 complete analyses and 300 field analyses (for chloride only) were used for study. Fifty incomplete analyses from wells drilled by the Department of Health and the Irrigation Department were also made available. In addition, 110 complete analyses of surface waters are at hand. Ground-water samples were collected by both the contractor's personnel and Thai geologists and engineers. All surface-water samples were collected by Thai engineers. Fifty percent of the surface-water samples were collected by the author from rivers, streams, and ponds. All samples were analyzed by the Thai Geological Survey laboratory.

Other than data mentioned, 424 sample logs, 85 electric logs, 119 pumping tests, and all well records were available for study of the geology and ground-water hydrology of the area.

Surface geologic data and a topographic map made by the U. S. Army Map Service were also available.

### Well-Numbering System

The well-numbering system used by the contractor was designated by the Royal Department of Mines. The following is quoted from Haworth, Charaljavanaphet, and Na Chiangmai (1959):

A well numbering system was devised for ready reckoning. This consists of a capital letter followed by a number, another capital letter or letters and another number. The first letter designates a particular rig, viz. rig A, B, C, and D, respectively. The following number shows the total number of wells drilled to date by that particular rig. The next letter or letters is abbreviation of the changwat as shown in the preceding tabulation. The last number is the total number, to date, of wells drilled by that rig in that changwat. Thus A10S9 designates the tenth well drilled with rig A and the ninth well drilled by rig A in changwat Surin.

The Department of Health and the Irrigation Department designated a numbering system by their abbreviations—"H" for the former and "I" for the latter. Following those letters are "1" and "2" representing rig numbers, then a dash (-), and another number representing total wells drilled by a particular rig. Thus, H1-25 and I2-4 indicate the 25th well drilled by Health Department rig number 1, and the 4th well drilled by Irrigation Department rig number 2, respectively.

### Acknowledgments

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## GEOGRAPHY

### Physiography and Drainage

A general feature of the Khorat Plateau is the shallow basin or saucer-shaped area tilted slightly to the southeast. At margins of the plateau, relatively well-cemented sandstone crops out as flat-topped mountains or dissected old peneplain surfaces, from 500 to more than 1,000 meters above mean sea level. The ridge-forming sandstone dips gently, about  $3^{\circ}$  to  $10^{\circ}$ , toward and under the center of the plateau, which contains a monotonous plain of 150 meters in elevation, broken hills or monadnocks, cuestas, and swamps. Immediately northeast of the center of the plateau there is a series of folded mountains of 700 to 1,000 meters in elevation. These mountains, the Phu Phan Range, trend northwest-southeast and slope gently northeast-southwest. The inclined rocks of both marginal ridges and the Phu Phan Range form two flanking shallow depressions or structural and topographic basins within the bowl-shaped area described.

The larger basin southwest of the Phu Phan Range is called the Khorat Basin, comprising an area of about 137,000 square kilometers, with an altitude of 150 meters at the center. This basin is drained entirely by the Mun River system with headwaters in the



southwesternmost range of hills and a course due east along the southern part of the basin. The watershed area is about 82,000 square kilometers. The Mun River receives part of its water from its principal tributary, the Chi River, which originates from the western margin of the plateau. The Chi River, with 55,000 square kilometers watershed area, flows in an arc through the center of the basin and joins the Mun River at Ubon Ratchathani. From there the two rivers and their tributaries flow through a series of rapids, and drain to the Mae Khong River at the southeast corner of the plateau (pl. I).

The smaller basin northeast of the Phu Phan Range is called Sakon Nakhon Basin, comprising an area of about 43,000 square kilometers with approximately the same elevation as the Khorat Basin. Most streams within this basin discharge into Nong Lahan which is the depression containing the largest fresh-water lake in Thailand. The lake has an area of about 170 square kilometers and drains to the Mae Khong River by Nam Kam Stream. The Songkhram River, located in the northern part of the basin, forms a minor drainage system by discharging into the Mae Khong River at the northeast corner of the plateau.

Both the Khorat Basin and the Sakon Nakhon Basin undoubtedly owe their flatness to long continued action of streams, including both lateral corrosion and vertical accretion. Most streams and rivers are at equilibrium profiles with very low gradients. Some of them, especially the Mun and Chi, may be considered as old age rivers, as

indicated by meanders, flood plains, and oxbow lakes. The flat surfaces of the basins may, therefore, be considered as peneplains. However, the lower Mun River and the Mae Khong River, to which it is tributary, are not graded, but both are actively downcutting and forming gorges. This downcutting of the lower Mun River led Lee (1923) to postulate that the Khong region has been raised since the grade of the upper Mun River was established, and that not sufficient time has elapsed for the upper part of the river to deepen its channel.

The areas mentioned so far do not include the northwestern part of the plateau which is higher than the basins, and where the features and drainage patterns are rather different. The general topography is of the ridge and valley type. A few monadnocks show remnants of a once extensive older surface, now nearly everywhere destroyed by erosion. Among those structures one mesa, the Phu Kading, stands some 1,000 meters above the plain nearby. The elongated, west-facing Nong Bua Lamphu cuesta just west of Udon Thani rises about 50 meters above the inner lowland where the altitude is about 200 meters, and acts as the borderline between the Sakon Nakhon Basin to the east and the ridge and valley region to the west. The drainage system of this region is rather complex. Some streams flow along the water gaps of the Nong Bua Lamphu cuesta and drain into the Sakon Nakhon Basin, while others are beheaded and flow along the inner lowland either north or south, leaving their old courses as wind gaps. The south-flowing

streams discharge into the Chi River and the north-flowing streams into the Mae Khong River.

### Climate

The Khorat Plateau experiences the influence of monsoon winds of seasonal character. During the period of southwest monsoon, from May to September, a stream of warm moist air is brought from the Indian Ocean, causing abundant rain over the plateau. The average monthly rainfall during this season is about 200 mm in comparison with 1,330 mm of annual rainfall. During the retreat of the southwest monsoon from the end of September to October, variable winds are experienced and rainfall usually decreases markedly. It is the transitional period from the southwest to northeast monsoon season which starts from November to February. This latter monsoon tends to invade the plateau with dry and cold air, but is not so persistent as the southwest monsoon. From November on, rainfall diminishes gradually, and the weather becomes dry and relatively cool in December and January. The daily temperature difference during this period is about  $23.4^{\circ}\text{F}$  to  $36^{\circ}\text{F}$ , with maximum temperatures of about  $87.8^{\circ}\text{F}$  and a minimum of about  $59^{\circ}\text{F}$ . However, outbreaks of cold air from Siberia and China occasionally bring down the temperature to about the freezing point. In summer, from March to April, or during the transition period from the northeast to southwest monsoon, the weather becomes hottest. The

temperatures range from about  $91.4^{\circ}\text{F}$  to  $100.4^{\circ}\text{F}$ , and unusually high temperature may rise up to  $110^{\circ}\text{F}$ . The rainfall during this season is relatively slight, except for some thunderstorm days.

The annual mean relative humidity over the plateau is between 70 and 80 percent. The lowest relative humidity is about 65 to 70 percent during the cool or northeast monsoon season, and the highest is about 85 percent during the summer.

## GEOLOGY

The Khorat Plateau is made up mostly of sedimentary rocks such as sandstone, siltstone, and shale. Igneous rocks and metamorphic rocks are present in places. The age of these rocks is still in debate among the geologists. Only a few fossils have been found in the plateau, except for a relatively large amount of petrified wood. The designation for ages of rocks is made entirely by the correlation with rocks of known ages in other areas where the lithology and stratigraphy are similar.

### Rock Units

#### Kanchana Buri Series (Cambrian-Devonian?)

Rocks of the Kanchana Buri Series underlie the plateau and crop out along the base of the escarpment and along roadcuts both in the southwest and northeast corners of the plateau. They comprise complexly folded shale, sandy shale, and sandstone which have been metamorphosed in places to slate, phyllite, and quartzite. The shale is massive, hard, nodular in places, and dark to light gray in color. The recent discovery of a trilobite (Thaiaspis sethaputi Kobayashi) in Loei indicates that rocks of the Kanchana Buri Series in that area may

be Cambrian in age.

### Rat Buri Series (Permian)

Rocks of the Rat Buri Series are dominantly marine limestones with interbedded gypsum in places. The Permian dolomitic limestones, lying unconformably on the Kanchana Buri rocks, are massive, crystalline, and light gray to gray. The limestones, for the most part, have been folded and in some localities recrystallized to marble. The outcrops are found only in the southwest and northwest corners of the plateau, but reappear again in Laos or east of the Mae Khong River. This forms the basis for the assumption that the Rat Buri limestone underlies the entire area of the plateau, although it has never been reached by any wells drilled within the basins.

### Khorat Series (Triassic?)

Rocks of the Khorat Series crop out in a large continuous circular pattern. They consist of indurated shale, shaly sandstone, fine- to coarse-grained sandstone, and conglomerate. The age of this series is still discussed. Lee (1923, p. 6) suggests a Lower or Middle Triassic age. Brown, et al. (1951, p. 25) give the age as Triassic and Jurassic on the basis of pelecypods and gastropods found in rocks of the same lithology at Chiang Rai near the northern border of Thailand.

LaMoreaux, et al. (1959, p. 19) believe in an age of Triassic. Marren (1961, p. 23) disagrees with the previous considerations, but gives the age of Jurassic on the basis of correlation with Jurassic rocks, in Laos and Cambodia, of which the age was assigned by French geologists. However, for the sake of simplicity the age of the Khorat Series will be assumed to be Triassic and it is divided into three members as follows.

#### Phu Kadung member (Triassic)

The member consists of a basal conglomerate of red shale containing boulders of quartzite from the Kanchana Buri Series. The conglomerate is overlain by massive fine- to coarse-grained sandy and micaceous bright-red shale with some thin beds of purple to gray and green shale. This member lies unconformably on rocks of Paleozoic age.

#### Phra Wihan member (Middle Triassic)

The Phra Wihan member lies conformably on the Phu Kadung member and consists of sandstone and interbedded micaceous shale. The sandstone is very fine to fine grained, micaceous, and purplish gray to gray. The sandstone grades into the shale of the lower member. Some lignite layers and petrified wood are also present.

### Phu Phan member (Upper Triassic)

Rocks of this member are the most resistant of all the sedimentary rocks in the area. They comprise sandstone and conglomerate forming tops of monadnocks, mesas, cuevas, hills, and the escarpment of the plateau. The sandstone is fine to medium grained, pebbly to conglomeratic in places, arkosic, crossbedded, and grayish tan to white. Some thin beds of shale of the same colors are also present. The Phu Phan member is easily differentiated from the lower member by its white basal conglomerate and pebbly sandstone.

### Beds of Jurassic(?) and Cretaceous(?) Age (Unnamed)

Rocks of this series are dominated by shale and siltstone occupying the lower parts of basin surfaces, which are about 60 percent of the total area. The shale is very fine to silty and red to reddish brown. The siltstone is massive, hard, and reddish brown to grayish red. Both the shale and siltstone contain rock salt (halite) ranging from minute layers to more than 700 feet thick. Gypsum layers are also present but none are more than 10 feet thick. Lignite is also found in core samples.

### Alluvium and Terrace Deposits (Quaternary to Recent)

Alluvium is present as belts along most stream courses,



although in many places it is only a surficial veneer. The terrace deposits are found as valley fills along the limestone terranes on the northwest corner of the plateau. The bulk of alluvial deposits, of varying thickness, is mapped along Mun, Chi, and Mae Khong Rivers (pl. I). These deposits are of special interest because they form an excellent aquifer in the plateau.

Most of the alluvial deposits are less than 250 feet thick, although 550 and 500 feet of deposits has been penetrated by holes drilled in Nakhon Ratchasima and Ubon Ratchathani, respectively. The terrace deposits in Loei are not more than 100 feet thick. The deposits were probably laid down during two periods, as indicated by their composition and texture. The older deposit, mostly found in the Nakhon Ratchasima region, consists primarily of poorly sorted clay, silt, very fine to coarse sand, gravel, and well-rounded basaltic pebbles. Chips of petrified wood, granitoid rock fragments, and mica flakes are also found in the lower part of the deposit. The thickness ranges from less than 50 feet in most areas to the maximum of 200 feet in Nakhon Ratchasima. The younger alluvium is mostly of fluvial origin, and the sediments were originally derived from sandstone. The deposit consists of relatively well-sorted sand, gravel, silt, and clay. The sand and gravel are usually of angular to subrounded fragments, and are loosely compacted. The typical deposit is found along the banks of the Mae Khong River where sand and gravel beds are penetrated by dug

wells and yield adequate amounts of water for inhabitants all year round. The thickness of the deposit ranges from a few feet in most areas to about 250 feet along the courses of major rivers.

Characteristically associated with many erosional surfaces are residual capping layers of ferruginous laterite not more than 15 feet deep. The laterite is principally formed by the leaching effect of surface soils during alternating wet and dry seasons and is limited to the zone of fluctuation of the water table. Typical of these laterite layers is one found along the highway south of Sisaket where a spongy or vesicular structure with septa of limonite in the cavities is common.

The age determination of the alluvium and terrace deposits is based on fossil mammals found in the central plain of Thailand. The older alluvium is believed to be late Pleistocene, while the younger alluvium is designated as Recent in age.

### Igneous Rocks

Rocks of igneous origin were emplaced in the area during three periods. The first was a granite of Early Triassic age exposed at Chun Tuk near the southwest corner of the plateau where copper deposits have been found. The second igneous episode includes the basalt flows, dikes, and plugs occurring in Buriram, Surin, and Sisaket near the southernmost border of the plateau. Their ages are uncertain, but doubtfully considered as Tertiary by Brown, et al. (1951, p. 47). The

third and last igneous activity in Thailand was the intrusion of the rhyolite porphyry which crops out in the north-northwesternmost border of the plateau and extends across the Mae Khong River to Laos. The age of the rhyolite porphyry is presumably Late Tertiary.

### Geologic History and Structure

Prior to the Triassic period the Khorat Plateau area was a peneplain surface of complexly folded Paleozoic rocks. During Triassic time the area gradually subsided and became in part a flat alluvial plain and in part a broad shallow sea where Lower Triassic marine red beds were deposited. The red beds were covered by purplish-gray, gray, gray-tan, micaceous and very fine grained sandstone and sandy shale of Middle Triassic age. With modified depositional conditions, thin beds of white conglomerate and conglomeratic sandstone were deposited first and followed by fine- to coarse-grained, grayish-tan to white crossbedded arkosic sandstone and shale of Upper Triassic age. The alluvial plains and a very shallow sea might have existed until Late Tertiary.

At the end of the Triassic period the folded Phu Phan Range with faulting along both flanks was created by crustal movement. The Khorat Basin and Sakon Nakhon Basin were consequently formed along the two flanking depressions where large volumes of water were confined. The waters became highly saline with a change of climate from

humid to dry and with some occasional addition of saline water from the sea through the sinking of the basin floors. As a result, beds of rock salt and gypsum were deposited along with the beds of shale, siltstone, and some sandstone, which were formed by subsequent transgression and regression of the sea or by alluvial deposition.

During the rest of the Mesozoic and the Tertiary the land was uplifted in three stages, as shown by peneplain surfaces in the area. The first peneplain forms the flat-topped mountain of Dong Phrayayen Range, Phu Phan Range, and Phu Kadung Mesa. The second plain is reported by LaMoreaux, et al. (1959, p. 13) as the surface of elevation of about 180 meters. The third plain is the present basin surface where the elevation is about 150 meters.

The drop of 75 meters of the Mun River at the point of its entry into the Mae Khong River (Lee, 1923, p. 4) suggests a recent uplift, perhaps of Pleistocene age.

The abrupt lateral change from sandstone of Triassic age to shale of Jurassic age along both flanks of the Phu Phan Range, as shown by sample logs and geologic cross sections (pl. II), is attributed to the normal faults previously mentioned. The traces of these faults are difficult to discover because the areas are thickly covered with soil and forest. If the postulation of faulting is true, however, the occurrence of such faults might be consequent with folding.

## HYDROLOGY

The collection of data and study of some phases of hydrology in the Khorat Plateau have been recently begun, although rainfall data from several rain gages have been collected for more than 50 years by the Royal Irrigation Department. A flood-control study, interrupted by World War II, has been made since 1933 by the same department but data are not available. Only a brief discussion of the hydrology, based on the limited information available, is given in this report.

### Precipitation

The precipitation occurs in Thailand under tropical savanna and tropical monsoon climates. The characteristics of rainfall over the plateau are represented by graphs (fig. 2). The graphs show a small amount of rainfall from November to February as the northeast monsoon begins to retreat. The pattern of rainfall, then, gradually increases at the end of the pre-southwest monsoon and reaches its secondary peak in May. The primary maximum peak, under the influence of the southwest monsoon, occurs in August, September, or October. This behavior is related to the thunderstorm activities occurring during May and October. With 10 years of thunderstorm records

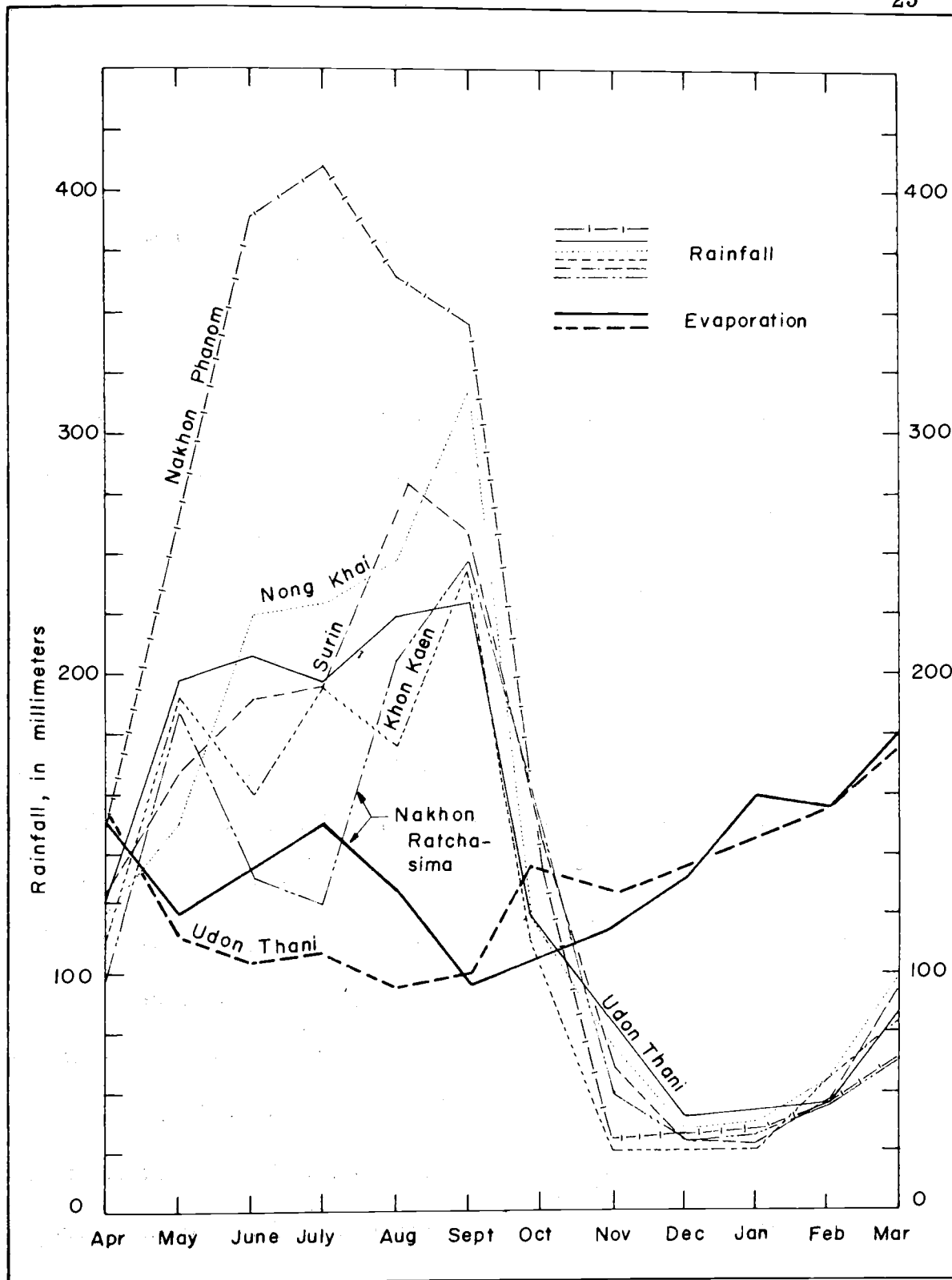


Figure 2- Graphs showing average monthly rainfall (1906-1952), and evaporation (1938-1948) in specified areas of the Khorat Plateau. Modified from U. S. Geological Survey Water-Supply Paper 1429.

from 1943 to 1952, the mean number of thunderstorm days over the plateau is 13.9 in May and 10.3, 9.4, and 5.1 in August, September, and October, respectively (Thailand, Past and Present, 1957). These thunderstorms mostly result from thermal convections and shearlines caused by occasional outbreaks of cold air from China.

The maximum total rainfall in the area, measured at Nakhon Phanom, is 2,210 mm; the minimum, at Chaiyaphum, is 1,040 mm.

### Evaporation and Transpiration

Data on evaporation in the area are not sufficient to be studied in detail. The general pattern of evaporation in Khorat and Udon Thani is shown by graphs in figure 2 along with the rainfall data. The curves show maximum evaporation occurring in March to April, during which time the temperature is highest. With the increasing of precipitation, the evaporation is lower and reaches its lowest value during September. This behavior of precipitation is undoubtedly affected by other phenomena, such as topography, soils, or types of vegetation.

### Infiltration

The behavior of infiltration over the plateau has not been studied in detail by any government agency. The work related to this field that was done by the Ground Water Exploration Project was the establishment of four automatic water-level well recorders in 1959 in

wells D1NR1 and H2-6 (alluvial aquifer), and wells A4S3 and C21KK1 (shale and siltstone aquifer). In general, the data on fluctuation of water levels can be studied for relative values of infiltration in the particular areas. From data shown in table 2, the primary maximum fluctuation of water level occurs in most wells during the rainy season in August, September, and October when the ground-water reservoirs receive water through infiltration. The secondary maximum fluctuation usually occurs during March to May when the thunderstorm activity reaches its secondary peak as described above. During this period, the rate of infiltration is undoubtedly high because more water is needed to replenish soil moisture that has been lost during the cold and dry season from November to February.

### Runoff

Runoff of the Khorat Plateau is much affected by both structure and lithology of the bedrock. The mountain ranges and the two structural basins form enormous watersheds with comparatively small drainage systems of low gradient. The Chi and Mun Rivers have gradients of approximately 12 cm per kilometer (Lee, 1923, p. 3). During the rainy season river flow is relatively small compared to the total amount of water stored in the basins. Infiltration through laterite soil, loam, clay, and sand is prevented by bedrock of impervious shale and siltstone. The result is overbank floods extending many kilometers from



TABLE 2  
RECORD OF FLUCTUATION OF WATER LEVELS  
FROM 1960-61

(Data taken from automatic water-level recorders)

Month	Water levels (feet, from surface)					
	Well A4S3			Well C21KK1		
	Maximum	Minimum	Net change	Maximum	Minimum	Net change
1960:						
January	9.2	8.7	0.50	18.56	17.31	1.25
February	10.45	9.82	0.63	18.41	17.64	0.77
March	11.53	10.62	0.91	17.96	17.41	0.55
April	12.55	11.9	0.65	18.5	17.7	0.80
May	12.75	11.5	1.25	18.6	17.65	0.95
June	9.2	8.6	0.60	-	-	-
July	10.8	10.65	0.12	-	-	-
August	10.6	9.6	1.00	16.59	15.92	0.67
September	10.6	9.1	1.50	17.3	15.74	1.56
October	10.0	7.57	2.43	15.34	14.25	1.09
November	9.2	8.6	0.6	14.47	13.98	0.49
December	-	-	-	-	-	-
1961:						
January	-	-	-	17.95	17.59	0.36
February	9.65	8.00	1.65	21.2	16.4	4.80
March	-	-	-	-	-	-
April	-	-	-	19.4	17.9	1.50
May	12.7	12.1	0.60	-	-	-
June	7.2	8.7	0.50	-	-	-
July	12.7	10.7	2.00	18.7	17.10	1.60
August	-	-	-	18.2	14.5	3.70
September	9.65	7.65	2.00	-	-	-
October	-	-	-	13.55	12.75	0.80
November	-	-	-	15.2	13.43	1.27
December	9.65	9.3	0.35	-	-	-

TABLE 2  
RECORD OF FLUCTUATION OF WATER LEVELS  
FROM 1960-61  
CONTINUED

(Data taken from automatic water-level recorders)

Month	Water levels (feet, from surface)					
	Well DINR1			Well H2-6		
	Maximum	Minimum	Net change	Maximum	Minimum	Net change
1960.						
January	11.05	10.18	0.87	27.2	24.48	2.72
February	-	-	-	29.5	27.42	2.08
March	9.3	8.8	0.50	31.95	28.15	3.80
April	12.4	11.45	0.95	-	-	-
May	12.7	12.3	0.40	31.9	30.5	1.40
June	13.0	11.32	1.68	30.8	29.32	0.48
July	11.38	10.87	0.51	29.12	28.59	0.53
August	12.15	8.75	3.40	31.19	29.48	1.71
September	9.35	4.9	4.60	29.6	25.30	4.30
October	-	-	-	24.65	17.85	6.80
November	9.1	7.95	1.15	-	-	-
December	-	-	-	25.62	24.64	0.98
1961.						
January	-	-	-	-	-	-
February	-	-	-	28.1	26.35	1.75
March	16.61	10.28	5.33	-	-	-
April	-	-	-	-	-	-
May	-	-	-	-	-	-
June	9.9	9.09	0.81	-	-	-
July	-	-	-	29.85	27.43	2.42
August	-	-	-	-	-	-
September	-	-	-	30.9	30.09	0.61
October	8.8	8.5	0.30	31.0	29.56	0.44
November	9.25	8.1	1.15	30.3	29.27	1.03
December	10.25	8.9	1.35	30.75	30.30	0.45

the rivers. When the rainy season ceases, waters are drained out by both runoff and evaporation, leaving the area dry and unusable during dry and hot seasons. Some of these desiccated areas have crusts of salt efflorescence resulting from capillarity and evaporation of water from soil moisture and the water table. River flow at this time reaches a minimum and some streams become intermittent.

Only two water-stage recorders have been installed in the area—one in the Chi River at Yasothon and another in the Mun River at Ubon Ratchathani. The data from these two stations are listed in table 3.

Under the Development of Water Resources in the Lower Mae Khong Basin Project, runoff has been measured at several places along the Mae Khong River (United Nations, Flood Control Series No. 12, 1957), but the data are not available.

TABLE 3  
HYDROLOGIC DATA OF MAJOR RIVERS IN THE  
KHORAT PLATEAU

After United Nations, Flood Control Series No. 14, 1959

Hydrologic data	Chi River	Mun River
Length (km)	600	620
Total drainage area	54,100	125,550 (including Chi)
Annual rainfall (mm)	1,257	1,294
Gaging at	Yasothon	Ubon Ratchathani
Drainage area above gaging station (km <sup>2</sup> )	44,100	103,260 (including Chi)
Annual runoff (10 <sup>6</sup> m <sup>3</sup> )	18,400	43,400
Annual mean discharge (m <sup>3</sup> /sec)	584	1,376
Recorded max. peak discharge (m <sup>3</sup> /sec)	1,900 (1956)	3,000 (1949)
Min. discharge during dry season (m <sup>3</sup> /sec)	10	28

## GROUND WATER

### Water-Bearing Characteristics and Extent of Aquifers

Ground water in the Khorat Plateau occurs in five aquifers which are differentiated by their lithology and water-bearing characteristics. Rocks of pre-Permian age exist in small areas of the northwest and southeast corners of the plateau, but are excluded here because of their poor water-bearing character.

The aquifer constants reported are derived from the pumping tests and original reports are revised where a mistake in plotting is obvious. It may be noted that the transmissibility of the alluvial deposits is an approximation due to some difficulties in pumping tests, such as the short time of pumping and the heterogeneity of the aquifer. The transmissibility of the consolidated rocks is believed to be reliable.

#### Rat Buri Limestone Aquifer (Permian)

The Permian limestone is mostly buried by the younger sediments, consisting largely of thick plastic clays. Wells penetrate this aquifer in only a small area of Loei and in the southwesternmost part

of Nakhon Ratchasima (pl. I). The thickness of the aquifer is uncertain, as the deepest well drilled was 1,044 feet and did not reach the bottom of the limestone. The limestone is usually impermeable, but where highly fractured zone or solution channels are reached by wells it produces a considerable amount of water. Of eight wells drilled in Loei, only one well is dry and the other seven wells yield from 10 to 180 gpm (gallons per minute), with specific capacities ranging from 0.1 gpm per foot of drawdown to 24.0 gpm per foot of drawdown. All wells are nonflowing artesian. The transmissibility averages about 600 gpd (gallons per day) per foot.

#### Phu Kadung and Phra Wihan Aquifer (Middle and Lower Triassic)

Rocks of these two members are grouped together because of their similarity in water-bearing conditions. The outcrops are found as a semicircular belt along the western and northwestern part of the plateau, along foothills of concentric cliffs, and in the bottom of the topographic basin on the crests of Phu Phan folds. According to the lithology described, the rocks themselves are rather impermeable, but yield small amounts of water through joints or bedding planes. The specific capacities of wells that penetrated this aquifer range from 0.4 gallons per foot of drawdown to 1.1 gallons per foot of drawdown. The thickness of the aquifer is uncertain. Data from pumping tests indicate

that the aquifer is under artesian conditions, and only one flowing well of a few gallons per minute has been found.

### Phu Phan Sandstone Aquifer (Upper Triassic)

Although the sandstone of this aquifer is fine to coarse grained, being pebbly and conglomeratic in places, its permeability is relatively low because of its richness of cementing agents, which are clay minerals, silica, and calcareous materials. From pumping-test determinations, the transmissibilities range from 53 gpd per foot to 1,103 gpd per foot, with an average of about 380 gpd per foot. An example of plotting the pumping-test data and the determination of aquifer constants is shown in figure 3. Because of wide extent, the aquifer is regarded as one of the most important ground-water producers in the plateau. The Phu Phan sandstone is exposed in two circular patterns and dips beneath rocks of younger age to the centers of Khorat and Sakon Nakhon Basins (pl. I). Under these conditions an excellent artesian aquifer was expected, and evidence has been shown by several flowing wells. The thickness of the aquifer is difficult to determine. The permeability seems to decrease with an increase in depth because of the interbedded hard shales and the decrease of fractures, as can be seen in most sample logs and electric logs.

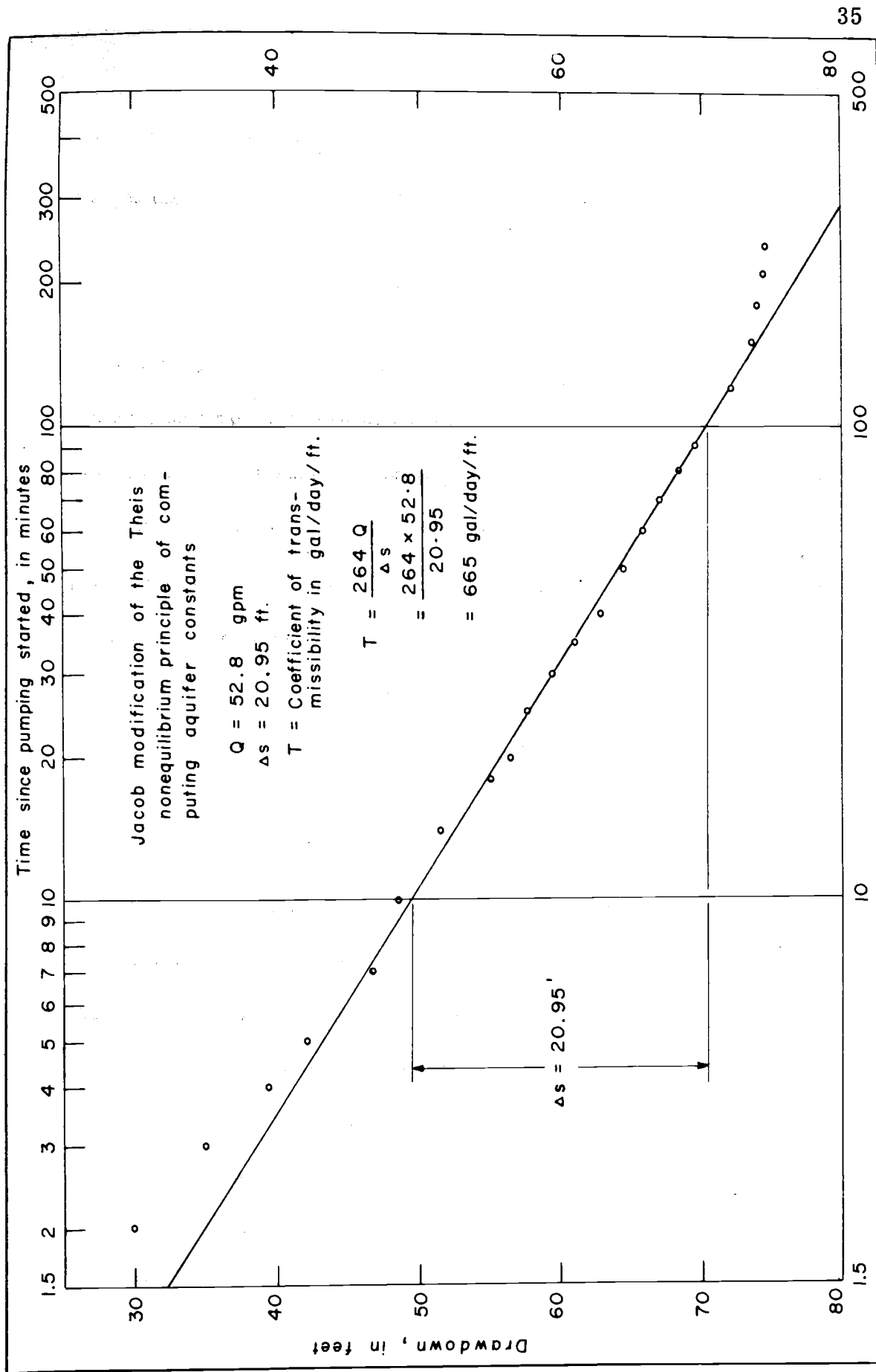


Figure 3- Semi-logarithmic plot of pumping-test data from pumping well E39Ud20. Data taken from hydrograph of the pumping well in the contractor's April 1961 report.



### Upper Shale and Siltstone Aquifer (Jurassic to Cretaceous?)

Shale and siltstone are usually impermeable and retard the flow of ground water. Shale and siltstone of the Khorat Plateau are of importance as a water producer, although they are not a good aquifer. Most of the flat surfaces of the two basins, which are highly populated, are underlain by these rocks. The wells pump water from fractures and fissures of the aquifer. Many tens of wells have been pumped dry, while hundreds of others yield from 1 gpm to 100 gpm with specific capacities ranging from insignificance to about 2.0 gpm per foot of drawdown. Moreover, most brackish and salty water wells in the area have been constructed in this aquifer. The average transmissibilities are about 160 gpd per foot. The thickness of the aquifer is uncertain, as it is determined by rock fractures which decrease with depth.

### Alluvial Aquifer (Quaternary to Recent)

Alluvium and terrace deposits occur as clay, sand, and gravel in a long belt along the Mun, Chi, and Mae Khong Rivers. The thickness ranges from a few feet to more than 250 feet. The deposits form an excellent unconfined aquifer, although the areal extent is not so great as that of the upper shale and siltstone just described. The deposits may be classified as a younger and older alluvium on the basis of water-bearing characteristics. The younger alluvium is composed of fairly

well sorted sand and gravel occurring along the Mae Khong River course. The wells in this locality have been pumped about 200 gpm with not more than 10 feet of drawdown. The average transmissibility is about 18,000 gpd per foot<sup>2</sup>. The older deposits of poorly sorted clay, sand, and gravel are located along river courses in the Khorat and Sakon Nakhon Basins. An average transmissibility of this aquifer is about 1,900 gpd per foot in the former and about 1,000 gpd per foot in the latter basin. The transmissibility of the narrow valley fill in Loei is about the same as that of the alluvium in the Sakon Nakhon. The storage coefficient of these deposits is not determined because the pumping tests are not reliable.

### Perched Water

Perched water is a water body separated from an underlying body of ground water by unsaturated rock (Meinzer, 1923, p. 40). Perched water can be found almost everywhere below flat surfaces of the plateau where beds or layers of lateritic sand and clay are not more than 60 feet deep. These lateritic beds are rather impermeable and act as water reservoirs in leached zones. Most dug wells and ponds in the area penetrate this zone and supply adequate amounts of water during rainy seasons. During hot and dry periods most of these reservoirs are empty because water levels are lowered down to a water table which is difficult to reach by dug wells. Some of these wells, however, still

maintain their water, but a problem of water quality exists due to a higher evaporation rate resulting in a higher concentration of salts. This inferior water also affects ground-water quality in wells in which the casing is not effective and deep enough to prevent mixing and pollution from the perched zone.

### Ground-Water Movement and Recharge

A water-table map or piezometric-pressure map of the plateau has not been made because of difficulties and financial problems. It is believed that the movement of ground water in the area is much influenced by geology, topography, and hydrology. The movement of ground water in unconsolidated rocks is assumed to correspond to the slope of the ground surface, which is to the southeast in the Khorat Basin and to the east in the Sakon Nakhon Basin. These assumptions are supported by the study of water levels and water quality in wells. The movement of ground water in the upper shale and siltstone is difficult to interpret, but it must depend on the character and continuity of fractures and fissures. Vertical movement is probably slight or absent, as indicated by the great thickness of halite and the reduction of fractured zones as shown by the electric logs. The movement of ground water in sandstone is presumably along the bedding planes—that is, toward the lower parts of basins where the high hydrostatic pressures exist and result in artesian flow in wells that penetrate the aquifer. In

the limestone aquifer, which exists in a small area of Loei, the ground water flows to the north and discharges into the Mae Khong River where the limestone is exposed.

The rate of ground-water flow is uncertain but it must be dependent on the gradient, which is variable in each aquifer, and on the recharge which is mostly from the infiltration of rainfall, with minor amounts from streams and rivers during their flood stages.

## WATER QUALITY

### General Nature of Chemical Problems With Respect to Uses

The first attempt to use ground water in the area was made by the Department of Public Works in early 1900, but the project had to be abandoned because bored wells encountered salty water. Water from dug wells in some localities, especially east of Nong Khai, along the Songkhram River, contain such high concentrations of native salt that the villagers earn their livings by producing salt by evaporation. Surface soils in many areas, especially in Nakhon Ratchasima, Chaiyaphum, Roi-et, Khon Kaen, Udon Thani, Nakhon Phanom, and Sakon Nakhon, also provide natural salts which are left as thin layers on surfaces by capillarity and evaporation of soil water. The problem of drinking water in many communities is also affected by hard water. Water from many areas contains high concentrations of soluble iron which turn red, form precipitates, and have a rusty odor on exposure to the air. This poor quality of water not only affects the domestic, agricultural, or industrial utilization, but also results in a serious health and sanitary problem. The predominant sickness resulting from these chemical characters are intestinal diseases and urinary concretions.

### Chemical Constituents in Natural Water

Minerals are present in water in either insoluble or soluble forms, according to their degree of solubility. The minerals that are insoluble, such as silica, are usually present in colloidal particles. When soluble minerals are contained in water they are dissociated into charged particles called ions or may be in undissociated forms. However, the dissociated ions, in the form of cations and anions, are dominant in natural water. The cations or basic radicals are those having positive charges, and anions or acidic radicals constitute the negative charges. The principal cations in the ground water of the Khorat Plateau are sodium, calcium, magnesium, iron, manganese, and aluminum, while chloride, bicarbonate, sulfate, and phosphate are among the major anions in the same water.

In addition to cations and anions, the undissociated minerals, organic matter, and dissolved gasses may be present in water. Table 4 lists all significant chemical constituents and other values appearing in common chemical-analysis reports.

### Chemical Analysis

As stated before, all analytical data studied for this report were made by the Thai Geological Survey chemical laboratory. The laboratory is equipped with an almost complete set of instruments, and

TABLE 4  
CHEMICAL CONSTITUENTS AND OTHER DATA EXPRESSED  
IN CHEMICAL-ANALYSIS REPORTS

(Modified from Hem's U. S. Geological Survey Water-  
Supply Paper 1473)

Silica ( $\text{SiO}_2$ )

Cations—heavy metal ions

Aluminum (Al)

Iron (Fe), in solution at time of analysis

Iron (Fe), total (all forms of soluble iron plus iron extracted  
from suspended materials—turbid samples)

Manganese (Mn), in solution when analyzed

Manganese (Mn), total (see total iron)

Chromium (Cr)

Copper (Cu)

Arsenic (As)

Lead (Pb)

Zinc (Zn)

Selenium (Se)

Tin (Sn)

Cations—alkali earths and metals

Calcium (Ca)	)	
Magnesium (Mg)	)	Earths
Barium (Ba)	)	

TABLE 4  
CHEMICAL CONSTITUENTS AND OTHER DATA EXPRESSED  
IN CHEMICAL-ANALYSIS REPORTS  
CONTINUED

(Modified from Hem's U. S. Geological Survey Water-  
Supply Paper 1473)

Sodium (Na)	)	
Potassium (K)	)	Metals
Lithium (Li)	)	

Anions

Bicarbonate ( $\text{HCO}_3$ )

Carbonate ( $\text{CO}_3$ )

Hydroxide ( $\text{OH}$ )

Sulfate ( $\text{SO}_4$ )

Chloride ( $\text{Cl}$ )

Fluoride ( $\text{F}$ )

Bromide ( $\text{Br}$ )

Iodide ( $\text{I}$ )

Nitrite ( $\text{NO}_2$ )

Nitrate ( $\text{NO}_3$ )

Phosphate ( $\text{PO}_4$ ), in solution at time analyzed

Phosphate ( $\text{PO}_4$ ), total (see total iron)

Cyanides as ( $\text{CN}$ )

Boron ( $\text{B}$ )

Organic, nonionic, and calculated values

Phenolic material as  $\text{C}_6\text{H}_5\text{OH}$



TABLE 4  
CHEMICAL CONSTITUENTS AND OTHER DATA EXPRESSED  
IN CHEMICAL-ANALYSIS REPORTS  
CONTINUED

(Modified from Hem's U. S. Geological Survey Water-  
Supply Paper 1473)

Total solids (dissolved and suspended)

Loss of ignition

Dissolved solids

Calculated

Residue on evaporation

Total suspended solids

Hardness as  $\text{CaCO}_3$

Noncarbonate hardness as  $\text{CaCO}_3$

Alkalinity as  $\text{CaCO}_3$

Acidity as  $\text{H}_2\text{SO}_4$

Dissolved gasses

Dissolved oxygen

Free carbondioxide ( $\text{CO}_2$ )

Chlorine ( $\text{Cl}_2$ )

Sulphide as  $\text{H}_2\text{S}$

Ammonia ( $\text{NH}_3$ )

Other data

Specific conductance  
pH

Color  
Turbidity

some advanced apparatus—such as spectrophotometer, flame photometer, and potentiometer—so that relatively complete analytical data can be obtained. All analytical procedures have been made by following those of the U. S. Geological Survey laboratory, with the exception of a few methods for which the apparatus is not available (Chotidilok, written communication). Some single constituents were determined by many methods in order to provide the analyst with the means of checking suspected results and to permit a flexible laboratory routine.

### Unit Expression for Chemical Constituents

#### Parts Per Million

The concentrations of chemical constituents and other calculated values are reported in terms of parts per million. Exception is made for specific conductance, pH value, and color. The unit of specific conductance is micromhos, and dimensionless for pH and color. The parts per million (ppm) is the weight-per-weight unit, and 1 ppm represents 1 milligram of solute in 1 kilogram of solution. Its use is more or less universal and unquestioned because a liter of water weighs approximately 1 kilogram or 1,000,000 milligrams, and hence the formerly used milligrams per liter unit can be directly replaced by the parts per million unit.

### Equivalents Per Million

The equivalents per million (epm) are the modified units of parts per million. They are not generally expressed in chemical-analysis reports, but are commonly used in the study and interpretation of chemical quality of water in so far as the equivalents per million show more clearly the chemical character of water with reference to the dissociated ions. The evaluation of analytical data, the classification of water, and the modification of water are also easily interpreted by the use of equivalents per million. Hem (1959, p. 32) explains the term "equivalents per million" as "...a contraction which has been generally adopted for the sake of convenience. In more exact language, these units are 'milligram equivalents per kilogram' if derived from parts per million data, or 'milligram per liter' if derived from data expressed in milligram per liter."

The equivalents per million are obtained by dividing parts per million of the element or ion with its equivalent weight in grams. Table 5 gives the conversion factors for converting the units.

### Representative Chemical Analyses

From the 302 complete chemical analyses, 94 representative samples are selected for study in this report. The selection of representative analyses is based on typical water native to each aquifer

TABLE 5  
CONVERSION FACTORS FOR CONVERTING PARTS  
PER MILLION TO EQUIVALENTS PER MILLION

<u>Ion</u>	<u>Multiply by</u>
Calcium	0.0499
Magnesium	0.0822
Sodium	0.0435
Potassium	0.0256
Chloride	0.0282
Sulfate	0.0208
Carbonate	0.0333
Bicarbonate	0.0164

described above. To accomplish this requirement, the location, completeness of development, sealing, perforation, or screening of wells are taken into consideration. For water in the upper shale and siltstone aquifer where the productive zone is not more than 300 feet, the selection of representative data will be limited to the wells within this depth. The reason for this is to prevent conflict in interpretation of chemical character of water in the productive zone and zones of rock salt. The representative analyses of other aquifers will not be limited to depth in so far as the sources of contamination, if any, are not so obvious. The analytical data selected are presented in table 7 in which some minor constituents are excluded.

### Evaluation of Chemical Analyses

The accuracy of complete analyses may be checked by several methods, but only the cation-anion balance procedure will be presented here. The theoretical background of this procedure is that in most water the total cations are balanced with the total anions expressed in the same unit. In reliable data the difference between the two sums should not be greater than 1.00 percent, but less than 5 percent is allowed for analysis of water having low pH or containing much iron and manganese. The reason for these allowances is that in acid water (pH less than 7) many anions are used up in the hydrolysis process, and in water with high contents of iron and manganese the total cations tend to

be increased. Larger deviation of cation-anion balance is suspected to be due to incomplete analysis or errors in the laboratory.

By the above procedure, the evaluation of the 94 representative analyses yields the following results:

- (1) 75.5 percent of total analyses having the difference of total cations and anions less than 0.5 percent;
- (2) 12.8 percent of total analyses having the difference between 0.6-1.00 percent;
- (3) 4.2 percent of total analyses having the difference between 1.1-2.0 percent;
- (4) 5.4 percent of total analyses having the difference between 2.1-3 percent
- (5) 2.1 percent of the analyses having the difference more than 3.00 percent.

These figures indicate that the analyses used in the study of water quality are correct and reliable.

## SIGNIFICANCE OF PROPERTIES OF MAJOR CONSTITUENTS IN THE GROUND WATER

Calcium, sodium, magnesium, iron, chloride, sulfate, bicarbonate, and silica constitute major components and influence quality of the ground water in the plateau. Among minor constituents, potassium, manganese, fluoride, nitrate, and phosphate are also present with relatively insignificant values. Some dissolved gasses, oxygen, chlorine, and carbondioxide, are present in many analyses. The following chapters are devoted to the discussion and interpretation of individual constituents, regarding their significance as to major properties, sources, and limit of concentration in water to be used for different purposes. For better understanding, the ionic concentrations in water of each aquifer are plotted in bar diagrams in plates III-A and III-B to show the mutual relations and variations of each ion. The data plotted are selected from the 94 representative samples on the basis of their chemical dissimilarities within the same aquifer. This will provide a study of individual ions with relation to geologic and hydrologic environments, and to the modifications of chemical quality. The overall distribution of each major chemical substance over the area will be shown by its isopachous map.

## Silica (SiO<sub>2</sub>)

### Technology

Silicon is present in natural water in colloidal form of silica or dissociated ionic form of silicate (Mason, 1952; Roy, 1954). According to Iler (1955) the dissociated silicate ions are rather rare in natural water, because silicate minerals are among the most resistant to attack by water. Silica, however, is dissolved from practically all silicate rocks under the decomposition or weathering processes. Its concentration in water is essentially dependent on movement of water and the types of rocks themselves. Alkaline silicates are likely to release proportionally more silica than ferromagnesian silicates (Pirsson and Knopf, 1947). The presence of CO<sub>2</sub> in water is another factor that accelerates the yield of silica. The consolidated sedimentary rocks, such as sandstone or conglomerate, also release to water a considerable amount of silica for their silicate or silica cementing materials. The chemical precipitates of silica, such as chert and tufa, may yield colloidal silica or ionic silicate to natural water.

Silica does not practically affect the use of water for domestic supply or even in irrigation, but is significant in water used for industrial purposes. Water of high silica content will contribute to the formation of boiler scale, and an incrustation at well screens in the form of calcium or magnesium silicate (The Johnson National Driller



Journal, 1960).

The upper limit of silica concentration is 1 ppm in water used for boilers operating at 400 psi or above, and 0.1 ppm for steam turbines (Rainwater and Thatcher, 1960).

### Sources of Silica in Ground Water

Although water from alluvium in some localities contains as much as 25 ppm silica, there are many waters from the same aquifer carrying less silica, or none. The mineral composition of alluvial deposits is undoubtedly a major factor influencing sources of silica in water. Where feldspathic sand or basaltic gravel are present, the water is expected to carry high concentrations of silica, as may be shown by analyses C2NR2 and G21NP13 in plate III-A. Alluvium consisting largely of clay is also considered as a source of silica released from decomposition of silicate minerals, such as feldspar, mica, and clay minerals. Analysis D59Ms19 characterizes the water collected from such a deposit along the course of the Chi River. Analysis A30Ub5 indicates that no silica is present in water which was collected from alluvium of almost pure quartz sand and gravel in Ubon Ratchathani. An absence of silica in analysis D1NR1 is probably not related to the above postulation because the water was collected from a well drilled in the same alluvial belt as C2NR2. The explanation is probably that the flushing effect of ground-water movement tends to increase silica in analysis

C2NR2 relative to that in D1NR1.

Silica content in waters from shale and siltstone at some localities is as high as 60 ppm, while in other areas silica is practically absent. The major source is undoubtedly the clay minerals in shale, as shown by analysis D10R10 and analysis C22KK2 in plate III-A. The extremely high concentration of 50 to 60 ppm may have originated from other unknown sources existing in the area. Analysis B7B4 shows a typical water from the basalt-flow region of Buriram. A considerable amount of silica is probably derived from the alteration of ferromagnesian minerals and calcium-sodium feldspar of basalt. An absence of silica ions in analysis C19NR19 suggests either the lack of sources or the destruction of dissociated silica by the presence of excess sodium bicarbonate in water (Roy, 1945).

Water from most wells drilled in sandstone aquifers is practically free of silica because quartz grains and silica and feldspathic cementing materials in rocks are hardly dissolved by water. The 4.8 ppm silica in analysis G29NP19 (pl. III-B) is not believed to be derived entirely from minerals in the aquifer, but may be released by percolating water from alluvium directly overlying the sandstone.

#### Range and Distribution

Silica in the ground water has a wide range of concentration and distribution throughout the area. The lowest limit is zero in all

aquifers, but the highest limit varies from changwat to changwat. The geology and hydrology undoubtedly played a major role in these variations. Within the alluvial aquifer, the maximum concentration is 2.5 ppm in Ubon Ratchathani, 25 ppm in Nakhon Phanom, 58 ppm in Khon Kaen, 60 ppm in Loei, and 68 ppm in Nakhon Ratchasima. In the shale and siltstone aquifer, the highest content is reported to be 20 ppm in Udon Thani, 32 ppm in Khon Kaen and Ubon Ratchathani, 50 ppm in Surin, 75 ppm in Buriram and Roi-et, 80 ppm in Sisaket, and 93 to 260 ppm at Nakhon Ratchasima. A somewhat lower maximum limit is found for sandstone aquifers; 6.2 ppm in Kalasin and 29 ppm in Nakhon Ratchasima are reported. The concentration in the Rat Buri limestone averages 2 ppm, with more or less regular distribution.

### Iron (Fe)

#### Technology

Iron is present in water as both readily soluble ferrous iron and insoluble ferric iron. Under reducing conditions, iron in ground water tends to exist in the ferrous state, but on exposing to air an oxidation process will convert ferrous iron to precipitated ferric oxide or hydroxide, which give a red color and undesirable odor to water. Iron may be delivered to water by many sources, such as dark minerals of igneous rocks, sulfide minerals ( $\text{FeS}_2$ ), iron ores, iron cementing

materials in sedimentary rocks, and impurities in carbonate rocks. In addition, iron may be released to water from contact with well casing, pump parts, pipes, tanks, and wastes.

The amounts of iron in water are dependent upon the degree of solubility of ferric iron or ferrous carbonate (siderite) from rocks or soils which are associated with the water. The solubility of ferric iron is limited in waters of alkalinity and more soluble in acid waters. The presence of  $\text{CO}_2$  in water will always accelerate the solubility of ferric iron and a ferrous carbonate will be formed. Biological change or biological reaction are also effective in the concentration and distribution of iron in water (Sawyer, 1960, p. 311).

Iron in solution will cause reddish-brown stains on white porcelain or enameled ware and fabrics washed in the water. It is not harmful in drinking water, but the U. S. Public Health Service (1946) recommends that public water supplies should not contain more than 0.3 ppm of iron and/or manganese. Livestock are sensitive to the taste of iron and may not drink water of high iron content (Rainwater and Thatcher, 1960). Water of high iron content is usually undesirable for industrial use because of corrosive effects. The California State Water Pollution Control Board (1952) states that concentrations of more than 1 to 2 ppm are generally not satisfactory for industry. Iron-bearing water also favors the growth of iron bacteria, such as *crenatrix*, and may clog the pipes in circulating systems and cause incrustation

at well screens (The Johnson National Driller Journal, 1960).

### Sources of Iron in Ground Water

The amount of iron in many wells is far above limits given by both the U. S. Public Health Service and the California State Water Pollution Control Board. Some water contains as high as 55 ppm iron, whereas many other waters have none to only a few parts per million. Analyses of water from alluvium are shown in plate III-A. Iron is believed to be delivered to water by a leaching of lateritic soils or laterite that exists on or beneath soil surfaces. Iron minerals or iron silicate sands in alluvium itself may yield some considerable amounts of iron to water. An example is given by analysis D1NR1 which represents water from wells in such deposits in Nakhon Ratchasima.

The high concentration of iron in the shale and siltstone aquifer, as shown by analysis B7B4, and analyses C19NR19, C22KK22, and D10R6 in plate III-A, may be because of the presence of iron minerals in the form of oxide, carbonate, and sulfide in shales. By association with water containing dissolved  $\text{CO}_2$ , iron is dissolved in part into ionic form, and is weathered in part into colloidal form. The slow movement of ground water tends to increase the concentration in the flat-lying part of the aquifer, but may have a flushing effect in the higher part, as shown by an absence of iron in analysis C22KK2.

The concentrations of iron in water of sandstone aquifers are

slightly lower than those of shale and siltstone aquifers, as shown by analyses in plate III-B. The highest iron content is 14 ppm in well B59Ub11 near the southeastern corner of the plateau. The comparatively high concentration is in the vicinity of the Phu Phan Range. The major sources of iron in water are presumably the iron oxides in the cementing materials, and mica in the formation. However, iron from these sources is not rich enough to deliver iron of high concentration, in so far as most of the cementing materials of the sandstone are silica and clay minerals. A percolation of water directly from the leached zone may be another source of iron. The absence of iron in some wells may be accounted for by the flushing effect of the movement of ground water toward centers of basins.

The concentration of iron in water from limestone is moderately high because the most important source is pyrite ( $\text{FeS}_2$ ), which is easily attacked by water containing carbondioxide. The percolation of surface water previously associated with diorite and iron-ore deposits near the limestone outcrop may also yield a considerable quantity of iron to ground water.

### Range and Distribution

The range of concentration and distribution of iron are shown by the isopach map in figure 4. The general pattern of equiconcentration lines is most likely controlled by directions of movement of both

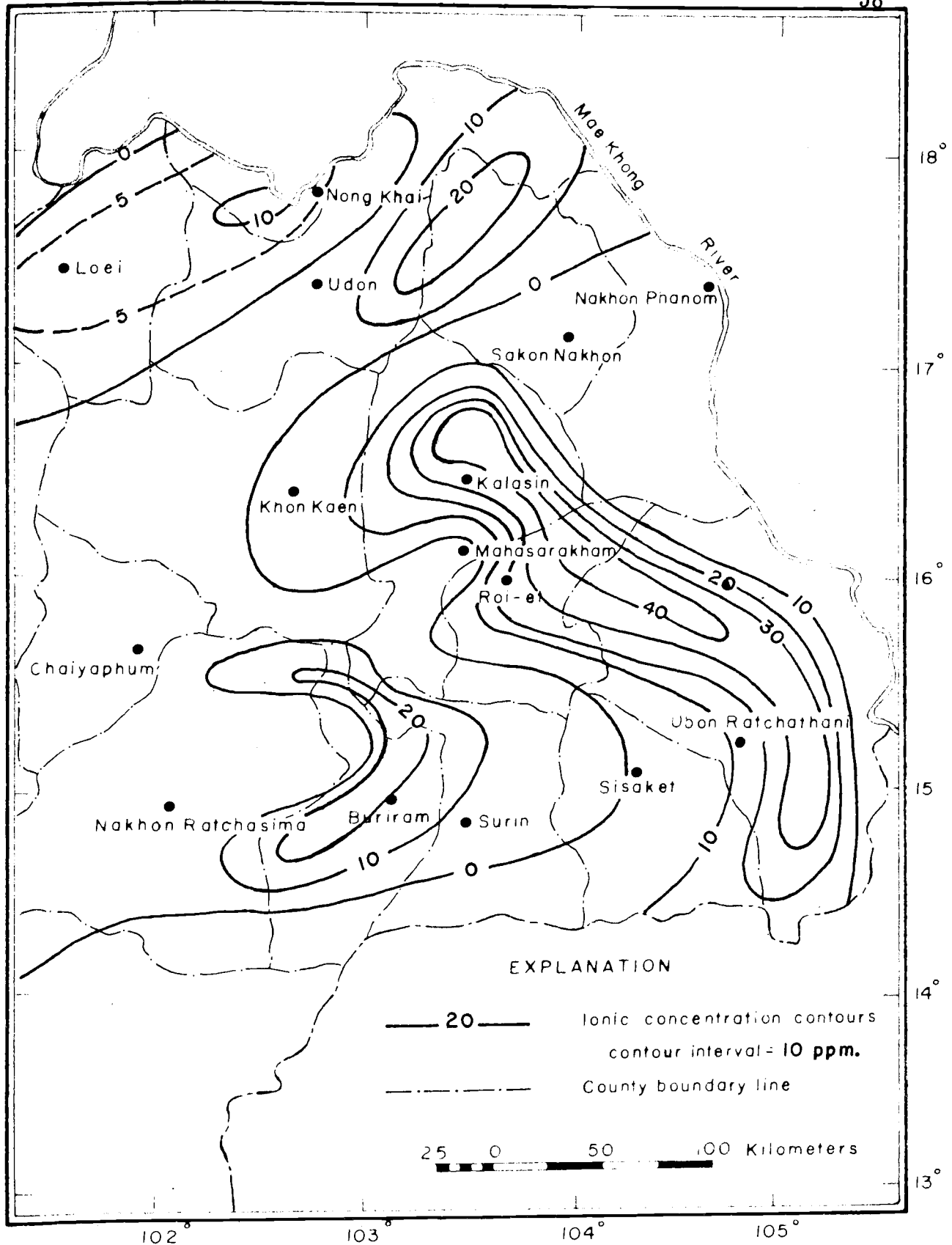


Figure 4- Isopachous map of iron.

surface water and ground water. The concentrations in the western and southern parts of the plateau are less than 10 ppm, but gradually increase to the northeast and southeast in the directions of flow of water in the Sakon Nakhon and Khorat Basins, respectively. Exception is made for a small area at the southern border, in the vicinity of Surin and Buriram, where the concentrations range up to 20 ppm due to the prominent source of iron from basalt outcrops. The topography seems to have some effect on the concentrations; the higher the topography, the lower the concentration expected. This is probably due to the flushing action from higher to lower elevations. The evidence can be seen along the margin of the plateau where iron content is low, and along the synclinal trough of the Phu Phan Range where the content is high. A high concentration along the trough of the limestone syncline in the northwest corner of the plateau also supports the above hypothesis.

### Calcium (Ca)

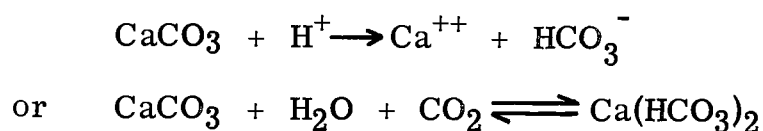
#### Technology

Calcium is generally the most abundant chemical constituent in natural water because it is readily soluble in water and occurs commonly in rocks and soils. Igneous rocks yield calcium to water through chemical weathering of their silicate and nonsilicate minerals of calcium, such as feldspar, pyroxene, amphibole, calcite, and anorthosite



(Rankama and Sahama, 1950). The source of most calcium in water is the nonclastic sedimentary rocks, especially limestone, dolomitic limestone, fluorite, gypsum, and anhydrite. Calcareous cementing agents in sandstone and other detrital rocks also add a considerable amount of calcium to water. Calcium carbonate and gypsiferous soils may be the other sources of calcium in water.

The amount of calcium in water is dependent largely on the degree of solubility of calcium minerals in rocks. In the presence of  $H_2$  and  $CO_2$  in water, calcium minerals are readily soluble. This is shown by the following equations:



In the ground-water system where dissolved  $CO_2$  is present, calcium concentrations, in the form of  $Ca(HCO_3)_2$ , will be high, but are lowered when  $CO_2$  is reduced by some processes—such as a rise of water table, a reduction of head by pumping, or evaporation. Under these conditions equilibrium in solution is altered and  $CaCO_3$  may precipitate until  $CO_2$  at atmospheric pressure is in balance with dissolved  $Ca(HCO_3)_2$ . The solubility of calcium carbonate will also increase with the presence of sodium and potassium salts, according to Hem (1959, p. 74). Waters in contact with gypsum may have a large amount of calcium, although no  $CO_2$  is present because gypsum is soluble in water (Hulett and Allen,

1902). Gypsum is also reported to be soluble to the extent of about 2,400 ppm of calcium in water saturated with NaCl.

Calcium causes hardness in water and is largely responsible for boiler scale and deposits in hot-water heaters and pipes and in water systems. A high ratio of calcium to sodium is desirable in water used for irrigation because calcium flocculates the soil colloids and tends to maintain good soil structure and permeability (Rainwater and Thatcher, 1960). By pumping of water in wells,  $\text{CO}_2$  in water is released and causes the deposition of  $\text{CaCO}_3$  in sand or gravel packed around well-screen openings. This  $\text{CaCO}_3$  deposit will, then, contribute to incrustations on the screen.

### Calcium in Base-Exchange Reactions

A low concentration of calcium with comparison to sodium may indicate a base-exchange reaction in water and the solid phases of water-bearing reservoirs, whereby  $\text{Ca}^{++}$  originally in water has been exchanged for  $\text{Na}^+$  in sediments. The base-exchange process is an exchange of bases between ground water and minerals in which the chemical composition is not in equilibrium. Any of these particular minerals has the property of releasing to water a part of the base or bases most loosely held, and of adsorbing from the water an equivalent amount of the base or bases for which it has a stronger bond. This process will go on until an equilibrium is reached or until the exchangeable

bases are exhausted in either the water or the minerals, so that the water is modified in its ratios of  $\text{Ca}^{++}$ ,  $\text{Mg}^{++}$ , and  $\text{Na}^+$  to one another without substantial change in concentration (Piper, Garnett, and others, 1953).

The exchange process is essentially a reversible chemical reaction which obeys the law of mass action, and involves only cations. The degree and readiness of base exchange are dependent on the excess of exchangeable ions and their exchangeabilities. Among the cations, calcium possesses the highest power of exchange, followed by Mg, K, and Na. Calcium in sediments is usually ready for exchanging for sodium in water, and in the same manner, calcium in water can be easily exchanged for sodium in the sediments.

### Sources of Calcium in Ground Water

The Khorat Plateau is made up almost entirely of sedimentary rocks which yield a considerable amount of calcium. The concentration of calcium, however, varies from place to place due to the irregular distribution of sources. Plates III-A and III-B show the calcium content of representative samples from each aquifer.

#### Calcium in alluvium

The calcium concentration in the alluvial aquifer has a source from  $\text{CaCO}_3$  in soils from which  $\text{Ca}^{++}$  is leached to ground water by

percolating water. The quantity of calcium in the aquifer is relatively low in comparison to that in the shale and siltstone aquifers where the gypsum is a principal source. However, alluvium, which is contaminated by water from the underlying shale and siltstone, carries high concentrations of calcium and also sulfate. This is evidenced by analyses C2NR2 and G21NP13 in plate III-A. Analysis A30Ub5 shows a very low calcium concentration, but high sodium and sulfate. This suggests that calcium originally released by  $\text{CaSO}_4$  water has been subjected to base exchange for Na in clay. The chemical weathering of feldspathic sand and gravel may be a minor but important source of calcium in the water.

#### Calcium in shale and siltstone

The main sources of calcium in the aquifers are undoubtedly the soluble gypsum interbedded in shale and siltstone, and other calcium minerals or salts in the formation. This is shown by the high concentrations of calcium along with high  $\text{SO}_4^{=}$  and  $\text{CO}_3^{-}$  in analyses B7B4, C19NR19, C22KK2, and D10R6 in plate III-A. Calcium of analysis B7B4 probably originated from calcium silicate of basalts in the Buriram region. In an area where shale or siltstone are directly overlain by surface soils, ground water may receive part of its calcium through leaching processes.

### Calcium in the Phu Phan sandstone

The concentration of calcium in this aquifer is relatively low, as shown by analyses A50Ub24, B56Ub18, E3NR3, and F4K3. The main source of calcium is possibly the  $\text{CaCO}_3$  cementing agents of sandstone because the water also contains a considerable amount of  $\text{CO}_3^{=}$ . The feldspathic cementing agents and calcareous impurities in rocks may deliver some calcium to the water, but gypsum is insignificant as a source of calcium as the water contains very little sulfate. Calcium from contaminating water of the upper shale and siltstone may be added to the aquifer in the lower parts of basins.

### Calcium in the Phra Wihan and Phu Kadung sandstones

The Phra Wihan and Phu Kadung sandstones are interbedded with micaceous shale in the upper part, and grade down to red shale in the lower part. The calcium salts or other impurities of these shales may yield a large amount of  $\text{Ca}^{++}$  to water in the aquifer. The calcium concentration, as shown by analyses C40C2 and C65Ud3 in plate III-B, is higher than that of the Phu Phan sandstone. Analysis G27NP19 indicates that very little calcium is present in the water. The amount of calcium in this water is presumably modified by some processes, as the formation directly underlies the Mae Khong River near the site of the well. In many places where the formation crops out or is directly

overlain by top soils, calcium may be added to the aquifer by leaching of  $\text{CaCO}_3$  in soils.

### Calcium in the Rat Buri limestone

Two major sources of calcium in this aquifer are calcium carbonate from dolomitic limestone and  $\text{CaSO}_4$  from interbedded gypsum. The calcium from gypsum far exceeds that from limestone. This is shown by the higher  $\text{SO}_4^{=}$  than  $\text{CO}_3^{=}$  in analyses C45L3 and C48L6 in plate III-B. The reason, as previously explained, is that gypsum is readily soluble in water in either the presence or absence of dissolved  $\text{CO}_2$ , while limestone is soluble only in water containing  $\text{CO}_2$ .

### Range and Distribution

The lowest amount of  $\text{Ca}^{++}$  is reported to be zero in many analyses, but the highest amount may reach 1,206 ppm in the shale and siltstone aquifer in certain areas where the major source is gypsum. An exception is the uniform distribution in the limestone located in the northwest corner of the plateau. Figure 5 is the isopachous map of calcium showing equiconcentration lines in parts per million. About 70 percent of the total area contains less than 100 ppm of calcium. The higher concentration in Loei and Chaiyaphum (upper and lower left of the map, respectively) is due to gypsum and limestone sources. Gypsum may not have a major role in the high concentration in Sakon

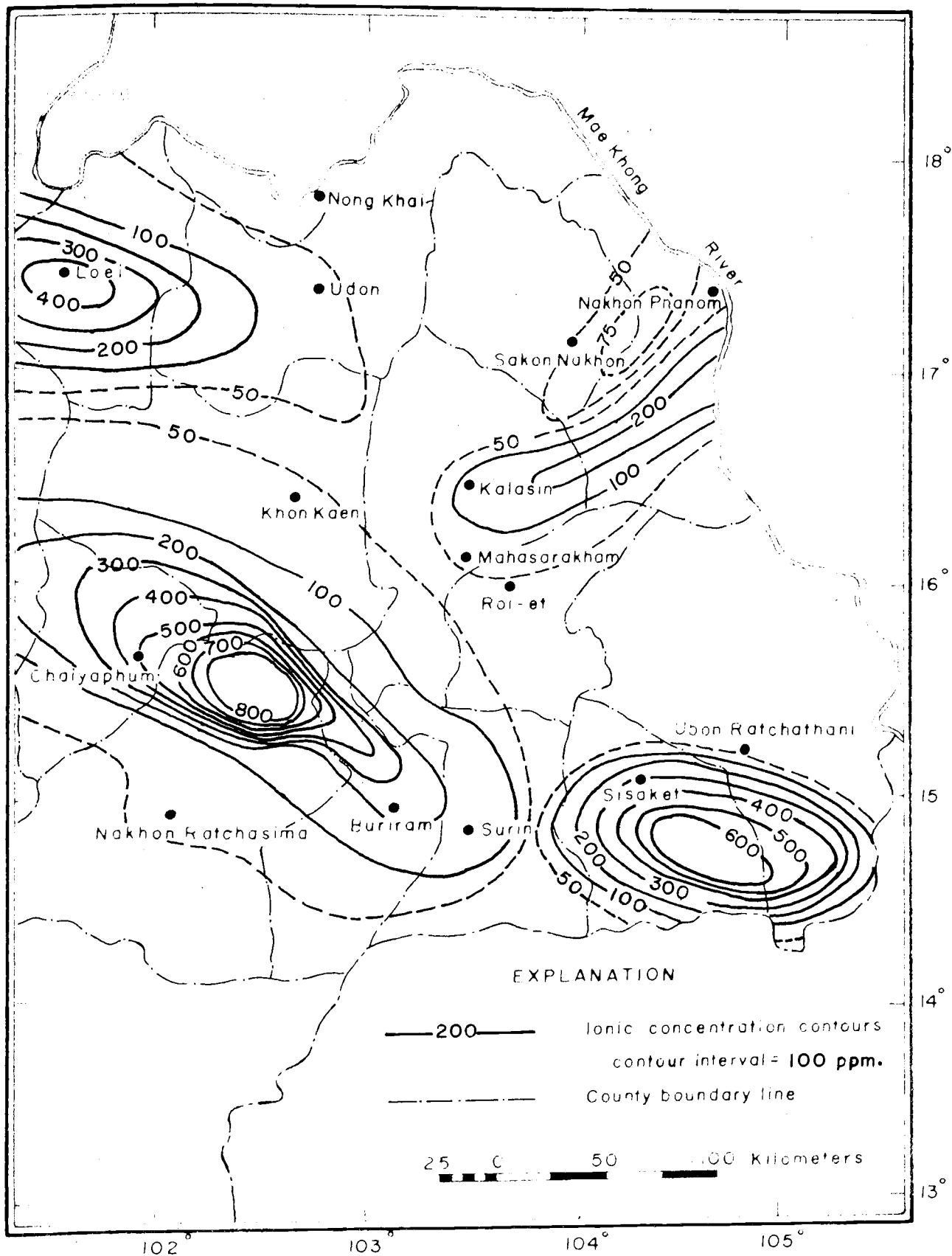


Figure 5 - Isopachous map of calcium.

Nakhon and Nakhon Phanom area (upper right) because the calcium content does not exceed 600 ppm (Hem, 1957, p. 76). The highest concentration in the area lies along the course of the Nam Kam River which receives its water from Nong Han Lake of Sakon Nakhon. The movement of surface water and ground water toward the Mae Khong River may be of some significance to the modification of water quality. The cause of high concentration in Sisaket and Ubon areas (lower right on the map) is obscure, but the presence of gypsum layers shown by the sample logs may be involved. The geologic and hydrologic environments do not seem to offer an explanation.

### Magnesium (Mg)

#### Technology

Magnesium ( $\text{Mg}^{++}$ ) is rather abundant in the earth's crust, but is relatively less than  $\text{Ca}^{++}$  in natural water, except in sea water. The silicate minerals of ferromagnesian and ultrabasic rocks are considered to be the major sources of  $\text{Mg}^{++}$  in water associated with them. The other principal source of  $\text{Mg}^{++}$  is the sedimentary rocks in which non-silicate minerals of magnesium, such as dolomite, magnesite, and spinel, are the major constituents. Magnesium chloride and magnesium sulfate, which are associated with most salt deposits, yield considerable quantities of  $\text{Mg}^{++}$  to water (Beck, 1941, p. 3).



The amount of  $\text{Mg}^{++}$  in water depends largely on the degree and relative solubility of magnesium minerals. The magnesium silicates may be altered by water containing carbondioxide under serpentinization reaction and yield magnesium carbonate which may be dissolved in circulating water. The solubility of  $\text{MgCO}_3$  is increased by the presence of  $\text{CO}_2$  and is converted to more soluble magnesium bicarbonate. With the absence of  $\text{CO}_2$ , magnesium carbonate is not very soluble, although its solubility is higher than that of calcium carbonate (Hem, 1957). Unlike  $\text{Ca}^{++}$ ,  $\text{Mg}^{++}$  is not deposited as  $\text{CO}_3^{=}$  when it is exposed to  $\text{CO}_2$  in the air or sample bottle (Clarke, 1924, p. 204). This is why magnesium is predominant over calcium in some water. Magnesium carbonate is more readily dissolved by water containing sodium salt than by pure water (Cameron and Seidell, 1904). Dolomite, however, is less readily dissolved than limestone under ordinary weathering conditions (Clarke, 1924), but magnesium sulfate and chloride are the most soluble in water.

Magnesium is the other cause of hardness in water. Salts of magnesium act as cathartics and diuretics. The U.S. Public Health Service (1946) recommends that magnesium should not exceed 125 ppm in drinking water and culinary water, but water that contains less than 5,000 ppm magnesium is harmless to cattle. Magnesium, like calcium, flocculates soil colloids and tends to maintain good soil structure and permeability (Rainwater and Thatcher, 1960, p. 197).

## Calcium-Magnesium Ratio

The ratio of calcium:magnesium in water in epm units may give an indication of the chemical quality of water. Generally, Ca:Mg in water ranges from 5:1 to about 1:1. A high ratio of Ca:Mg suggests that the water obtains  $\text{Ca}^{++}$  from relatively pure limestone or gypsum, while a low ratio is a result of pollution by magnesium industrial wastes or, in some instances, is a result of precipitation of  $\text{CaCO}_3$ . Contamination by sea water also causes the low ratio, because Ca:Mg in sea water is about 1:5. The ratio of 1:1 indicates that water is associated with dolomite terrane (Hem, 1957).

## Sources of Magnesium in Ground Water

The magnesium concentration in the ground water in the Khorat Plateau is relatively low in comparison to that of calcium. Many water analyses are reported to contain no magnesium. It may be because of the deficiency of good sources in the area. The ratios of Ca:Mg in epm range from 1:1 to 27:1, with the exception of wells A38Ub13, E14NK4, A50Ub24, and D63Ms23, in which the Ca:Mg ratios of the first two wells are 1:2 and those of the last two wells are 1:3. The excess of magnesium over calcium in those wells is not caused by either pollution from magnesium industrial disposals or contamination by sea water, because there is no magnesium industry in the area, and also, the area is far

from the sea and high above it. The only possible explanation is that  $\text{Ca}^{++}$  has been precipitated as  $\text{CaCO}_3$  either before or after collection of the samples.

The principal sources of magnesium in the plateau are the dolomitic limestones, which deliver the ion to water associated with them. Analyses C45L3 and C48L6 (pl. III-B) are of waters collected from wells drilled in the limestone area. They indicate much less magnesium than calcium, and suggest that  $\text{MgCO}_3$  is less abundant than  $\text{CaCO}_3$  and  $\text{CaSO}_4$  in the limestones. The other principal sources of  $\text{Mg}^{++}$  are possibly  $\text{MgCl}_2$  and  $\text{MgSO}_4$ , which are associated with rock salt, and yield considerable amounts of  $\text{Mg}^{++}$  to water in the shale and siltstone aquifer in particular localities—such as Chaiphum and Nakhon Ratchasima. Biotite and other ferromagnesian impurities in both the upper shale and the Phra Wihan and Phu Kadung sandstones may yield some significant quantities of  $\text{Mg}^+$  to waters of the aquifers. Basaltic sand and gravel in alluvium may be another source of  $\text{Mg}^{++}$  in that aquifer, although the bulk is believed to be the result of contamination from water of underlying shale and siltstone. Of all the aquifers, the Phu Phan sandstone contains the least magnesium (pl. III-B). This is presumably because of the lack of sources.

The lack of magnesium along with high concentrations of calcium in alluvium or shale and siltstone aquifers is not believed to be due to base-exchange reactions, because calcium is more readily

exchangeable than magnesium, but must be due to lack of sources. Another possibility is that any small amounts of magnesium present have been flushed out by the movement of ground water.

### Range and Distribution

The concentrations of magnesium in the ground water cover a wide range—from zero in the alluvial aquifer to the maximum of 314 ppm in the shale and siltstone aquifer. Within each aquifer the concentration varies markedly. Figure 6 shows the isopachous map of magnesium in the plateau. The magnesium content in an alluvial aquifer of Nakhon Ratchasima ranges from 11 ppm in the higher areas to 65 ppm in the lower areas. The alluvium of Khon Kaen, Mahasarakham, Roi-et, and Ubon Ratchathani along the course of the Chi River contains magnesium with ranges of zero to 18 ppm; the concentrations in the alluvium of the Sakon Nakhon Basin range from 2.9 to 51 ppm in a well at That Phanom. The amounts of  $Mg^{++}$  in shale and siltstone range from 11 ppm to 314 ppm in the Khorat Basin, and not more than 30 ppm in the Sakon Nakhon Basin. The difference in quantities of magnesium in these two basins is due to the sources of  $Mg^{++}$ , as previously stated. The magnesium in water of the Phu Phan sandstone is generally low along the western and southern margins of the plateau, but slightly higher in the Phu Phan Range. In the limestone aquifer the magnesium content is moderately high, and the maximum of 64 ppm is reported.

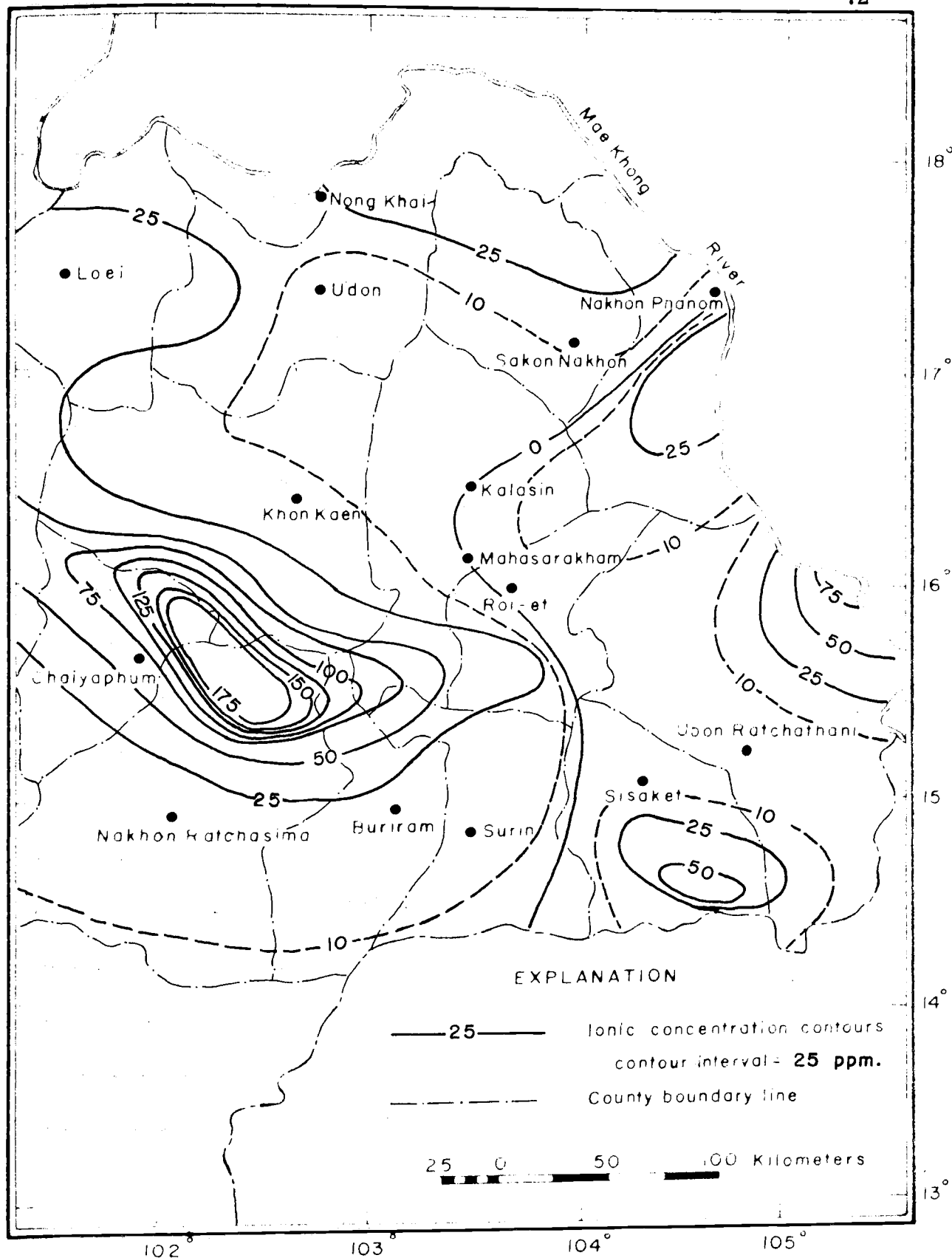


Figure 6- Isopachous map of magnesium.

The overall pattern of distribution is similar to that of calcium, and the four areas of very high concentrations are coincident. An exception is one additional area of high magnesium (middle-right of figure 6) where the Ca:Mg ratio is 1:3, as previously mentioned.

### Sodium and Potassium (Na & K)

#### Technology

Sodium ( $\text{Na}^+$ ) and potassium ( $\text{K}^+$ ) are in the same alkaline metals group, but sodium is more abundant than potassium in natural water. However, in water of low dissolved solids the ratio of potassium to sodium is nearly 1:1, and decreases with increase of dissolved solids (Hem, 1957). This is the case in the Khorat Plateau, where the amount of potassium in most wells is reported to be zero. In only a few wells the potassium concentrations range from 1 to 7 ppm. Because it is an unimportant constituent in the ground water of the plateau, potassium is grouped together with sodium for this report. Although the chemistry of potassium is somewhat different from that of sodium, it is not believed water quality will be much effected by potassium.

Albite is the major source of sodium in water associated with igneous rocks, while orthoclase, microcline and mica of the same rocks may give up part of their potassium to water in weathering processes (Rankama and Sahama, 1950, p. 431). In sedimentary clastic

rocks,  $\text{Na}^+$  and  $\text{K}^+$  may occur in the form of silicate minerals, clay minerals, impurities in cementing agents, or salts laid down with sediments. The principal source of  $\text{Na}^+$  and  $\text{K}^+$  in natural water is evaporites—such as  $\text{NaCl}$ ,  $\text{Na}_2\text{CO}_3$ , and  $\text{Na}_2\text{SO}_4 + 10\text{H}_2\text{O}$  (mirabilite), and some other potassium salts. In limestone or gypsum,  $\text{Na}^+$  and  $\text{K}^+$  may be present in impurities, but this is generally considered as an insignificant source. Sodium and potassium can be also added to water by waste disposal.

As previously mentioned, the chemistry of sodium is rather different from potassium. Sodium, when leached from rocks, tends to remain in solution, and will not precipitate like calcium or magnesium upon exposure to the air. An explanation is that nearly all sodium compounds are readily soluble in water. Potassium, unlike sodium, is not easily dissolved from rocks (Goldich, 1938), and once it is dissolved in water it tends to be converted to solid phases by either base exchange of clay (Mason, 1952, p. 136-137), or by formation of mica or mica-like minerals which are resistant to chemical weathering (Hem, 1957, p. 90). Some potassium in water is also used up by plants. These facts explain why potassium concentrations in water are less than those of sodium. In base-reaction, sodium and potassium may be taken up by clay, and, at the same time, release calcium to water. But if the clay has already been saturated with sodium the process will be reversed, and the sodium proportion in water will be increased.

However, extremely high concentrations of both  $\text{Na}^+$  and  $\text{K}^+$  in water indicate that the water is associated with beds of evaporites or brine.

Sodium and potassium are not particularly harmful in drinking water, but have some significance to industrial purposes. The concentration of more than 50 ppm sodium plus potassium in boiler-feed water causes foaming, and a concentration of 2 to 3 ppm is recommended for water used in high-pressure boilers (Rainwater and Thatcher, 1960). A high ratio of sodium to calcium plus magnesium is unsatisfactory for irrigation, because it tends to disperse the soil colloids, with the resultant loss of good tilth and permeability (U.S. Salinity Laboratory Staff, 1954, p. 69-82).

#### Sources of Sodium and Potassium in Ground Water

Wide variation of sodium concentration is always expected in ground water of the plateau. Potassium is practically absent. The principal source of sodium is undoubtedly the salt deposits existing in both the Khorat and Sakon Nakhon Basins. Some significant quantities of  $\text{Na}^+$  in the water may be delivered from clay impurities in both shale and sandstone beds. The reported zero potassium in water of low sodium content indicates the lack of sources of potassium, because there should be nearly equal amounts of  $\text{Na}^+$  and  $\text{K}^+$  in this type of water. The analyses of zero potassium with high  $\text{Na}^+$  concentrations indicate either the lack of sources of potassium or the modification of water through



base-exchange reaction or conversion of potassium to solid phases.

Plates III-A and III-B illustrate the amounts of ( $\text{Na}^+ + \text{K}^+$ ) in representative samples.

#### Sodium and potassium in alluvium

Sodium and potassium in this aquifer may be classified into three groups, according to their sources. The first is sodium that has been picked up in the form of normal salt from the ground surface by running water and then recharged to the aquifer. The second is sodium or potassium released to ground water by means of chemical weathering of sodium and potassium silicate minerals within the aquifer. The third is sodium and potassium that is added by means of contamination of NaCl water from the underlying shale and siltstone. Analyses C2NR2 and G21NP13 in plate III-A show the result of contamination by NaCl water because the amounts of sodium and chloride are nearly equal. Analyses A30Ub5 and D1NR1 suggest both contamination by NaCl water and the base-exchange reaction by which calcium and magnesium in water have been exchanged for sodium by clay.

#### Sodium and potassium in shale and siltstone

Sodium is most abundant in water of this aquifer. The concentrations range from zero to a maximum of 3,926 ppm in Nakhon Ratchasima. Potassium is mostly absent except in a few wells where

the concentrations range from 1 ppm to a maximum of 7 ppm. The principal source of sodium is surely from the rock salts in both minute layers and thick beds (400 feet) within the formation. Connate water existing since the deposition of shale and siltstone is believed to yield some considerable quantities of both sodium and potassium to the water. Circulation of salt-bearing surface water possibly adds to the quantity of  $\text{Na}^+$  or  $\text{K}^+$  in water. Analysis C19NR19 in plate III-A indicates that the water is in direct contact with rock salts. Analyses C22KK2 and D10R6 suggest that NaCl is the major source of  $\text{Na}^+$  in these waters. Analysis B7B4 shows a small quantity of  $\text{Na}^+$  with comparison to  $\text{Ca}^+$  and  $\text{Cl}^-$ . This is the result of exchanging of  $\text{Ca}^+$  in basaltic clay for  $\text{Na}^+$  in water.

#### Sodium and potassium in sandstone

The concentrations of sodium and potassium in both the Phu Phan sandstone aquifer and the Phra Wihan and Phu Kadung aquifer are comparatively low due to the lack of important sources. Sodium and potassium are presumably acquired by leaching of sodium and potassium silicate impurities in cementing materials, by solution of salt, or from connate water within the interbedded shales. Contamination by NaCl from surface water is a possible source of  $\text{Na}^+$  in some wells. This is evidenced by the analysis C40C2. Analysis G27NP9 shows the absence of a source of  $\text{Na}^+$  because no  $\text{Na}^+$  or  $\text{Cl}^-$  is present. The small amount

of  $\text{Ca}^+$  and  $\text{Mg}^+$  in the water does not indicate base-exchange reaction, as the amount of sodium is also small.

### Range and Distribution

Rock salts are the principal sources of sodium and potassium and tend to be concentrated in the centers of the basins where salt deposits exist. Figure 7 is the isopachous map of  $\text{Na}^+ + \text{K}^+$ , showing distribution of the ions over the plateau. The highest concentration, as much as 3,926 ppm  $\text{Na}^+$ , is located in Chaiphum and Nakhon Ratchasima where rock salt is near the surface and salt layers on ground surfaces are abundant. Similar situations hold for the other two areas of high concentration in Sakon Nakhon, Sisaket, and Ubon Ratchathani. A large amount of  $\text{Na}^+$  in an area south of Nakhon Ratchasima is difficult to explain. The geologic and hydrologic environments, however, have some influence on the distribution of the ions, because their concentrations tend to increase downdip and the trends of distribution more or less correspond to the courses of rivers. Flushing effects undoubtedly occurred in the direction of movement of ground water.

### Chloride (Cl)

#### Technology

Chloride ( $\text{Cl}^-$ ) is present in practically all natural water. Its

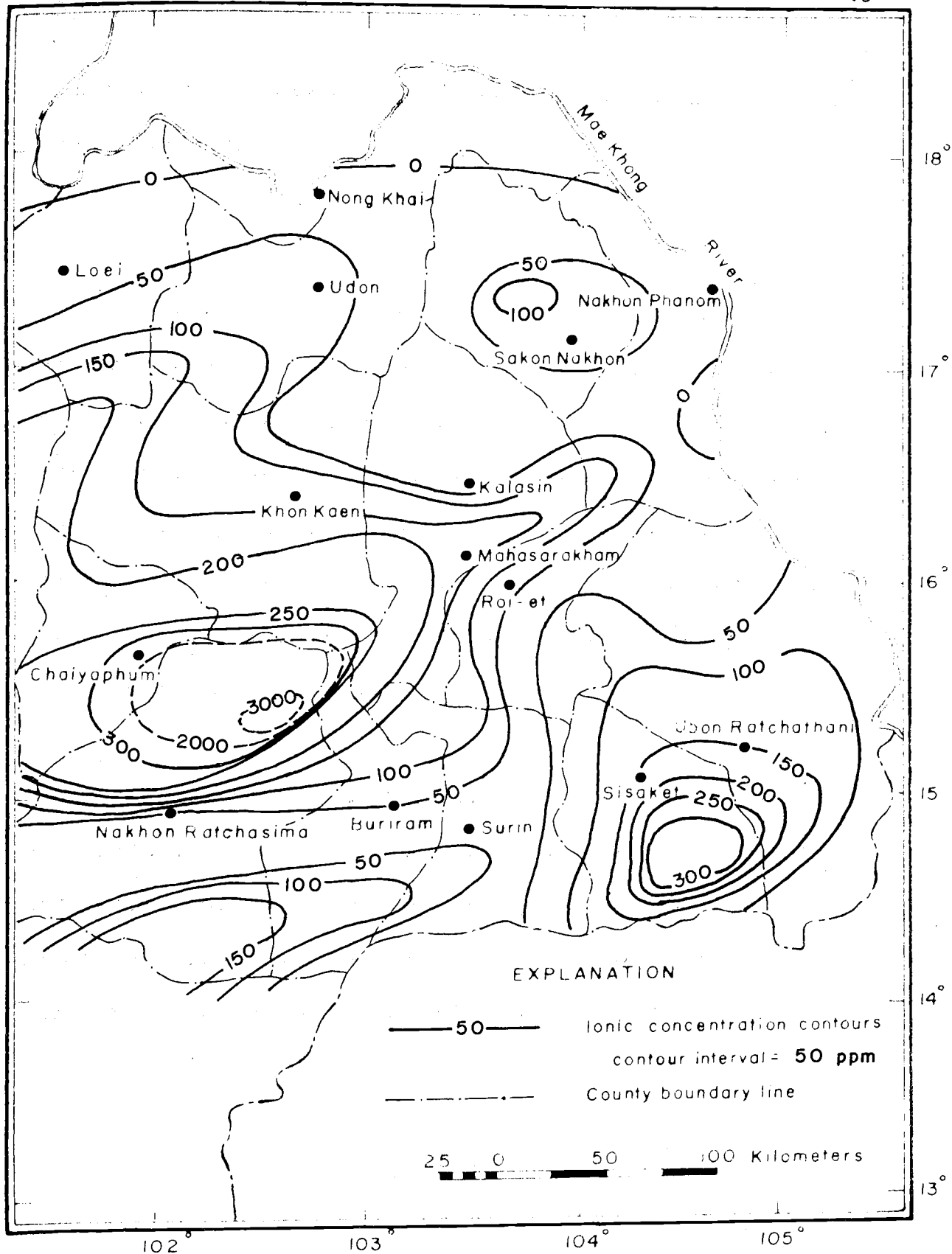


Figure 7 - Isopachous map of sodium plus potassium.

quantities may range from only a few parts per million in many surface waters to several thousand parts per million in ground water which is in direct contact with salt deposits or brine. Generally, the sources of chloride in water are similar to those of Na, as both are derived mainly from NaCl minerals. Sedimentary rocks, especially evaporites and hydrolyzates, are important sources of chloride. Other clastic sedimentary rocks may contain NaCl salts as a result of inclusion of connate water, or as a result of impregnation by soluble salts at any time after their deposition. The circulation of surface water through soils containing salts may add considerable quantities of chloride to ground water. Igneous rocks are a minor source of chloride, except some granites or glassy rocks that contain residual chloride water in their pores (Shand, 1952, p. 34; Kuroda and Sandell, 1953). Rainwater, carrying windblown salts from the sea, may add a small amount of chloride to water (Riffenburg, 1925). Industrial wastes and human and animal excreta are reported to deliver a large amount of chloride to water.

Chlorides in reasonable concentrations are not harmful to man. The range of concentrations that effect the uses of water for drinking and other domestic purposes depends on individuals whose sensitiveness to the salty taste of chloride is different. The U.S. Public Health Service (1946) recommends that chlorides be limited to 250 ppm in public water supplies. The Johnson National Drillers Journal (January

to August 1960) gives the following characteristics of water regarding the chloride content:

Water of less than 150 ppm  $\text{Cl}^-$  is satisfactory for most purposes.

Water of more than 250 ppm  $\text{Cl}^-$  is objectionable for water supplies.

Water of more than 350 ppm  $\text{Cl}^-$  is objectionable for most irrigation or industry.

Water of more than 500 ppm  $\text{Cl}^-$  is of disagreeable taste.

In addition, chlorides may accelerate corrosion in pipes, boilers, well casing and screens, and other fixtures (Taylor, 1949).

#### Sources of Chloride in Ground Water

Water having a high  $\text{Na}^+$  content will also contain high  $\text{Cl}^-$ .

This generalization is most applicable to the ground water of the Khorat Plateau where both  $\text{Na}^+$  and  $\text{Cl}^-$  are derived mainly from the same sources. Rock salt deposits and salt laid down on ground surfaces are considered as the principal sources. The concentration of chloride in many wells, however, is far above that of sodium, because the latter has been undergoing chemical modification through base-exchange or other reactions. Plate III-A and Plate III-B demonstrate the chloride content in representative samples. Analyses A30Ub5, C2NR2, C21NP3 show nearly equal amounts of  $\text{Na}^+$  and  $\text{Cl}^-$  in water collected from wells drilled in alluvium. Contamination of surface water and introduction of

NaCl from the underlying shale and siltstone are possible. Analysis D1NP1 indicates the same sources of  $\text{Cl}^-$  as those just mentioned, but the water had been subjected to base exchange with clay so that  $\text{Na}^+$  is released to the water. Analysis D59Ms19 is also chemically modified, but the process is reversed—that is, sodium has been exchanged for  $\text{Ca}^+$  in clay, and the result is a low concentration of  $\text{Na}^+$  as compared to  $\text{Cl}^-$ . This process is true for the water of analysis B7B4. Analysis C19NR19 shows a high concentration of both  $\text{Na}^+$  and  $\text{Cl}^-$ . It suggests that the water is directly associated with rock salt deposits. The analyses of water from the Phu Phan sandstone in plate III-B show somewhat higher concentrations of sodium than those of chloride. This is probably not caused by base-exchange reactions, because such reactions rarely occur in sandstone. The possible reason is that sodium is not entirely derived from residual salts in pore spaces or from NaCl impurities in cementing agents. The sodium is partly released from sodium silicate minerals which never contain chloride. Analysis C40C2 indicates that the water is contaminated by percolating surface water, because the sandstone into which the well was drilled is directly exposed to surface soil. Analyses C45L3 and C48L6 show very little chloride in limestone.

### Range and Distribution

Like  $\text{Na}^+$ ,  $\text{Cl}^-$  is highly concentrated in the shale and siltstone

aquifer where rock salts exist. The concentrations range from tens of parts per million in higher elevations to many thousands of parts per million in the central portions of basins, such as in the Chaiyaphum and Nakhon Ratchasima areas. Alluvial aquifers, receiving chloride through contamination, attain the next rank of high concentrations which range from more than 10 ppm to 304 ppm in Nakhon Ratchasima, 161 ppm in Nakhon Phanom, 351 ppm in Mahasarakham, and somewhat lower in Ubon Ratchathani. The sodium in the Phu Phan sandstone aquifer and Phra Wihan and Phu Kadung aquifer is less than in the above two aquifers because of a lack of sources. The Rat Buri limestone aquifer carries the least concentration. Figure 8 shows equi-concentration lines of chloride in the area. The general pattern of distribution is similar to that of Na, except in some areas where the sodium has undergone chemical modification. The geologic and hydrologic environments may have the same influence—that is, flushing and decrease of concentration down the dip of rocks, and the modification of chemical quality of water in the direction of flow of ground water.

### Carbonate and Bicarbonate

#### Technology

Bicarbonate ( $\text{HCO}_3^-$ ) is a chief anion in many natural waters and in most water used for public supply. It occurs in water largely



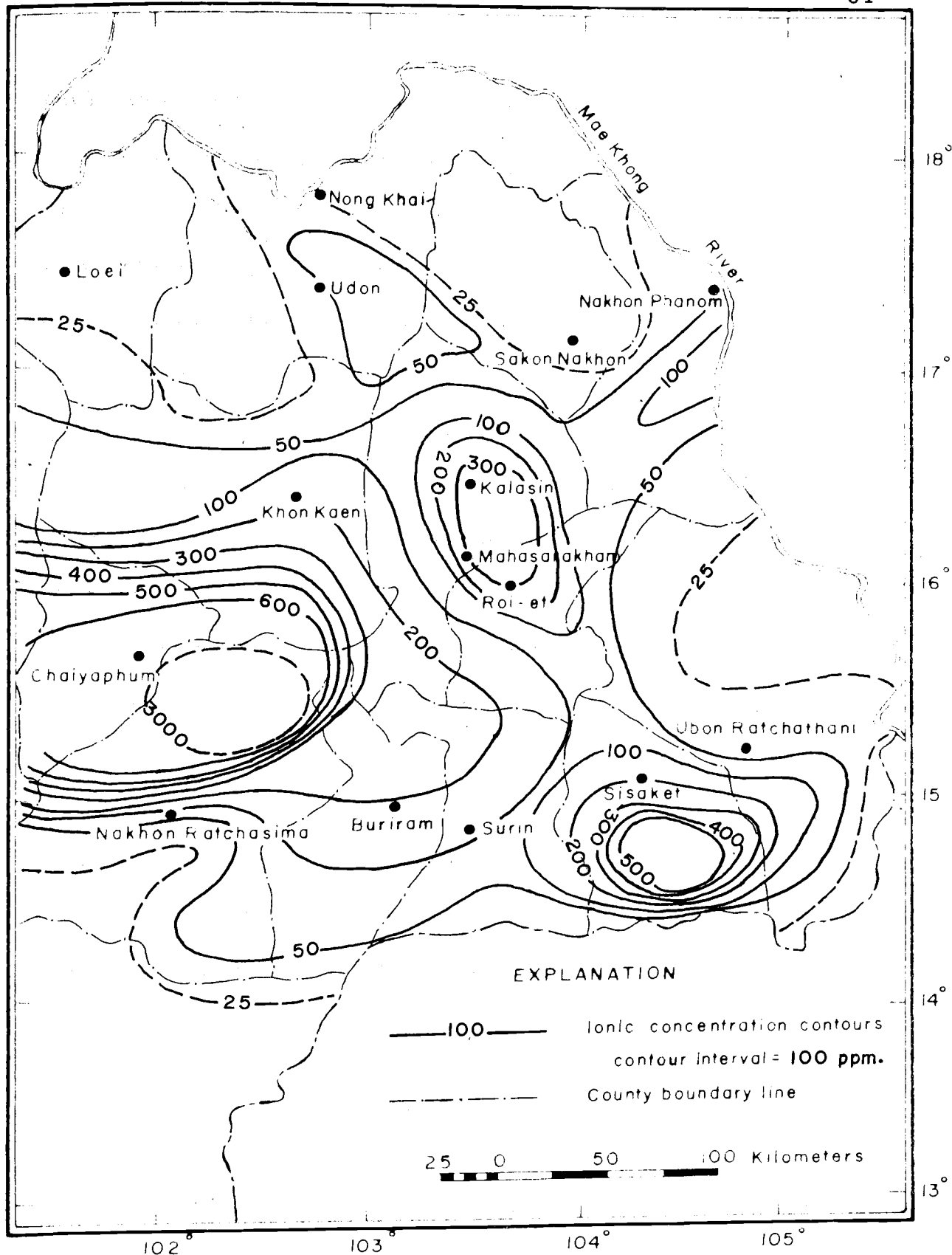


Figure 8 - Isopachous map of chloride.

through an action of  $\text{CO}_2$ , which enables the water to dissolve carbonate rocks or minerals. Carbonate ( $\text{CO}_3^{--}$ ) as such is present in water in inappreciable amounts or not at all. The principal sources of bicarbonate in water are limestone and allied carbonate rocks. Calcium carbonate, magnesium carbonate, sodium carbonate, or sodium bicarbonate in soils are also important sources of carbonate and bicarbonate in water associated with them. Calcium or magnesium carbonate minerals in cementing materials of clastic rocks also yield considerable amounts of bicarbonate to water. Water in contact with granitic rocks or rocks of similar characteristics usually contains less than 50 ppm of  $\text{HCO}_3^-$  and frequently less than 25 ppm (Love and Lohr, 1954). The combination of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  or the combined carbonic acid may be present as bicarbonate in water. The quantities of bicarbonate in water depend largely on the ability of the water to convert  $\text{CO}_3^{--}$  in rocks to soluble bicarbonate. The ability to dissolve is produced in soil where  $\text{CO}_2$  is released by bacterial action (Sawyer, 1960). The presence of large amounts of carbonate or bicarbonate in a soil solution is usually regarded as an indication of the presence of more soluble sodium carbonate or sodium bicarbonate in soil (Meinzer and Hare, 1915).

Bicarbonate in moderate concentration in water is not harmful, although it produces temporary hardness.  $\text{CO}_3^{--}$  and  $\text{HCO}_3^-$  in water are usually desirable in soils, but cause scales of  $\text{Ca}$  or  $\text{MgCO}_3$  in boilers.  $\text{HCO}_3^-$  and  $\text{CO}_3^{--}$  are reported to aid in coagulation of water (U. S.

Geological Survey, 1955).

### Sources of Bicarbonate in Ground Water

Carbonate is absent in all water samples of the plateau, even in the limestone areas. The reason for this absence may be either that all carbonates are converted to soluble bicarbonate or that carbonates exist only in precipitated forms.

The range of concentration of bicarbonate is not as wide as that of  $\text{Na}^+$  and  $\text{Cl}^-$ , although the highest range reaches 596 ppm in some areas. All aquifers, essentially, carry considerable quantities of bicarbonates, of which the average highest concentration is in limestone and sandstone, and the average lowest is in shale and alluvium. Plate III-A and Plate III-B also show the concentrations of bicarbonate in representative samples from each aquifer.

#### Bicarbonate in alluvium

The principal source of bicarbonate in the aquifer is presumably carbonate salts in soils which are leached down to the aquifer by percolating water. The recharge of surface water carrying bicarbonate is possibly another source of the ions in ground water. The carbonate impurities of clay in the aquifer may provide some, if not all, essential amounts of bicarbonate to water. Analysis A30Ub5 shows only a small amount of bicarbonate and indicates a scarcity of sources. Analysis

C2NR2 suggests that bicarbonate is given to the water by  $\text{CaCO}_3$  and  $\text{MgCO}_3$ , although a large part of  $\text{Ca}^+$  and  $\text{Mg}^+$  is derived from sulfate salts. Analyses D1NR1 and D59Ms19 also show that the sources of bicarbonate are calcium and magnesium carbonates, but calcium and magnesium have been subjected to base exchange. Analysis G21NP13 reveals that only  $\text{CaCO}_3$  is the source of bicarbonate as  $\text{Mg}^+$  is absent and base exchange has not occurred.

#### Bicarbonate in shale and siltstone

The characteristics of bicarbonate concentration in this aquifer are quite opposite to those of chloride; that is, water of high  $\text{Cl}^-$  content contains low  $\text{HCO}_3^-$ , and water of low chloride has high  $\text{HCO}_3^-$ . These facts explain why total cations are balanced by total anions. However, the  $\text{HCO}_3^-$  concentration in some particular areas, such as that between Nakhon Ratchasima and Khon Kaen, is abnormally high. The sources of the ions in the area named are undoubtedly the soluble sodium carbonate or sodium bicarbonate existing as residual salts in shales. Calcium and magnesium carbonate salts occurring within the shale and siltstone formations, or accompanying rock salt deposits, are believed to be the other sources. Connate water in shales may yield some  $\text{HCO}_3^-$  to water. Contamination of both surface water and water from alluvium may be minor sources. Analysis C19NR19 indicates that  $\text{HCO}_3^-$  has been released to water by solution of sodium, calcium, and magnesium

carbonates.  $\text{HCO}_3^-$  in analyses B7B4 and C22KK2 is from the solution of  $\text{CaCO}_3$  and  $\text{MgCO}_3$ , while  $\text{HCO}_3^-$  in analysis D10R6 is derived mainly from  $\text{CaCO}_3$ .

#### Bicarbonate in sandstone

Concentrations of  $\text{HCO}_3^-$  in the Phu Phan sandstone aquifer are slightly less than those in the Phra Wihan and Phu Kadung sandstones, owing to the difference of sources. Water of the Phu Phan sandstone receives its  $\text{HCO}_3^-$  only from the carbonate cementing materials or carbonate impurities, while water of the Phra Wihan and Phu Kadung sandstones gains additional  $\text{HCO}_3^-$  from residual salts existing within the interbedded shales. The water in both aquifers may also acquire bicarbonate from percolating water through streams or surface soils, as exemplified by sample A50Ub24, which was collected from a well drilled near the bank of the Mae Khong River. Other analyses show evidence of solution of  $\text{CaCO}_3$  and  $\text{MgCO}_3$  within the aquifers. An exception is the analysis of well C40C2, which gains part of its  $\text{HCO}_3^-$  from surface soils.

#### Bicarbonate in the Rat Buri limestone

$\text{CaCO}_3$  and  $\text{MgCO}_3$  in the dolomitic limestone yield great quantities of  $\text{HCO}_3^-$  to water. The  $\text{HCO}_3^-$  content is, however, not as high as the  $\text{SO}_4^{2-}$  in the same aquifer because of the lower degree of

solubility of limestone than gypsum. The low concentration of  $\text{HCO}_3^-$  in the aquifer may indicate a small amount of  $\text{CO}_2$  in the water. Analyses C45L3 and C48L6 show the typical water in limestone of the area where  $\text{SO}_4^{=}$  is far higher than  $\text{CO}_3^{=}$ .

### Range and Distribution

The highest concentration of  $\text{HCO}_3^-$  is in shale and siltstone, but this does not mean that the aquifer contains the highest average. Sandstone aquifers tend to contain many hundreds of parts per million in the western and eastern margins of the plateau, but decline in some parts of the southern border and along the Phu Phan Range. In shale and siltstone, the concentration is low in the Sakon Nakhon Basin, but considerably higher in the Khorat Basin in which the  $\text{HCO}_3^-$  content abruptly increases in the area between Khon Kaen and Nakhon Ratchasima. Bicarbonate in the alluvium is relatively low along the courses of the Mun and Chi Rivers, but somewhat high along the banks of the Mae Khong River. The large quantities of  $\text{HCO}_3^{=}$  in the limestone aquifer are unique in the plateau. Figure 9 is the isopachous map showing the distribution of  $\text{HCO}_3^{=}$  over the plateau.

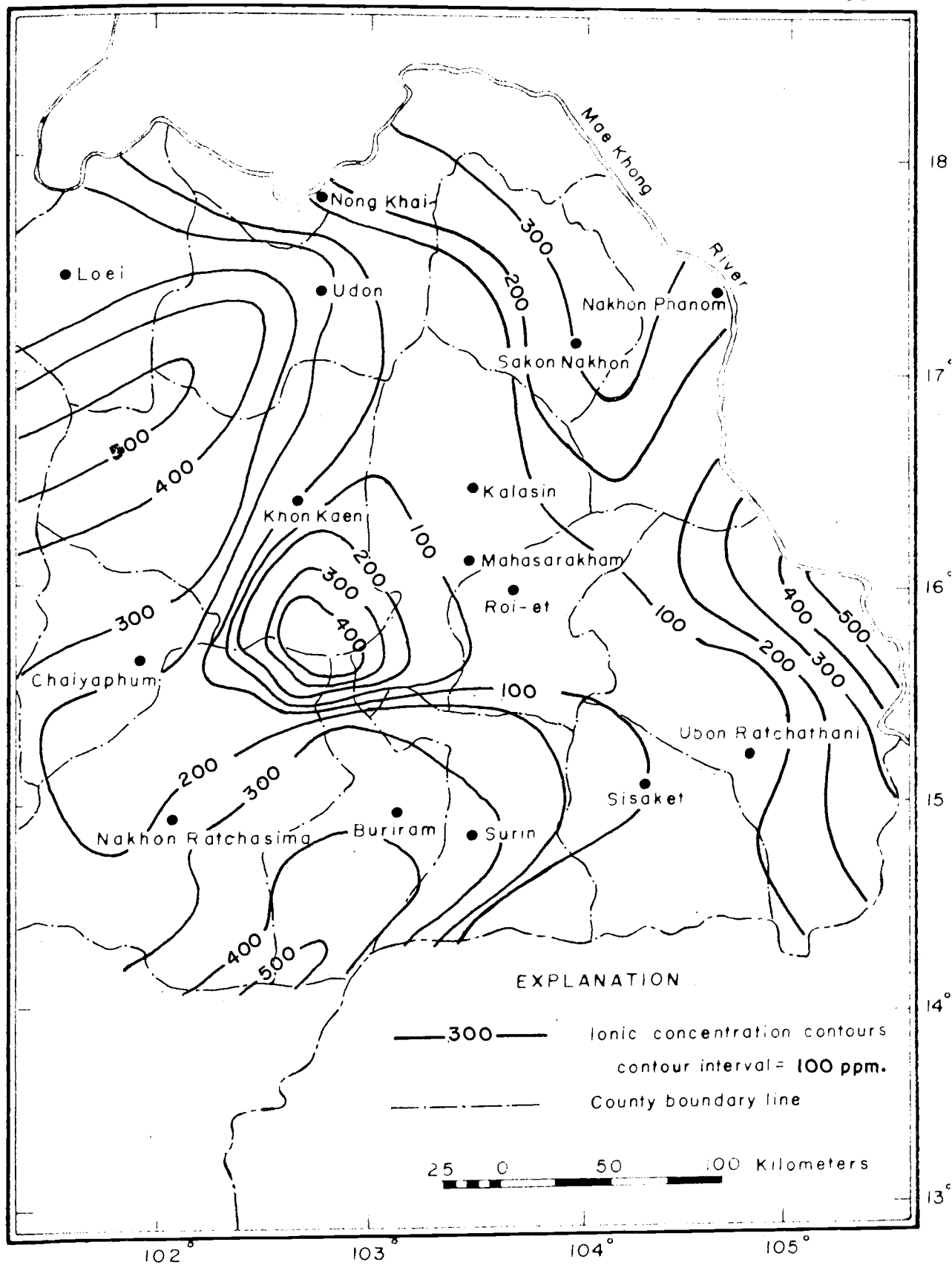


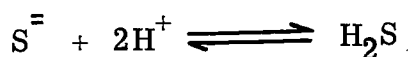
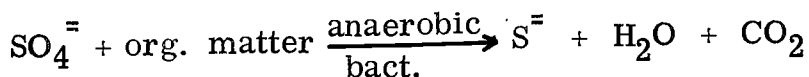
Figure 9- Isopachous map of bicarbonate.

## Sulfate ( $\text{SO}_4$ )

### Technology

Sulfate ( $\text{SO}_4^{=}$ ) is present in most water associated with sedimentary rocks, especially gypsum and anhydrite. Evaporite beds containing highly soluble  $\text{Na}_2\text{SO}_4$  and  $\text{K}_2\text{SO}_4$  may release an extremely high amount of sulfate to water. Shale containing sulfate or sulfide impurities may be another source of sulfate. Sulfide of heavy metals or sulfide ores, especially pyrite ( $\text{FeS}_2$ ), are partly oxidized in the weathering process to give soluble sulfate. High  $\text{SO}_4^{=}$  content is, thus, expected in water from mines.

Most sulfate salts are readily soluble in water and once they are formed their stability is maintained in most environments (Hem, 1957).  $\text{SO}_4^{=}$  in water may be deposited on ground surfaces through capillary action and evaporation. Under anaerobic conditions, sulfate in water may be reduced to hydrogen sulfide by bacteria (Rankama and Sahama, 1950, p. 341; Sawyer, 1960, p. 320).  $\text{HCO}_3$  and  $\text{CO}_2$  are formed as byproducts, as shown in the following equations:



Sulfate is important in public water supplies because of its cathartic effect upon humans when it is present in excessive amounts.



The U. S. Public Health Service (1946) recommends that the upper limit of sulfate in drinking water should not exceed 250 ppm. High concentration of sulfate in water for feeding livestock may result in detrimental effects (Rainwater and Thatcher, 1960). Calcium and magnesium sulfates in water are also reported as causes of hard formations of scale in steam boilers (U. S. Geological Survey, 1955).  $\text{H}_2\text{S}$  in water under reduction of sulfate is claimed as the cause of corrosion in well casings and screens.

#### Sources of Sulfate in Ground Water

The principal sources of  $\text{SO}_4^{=}$  in the ground water of the Khorat Plateau are gypsum and anhydrite, which exist as thin layers and impurities in shale and siltstone beds. Other highly soluble sulfate salts may also be associated with rock salts and yield high concentrations of  $\text{SO}_4^{=}$  to every water of high  $\text{Cl}^-$  content, as in the case of the shale and siltstone aquifer. With such information, it can be postulated that most water in shale and siltstone contains more  $\text{SO}_4^{=}$  than that in other aquifers except in the Rat Buri limestone, which also obtains sulfate from thick beds of gypsum. Plates III-A and III-B illustrate the concentrations of  $\text{SO}_4^{=}$  in each aquifer.

In alluvium, water gains  $\text{SO}_4^{=}$  mostly through surface water leaching  $\text{SO}_4^{=}$  out of soils and from the sulfate water of the underlying beds. This is shown by analyses A33Ub5, C2NR2, D1NR1, and

G21NP13. Analysis D59Ms19 shows no  $\text{SO}_4^{=}$ . With the concentration of 0.50 ppm  $\text{H}_2\text{S}$ , it is believed that the water has undergone reduction of sulfate by anaerobic bacteria.

Water from shale and siltstone mostly contains high concentrations of  $\text{SO}_4$  which may reach the upper limit of 1,629 ppm in certain areas. Exceptions are a few localities where the concentrations are very low due to either the lack of sources or the reduction of sulfate. Water associated with evaporites is represented by analysis C19NR19. Analyses C22KK2 and D10R6 indicate that the sources of sulfate are very rare in the areas, and any small amounts of sulfate once present, if any, have been reduced. The evidence for this is the small amount of calcium, suggesting little solution of gypsum, and by the fact that most of the calcium probably has been released from  $\text{CaCO}_3$  in soils or by the base-exchange process. Analysis B7B4 shows the concentration of  $\text{SO}_4^{=}$  in a well drilled in the vicinity of a lava flow.

In sandstone, the concentration of sulfate approaches zero in many wells because of a lack of sources. Small amounts of sulfate that are present in water may originate from sulfate impurities in cementing materials or residual sulfate salts within the interbedded shales. Of all representative samples, only analysis C40C2 shows a high concentration of sulfate, which is principally from contaminants in surface water.

$\text{SO}_4^{=}$  is the most abundant of all anions in limestone, due to the presence of gypsum previously mentioned. This  $\text{CaSO}_4$  water is

characteristic of the aquifer.

### Range and Distribution

The concentrations of sulfate over the plateau range from zero in alluvium, sandstone, and some areas of shale and siltstone, to 1,134 ppm in Sisaket, 1,629 ppm in Nakhon Ratchasima, and 1,703 in Loei. Figure 10 is the isopachous map showing the distribution of sulfate by the equiconcentration lines or contours. In general, in topographically high areas the concentrations reach zero, as in the areas along the western and southern margins of the plateau and along the Phu Phan Range. An exception is the limestone area in the northwest corner of the plateau. In the lower elevations the concentrations tend to increase and reach the maximum in the center of the basins where salt deposits are not far below the surface. All these reflect the influence of geology of the plateau. Hydrology also plays a major role in effecting the higher concentration of sulfate down rivers, as shown along the Chi and Mun Rivers in the Khorat Basin, and the Nam Kam River just south of Nakhon Phanom.

### Phosphate ( $\text{PO}_4$ )

#### Technology

Phosphate ( $\text{PO}_4$ ) is a negligible constituent and is not reported

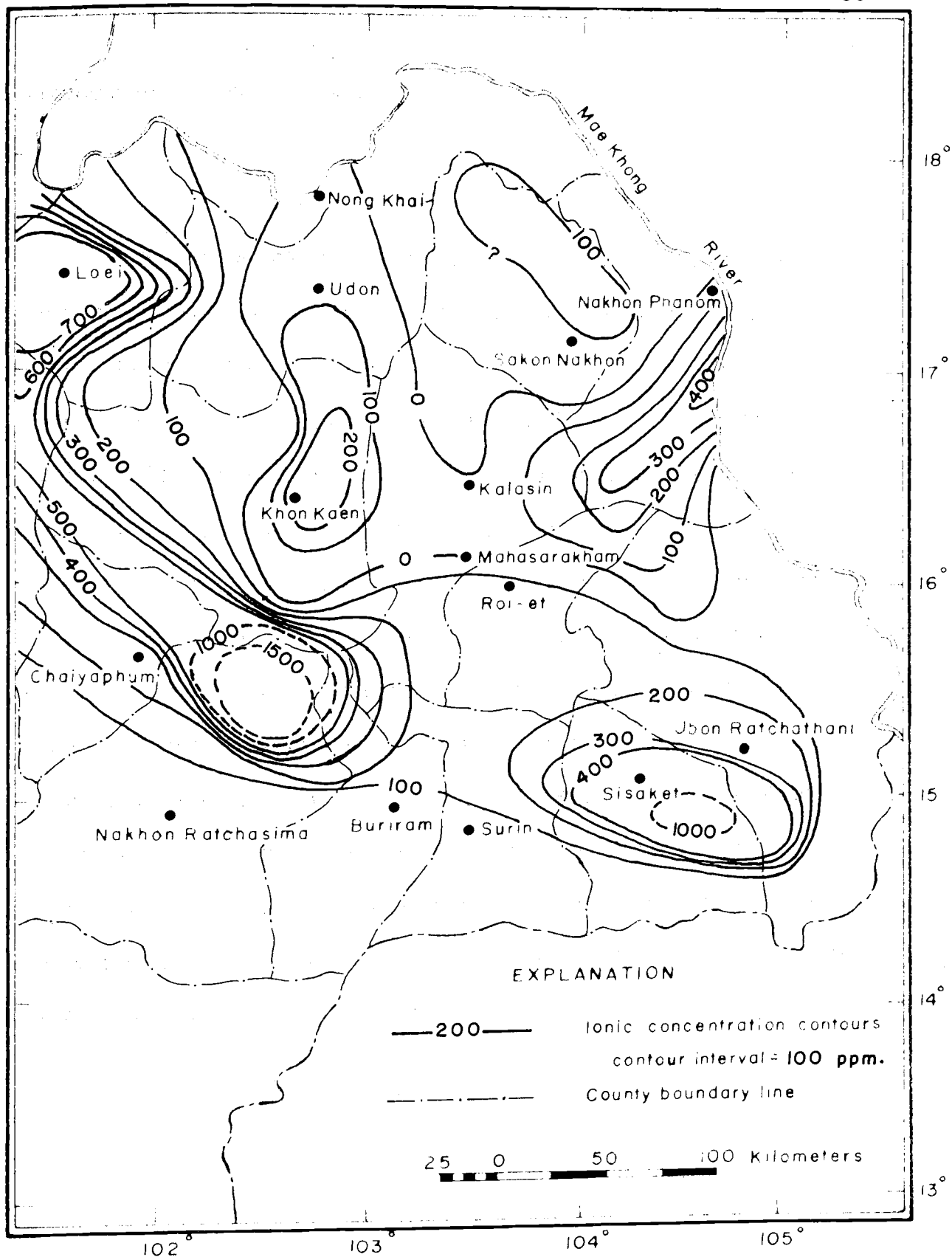


Figure 10- Isopachous map of sulfate.

in most of the chemical quality literature. A discussion of phosphate in this chapter is given because ground water of the Khorat Plateau contains a high concentration of phosphate in many localities and the study is believed to be worthwhile.

Phosphorus is common in nature as an essential element in growth and metabolism of animals and plants. The phosphate in natural water may result from organic waste, leaching of soils, and from fertilizer (Hem, 1957; Rainwater and Thatcher, 1960). Small amounts of phosphate in water may result from weathering of apatite in igneous rocks. Upon chemical attack, the rocks tend to release calcium phosphate which is at first soluble in water containing  $\text{CO}_2$ , but at last redeposits in clay or shale (Rankama and Sahama, 1950). Some considerable amounts of phosphate may be added to water by industrial waste and sewage which gain the ion from human waste and household detergents.

The normal range of concentration of phosphate in water is not more than a few parts per million, and a concentration as high as 30 ppm is regarded as unusually abnormal (Hem, 1957). The concentrations found in most water are not reported to be toxic to humans and animals; however, phosphate in water tends to encourage the growth of algae which causes troublesome odor in water supplies. The critical level for phosphorus has been recommended as near 10 ppm (Sawyer, 1960). Phosphate water is widely used in steam power plants to control scaling

in boilers.

### Sources of Phosphate in Ground Water

The principal source of phosphate in ground water of the Khorat Plateau is tropical plants which are decomposed by monsoon rainwater or floods during rainy seasons. The decaying of these plants and trees may yield very significant amounts of phosphate to the aquifers so that in some localities the concentrations range up to 180 ppm (well C14NR14 at Bau Yai, Nakhon Ratchasima). In highly populated cities where the sewage systems are not good, many parts per million of phosphate may be released to ground-water reservoirs, such as the case of Nakhon Ratchasima City whose phosphate concentration reaches 86 ppm. Many thousands of cattle raised in the plateau may add some amount of phosphate to water through their wastes. Phosphate minerals are believed to be insignificant sources of  $\text{PO}_4^{=}$  in water. Industrial waste is not considered as a phosphate source, as industrial plants are very rare in the area.

### Range and Distribution

Figure 11 is the isopachous map of  $\text{PO}_4^{=}$  showing the concentration and distribution of the ion over the plateau by means of contour lines. The highest concentration lies along the escarpment of the plateau where the sandstone is exposed and jungles (Dong Phraya Yen and

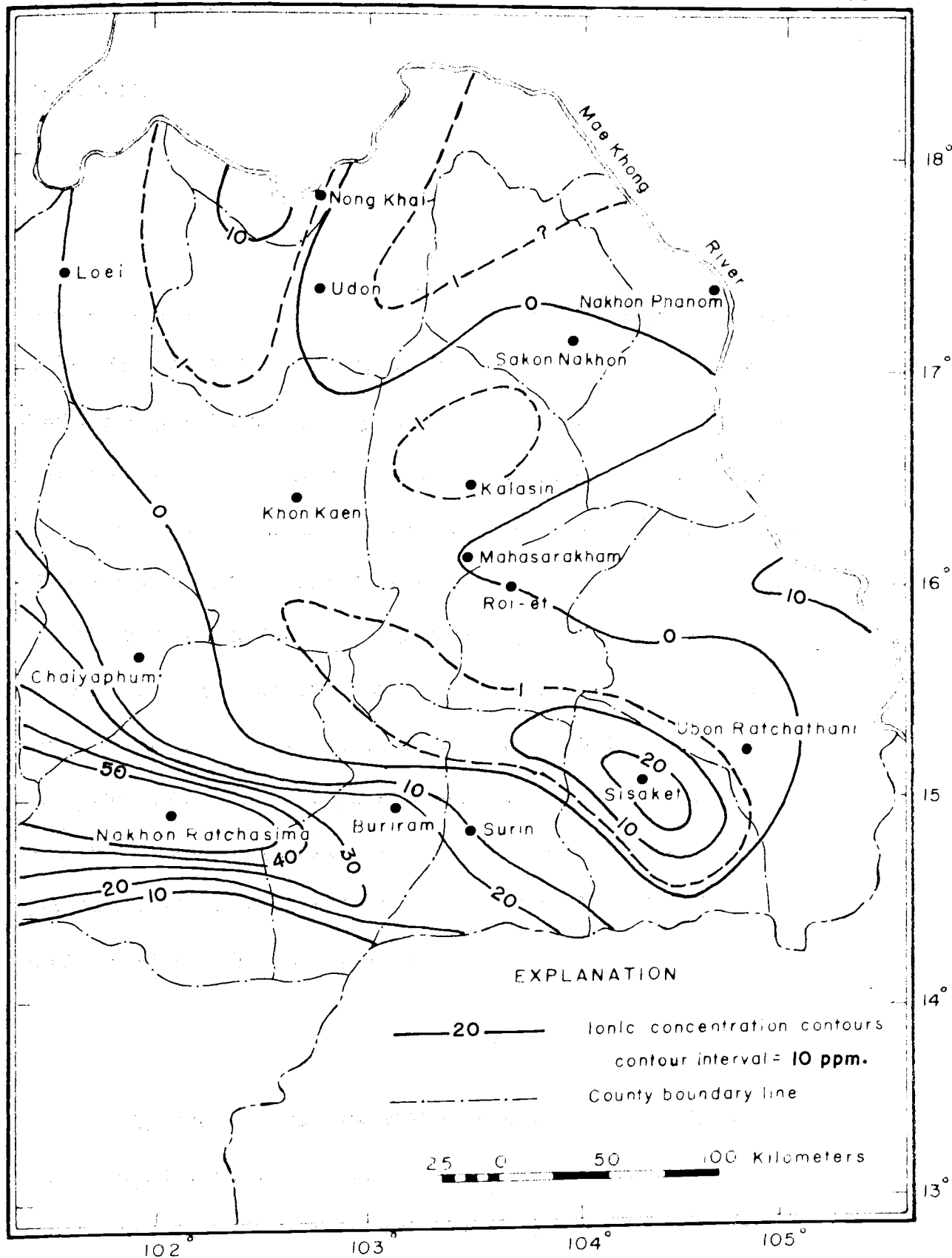


Figure II- Isopachous map of phosphate.

Dong Rek) are thick. Sandstones of the same age, whose outcrops are found along the Phu Phan Range, contain a lesser quantity of phosphate because the forest is not thickly grown and the flushing effect of rain-water may occur along the more highly dipping beds. The limestone area has insignificant amounts of phosphate in its water. In the central parts of basins which are grass and bush lands, waters carry not more than 1 ppm phosphate, and the range of 0 to 1 ppm is common.

### Nitrate ( $\text{NO}_3$ )

#### Technology

Nitrogen is present in natural water in the combined forms, of which ammonia ( $\text{NH}_3$  and  $\text{NH}_4^+$ ) and nitrate ( $\text{NO}_3^-$ ) are common. Nitrate is usually the dominant form of nitrogen in water because it is considered as a final product of oxidation of nitrogenous materials. Nitrate that is leached to water is postulated to be a result of oxidation of nitrogen in the air by bacteria, or a result of decomposition of organic materials in the soil. Human and animal excrements, inorganic fertilizer, and sewage may add nitrate directly to water resources. Igneous rocks and ocean water are reported to yield a minor amount of nitrate to water.

Nitrate in water is probably most stable when plenty of  $\text{O}_2$  is present (Hem, 1957), but under anaerobic conditions it may be reduced



by bacteria to ammonia and nitrogen gas (Sawyer, 1960, p. 291).  $\text{NO}_3$  may be lost from ground water at depth through anion-exchange reaction (George and Hasting, 1951).

Nitrate is generally present in water in a small amount, but a high concentration, with more than 0.1 ppm  $\text{NH}_3$ , is an indication of organic pollution (Rudolph, 1931). The concentrations of not more than 5 ppm have no effect in water for ordinary use, but the amounts ranging from 44 to 88 ppm may contribute to methemoglobinemia in infants (Waring, 1949). It is widely recommended that water containing more than 44 ppm of nitrate is unsafe for infant feeding (U.S. Geological Survey, 1955). It has been reported that nitrate of as much as 2 ppm in boiler-feeding water tends to prevent intercrystalline cracking of steel boilers.

#### Sources of Nitrate in Ground Water

Most ground water in the Khorat Plateau carries no nitrate, except for a few wells having from less than 1 ppm up to the highest value of 2 ppm in well F13SN7 (56 km southeast of Sakon Nakhon). These extremely low concentrations indicate that the principal source of nitrate is not available in the area. The only possible source is believed to be the nitrate in soils. The absence of  $\text{NH}_3$  in most water analyses suggests that there is no nitrate reduction occurring in the plateau.

## Range and Distribution

The concentrations of nitrate range from 0 to 0.1 ppm in shale, 0.7 ppm in alluvium, and 2 ppm in sandstone, but nitrate is completely absent in the limestone aquifer. The distribution of ions is more or less similar to that of phosphate. The geology seems to have insignificant effect on the distribution of nitrate, but the percolating waters do.

## Fluoride (F)

### Technology

Although fluorine is in the same group of halogens as chlorine and is reported as being present to about the same amount in some rocks, the fluoride ion ( $F^-$ ) in water is rare because of its low solubility. Fluorite ( $CaF_2$ ) is always regarded as the principal source of fluoride in water. Solution of mica containing fluoride is postulated as the other source of the dissociated ions (Cederstrom, 1945). Residual sea water entrapped in marine beds since the time of deposition is also a possible source of fluoride (LaMoreaux, 1950). Many authors suggest that fluoride may originate from magmatic sources or complex fluoride-bearing minerals.

Fluoride concentrations of 10 ppm or more in ordinary water are rare, but the maximum of 67 ppm  $F^-$  has been reported (Hem,

1957). High concentration of fluoride in water supplies causes mottling of children's teeth, but the lack of fluoride in water may result in tooth decay in children.

The amounts of 0.88 to 1.5 ppm  $F^-$  in water, however, are found to be safe in both respects (Rainwater and Thatcher, 1960). The U. S. Public Health Service recommends that the concentration of fluoride in drinking water should not exceed 1.5 ppm. Fluoride in water has the same effect on livestock as on the human (California State Water Pollution Control Board, 1952, p. 256).

#### Sources of Fluoride in Ground Water

Fluoride is rarely present in ground water of the Khorat Plateau. The maximum concentration is found to be 3.5 ppm in well D1NR1 within the city of Nakhon Ratchasima. The normal range lies between 0 to 1.2 ppm, and the highest average concentrations occur within the shale and siltstone aquifer. To the many hypotheses of sources of fluoride in natural water may be added the possibility that fluorite ( $CaF_2$ ) and other complex fluoride salts occurring as impurities in both salt deposits and sediments contribute fluoride to the ground water. This is suggested by relatively higher concentrations of fluoride in the shale and siltstone just mentioned. The connate water existing in shale may be another source. Impurities in cementing materials, if any, may yield some small amount of fluoride to sandstone. Solution of mica

never yields any fluoride to the ground water, as water from all wells drilled in micaceous sandstone of Middle and Lower Triassic age contains no fluoride.

### Range and Distribution

The geologic setting of the plateau must have the most influence on the range of concentration and distribution of fluoride. Water from almost every well drilled in the Sakon Nakhon Basin and other areas in the northern half of the plateau contains no fluoride, while more than half of the wells drilled in the Khorat Basin and even in the sandstone areas contain fluoride ranging from 0.2 to 3.5 ppm. The highest concentration tends to occur within the center of the basin where the source is dominant. Flushing and contamination may occur in the region because water in some alluvium contains a considerable amount of fluoride while others have none.

### Total Dissolved Solids

#### General Consideration

Total dissolved solids are the total amounts of dissolved chemical constituents, expressed in parts per million, in each water analysis. The total dissolved solids reported are obtained by either residue-on-evaporation or calculation methods. Residue-on-evaporation is

determined by evaporating a certain volume of water just to dryness in a steambath, and completing the process of drying by heating the sample in an oven at  $180^{\circ}\text{F}$  for an hour, then weighing the residue immediately after cooling in a desiccator. The result obtained from this method does not absolutely represent the original materials in the water because dissolved gases are driven off by heat, bicarbonate is converted to carbonate with loss of  $\text{CO}_2$  and  $\text{H}_2\text{O}$ , some salts may be volatilized, and residue of water of crystallization may be present. In the calculation method, the total dissolved solids are computed by summation of all analyzed dissolved materials reported in the analytical statement, with the exception of bicarbonate. Bicarbonate in solution is expected to exist as carbonate in the residue. It is, therefore, necessary to convert parts per million of bicarbonate to parts per million of carbonate before adding to other constituents. This is done by dividing parts per million of bicarbonate in the analytical data by 2.03. The accuracy of this method depends on the completeness of analysis. The total dissolved solids value computed by calculation is usually slightly lower than that determined by residue-on-evaporation, due to uncertain knowledge of ionic characters of some heavy metals and other constituents, but the result is believed to be reliable.

#### Range and Distribution

Water in the shale and siltstone aquifer, especially in the

central part of the Khorat Basin, carries the highest amounts of dissolved solids, exceeding 10,000 ppm in many wells. The range of concentration from 140 ppm to 14,135 ppm is caused mainly by the large amounts of  $\text{Ca}^{++}$ ,  $\text{Na}^+$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{=}$ , and  $\text{HCO}_3^-$  in water. Especially high in  $\text{Ca}^{++}$ ,  $\text{SO}_4^{=}$ , and  $\text{HCO}_3^-$ , water in the limestone aquifer has the next highest concentration of dissolved solids, ranging from 412 to 2,565 ppm. The alluvium, not only mineralized by its own contents but also contaminated by water from both the surface and the underlying shale and siltstone, contains a considerable amount of dissolved solids, which range from 110 to 1,475 ppm. The least mineralized water exists within the sandstone aquifers where dissolved solids are between 65 and 588 ppm. Figure 12 is the isopachous map showing the distribution of total dissolved solids by contour lines. The distribution shown in the map is more or less uniform in the limestone area and in the Khorat Basin, but rather irregular in the Sakon Nakhon Basin and the Phu Phan area. In general, water in the Sakon Nakhon Basin contains much less dissolved solids than that in the Khorat Basin. This is due to the fact that salt deposits, which yield the major amounts of dissolved solids in the former basin, are far deeper in the ground than those in the latter basin. The unequal degree of contamination by surface water carrying salts from the ground may be another main reason, because the watershed areas of the two basins are much different.

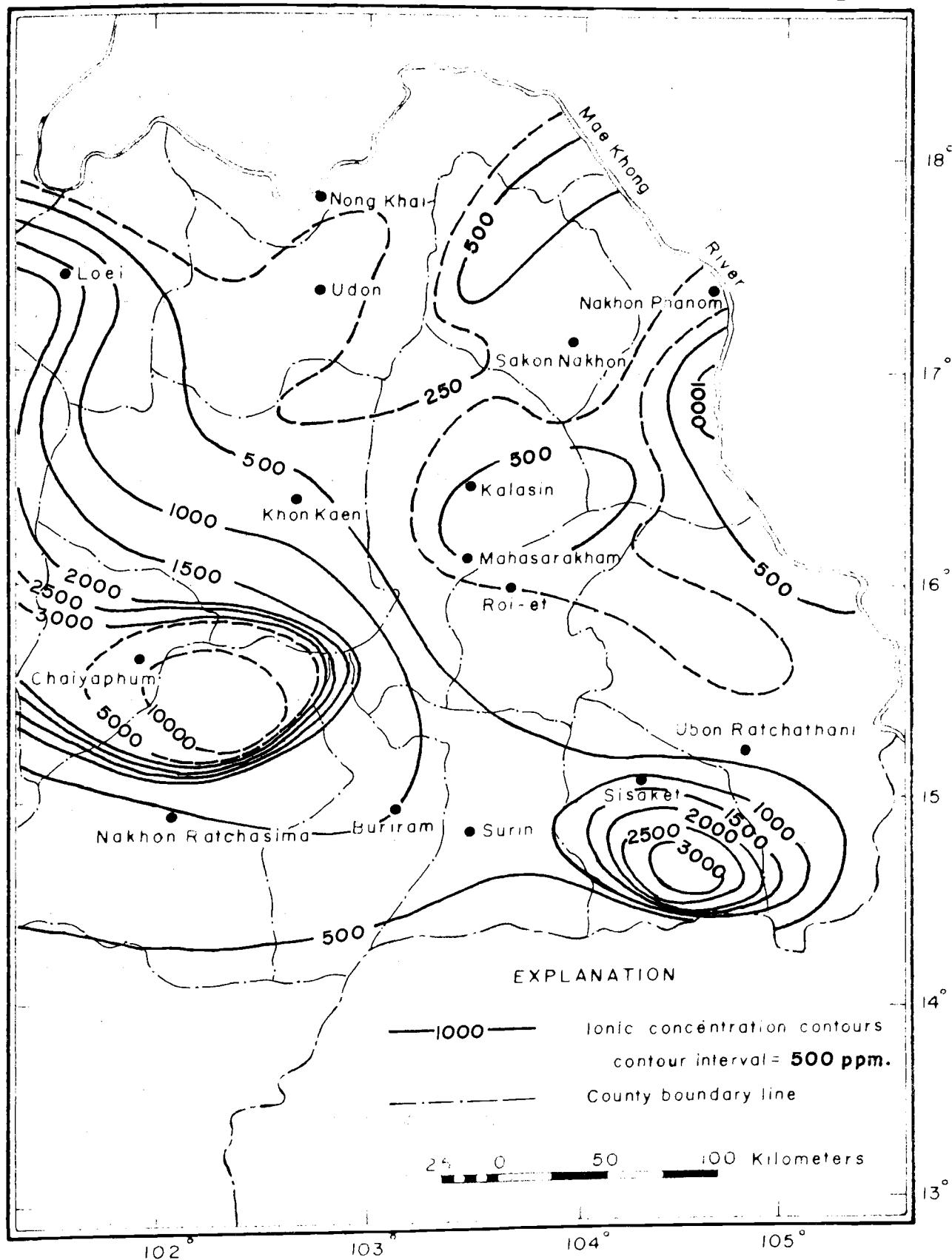


Figure 12- Isopachous map of total dissolved solids

## Significance in Water Supplies

Much is written in the literature about the use of total dissolved solids as an indication for quality of water. The exact limit of concentration in water used for some purposes, especially drinking water, is difficult to recommend because people in different places may be accustomed to different limits of dissolved solids. The U.S. Public Health Service (1946), however, recommends that total dissolved solids in drinking water should not exceed 500 ppm, but a concentration as high as 1,000 ppm is permissible. Rainwater and Thatcher (1960), with reference to the Colorado Agricultural Experiment Station (1943), Heller (1933), and Leghetti (1951), state that livestock may tolerate water containing from 3,000 to 15,000 ppm of total dissolved solids. The same authors classify water as: up to 2,500 ppm, good; 2,500 to 3,000 ppm, fair; 3,500 to 4,500 ppm, poor; and over 4,500 ppm, unsatisfactory. Water containing less than 500 ppm dissolved solids is reported to be tolerated by some industries, and concentrations of several thousand parts per million may be allowed in irrigation water (U.S. Geological Survey, 1955).

So far as the total dissolved solids are concerned, ground water of the Khorat Plateau is satisfactory for domestic use in most areas, except in Loei, south of Sisaket, and north of Nakhon Ratchasima (see the areas of high concentration of total dissolved solids



in figure 12). Because of the higher tolerance of livestock, water in Loei and Sisaket is usable for animals, but water in shale and siltstone just north of Nakhon Ratchasima is objectionable for all purposes.

## PROPERTIES OF WATER

### Specific Conductance

#### General Consideration

Specific conductance of water is the electrical conductance of a cube of the water of 1 square centimeter cross section and 1 centimeter thickness. The specific conductance is essentially the reciprocal of specific resistance; therefore its unit is the reciprocal of ohms, or mhos. In an analytical report the unit of specific conductance is expressed as micromhos ( $= \text{mhos} \times 10^{-6}$ ) because most water has a conductivity of only fractions of a mho.

The specific conductance increases with concentration and degree of ionization of different constituents in water. It is also reported that the conductance increases about 2 percent for each increase of  $1^{\circ}\text{C}$  in temperature of water. In common practice, the following relation is given:

$$\text{Specific conductance} \times (0.65 \pm 0.1) = \text{Total dissolved solids}$$

This generalization is not always true because there are many factors controlling and effecting the electrical conductivity of water. The most important factors are probably the numbers and kinds of ions

present, freedom of ions to act as conductors, and degree of hydration of ions. The presence of silica colloids, carbonaceous materials, organic matter, well-leached soil, or other insoluble materials tends to decrease specific conductance to the degree that the relationship of specific conductance to total dissolved solids given above is unreliable.

Although the formula given is not necessarily applicable in all water, the statement that conductivity is high in water of high dissolved solids is always true. This fact is useful in rough estimates of quality of all water.

#### Range and Relation to Total Dissolved Solids

The specific conductance of the ground water of the Khorat Plateau ranges from 75 to 3,200 micromhos in alluvium, 150 to 20,000 micromhos in shale and siltstone, 80 to 3,000 micromhos in sandstone, and 1,100 to 4,000 micromhos in limestone. If the specific conductance-total dissolved solids relation is written as specific conductance  $\times$  (A) = total dissolved solids, the value of (A) of all representative samples falls in three ranges: 0.61 to 0.70 in 63 percent of samples, 1.00 to 1.14 in 4 percent of samples, and 1.50 to 1.56 in 33 percent of samples. By checking dates of completion of well development and dates of sample collection, it is found that all samples having "A" ranges of 1.00 to 1.14 and a few others with the ranges of "A" from 1.50 to 1.56 were collected only a few days after the wells were finished, or even at the

time of bailing tests. All samples with "A" ranges of 1.50 to 1.56 in Surin, Buriram, and Sisaket were collected during pump repair operations in February to March 1960. Some sand, mud, insoluble matter, organic material, and other nonconducting colloids were possibly in water samples of new wells or redevelopment wells, and account for the high solids with low electric conductance in the analyses. Another main factor affecting the specific conductance-total dissolved solids relation in ground water of the plateau is an unusual presence of undissociated substances, nonionized silica, mixed salts, and salts containing undissociated particles (Chotidilok, written communication).

For water of normal composition, the composite data of specific conductance against total dissolved solids, plotted on the same scale, should fall on a straight line. The curve derived may be regarded as the rating curve for the area where water was collected. The rating curve is useful in the field for estimating either specific conductance or total dissolved solids if one of the two is known. Plate IV shows the composite plotting of such rating curves of wells drilled in the Khorat Plateau. There are two curves. The one above is the rating curve for water, with "A" from 0.61 to 0.70, collected from long finished wells; and the one below, practically parallel to the one above, is that of water with "A" from 1.50 to 1.56 collected from recently finished or recently redeveloped wells. The data from both curves do not deviate much from linearity, and most of them fall on

straight lines. Both rating curves, especially the one for recently finished wells, are believed to be useful in the design of wells so far as the plugging, sealing, and perforation are concerned. The same types of curves are expected to be applicable for surface water of normal flow and flood flow.

### Hardness

#### General Consideration

Hardness is the characteristic of water related to reactions with soap under normal use and to production of scale in boilers, heaters, or other containers when the temperature of water is raised. It is an indication of the presence of some substances in water. The principal ions contributing to hardness in water are calcium and magnesium. Other metallic ions, such as strontium, iron, and manganese, also cause hardness in water but are insignificant in most water supplies. Among anions, carbonate, bicarbonate, sulfate, chloride, and nitrate are responsible for hardness. The total hardness in water is reported in terms of an equivalent quantity of  $\text{CaCO}_3$ , and along with this value the term "noncarbonate hardness" and its concentration are also reported in most water analyses. This reflects the classification of hardness in water into two types: the carbonate hardness, and the non-carbonate hardness. The carbonate hardness, formerly called "temporary

hardness," is the part of total hardness which is equivalent to the amount of carbonate and bicarbonate. This hardness is essentially equivalent to the alkalinity of water since alkalinity is the expression of bicarbonate and is also reported in terms of  $\text{CaCO}_3$ . The noncarbonate hardness, formerly called "permanent hardness," is any hardness in excess of carbonate and bicarbonate.

Other than the prevention of cleansing action of soap and the formation of scale in industrial boilers or other hot-water equipment, hardness is not reported to be harmful or toxic to man. Urinary concretions, which is one of the most dominant sicknesses in the Khorat Plateau, however, is believed to be caused by hardness. The degree of hardness determines the water as: 0 to 75 ppm, soft; 75 to 150 ppm, moderately hard; 150 to 300 ppm, hard; and more than 300 ppm, very hard (Sawyer, 1960).

### Range and Distribution

The range of hardness in ground water of the Khorat Plateau depends largely on the major constituents present. In the limestone area where  $\text{Ca}$ ,  $\text{SO}_4$ , and  $\text{HCO}_3$  are predominant, the total hardness reaches 1,960 ppm with 1,781 ppm reported as noncarbonate hardness. In sandstone, the least amount of  $\text{Ca}$ ,  $\text{Mg}$ , and  $\text{HCO}_3^-$  are present, and total hardness is not over 400 ppm with zero noncarbonate hardness reported in many wells. The shale and siltstone formation contains

large amounts of  $\text{Ma}$ ,  $\text{Cl}$ , and  $\text{SO}_4$ , which tend to produce total hardness as high as 4,300 ppm, with 4,225 ppm being the noncarbonate hardness. In alluvium, the hardness ranges from 15 to 820 ppm with no noncarbonate hardness in many wells. Figure 13 shows the distribution of hardness over the plateau by means of an isopachous map.

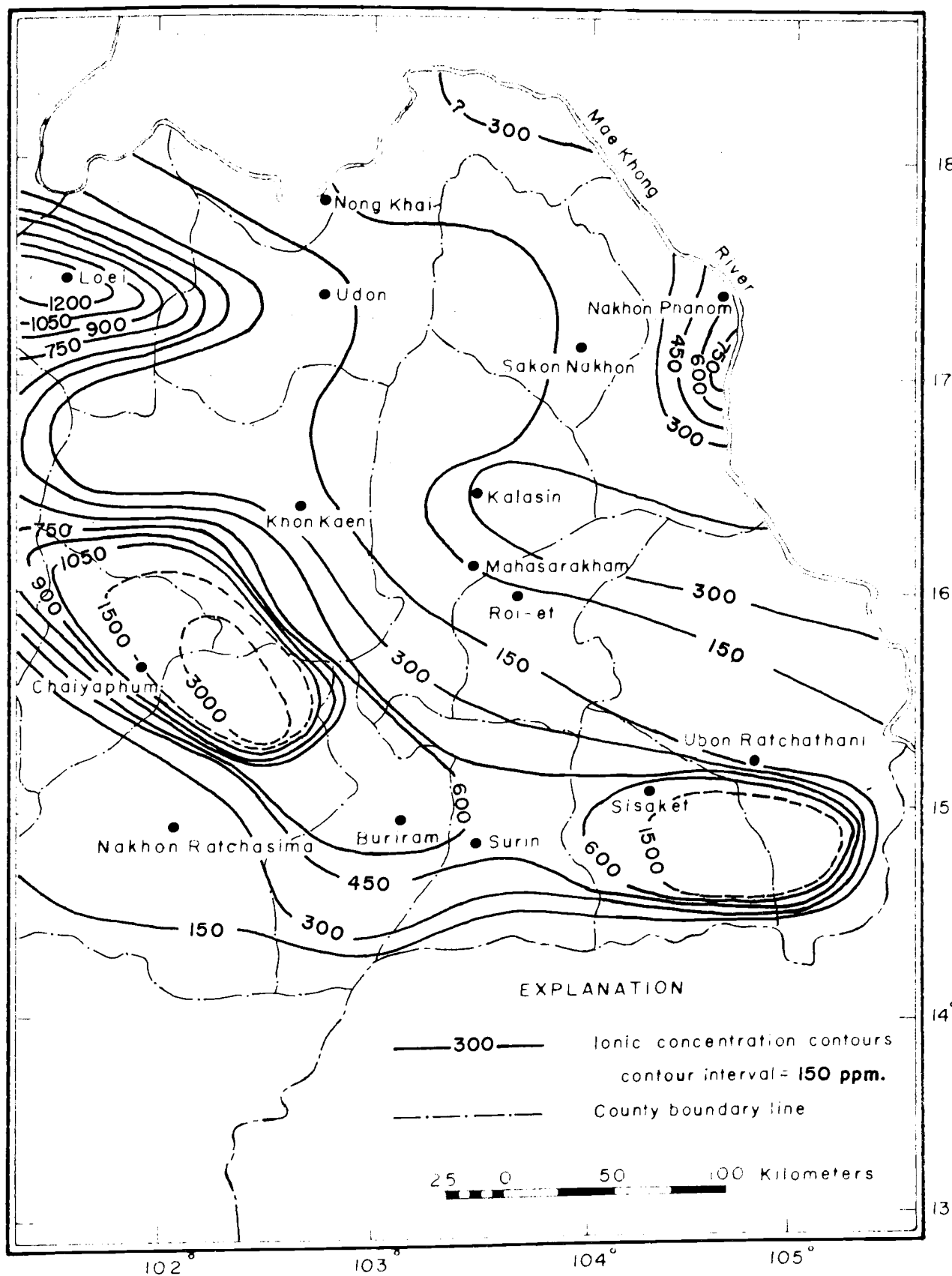


Figure 13- Isopachous map of hardness as  $\text{CaCO}_3$ .



## CHEMICAL CHARACTER OF GROUND WATER

The knowledge of types, properties, and chemical characters, and mineral composition of water aids the chemist and sanitary engineer in appropriate treatment of water in various categories—such as in domestic water supplies, sewage, industrial-feed water or industrial wastes, and in corrosion control. In addition, the knowledge provides the ground-water geologist and related professional workers with a useful tool to determine the sources of minerals in water, or physical and chemical modifications such as mixtures, base exchange, and reductions of constituents. From the agricultural point of view, the knowledge of types of water related to alkalinity and salinity is the most important. The following sections are devoted to a general consideration of the characters of ground water in the Khorat Plateau, analyzed by widely accepted methods. Geochemical problems related to sources and uses of water will be included.

### Character of Ground Water Determined by Graphic Procedure

#### General Consideration

The graphic plotting of chemical analyses is very useful in a study and interpretation of water quality, as it can be used as an

effective tool to classify water on the basis of its major chemical constituents, to recognize the modifications of water, and to determine the sources of dissolved constituents in water. The method of graphic study was suggested by Hill (1940), Lingelier and Ludwig (1942), and Piper (1944), who base their designations of character of water on the mathematical classification proposed by Palmer (1911). Palmer recognizes four major groups of constituents in water, and designates them as the alkaline cations (Na, K) or "primary," the hardness cations (Ca, Mg) or "secondary," the strong acid anions ( $\text{SO}_4$ , Cl,  $\text{NO}_3$ ) or "salinity," and the weak acid anions ( $\text{HCO}_3$ ,  $\text{CO}_3$ ) or "alkalinity." Since in all water the cations and anions are in equilibrium with each other, the mineral character of the water can be distinguished by the relative amount of each group expressed as percentage of the total equivalents per million of the four groups. Thus, primary salinity is ascribed to water having alkaline cations (Na, K) in balance with strong acid anions ( $\text{SO}_4$ , Cl); primary alkalinity is applied to water having alkaline cations in excess of strong acid anions but in balance with weak acid anions ( $\text{HCO}_3$ ,  $\text{CO}_3$ ); secondary salinity is used for water having hardness cations (Ca, Mg) in excess of weak acid anions, but in balance with strong acid anions; and secondary alkalinity refers to water having hardness cations in balance with weak acid anions. Palmer also says that primary alkalinity and secondary salinity are not present in water at the same time, but are rather mutually exclusive. With the above

concept, the sum of three properties must be unity and can be plotted as a single point on trilinear coordinates (Piper, 1944).

In graphic procedure ( $\text{Ca} + \text{Mg}$ ), ( $\text{Na} + \text{K}$ ), ( $\text{SO}_4 + \text{Cl}$ ), and ( $\text{CO}_3 + \text{HCO}_3$ ), in terms of percentage of total equivalents per million of cations and anions, respectively, are plotted in a diamond-shaped field with scales reading in 100 parts (see figs. 14, 15, 16, and 17). According to the balance between cations and anions in water as just described, the plotting will be represented as a single point in the field, and this point serves as the indication of chemical character of a given water. In order to designate types of water with respect to Palmer's classification, the plotted field is divided into 5 areas so that areas 1, 2, 3, 4, and 5 represent, respectively, carbonate hardness ("secondary alkalinity") exceeding 50 percent, carbonate alkaline ("primary alkalinity") exceeding 50 percent, noncarbonate hardness ("secondary salinity") exceeding 50 percent, noncarbonate alkaline ("primary salinity") exceeding 50 percent, and none of the preceding characteristics exceeding 50 percent (see the key diagrams in figs. 14, 15, 16, and 17).

The graphic method of plotting chemical analyses can be effectively used as an indication of mixtures of two waters by the fact that three plotted points, two for each water and one for mixed water, will lie on a straight line. The graphic procedure is also applicable in solving for some geochemical problems, such as contamination, progressive concentration by evaporation, base exchange, sulfate reduction, or

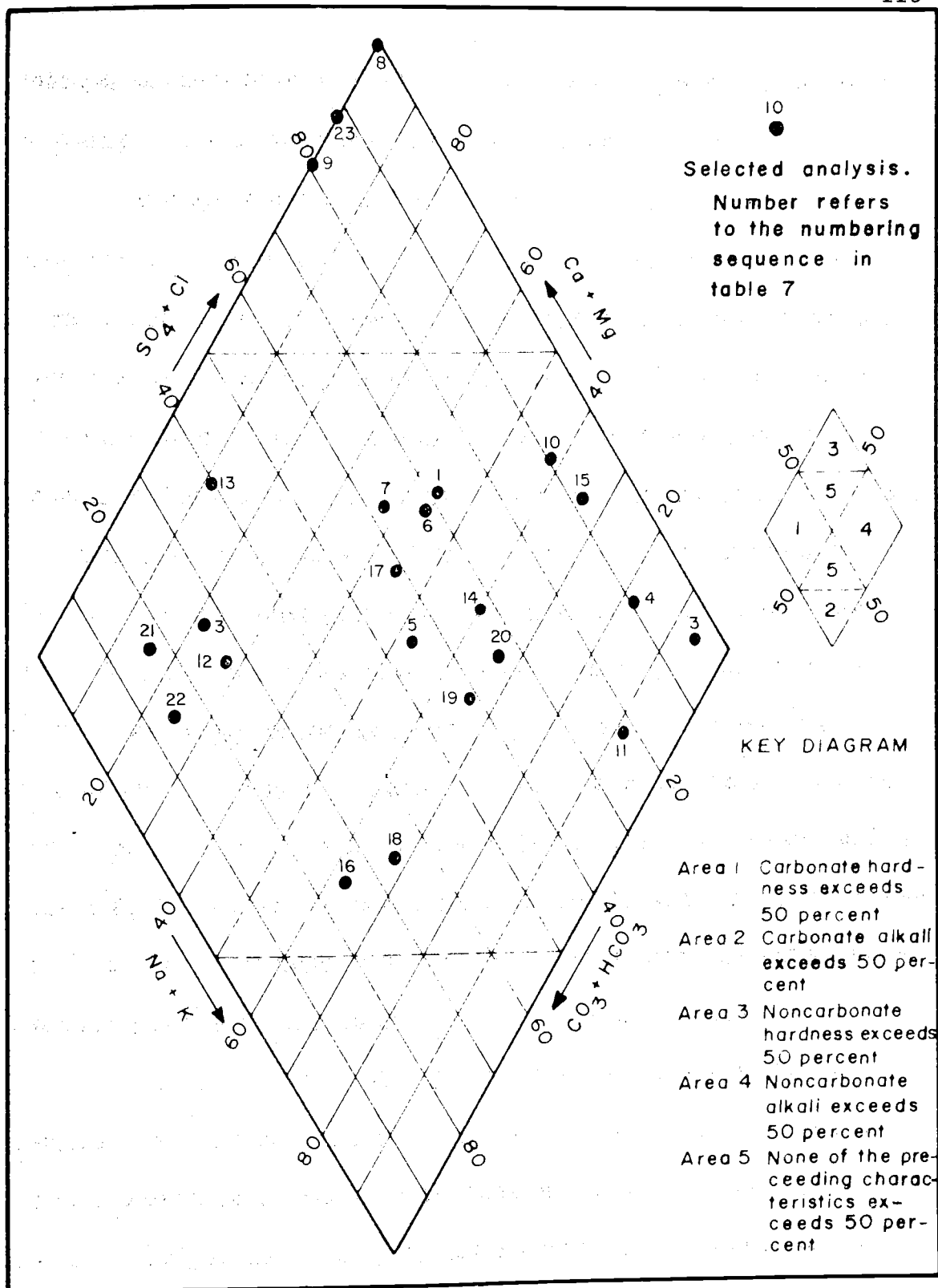


Figure 14 - Graph showing chemical characteristics of ground water in alluvial aquifer.

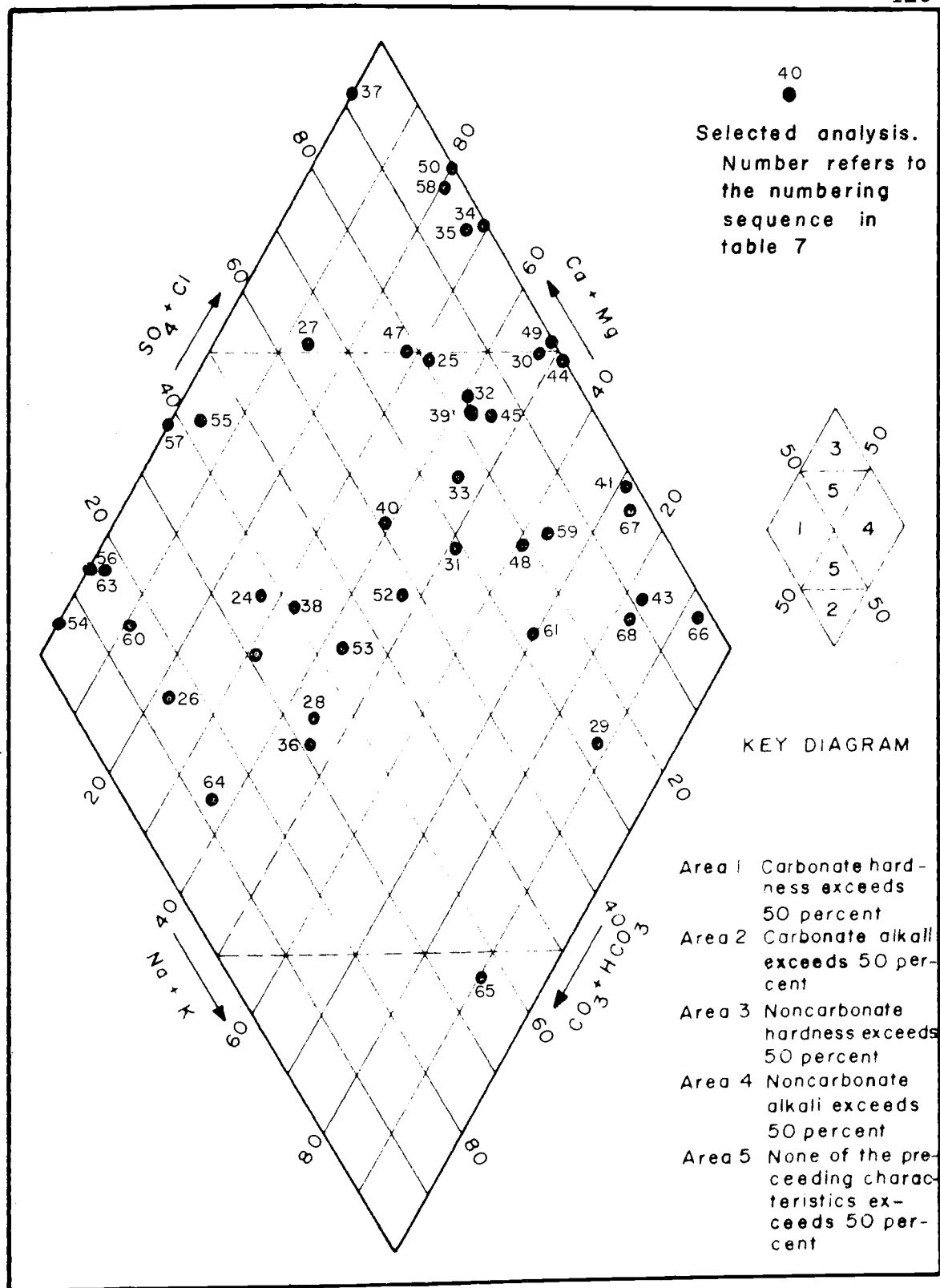


Figure 15- Graph showing chemical characteristic of ground water in shale and siltstone aquifer.

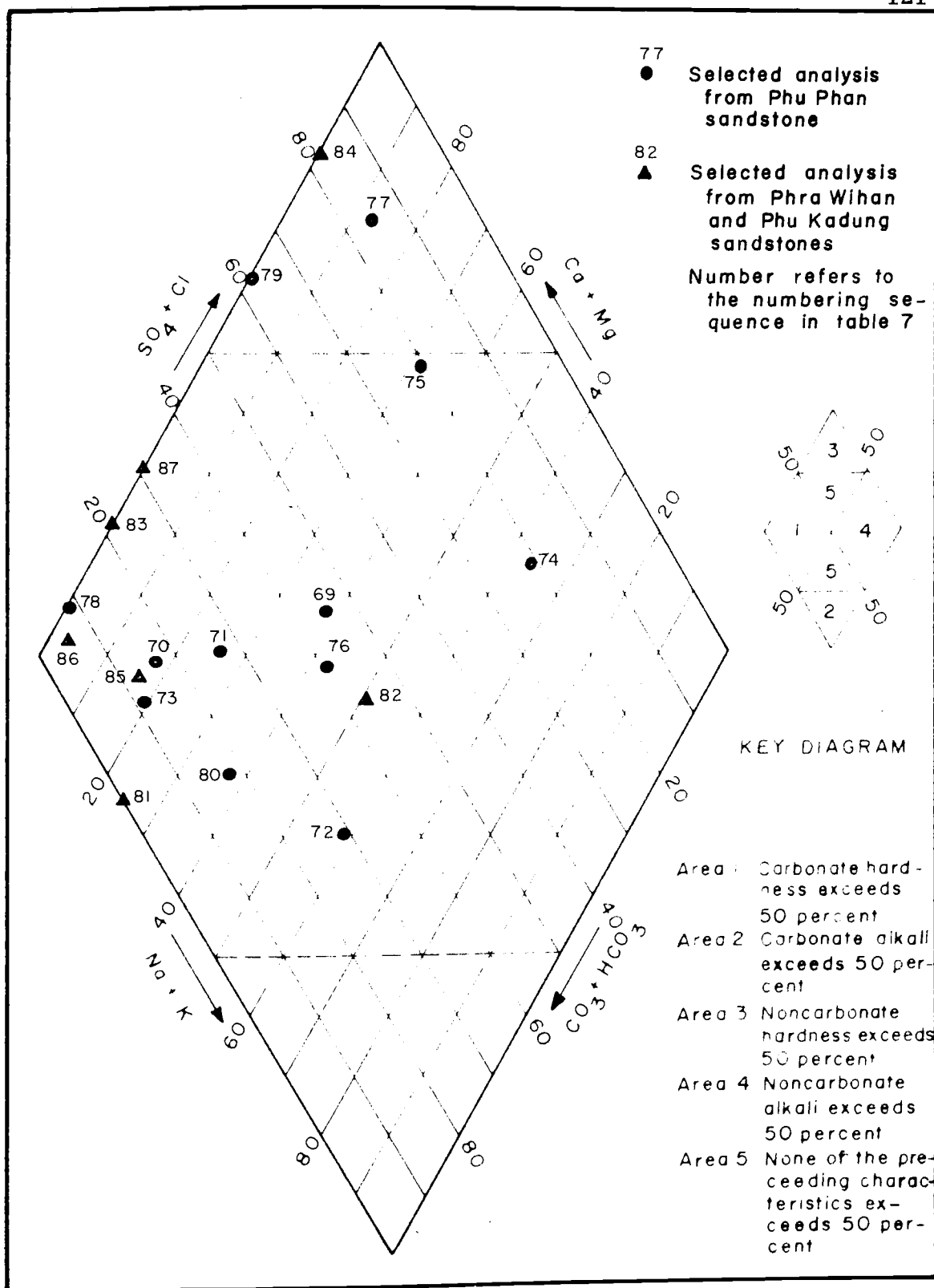


Figure 16- Graph showing chemical characteristics of ground water in Phra Wihan and Phu Kadung sandstones aquifer.

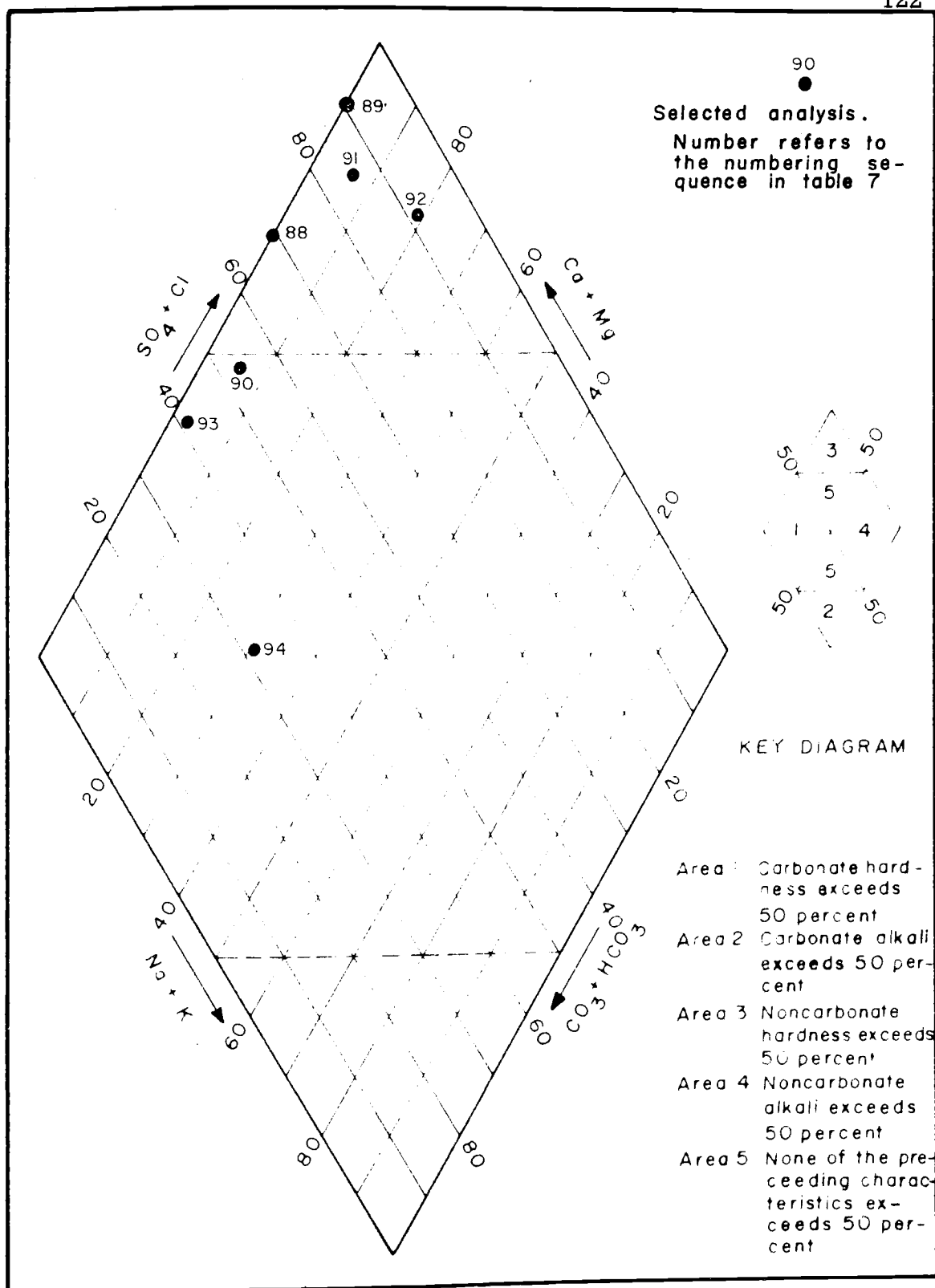


Figure 17- Graph showing chemical characteristics of ground water in Rat Buri limestone aquifer.

solid phase product of reaction. These are described in detail by Piper (1944). All these problems will not be discussed for ground water of the Khorat Plateau, because analyses of repetitive water sampling which are prerequisite for this method are not available.

The general character of ground water in the Khorat Plateau is shown by the single point plotting for each aquifer in figures 14, 15, 16, and 17. The data plotted are listed in table 7 in the appendix.

#### Chemical Character of Ground Water in the Alluvial Aquifer

The character of water in the aquifer is widely variable according to the geologic and hydrologic controls. Alluvium or terrace deposits in the limestone area usually produce noncarbonate hardness ("secondary salinity") water having high concentrations of Ca and  $\text{SO}_4$ , as shown by plot numbers 8 and 9 in figure 14 (well numbers C54L12 and C56L14 in table 7). Water in alluvium traversed by the Mae Khong River tends to contain carbonate hardness ("secondary alkalinity") exceeding 50 percent of total constituents, as shown by plot numbers 21 and 22 in figure 14 (well numbers G13NP5 and G18NP10 in table 7). This is not always true, however, because well G12NP4 (plot number 20) which was drilled in the same area tends to contain noncarbonate alkalines exceeding 50 percent in which Na and Cl are predominant. This is possibly the result of contamination by water of the lower aquifer. In alluvium underlain directly by shale and siltstone, the



character of water varies considerably according to degrees of intense contamination by percolating water and water from the lower beds which result in high concentration of NaCl in one place and  $\text{CaSO}_4$  in other places. In general, where the well was drilled in alluvium located at the centers of basins, such as in Khon Kaen, Mahasarakham, Roi-et, and Ubon, the water tends to be noncarbonate alkaline (see area 4 in key diagram of fig. 14), but in alluvium of higher elevations, such as in the city of Nakhon Ratchasima, part of Surin, and west-central Sakon Nakhon, the water contains not more than 50 percent of hardness or alkalines (see area 5 in key diagram of fig. 14). However, the above statement will not hold true in cases of some modification of water. The plot number 23 (well G21NP13 in table 7) is exemplified by the fact that the water has undergone base exchange of sodium for calcium in the sediments.

#### Chemical Character of Ground Water in the Shale and Siltstone Aquifer

It has been stated before that rock salt and gypsum in rocks and calcium carbonate in soils are the major mineral sources of dissolved constituents in water. With this graphic study, the influence of these minerals are shown up clearly. In Surin, Buriram, Sisaket, the southern part of Nakhon Ratchasima, the northern part of Udon, and Nong Khai the water is characterized by its carbonate hardness, in which

$\text{Ca}^{++}$  and  $\text{HCO}_3^-$  are dominant (see area 1 in key diagram of fig. 15).

In the central part of basins or areas containing local salt, such as the area just north of Nakhon Ratchasima, the eastern part of Chaiyaphum, the southern part of Khon Kaen, Mahasarakham, Roi-et, Kalasin, Udon, and the northeastern part of Sakon Nakhon, the water tends to contain high concentrations of NaCl which is recognized as carbonate alkalinity (see area 4 of key diagram in fig. 15). In some parts of the areas mentioned above, the occurrence or solubility of rock salts and gypsum are not enough to mineralize water; therefore, the water tends to contain not more than 50 percent of each cation or anion group present in the diagram (see area 5 of key diagram in fig. 15). The plots 34, 35, 37, 50, and 58 (well numbers B38SK11, B41SK14, B52Ub4, and E21Ud8 in table 7, respectively) indicate the water of noncarbonate hardness in which very little Na + K but very high Ca + Mg percentages are present. This is probably an indication of base exchange of Na for Ca and Mg in clay. In conclusion, the aquifer contains every type of water suggested by Palmer (1911), except the carbonate alkali ('primary alkalinity'), which, as shown by the plotting, is possessed only by water from well H1-5 (plot number 65 in fig. 15) about 28 km south of Nakhon Ratchasima.

### Chemical Character of Ground Water in Sandstone Aquifers

All chemical constituents of representative samples are plotted on the same sheet (fig. 16), in order to show the relationship of water

in both the Phu Phan sandstone and the Phra Wihan and Phu Kadung sandstones. Because of the similar sources of chemical constituents, water from both aquifers has the same character, carbonate hardness (see area 1 in the key diagram of fig. 16). The plot numbers 77, 79, and 84 (well numbers F3K2, F5K4, and C40C2 in table 7, respectively) carry noncarbonate hardness due to high concentration of  $\text{Ca}^{++}$  and  $\text{SO}_4^-$ . This is presumably explained by the fact that water in sandstone is locally contaminated by seepage through the soils overlying it. Contamination by NaCl water in shale and siltstone has been previously postulated, and the evidence is shown again by plot number 74 (well D46K12 in table 6), which indicates the noncarbonate alkalinity in water. The contamination is possibly not the simple mixing of water, as the plotted point does not align with any points representing water in shale and siltstone in the same area. The plotted points 72, 75, and 83 (wells B56Ub8, D47KK13, and C37KK17 in table 7, respectively) seem to be in a straight line, but it cannot be interpreted that water in well C37KK17 is the result of mixing of water in well B56Ub8 and well C37KK17, as postulated by Piper (1945), because both wells are hundreds of miles apart and the hydrologic and geologic settings are not permissible.

#### Chemical Character of Ground Water in the Limestone Aquifer

Most ground water in the Rat Buri limestone has noncarbonate hardness or secondary salinity according to its high concentration of

calcium and magnesium sulfate, as shown in figure 17. This is the characteristic of water in limestone whose depth is more than 200 feet from the surface. Within depths less than 200 feet, gypsum is not present in the limestone; therefore, the water contains mostly calcium and magnesium bicarbonate which are designated as carbonate hardness or secondary alkalinity, as shown by plot numbers 93 and 94 (wells C50L8 and C52L10 in table 7).

### Character of Ground Water Determined by Bar Pattern Diagrams

#### General Consideration

In the single point graphic method, the absolute quantity of each constituent or the ratio of relative amounts cannot be shown. For such information, another procedure of studying water analyses, the bar pattern diagram, has been introduced by Collin (1923). This method is widely accepted and used in most water-quality literature. The bar diagram is made with the vertical bar graph plotted so that the two vertical segments of the bar show the total amounts of cations and anions in order. Each segment is subdivided into sections, in order that each section can be used for plotting each cation or anion to scale. In general practice, the bar is divided into six divisions, three in the left half representing Ca, Mg, and Na + K, and three in the right half representing  $\text{CO}_3 + \text{HCO}_3$ ,  $\text{SO}_4$ , and Cl. Other constituents of particular

interest, such as Fe or  $\text{SiO}_2$ , can also be plotted by other bar or bars along one side of either cation or anion patterns. The unit of concentration of each constituent plotted by this method can be expressed in three ways: parts per million, equivalents per million, and percentage of total cations for cationic ions and of total anions for anionic ions. The parts per million unit is limited to those waters of low total dissolved solids, because the spaces will not permit plotting of higher concentrations. The unit of equivalents per million is most preferable, because the absolute value of equivalent weight of each constituent is easily comprehended. The percentage unit is advantageous in that the ratio of relative amounts of each constituent can be shown. Examples of plotting bar pattern diagrams in the equivalents per million unit and percentage are shown (pls. III-A, III-B, V-A, and V-B, respectively). The bar pattern study for water quality is widely used in comparing the resemblances or differences among waters, and in identifying the sources of each chemical constituent or the modification of waters. The other important application of bar diagrams is in the classification of water on the basis of chemical components, such as sodium chloride water, calcium bicarbonate water, magnesium sulfate water, etc. In this classification, the terms will automatically describe the general chemical character of water. The designation of types of water on this basis is given by Poland, Garrete, and Simnott (1959) as follows: calcium bicarbonate water is that containing more than 50 percent of calcium

among cations and more than 50 percent of bicarbonate among anions, in equivalents per million; sodium calcium bicarbonate water is that containing sodium and calcium in first and second degree of abundance, but neither comprising more than 50 percent of total cations; sodium sulfate bicarbonate water is that containing sulfate and bicarbonate in first and second degree of abundance, and also neither comprising more than 50 percent of total anions.

The selected plots of chemical constituents in ground water of the Khorat Plateau by bar patterns are shown in plates III-A, III-B, V-A, and V-B, in which the equivalents per million unit and the percentage of total cations and anions are used, respectively. The data are selected from table 7 on the basis of dissimilarity of composition of waters within the same aquifer. By this scheme the variation and distribution of chemical characters will be readily comprehended.

#### Types and Characters of Ground Water of the Khorat Plateau

The designation of type and character of ground water in each aquifer is determined entirely by the percentage of cation or cations and anion or anions as stated above. Analyses A35Ub10, C54L2, C61KK2, D66Ms26, and G13NP5 in plate V-B represent the common types and general characters of ground water in alluvial deposits. Inspection of chemical constituents listed in the appendix and consideration of the geologic setting and hydrologic control reveal that ground water

in the alluvium of three different areas (Khorat Basin, Sakon Nakhon Basin, and narrow terrace deposits in Loei) is of somewhat different types and characters. Terrace deposits in Loei occur along the low limestone terrane starting from south of the city of Loei and extending toward the Mae Khong River to the north. Ground water in this area (analysis C54L12) is mostly of the calcium sulfate type, and locally of the calcium bicarbonate type. This is due to contamination by water from limestone and gypsum beds. Within the upper part of the Khorat Basin, types and characters of ground water are mostly calcium bicarbonate. The water is then converted to sodium bicarbonate (analysis D66Ms26) or sodium chloride sulfate (analysis C61KK23) in the lower part of the basin by means of base exchange or contamination. In an area down river—such as the Ubon Ratchathani area—however, the water still maintains its calcium bicarbonate (analysis A35Ub10). This is possibly due to the lack of  $\text{NaCl}$  or  $\text{NaSO}_4$  sources. Within the Sakon Nakhon Basin, water is essentially characterized by its calcium bicarbonate. The sodium chloride water or calcium sulfate water are rare.

Analyses B52Ub4, C11NR11, D63Ms23, E17NK17, and E28SN13 represent types and characters of ground water in the shale and siltstone aquifer. Sodium chloride water (analysis C11NR11) occurs mostly in the lower part of the Khorat Basin, especially in the area surrounded by Nakhon Ratchasima, Chaiyaphum, Khon Kaen, and Mahasarakham. The same type of water also occurs in a small area

south of Sisaket and in the city of Surin. In the higher elevations of the Khorat Basin, the aquifer tends to contain calcium bicarbonate water or magnesium bicarbonate water (analysis D63Ms23). The only exception is the calcium sulfate water existing in the southeastern part of Ubon Ratchathani (analysis B52Ub4). Inspection of the sample log of well B52Ub4 shows that gypsum and anhydrite beds as thick as 20 feet are interbedded in the shale formation of the area. Within the Sakon Nakhon, calcium bicarbonate water occurs in most localities (analyses E17NK7 and E28SN3). An exception is the central part of Udon Thani where sodium chloride water exists due to the presence of shallow and thick beds of rock salt.

The general types and characters of ground water in the Phu Phan sandstone are represented by analyses A13S12, A49Ub23, FSK4, and D46K12, and in the Phra Wihan and Phu Kadung sandstones by analyses C37KK17 and C65Ud3 (pl. V-B). Because of small amounts of dissolved solids, water in these aquifers is satisfactory for use for most purposes. The water in wells drilled along the margin of the plateau or about the top of the Phu Phan Range is classified by its calcium bicarbonate character (analyses A49Ub23 and C65Ud3). In the lower parts or down the dips of sandstone outcrops, the water is presumably contaminated by percolating water from top soil because its character is widely diversified. This is shown by calcium sodium bicarbonate water in southern Surin (analysis A13S12), sodium chloride



water in the trough of the Phu Phan syncline (analysis D46K12), calcium sulfate water in eastern Kalasin (analysis F5K4), and sodium calcium bicarbonate water in western Khon Kaen. The differences in characters of these waters are possibly controlled by the nature of contaminants, as explained in the preceding chapters.

Within the Rat Buri limestone, the nature of water is easily predicted because limestone of the deeper zones is interbedded with gypsum layers or beds which are not present at depths shallower than about 200 feet below land surface. The water is characterized by its calcium bicarbonate at the shallow depths, but sulfate gradually increases at the greater depths. Analyses C44L2, C47L5, and C50L8 indicate the calcium sulfate water at depths below 300 feet.

### Sodium Adsorption Ratio as an Indication for Quality of Irrigation Water

#### General Consideration

Base exchange in water and soil is considered a serious problem relative to the usefulness of water for agriculture. The base exchange of calcium in soils for sodium in water creates a hazard for plants when the sodium entering the soil exceeds the tolerance limits of a given plant. In addition, soils or clays taking up sodium from water tend to have reduced permeability and are sticky when wet. However, if irrigation water contains calcium and magnesium in amounts equal to

or exceeding the amount of sodium, a sufficient quantity of calcium or magnesium will be retained in soils to make them satisfactory for agriculture. The limiting amounts of sodium in irrigation water are generally determined by the percentage of total cations (Ca + Mg + Na + K) in the water. If the percent sodium is less than 50, the water is permissible for irrigation, but is hazardous for plants when the percent sodium rises above 50, because sodium is abundant for base exchange.

The percent sodium concept is, however, gradually being replaced by the sodium adsorption ratio (SAR) theory, which was suggested by the U.S. Department of Agriculture (U.S. Salinity Laboratory Staff, 1954). In fact, this new theory is a revised form of the percent sodium, but is based on an experiment for determination of adsorption of sodium by soil to which the water is supplied. The formula used for computing sodium adsorption ratio is as follows:

$$\text{SAR} = \frac{\text{Na (epm)}}{\sqrt{\frac{\text{Ca (epm)} + \text{Mg (epm)}}{2}}}$$

This formula apparently ignores the adsorbed potassium, owing to its very small concentration in water. This theory is, however, more significant in a study of water quality than the percent sodium concept, because it is directly related to the exchangeability of sodium.

In a study of irrigation water quality the computed sodium adsorption ratio is plotted against the specific conductance of water in the rating form given by the U. S. Salinity Laboratory Staff (1954), but modified by Hem (1957), as shown in plate VI. The advantage of this method is that water can be classified as of low, medium, high, and very high sodium hazard, corresponding to ranges of sodium adsorption ratios of less than 10, 10 to 18, 18 to 26, and more than 26, respectively. Moreover the water is also classified as of low, medium, high, and very high salinity hazard, corresponding to ranges of specific conductance of less than 250, 250 to 750, 750 to 2,250, and more than 2,250 micromhos, respectively.

#### Classification and Suitability for Irrigation

The sodium adsorption ratios of water from alluvium, sandstone, and limestone are listed in table 7 and are plotted against the corresponding specific conductances in plate VI. Water from the shale and siltstone formation is not studied because the quantity yielded by each well is so small that it is not sufficient for most agricultural uses. In the graph plotted, nearly all water from the alluvium can be classified as low sodium hazard, but ranges from low to high salinity hazard. An exception is a high sodium hazard water from well A30Ub5, in which 94.3 percent of sodium is present. In general, water from this aquifer is suitable for irrigation under most ordinary conditions, especially for

rice cultivation (U. S. Department of Agriculture, 1954). Sandstone produces water somewhat similar to that of alluvium so far as irrigation is concerned. The water is satisfactory for most agricultural uses. Water from limestone can be grouped as low sodium hazard and low to high salinity at shallow depths, but very high salinity in the deeper zones. As many plants cannot tolerate very high salinity (U. S. Department of Agriculture, 1954), water from more than 200 feet deep is hardly suitable for irrigation. The water of the upper zone, however, is satisfactory.

## RECOMMENDATION FOR USES

### Domestic Uses

The following recommendations are made on the basis of chemical quality, and no attempt will be based on the biological or bacteriological aspects because the analyses made by the Thai Geological Survey do not include these examinations. It must be primarily understood also that water of satisfactory chemical quality is not necessarily safe bacteriologically.

The upper limit of concentration of each major constituent with respect to drinking water is given in the preceding chapters. The U. S. Public Health Service (1946) also recommends for the upper limit of toxic substances as follows: fluoride 1.5 ppm, lead 0.1 ppm, arsenic 0.05 ppm, selenium 0.05 ppm, and hexavalent chromium 0.05 ppm. With respect to these limitations, the use of water is difficult to evaluate, because lead and arsenic were not determined in the laboratory. The waters are, however, safe from selenium and chromium, as their concentrations are reported zero in all analyses. Fluorides in all water are somewhat lower than limits recommended in all localities, except the extremely high concentration of 3.5 ppm in well D1NR1 within the

city of Nakhon Ratchasima. The concentration is only 1 ppm in well D3NR3 in that city. Objectionable water with respect to fluoride is then limited to that from well D1NR1 and in a small area nearby.

On the basis of upper limits of less restrictive constituents, the U. S. Public Health Service (1954) recommended that iron and manganese, magnesium, chloride, sulfate, and total dissolved solids should not exceed 0.3 ppm, 125 ppm, 250 ppm, 250 ppm, and 1,000 ppm, respectively. The analysts of the Thai Geological Survey laboratory always reject the use of hard and very hard water. These recommendations seem to be inapplicable for water of the Khorat Plateau where the people have been accustomed to higher concentrations in cloudy or muddy water from ponds, lakes, rivers, or dug wells. Many communities complain and refuse to drink water of low dissolved solids, claiming that it is flat or "light" as they term it. To these people, water is limited to drinking only by the rusty odor of iron and salty taste of NaCl. Nevertheless, objectionable drinking water according to U. S. Public Health Service standards exists in three areas. They are: (1) the central, northern, and northwestern parts of Loei where concentration of  $\text{SO}_4^{=}$  is very high, (2) northern Nakhon Ratchasima, Chaiyaphum, and southern Khon Kaen where calcium, sodium, chloride, and sulfate are very high, and (3) southern Sisaket and southern Ubon Ratchathani where the same inferior water as present in area 2 exists.

### Livestock Uses

The quality of water consumed by livestock is more or less related to that for human beings. Most animals tend to tolerate water of poorer quality than man does. According to Hem (1957), the upper limit of total dissolved solids concentrations to be consumed by poultry, pigs, horses, and cattle are 2,860, 4,290, 6,435, and 10,000 ppm respectively. With reference to these standards, ground water in all localities of the plateau can be used for livestock. Exception is always made for water in the area just north of Nakhon Ratchasima and east of Chaiyaphum where the total dissolved solids range up to 14,135 ppm, as previously mentioned.

### Agricultural Uses

The U. S. Salinity Laboratory Staff (1954) recommended that the quality of water to be used for irrigation should be first considered from the viewpoint of salinity and alkali (sodium) hazards. The recommendation related to these hazards have already been given in the previous chapter and will not be repeated. In addition, many investigators concerned with irrigation water suggest other hazards caused by independent constituents or toxic elements, such as boron, sulfate, or chloride, but the range and upper limit of concentration are controversial. Among these toxic constituents, boron has been claimed as a serious

hazard to plants. Hem (1957) with reference to Scofield (1936) gives the permissible upper limit of boron concentration of 1.00 ppm for sensitive crops and 3.00 ppm for tolerant crops. The concentrations of boron in the water are not reported, so that no recommendation can be made in this matter.

The use of ground water for irrigation is generally limited to cycles of recirculation or reuses. The concentration of chemical constituents tend to be gradually increased in each cycle, either by picking up minerals from soils or by closed-basin effects. So far as these factors are concerned, irrigation in the plateau is safe because little or no ground water has been used for this purpose.

### Industrial Uses

The very few small industrial factories in the plateau consist mainly of rice mills, sawmills, and sugar factories. The need of water for these factories is mainly for boiler feeding. The attempt to use ground water for this purpose is practically unsuccessful, due to the high concentration of "industrial forbidden" constituents, of which iron, silica, and calcium are predominant. The corrosive effect of NaCl water is the other main trouble for these industries. The suitability of water for industry is, however, difficult to recommend because the quality requirements are widely different. For example, in carbonate beverages total dissolved-solids content of 850 ppm is allowable, while



in the paper industry the maximum concentration of 200 to 300 ppm is required (Hem, 1957). On this basis, water in most alluvium and sandstone is usable for the carbonate beverage industry, but not all water is suitable for the paper industry. Because of this difficulty, it is recommended that specialized reports should be made for specific types of industry if their establishment is contemplated in the future.

## CONCLUSIONS

The major work consists of the compilation of basic chemical analytical data, the description and interpretation of sources and distribution of each chemical constituent, discussion of the general characters of ground water, and the recommendations for uses of waters for different purposes. The studies are closely related to the geology, geomorphology, and hydrology of the area, in order to find out the influences of these factors over the quality of water. However, the interpretive studies are made for generalization rather than specific detail because the area under study is very large and the analytical data and time are limited.

Although chemical analyses were made for all water samples from most wells drilled in the area, the samples were not repeatedly collected in each well. This makes it impossible to study variation of water quality with time. The data, however, are comparable in different localities. The determination of individual constituents with relation to geochemistry gives a good understanding of variable concentration in waters. These concentrations are also found to be closely related to lithology of rocks. The plotting of bar diagrams provides a great help in interpretation for sources of constituents, although the

origins of some ions are doubtful, due to the incomplete examination of well cuttings. The use of isopachous maps is found to be most comprehensive in showing the ranges and distributions of individual substances and properties of water. In addition, the rating curves plotting specific conductance against total dissolved solids clearly indicate the possibility for uses of the curves in estimating the total dissolved solids in water from both new and old wells.

The graphic procedures of interpretation successfully establish the classification of water on the basis of both character and mineral composition. The plotting of sodium adsorption ratio against the specific conductance on rating diagrams enables a reader to recognize types of irrigation water with alkalinity hazards or salinity hazards to cultivated crops. These interpretative methods, supplemented by the knowledge of quantity of individual constituents, are used as guides to recommendations for uses of water for different purposes. The recommendations are, however, generalized, rather than emphasized for specific localities. However, objectionable water for certain uses is pointed out for areas where water is highly mineralized.

As previously mentioned, shale and siltstone underlies more than half the total area of the plateau, and the study of water quality is limited to 300 feet of depth in potential water-bearing areas. Chemical quality within this aquifer is widely variable from place to place, due to the presence or absence and depth of evaporite beds. A close study of

well cuttings and repeated analysis of water samples are believed to be an excellent way to understand the exact nature of water in this aquifer. Study of electric logs of wells drilled in some areas regarded as inferior for water development reveals that water is stored in different zones, some of which contain fresh water and some salty water. Many electric logs show a salty zone in the upper part, at shallow depth, while a fresh zone lies beneath, as is the case of water wells within the city of Surin. With complete and correct development of wells, including plugging, sealing, and perforating, it should be possible to withdraw potable water from the aquifer. The use of electric logging is recommended for wells penetrating the aquifer. Close attention should be also given to the alluvial aquifer, in order to seal out the unavoidable contaminated zones. The inferior water in limestone tends to be difficult to control except for a quality treatment before use. Within the sandstone aquifers, water seems to be superior so far as the quality is concerned.

## **APPENDIX**

TABLE 6  
CHEMICAL ANALYSES OF REPRESENTATIVE WATER SAMPLES

Well number	Silica (SiO <sub>2</sub> )	Iron (Fe)	Calcium (Ca)		Magnesium (Mg)		Sodium (Na)		Potassium (K)		Chloride (Cl)		Sulfate (SO <sub>4</sub> )		Carbonate (CO <sub>3</sub> )		Bicarbonate (HCO <sub>3</sub> )		Fluoride (F)	Phosphate (PO <sub>4</sub> )	Nitrate (NO <sub>3</sub> )	Total dissolved solids	Hard- ness as CaCO <sub>3</sub>	Non- car- bonate	Specific conductance at 25°C	pH
	ppm	ppm	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	
A12S11	0.0	0.7	115	5.740	14	1.150	61	2,654	0.0	0.0	80	2.226	61	1.270	0	0	364	5.965	0.6	14	0.0	567	346	48	370	6.7
A13S12	0.0	5.2	17	0.849	5.2	0.427	18	0.874	0.0	0.0	5	0.141	37	0.770	0	0	68	1.115	0.8	26	0.0	195	64	8	130	6.2
A22S21	0.0	7.0	113	5.640	20	1.644	133	5.790	0.0	0.0	270	7.615	77	1.602	0	0	230	3.739	0.8	8	0.0	730	362	173	500	7.1
A25S24	0.0	2.1	340	16.950	35	2.879	216	9.400	0.0	0.0	280	7.900	747	15.540	0	0	346	5.675	1.0	7.6	0.0	1800	994	705	1200	6.9
A30Ub5	0.0	11	3.2	0.159	2.4	0.197	135	5.875	1.0	0.025	38	1.071	236	4.910	0	0	14	0.230	0.8	0.2	0.1	433	18	0	660	5.7
A35Ub10	0.0	0.02	40	1.996	0.0	0.0	13	0.565	0.0	0.0	25	0.705	0.0	0.0	0	0	114	1.870	0.0	0.3	0.0	130	100	7	200	7.4
A38Ub13	0.0	20	5.6	0.279	6.8	0.559	89	3.872	1.0	0.025	57	1.615	126	2.620	0	0	28	0.453	1.0	0.0	0.0	300	42	19	200	5.8
A39Ub4	0.0	1.1	32	1.595	0.0	0.0	28	1.219	0.0	0.0	10	0.282	61	1.270	0	0	76	1.248	1.0	2.4	0.0	170	80	18	110	6.5
A47Ub21	50	0.7	34	1.695	8.5	0.698	15	0.652	1.0	0.025	16	0.451	0.0	0.0	0	0	160	2.625	0.0	0.0	0.0	205	120	0	300	7.0
A49Ub23	0.4	4.8	61	3.043	10	0.822	17	0.740	3.0	0.077	6	0.169	28	0.582	0	0	240	3.940	0.0	0.0	0.0	235	196	0	360	7.3
A50Ub24	2.0	4.8	42	2.095	76	6.245	65	2.828	3.0	0.077	41	1.155	88	1.830	0	0	504	8.260	0.0	16	0.1	585	420	7	900	8.2
B7B4	6.2	20	249	12.430	22	1.801	53	2.370	0.0	0.0	353	10.040	33	0.680	0	0	356	5.840	0.6	26	0.0	1106	714	476	720	7.8
B16B13	6.2	0.05	99	4.940	13	1.069	112	4.875	0.0	0.0	82	3.313	36	0.749	0	0	480	7.875	0.6	30	0.0	590	304	0	375	7.5
B18B15	0.0	1.4	8.0	0.399	5.8	0.478	160	6.960	0.0	0.0	132	3.740	92	1.915	0	0	132	2.165	0.6	16	0.1	464	44	0	300	7.0
B25B22	20	10	200	9.975	97	7.975	392	17.050	0.0	0.0	1100	31.000	141	2.930	0	0	64	1.050	0.8	7.2	0.0	1931	900	847	1250	6.7
B26B23	0.0	3.5	229	11.42	30	2.465	342	14.890	0.0	0.0	548	15.460	209	4.350	0	0	546	8.950	0.6	60	0.0	1562	696	248	1020	7.3
B28SK1	0.0	0.03	144	7.199	41	3.365	172	7.490	0.0	0.0	201	5.670	453	9.430	0	0	182	2.984	0.2	0.0	0.0	1000	530	380	650	7.8
B34SK17	0.0	2.8	109	5.440	21	1.725	138	6.100	0.0	0.0	281	7.925	97	2.020	0	0	200	3.280	0.1	1.4	0.0	750	360	196	478	7.9
B38SK11	0.0	10	696	34.780	52	4.278	380	16.530	0.0	0.0	1910	53.9	59	1.23	0	0	24	0.394	0.6	0.0	0.0	3110	1950	1930	2000	7.0
B41SK14	0.0	1.4	604	30.150	25	2.058	275	11.980	0.0	0.0	675	19.040	1134	23.620	0	0	92	1.509	0.6	20	0.0	2760	1610	1535	1800	7.8
B48SK22	0.0	3.5	68	3.395	21	1.725	102	4.440	0.0	0.0	44	1.240	84	1.750	10	0.333	380	6.235	0.0	0.8	0.0	510	256	0	330	8.4
B52Ub4	0.0	28	432	21.580	10	0.822	0.0	0.0	0.0	0.0	123	3.460	823	17.120	0	0	110	1.805	0.0	0.0	0.0	1475	1192	1102	2300	7.5
B54Ub6	32	0.01	27	1.349	10	0.822	25	1.089	0.0	0.0	30	0.845	21	0.437	0	0	116	1.904	0.6	20	0.1	264	106	11	170	8.2
B56Ub8	0.0	0.7	44	2.195	6.8	0.569	91	3.960	0.0	0.0	22	0.620	64	1.332	0	0	290	4.760	0.4	1.6	0.0	464	138	0	300	7.3
B67Ub19	9.0	0.0	86	4.299	45	3.700	136	5.920	1.0	0.025	403	11.740	0.0	0.0	0	0	154	2.525	0.4	0.0	0.0	752	400	274	1200	7.8
C2NR2	25	0.7	176	8.790	65	5.345	237	10.610	0.0	0.0	304	8.575	511	10.640	0	0	316	5.190	0.8	0.3	0.0	1475	710	450	2200	7.2
C9NR9	10	1.4	280	13.950	6.1	1.501	216	9.400	0.0	0.0	680	19.185	83	1.730	0	0	180	2.955	0.6	16	0.0	1677	724	576	1100	7.0
C11NR11	0.8	3.5	1040	51.980	200	16.420	3926	172.000	0.0	0.0	7200	203.000	1590	33.100	0	0	156	2.560	0.8	0.3	0.0	14135	3400	3272	20000	6.9
C14NR14	60	10	1206	60.200	314	25.80	2133	92.750	0.0	0.0	5080	143.200	1629	33.800	0	0	92	1.059	1.2	18	0.1	12200	4300	4225	-	7.5
C19NR19	1.6	12	204	10.039	95	7.810	2111	91.850	0.0	0.0	2550	71.990	1352	28.150	0	0	596	9.770	0.0	1.0	0.0	6612	900	412	10000	7.4
C22KK22	10	0.01	164	8.195	39	3.205	281	12.430	1.0	0.025	600	16.900	0.0	0.0	0	0	410	6.725	0.0	1.1	0.1	1300	570	234	2000	8.1
C24KK4	32	2.1	199	9.940	46	3.780	260	11.600	0.0	0.0	132	3.720	841	17.500	0	0	226	3.708	1.0	30	0.0	1722	686	500	1300	7.6
C30KK10	12	6.3	96	4.795	24	1.970	95	4.135	0.0	0.0	151	4.259	122	2.539	0	0	250	4.100	0.8	30	0.1	727	338	133	700	7.9
C34KK14	0.0	0.0	56	2.795	24	1.970	62	2.699	2.0	0.051	6	0.169	0.0	0.0	0	0	446	7.320	0.8	0.0	0.0	372	240	0	570	7.9
C35KK15	0.0	4.8	135	6.740	0.0	0.0	46	2.000	6.0	0.154	0	0.0	0.0	0.0	0	0	496	8.145	0.0	5.5	0.0	465	340	0	720	8.1
C37KK17	0.0	3.5	80	3.999	15	1.231	123	5.350	3.0	0.077	67	1.889	144	2.999	0	0	390	6.400	0.0	0.1	0.0	588	264	0	900	7.9
C39C1	5.0	0.07	88	4.390	20	1.644	0.0	0.0	0.0	0.0	6	0.169	54	1.122	0	0	284	4.660	0.0	0.0	0.0	315	300	67	500	8.0
C40C2	0.0	4.2	400	19.950	146	12.000	0.0	0.0	0.0	0.0	450	12.690	656	13.650	0	0	344	5.645	0.0	3.0	0.5	1825	1600	1318	3000	7.2
C42KK20	16	4.2	61	3.055	20	1.644	21	0.914	0.0	0.0	13	0.366	15	0.312	0	0	300	4.920	0.8	40	0.1	409	236	0	260	7.6
C43L1	0.0	7.6	94	4.699	11	0.904	20	0.870	2.0	0.051	4	0.115	28	0.582	0	0	356	5.840	0.0	2.2	0.0	340	282	0	520	7.8
C44L2	8.0	4.8	110	5.499	8.1	0.666	0.0	0.0	0.0	0.0	10	0.282	170	3.540	0	0	102	1.673	0.0	16	0.0	372	308	190	600	7.0
C45L3	2.0	1.4	680	33.950	64	5.260	0.0	0.0	0.0	0.0	8	0.226	1703	35.40	0	0	218	3.580	0.0	0.0	0.0	2565	1960	1781	4000	7.6

TABLE 6  
CHEMICAL ANALYSES OF REPRESENTATIVE WATER SAMPLES  
CONTINUED

Well number	Silica (SiO <sub>2</sub> )	Iron (Fe)	Calcium (Ca)		Magnesium (Mg)		Sodium (Na)		Potassium (K)		Chloride (Cl)		Sulfate (SO <sub>4</sub> )		Carbonate (CO <sub>3</sub> )		Bicarbonate (HCO <sub>3</sub> )		Fluoride (F)	Phosphate (PO <sub>4</sub> )	Nitrate (NO <sub>3</sub> )	Total dissolved solids	Hard- ness as CaCO <sub>3</sub>	Non- car- bonate	Specific conductance micromhos at 25°C	pH
	ppm	ppm	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	ppm	ppm	ppm	ppm	ppm		
C47L5	60	3.5	228	11.4	0.0	0.0	17	0.740	1.0	0.025	12	0.338	294	6.120	0	0	344	5.650	1.0	0.1	0.0	725	569	287	470	6.9
C48L6	2.0	9.0	496	24.750	37	3.040	45	1.959	1.0	0.025	11	0.310	1210	25.190	0	0	258	4.230	0.8	0.0	0.0	1950	1390	1180	3000	7.5
C49L7	0.5	4.1	664	33.200	47	3.862	207	9.000	1.0	0.025	18	0.508	2002	41.640	0	0	234	3.840	0.0	0.1	0.0	3055	1850	1659	4700	7.0
C50L8	0.0	22	75	3.740	13	1.069	3.1	0.135	0.0	0.0	9	0.254	84	1.750	0	0	174	2.859	0.0	1.2	0.5	273	236	93	420	6.8
C52L10	0.0	22	18	0.900	10	0.822	17	0.740	1.0	0.025	4	0.116	32	0.666	0	0	104	1.709	0.0	1.2	0.0	136	86	0	200	6.6
C54L12	3.4	0.01	84	4.190	24	1.970	0.0	0.0	0.0	0.0	4	0.115	296	6.160	0	0	0.0	0.0	0.4	0.0	0.0	412	310	310	800	4.8
C56L14	3.4	25	124	6.190	31	2.545	0.0	0.0	0.0	0.0	53	0.149	286	5.950	0	0	86	1.410	0.0	0.8	0.1	540	440	319	840	6.3
C58L16	3.7	0.0	49	2.445	22	1.808	192	8.350	1.0	0.025	48	1.325	159	3.308	0	0	484	7.940	1.0	0.4	0.0	718	216	0	1100	7.5
C61KK23	0.0	4.1	57	2.845	18	1.480	138	6.000	5.0	0.128	170	4.790	220	4.580	0	0	60	0.585	0.0	0.7	0.1	640	216	167	940	6.0
C62KK24	5.2	0.01	48	2.395	7.3	0.600	16	0.696	1.0	0.025	15	0.423	0.0	0.0	0	0	202	3.319	0.0	0.1	0.0	194	150	0	300	7.2
C65Ud3	0.0	0.01	106	5.295	25	2.058	6.3	0.274	0.0	0.0	15	0.423	0.0	0.0	0	0	440	7.215	0.0	1.3	0.0	373	368	7	570	7.3
D1NR1	0.0	3.5	28	1.395	19	1.560	744	32.380	1.0	0.025	745	21.000	333	6.925	0	0	458	7.510	3.5	0.0	0.0	2100	150	0	3200	8.2
D3NR3	25	2.8	77	3.840	11	0.904	42	1.852	0.0	0.0	47	1.324	22	0.458	0	0	296	4.860	1.0	86	0.7	534	240	0	-	7.2
D8R4	0.0	0.70	48	2.395	31	2.545	43	1.870	3.2	0.082	134	3.779	75	1.560	0	0	92	1.509	1.0	0.1	0.1	380	250	174	247	7.1
D10R6	40	4.2	86	4.290	0.0	0.0	159	6.920	0.0	0.0	269	7.589	54	1.123	0	0	144	2.364	0.8	40	0.0	804	214	96	520	8.1
D20R16	6.4	4.8	4.8	0.239	1.0	0.082	8.9	0.387	0.0	0.0	10	0.282	0.0	0.0	0	0	26	0.426	0.0	4.8	0.0	50	16	0	75	6.2
D22R18	0.0	20	35	1.748	0.0	0.0	60	2.612	0.0	0.0	16	0.451	120	2.499	0	0	84	1.378	1.0	0.1	0.0	273	88	19	180	6.7
D31Ms6	16	2.1	725	36.200	556	45.700	1773	76.722	0.0	0.0	5500	155.1	35	0.729	0	0	198	3.250	0.8	32	0.0	10204	4096	3939	6500	7.3
D40K6	0.0	35	160	8.000	0.0	0.0	42	1.859	7.0	0.179	350	9.860	0.0	0.0	0	0	0.0	0.0	0.0	1.2	0.0	560	400	400	860	6.9
D44K10	20	0.0	7.2	0.359	1.4	0.115	3.6	0.156	0.0	0.0	6	0.169	0.0	0.0	0	0	26	0.426	0.8	0.3	0.0	52	24	30	80	7.1
D46K12	0.7	40	8.0	0.399	4.8	0.394	31	1.349	1.0	0.025	60	1.690	0.0	0.0	0	0	28	0.459	0.4	1.5	0.0	120	40	17	190	5.8
D47K13	0.0	2.8	174	8.695	17	1.397	110	4.784	0.0	0.0	80	2.254	462	9.600	0	0	182	2.985	0.0	0.0	0.0	935	504	355	600	7.5
D59Ms19	6.4	0.01	70	3.493	2.2	0.181	166	7.220	0.0	0.0	351	9.900	0.0	0.0	0	0	62	1.019	0.0	0.0	0.0	630	184	118	1000	6.4
D63Ms13	5.6	0.0	28	1.395	56	4.600	0.0	0.0	0.0	0.0	11	0.310	41	0.854	0	0	294	4.820	0.0	0.0	0.0	252	306	59	430	7.7
D66Ms26	0.0	0.0	16	0.800	7.8	0.641	57	2.480	0.0	0.0	32	0.902	5	0.104	6	0.199	166	2.720	0.0	24	0.0	202	72	0	310	8.5
E3NR1	0.0	1.4	48	2.395	11	0.904	56	2.438	0.0	0.0	34	0.958	66	1.373	0	0	210	3.440	0.2	5.0	0.1	300	166	0	200	7.6
E6Ud3	0.0	5.6	64	3.195	3.4	0.279	73	3.179	1.5	0.038	28	0.789	148	3.080	0	0	178	2.920	0.0	0.0	0.0	410	174	28	266	6.8
E9Ud6	20	0.0	58	2.399	10	0.822	64	2.784	3.0	0.077	60	1.690	60	1.250	0	0	228	3.740	0.0	0.4	0.0	390	188	1	600	7.7
E14NK4	6.2	2.8	30	1.499	29	2.380	0.0	0.0	0.0	0.0	7	0.197	0.0	0.0	0	0	222	3.640	0.0	0.0	0.0	185	220	10	300	7.4
E16NK6	0.0	11	18	0.900	12	0.987	2.0	0.087	0.0	0.0	30	0.846	0.0	0.0	0	0	68	1.115	0.0	15	0.2	96	94	33	150	6.9
E17NK7	9.2	0.0	45	2.224	32	0.263	0.0	0.0	0.0	0.0	17	0.479	0.0	0.0	0	0	124	2.039	0.0	28	0.0	128	154	52	190	6.8
E20NK10	0.0	9.8	91	4.542	20	1.641	0.0	0.0	0.0	0.0	79	2.227	0.0	0.0	0	0	222	3.632	0.0	0.0	0.0	300	312	130	460	6.9
E21Ud8	0.0	55	520	25.600	268	22.000	290	12.620	0.0	0.0	2100	50.220	0.0	0.0	0	0	86	1.041	0.0	0.6	0.0	3222	2400	2330	5000	6.3
E25Ud12	16	22	10	0.499	4.6	0.378	35	1.544	0.0	0.0	70	1.077	0.0	0.0	0	0	24	0.394	0.0	1.8	0.0	140	42	22	200	5.7
E28SN3	20	1.4	64	3.195	8.3	0.682	10	0.435	1.0	0.025	23	0.649	0.0	0.0	0	0	226	3.708	0.0	0.2	0.0	240	194	9	380	7.7
F3K2	6.2	11	400	19.999	0.0	0.0	70	3.042	0.0	0.0	39	1.100	879	18.30	0	0	220	3.607	0.8	50	0.0	1520	1000	819	1000	7.8
F4K3	0.1	2.8	88	4.390	7.2	0.592	0.4	0.017	0.0	0.0	14	0.395	0.0	0.0	0	0	282	4.622	0.0	0.0	0.0	250	250	19	370	7.5
F5K4	0.1	1.4	68	3.395	14	1.150	0.0	0.0	0.0	0.0	98	2.760	0.0	0.0	0	0	100	1.640	0.0	0.2	0.2	230	230	148	350	6.5
F7SN1	0.0	1.4	62	3.100	2.7	0.222	46	2.000	1.0	0.025	33	0.930	0.0	0.0	0	0	270	4.430	0.0	0.2	0.0	280	166	0	430	7.7
F13SN7	2.0	0.0	14	0.700	5.5	0.452	22	0.956	0.0	0.0	26	0.734	24	0.499	0	0	52	0.854	0.0	10	2.0	130	56	15	200	7.8
F21SN15	2.4	0.0	19	0.950	14	1.150	102	4.440	2.0	0.051	17	0.479	87	1.810	0	0	262	4.300	0.0	0.0	0.0	375	106	0	600	7.9
F26SN20	6.2	0.240	34	1.699	5.6	0.460	98	4.263	1.0	0.025	27	0.761	149	3.100	0	0	158	2.595	0.0	0.0	0.0	400	108	0	620	7.8

TABLE 6  
CHEMICAL ANALYSES OF REPRESENTATIVE WATER SAMPLES  
CONTINUED

Well number	Silica (SiO <sub>2</sub> )	Iron (Fe)	Calcium (Ca)		Magnesium (Mg)		Sodium (Na)		Potassium (K)		Chloride (Cl)		Sulfate (SO <sub>4</sub> )		Carbonate (CO <sub>3</sub> )		Bicarbonate (HCO <sub>3</sub> )		Fluoride (F)	Phosphate (PO <sub>4</sub> )	Nitrate (NO <sub>3</sub> )	Total dissolved solids	Hard- ness as CaCO <sub>3</sub>	Non- car- bonate	Specific conductance micro mhos at 25°C	pH
	ppm	ppm	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	ppm	ppm	ppm	ppm	ppm		
G4SN3	0.0	5.6	45	2.243	17	1.392	195	8.490	2.0	0.051	203	5.725	146	3.037	0	0	206	3.354	0.8	29	0.1	710	184	15	460	6.8
G8SN7	0.0	0.04	78	3.899	21	1.725	60	2.613	0.0	0.0	6.0	0.169	114	2.372	0	0	342	5.610	0.0	0.0	0.0	450	282	2	690	7.7
G10NP2	14	5.8	46	2.295	12	0.987	0.0	0.0	2.0	0.051	10	0.282	12	0.250	0	0	170	2.790	0.8	0.6	0.0	180	166	28	300	6.9
G12NP4	0.0	4.2	8.0	0.399	2.9	0.238	30	1.305	1.0	0.025	47	1.324	0.0	0.0	0	0	40	0.656	0.0	0.2	0.0	110	32	0	170	7.2
G13NP5	0.0	0.03	68	3.395	29	2.380	22	0.957	6.0	0.153	41	1.155	0.0	0.0	0	0	350	5.745	0.0	0.2	0.0	0	342	290	9	600
G18NP10	0.0	5.6	27	1.348	3.0	0.246	12	0.522	0.0	0.0	6.0	0.169	12	0.130	0	0	104	1.705	0.0	0.0	0.0	118	80	0	190	7.2
G21NP13	22	1.4	244	12.180	51	4.188	0.0	0.0	0.0	0.0	161	4.540	481	10.000	0	0	112	1.839	0.6	0.0	0.0	1015	820	728	2000	7.7
G27NP19	4.8	1.4	15	0.748	4.5	0.369	0.0	0.0	0.0	0.0	12	0.338	0.0	0.0	0	0	46	0.755	0.0	0.8	0.1	65	56	18	100	6.9
H1-3	0.0	7.0	29	1.450	20	1.644	41	1.784	0.1	0.003	14	0.395	11	0.223	0	0	273	4.480	0.4	8	0.0	530	204	0	-	7.3
H1-5	0.5	0.0	0.0	0.0	10	0.822	178	7.750	0.0	0.0	79	2.225	34	0.775	0	0	323	5.300	1.6	8	0.0	590	42	0	-	8.0
H1-36	0.0	3.0	94	4.695	32	2.630	2260	98.400	0.0	0.0	3570	100.8	128	2.664	0	0	126	2.070	0.5	4	0.0	7070	366	973	-	7.3
H2-16	0.0	0.03	565	28.200	61	5.010	2190	95.400	0.0	0.0	4210	118.8	277	5.770	0	0	240	3.940	0.0	4	0.0	9684	1661	1464	-	7.3
H2-24	0.0	4.0	47	2.343	11	0.904	378	16.45	0.0	0.0	560	15.799	13	0.271	0	0	134	2.200	0.0	50	0.0	1250	162	53	-	7.3



TABLE 7  
CHARACTER OF REPRESENTATIVE  
GROUND WATERS

(See table 6 for description for analytical data  
in parts per million and equivalents per million)

Aquifer	No.	Well number	Cations (percent equivalents)			Anions (percent equivalents)			Sod adsor tive ra
			Ca	Mg	Na+K	Cl	SO <sub>4</sub>	HCO <sub>3</sub>	
Alluvium	1	A22S21	43.2	12.6	44.2	58.5	12.3	28.2	3.
	2	A30Ub5	2.5	3.2	94.3	17.3	79	3.7	13.
	3	A35Ub10	78	0.0	22	27.4	0.0	72.6	1.
	4	A38Ub13	5.9	11.8	82.3	34.4	55.8	9.8	6.
	5	A39Ub14	57	0.0	53	10	45.5	44.5	1.
	6	C2NR2	35.5	21.5	43	35.2	43.6	21.2	4.
	7	C30KK10	44	18	38	39.2	23.2	37.6	2.
	8	C54L12	68	32	0.0	1.8	98.2	0.0	0.
	9	C56L14	71	29	0.0	1.9	79.3	18.8	0.
	10	C61KK23	27.2	14.2	58.6	46.3	44.2	9.5	4.
	11	D1NR1	4	4.3	91.7	59.3	19.5	21.2	32.
	12	D3NR3	58.3	13.7	28	20	7	73	1.
	13	D20R16	33.8	11.6	54.6	40	0.0	60	0.
	14	D22R18	40	0.0	60	10.4	57.8	31.8	2.
	15	D59Ms19	32	1.6	66.4	91	0.0	8	3.
	16	D66Ms26	20.4	16.4	63.2	23	2.6	74.4	2.
	17	F13SN7	33.2	21.4	45.4	35.4	23.8	40.8	1.
	18	F21SN15	14.2	17.5	68.3	7.3	27.5	65.2	4.
	19	F26SN20	26.4	7.1	66.5	11.8	48.0	40.2	4.
	20	G12NP4	20.2	12.2	67.7	67	0.0	33	2.
	21	G13NP5	49.3	34.6	16.1	16.8	0.0	83.2	0.
	22	G18NP10	63.8	11.6	24.6	8.5	6.5	85.0	0.
	23	G21NP13	74.4	25.6	0.0	27.6	61.2	11.2	0.
Shale & siltstone	24	A12S11	60.2	12.0	27.8	23.5	1.3	63	
	25	A25S24	58	9.8	32.2	27	53.5	19.5	
	26	A47Ub12	56.5	23	22.5	15	0	85	
	27	B7B4	75	11	14	60.5	4.3	35.2	
	28	B16B13	45.4	9.6	45	27.8	6.2	66	
	29	B18B15	5	6	89	47.8	24.5	27.7	
	30	B25B22	28.4	22.8	48.8	89	8	3	
	31	B26B23	39.8	8.6	51.8	53.7	15.1	31.2	
	32	B28SK1	39.8	18.7	41.5	31.4	52.1	16.5	
	33	B34SK7	41	13	46	60	15.2	24.8	

TABLE 7  
CHARACTER OF REPRESENTATIVE  
GROUND WATERS  
CONTINUED

(See table 6 for description for analytical data  
in parts per million and equivalents per million)

Aquifer	No.	Well number	Cations (percent equivalents)			Anions (percent equivalents)			Sodi adsc tic ra
			Ca	Mg	Na+K	Cl	SO <sub>4</sub>	HCO <sub>3</sub>	
Shale & siltstone continu- ed	34	B38SK11	62.5	7.7	29.8	97	2.3	0.7	
	35	B41SK14	68	4.6	27.4	43.2	53.6	3.2	
	36	B48SK21	35.3	18.2	46.5	13	18	69	
	37	B52Ub4	96.3	3.7	0.0	15.5	76.5	8.0	
	38	B54Ub6	41.4	25.2	33.4	26.5	13.7	59.8	
	39	B67Ub19	30.8	26.6	42.6	82.5	0.0	17.5	
	40	C9NR9	58.6	21	39.4	58.5	2.1	39.4	
	41	C11NR11	21.4	6.8	71.8	85	13.8	1.2	
	42	C14NR14	33.7	14.3	52	80	18.9	0.1	
	43	C19NR19	9.1	7.2	83.7	65.5	25.6	8.9	
	44	C22KK2	34.2	13.4	52.4	71.5	28.4	0.1	
	45	C24KK4	39.2	14.9	45.9	14.9	70.5	14.6	
	46	C65Ud3	69.4	27	3.6	5.5	0.0	94.5	
	47	D8R4	34.7	37	28.3	55.2	22.8	22	
	48	D10R6	38.3	0.0	61.7	68.5	10	21.5	
	49	D31Ms6	22.8	28.8	48.4	97.5	1.7	0.8	
	50	D40K6	80	0.0	20	100	0.0	0.0	
	51	D63Ms23	23	77	0.0	5.2	14.2	80.6	
	52	E6Ud3	47.8	4.2	48	11.6	45.4	43	
	53	E9Ud6	44	12.5	43.5	25.3	18.7	56	
	54	E14NK4	38.5	61.5	0.0	5	0.0	95	
	55	E16NK6	45.6	50	4.4	43	0.0	57	
	56	E17NK7	89.5	10.5	0.0	19	0.0	81	
	57	E20NK10	73	27	0.0	38	0.0	62	
	58	E21Ud8	42.5	36.5	21	98.5	0.0	1.5	
	59	E25Ud12	20.4	15.6	64	83.4	0.0	16.6	
	60	E28SN3	73.7	15.7	10.6	15	0.0	85	
	61	G4SN3	18.7	11.3	70	47.3	25	27.7	
	62	G8SN7	47.3	21	31.7	2.0	29	69	
	63	G10NP2	69	29.5	1.5	8.5	7.5	84	
	64	H1-3	29.7	33.6	36.7	7.6	4.4	88	
	65	H1-5	0.0	9.5	90.5	26.8	9.3	63.9	
	66	H1-36	4.6	2.4	93	95.6	2.5	1.9	

TABLE 7  
CHARACTER OF REPRESENTATIVE  
GROUND WATERS  
CONTINUED

(See table 6 for description for analytical data  
in parts per million and equivalents per million)

Aquifer	No.	Well number	Cations (percent equivalents)			Anions (percent equivalents)			Sodi- adsc- tic ra
			Ca	Mg	Na+K	Cl	SO <sub>4</sub>	HCO <sub>3</sub>	
Shale & siltstone continu- ed	67	H2-16	22.1	3.9	74	92.5	4.5	3	
	68	H2-24	12	4.6	83.4	86.5	1.5	12	
Phu Phan sand- stone	69	A13S12	41	21	38	7	38	55	0.
	70	A49Ub23	65	17.5	17.5	3.6	12.4	84	0.
	71	A50Ub24	18.5	55.5	26	10	16.5	73.5	1.
	72	B56Ub8	32.7	8.3	59	9.2	19.8	71	3.
	73	C62KK24	64.5	16.1	19.4	11.5	0.0	88.5	0.
	74	D46K12	18	18	64	79	0.0	21	2.
	75	D47K13	58.4	9.4	32.2	15.4	64.5	20.1	2.
	76	E3NR1	41.8	15.7	42.5	16.6	23.8	59.6	1.
	77	F3K2	86.6	0	13.4	4.4	80	15.6	0.
	78	F4K3	88	11.8	0.2	8	0.0	92	0.
	79	F5K4	75	25	0.0	62.7	0.0	37.4	0.
	80	F7SN1	58	4.2	37.8	17.3	0	82.7	1.
Phra Wihan and Phu Kadung sand- stones	81	C35KK15	75.7	0.0	24.3	0.0	0.0	100	1.
	82	C37KK17	37.5	11.5	51	16.7	26.5	56.8	3.
	83	C39C1	73	21	0.0	2.8	18.9	78.3	0.
	84	C40C2	62.5	37.5	0.0	39.7	42.7	17.6	0.
	85	C42KK20	54.5	29.2	16.3	6.5	5.5	88	0.
	86	C65Ud3	69.4	27	3.6	5.5	0.0	94.5	0.
	87	G27NP19	67	33	0.0	31	0.0	69	0.
Rat Buri lime- stone	88	C44L2	89.2	10.8	0.0	5.1	64.5	30.4	0.
	89	C45L3	86.6	13.4	0.0	0.5	90.4	9.1	0.
	90	C47L5	94	0	6	3	50.5	46.5	0.
	91	C48L6	83	10.4	6.6	1	85	14	0.
	92	C49L7	72	8.4	19.6	1.7	90	8.3	2.
	93	C50L8	75.8	21.6	2.6	5.2	36	58.8	0.
	94	C52L10	36.2	33	30.8	4.6	26.8	68.6	0.

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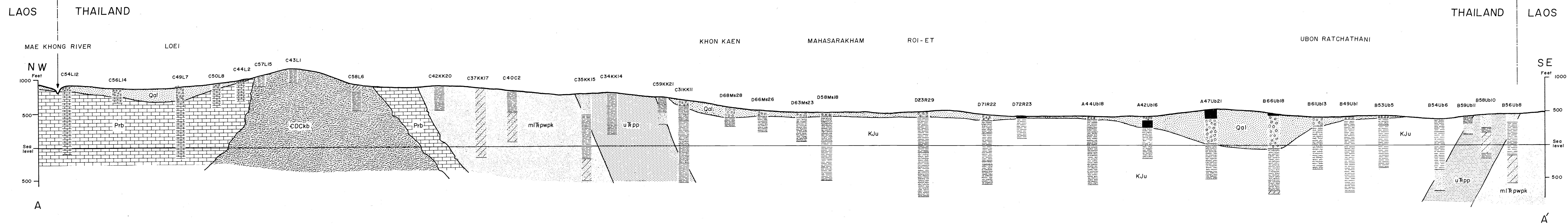
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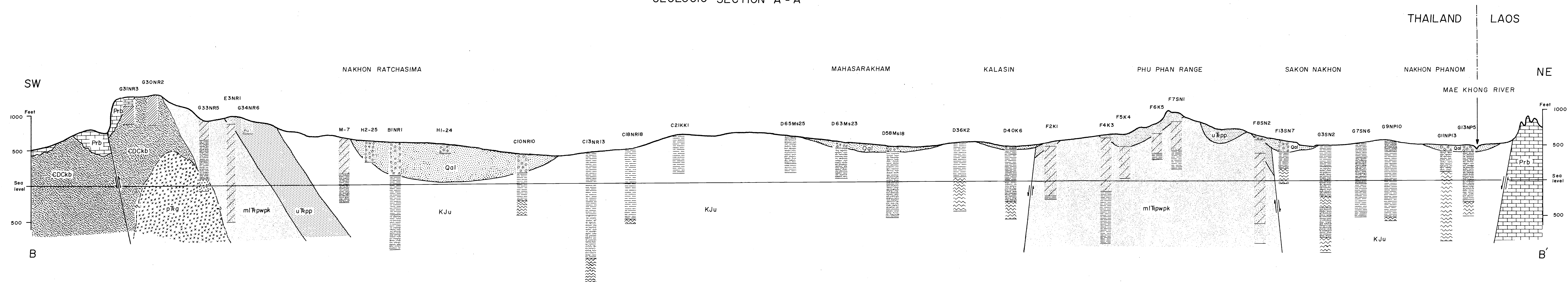








GEOLOGIC SECTION A - A'



GEOLOGIC SECTION B - B'

EXPLANATION

	Clay or sandy clay		Alluvium (Quaternary to Recent)
	Sand and gravel		Upper shale and siltstone (Jurassic and Cretaceous?, undifferentiated)
	Shale or sandy shale		Phu Phan sandstone (Upper Triassic)
	Siltstone		Phra Wihan and Phu Kadung sandstones (Middle and Lower Triassic)
	Very fine to fine grained sandstone		Rat Buri limestone (Permian)
	Medium to very coarse grained sandstone		Kanchana Buri Series (Cambrian, Devonian?, and Carboniferous?)
	Rock salt		Granite (pre-Triassic)
	Limestone		
	Slate or phyllite		
	Granite		

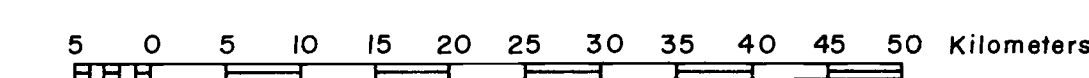


PLATE II

GEOLOGIC SECTIONS A - A' AND B - B', INCLUDING WELL LOGS

SCALE :	DATE :	DRAWN BY :
HORIZONTAL : 1 : 500,000 VERTICAL : 1" = 500'	JUNE 15, 1962	CHAROEN

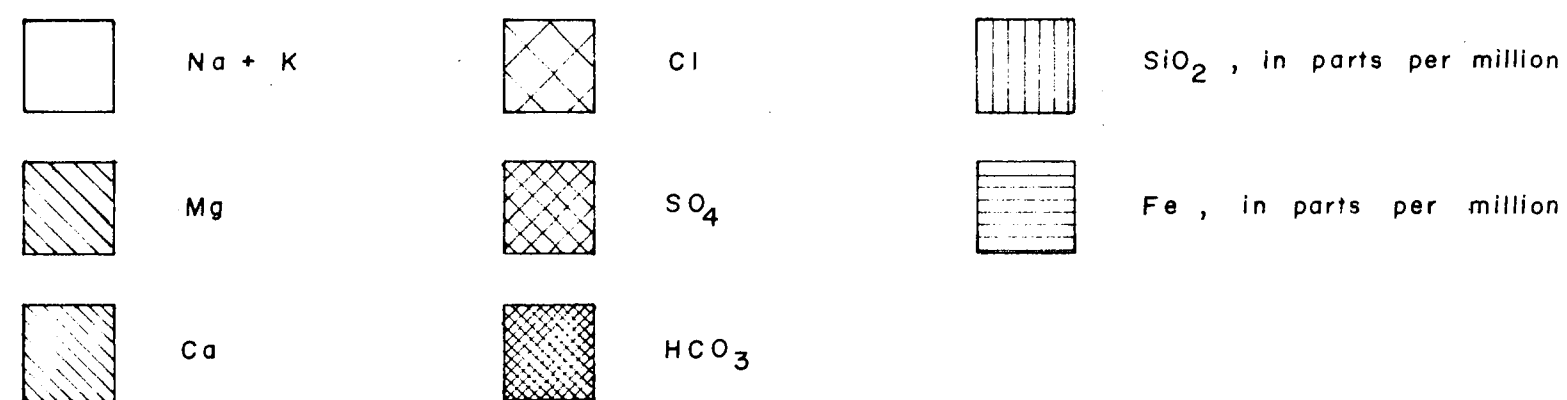
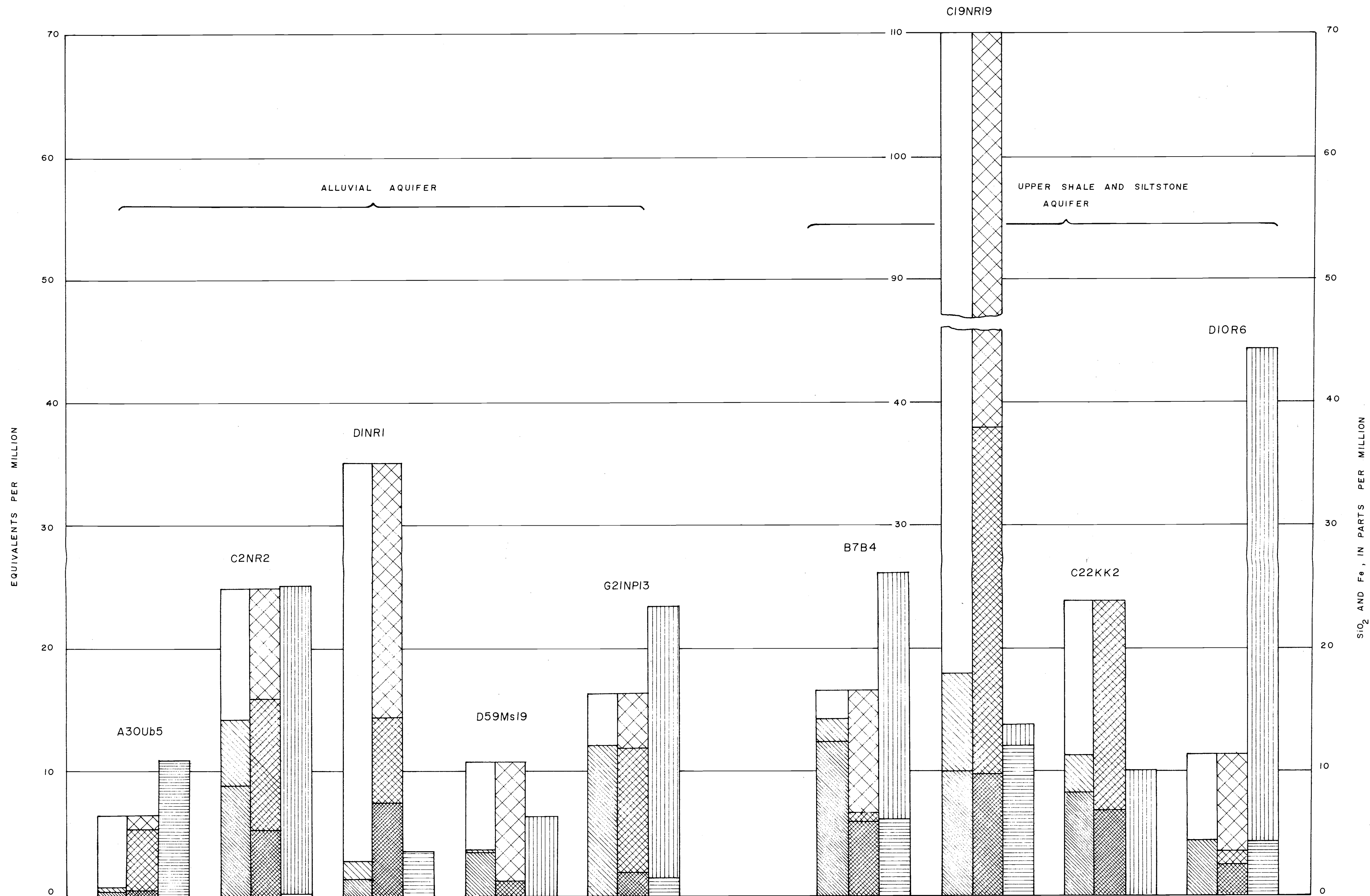


PLATE III - A

ANALYSES REPRESENTED BY BAR DIAGRAMS  
OF EQUIVALENTS PER MILLION

DATE	JUNE 14, 1962	DRAWN BY	CHAROEN
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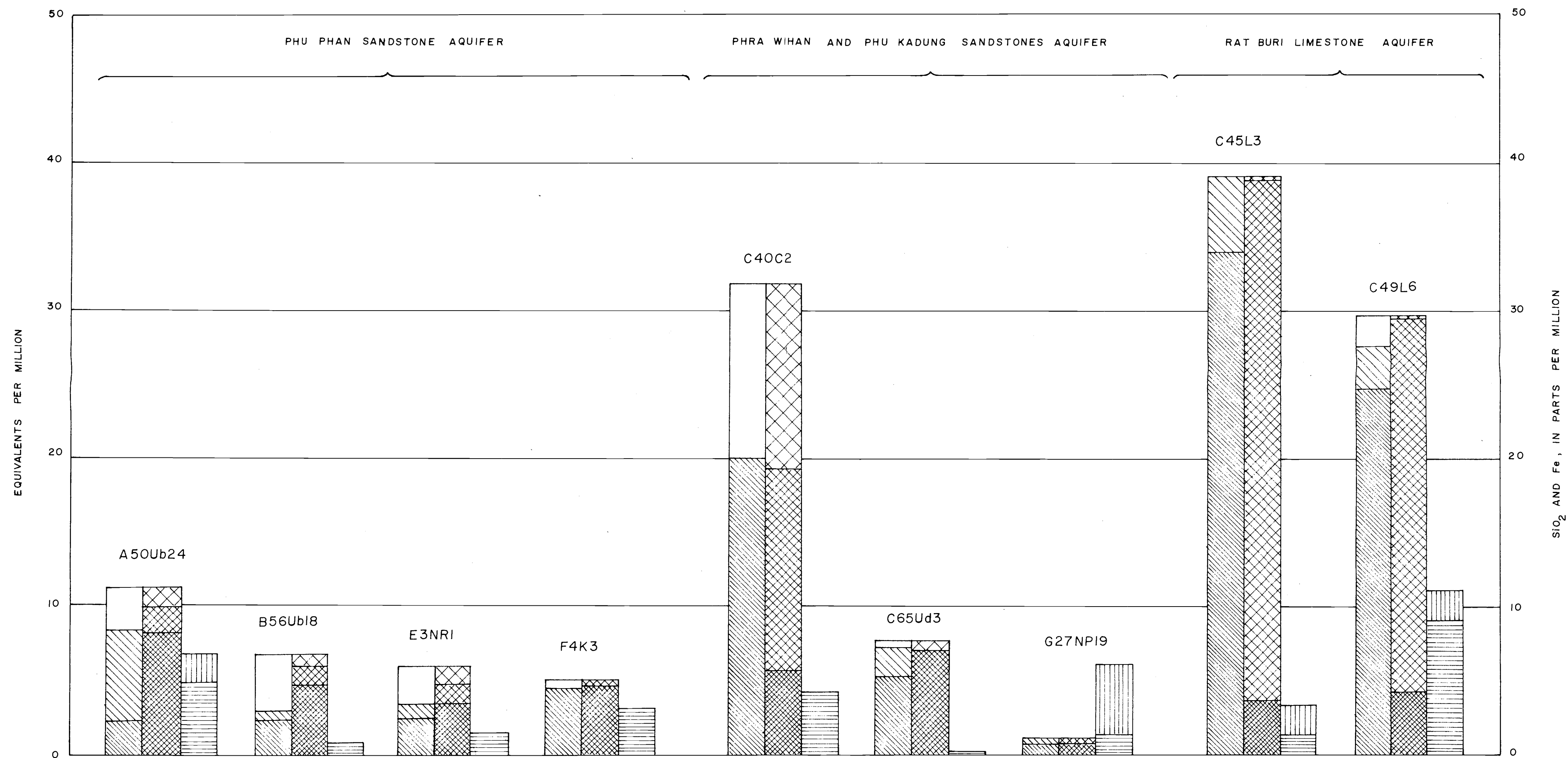


PLATE III - B

ANALYSES REPRESENTED BY BAR DIAGRAMS  
OF EQUIVALENTS PER MILLION

DATE: JUNE 14, 1962

DRAWN BY: CHAROEN

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1962  
131  
Plate 1

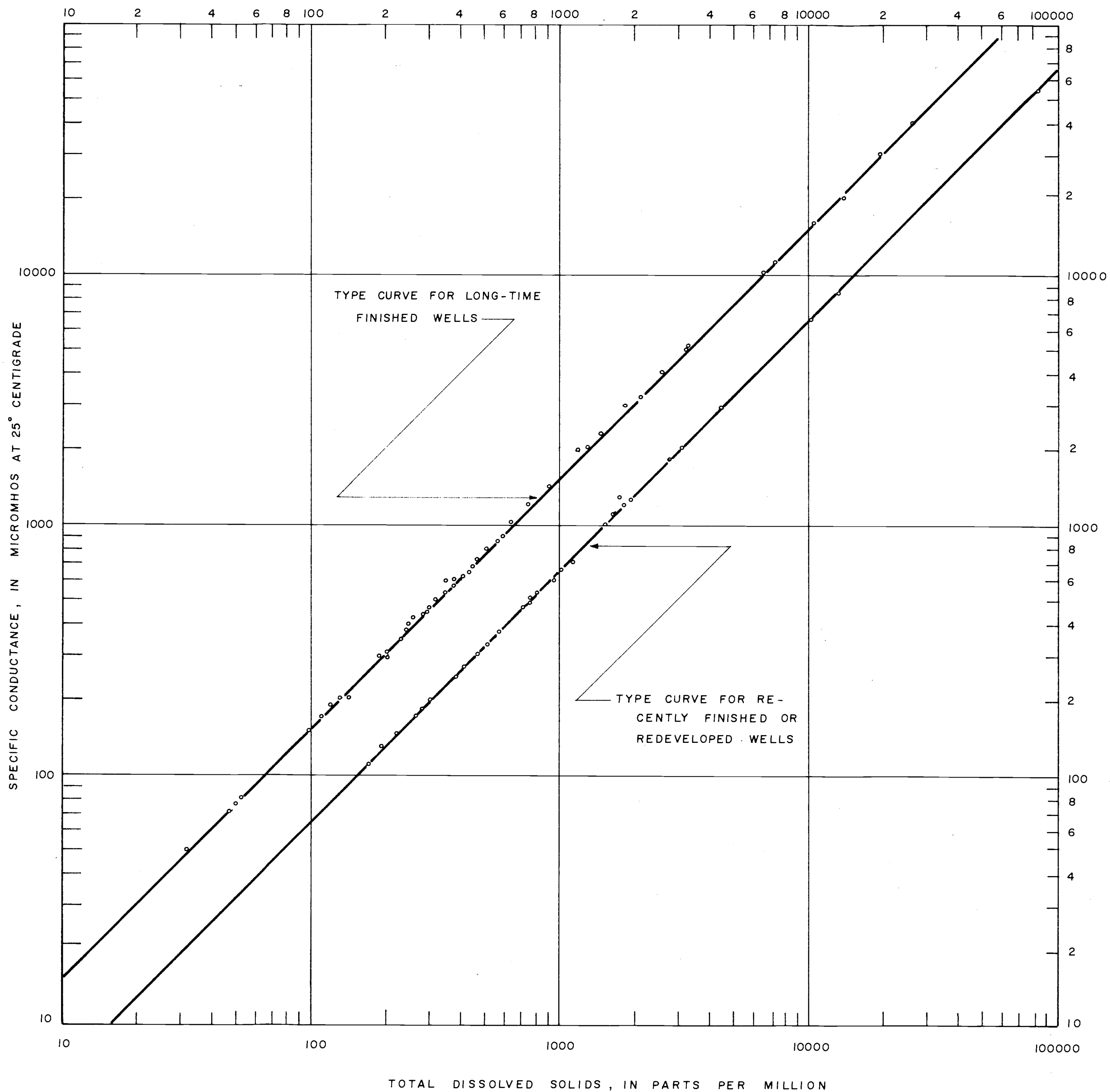


PLATE IV

TOTAL DISSOLVED SOLIDS AND SPECIFIC  
CONDUCTANCE RELATIONSHIP

DATE:

JUNE 16, 1962

DRAWN BY:

CHAROEN

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P/41



ALLUVIAL AQUIFER

UPPER SHALE AND SILTSTONE AQUIFER

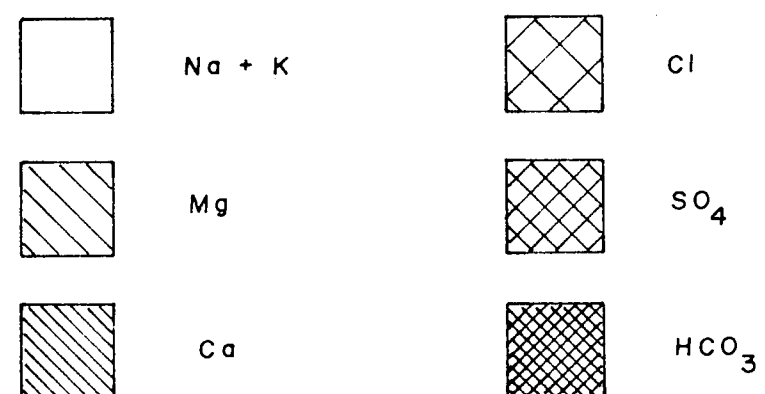
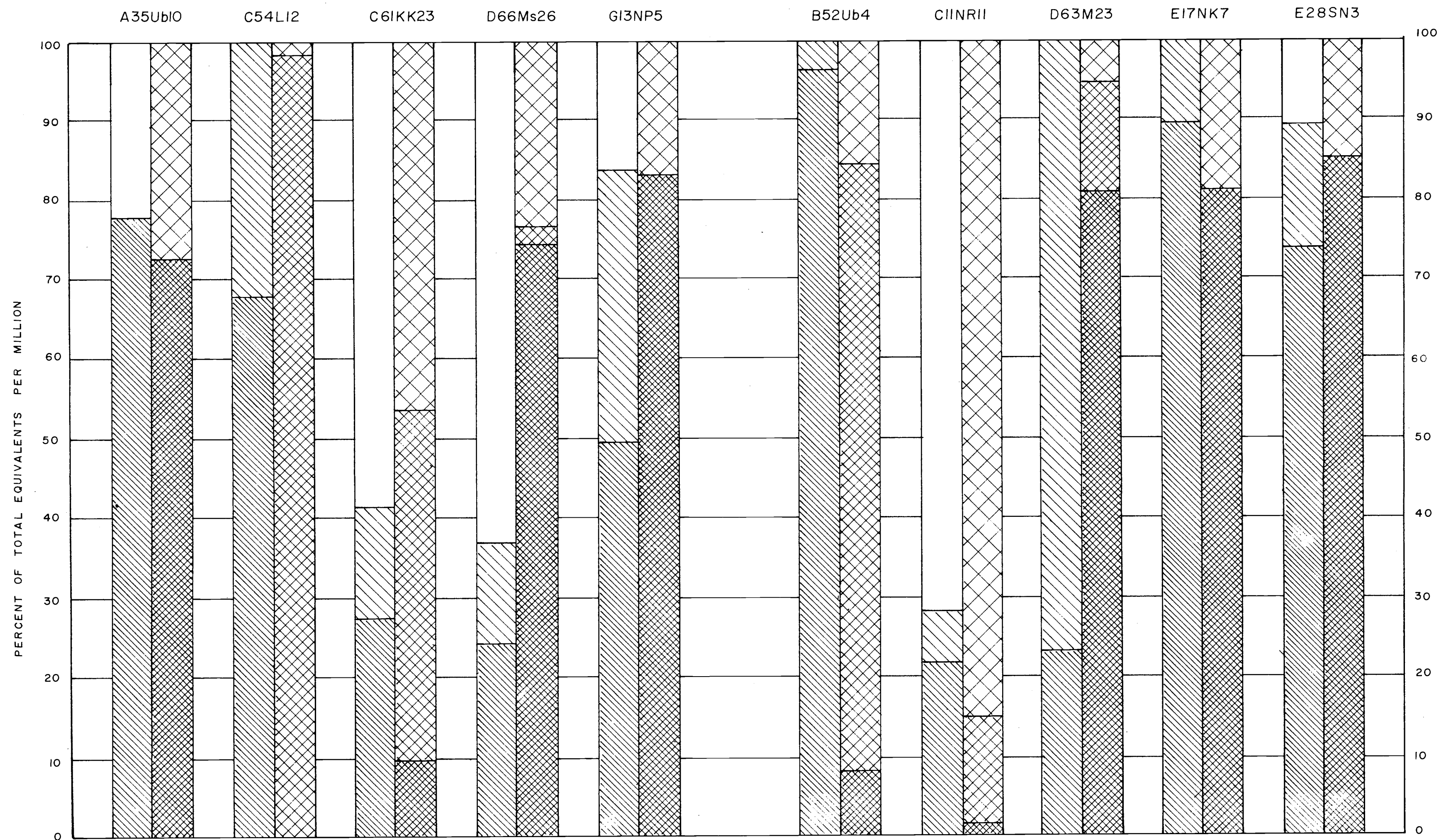


PLATE V - A

ANALYSES REPRESENTED BY BAR DIAGRAMS BASED ON  
PERCENT OF TOTAL EQUIVALENTS PER MILLION

DATE: JUNE 14, 1962

DRAWN BY: CHAROEN

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1962  
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Plate V

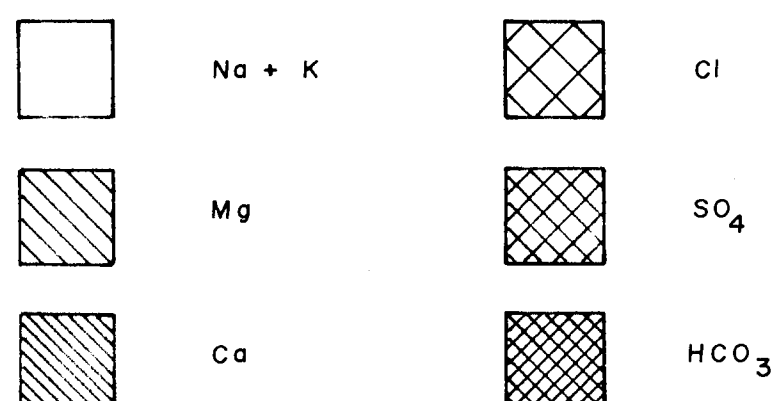
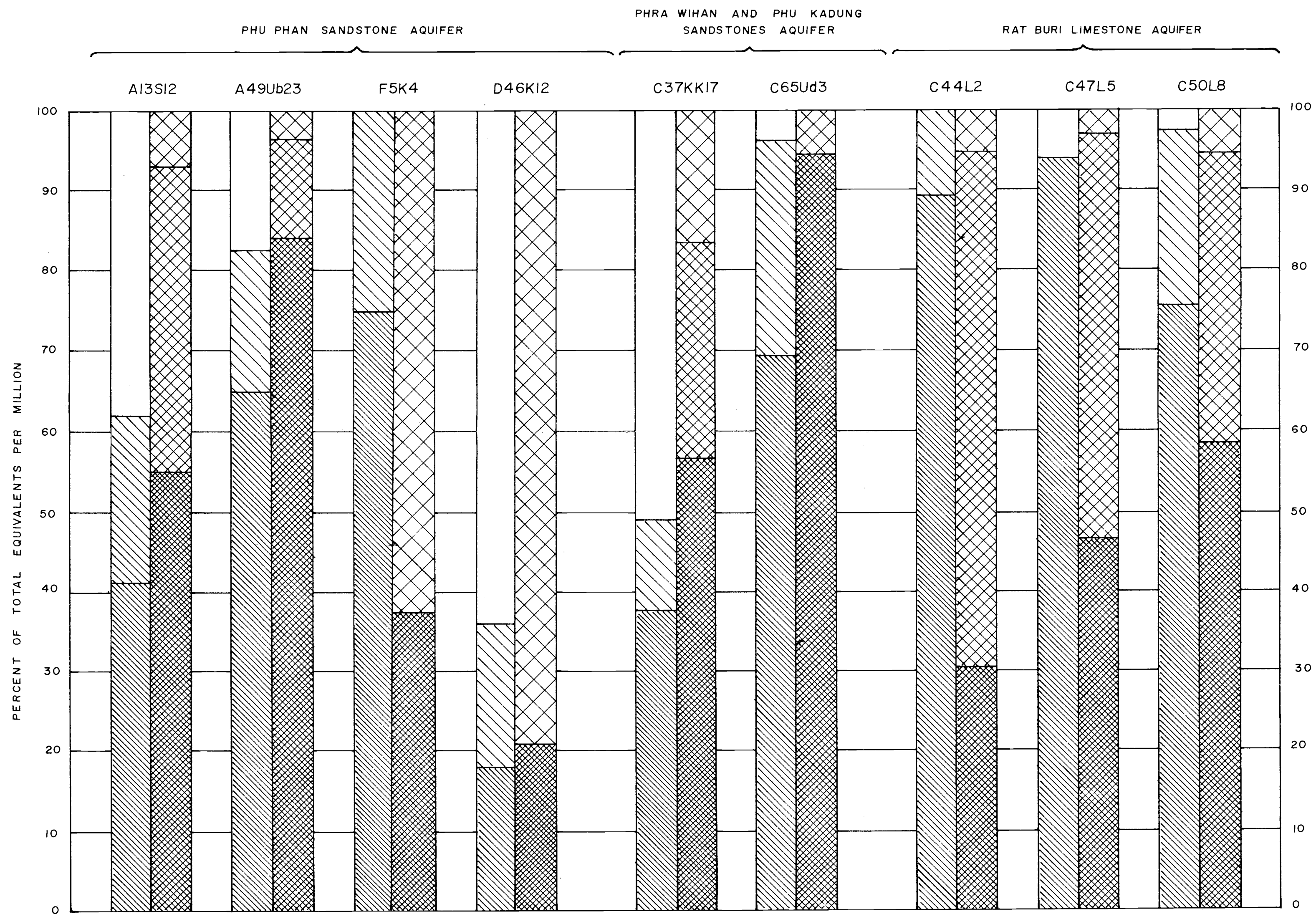


PLATE V-B

ANALYSES REPRESENTED BY BAR DIAGRAMS BASED ON  
PERCENT OF TOTAL EQUIVALENTS PER MILLION

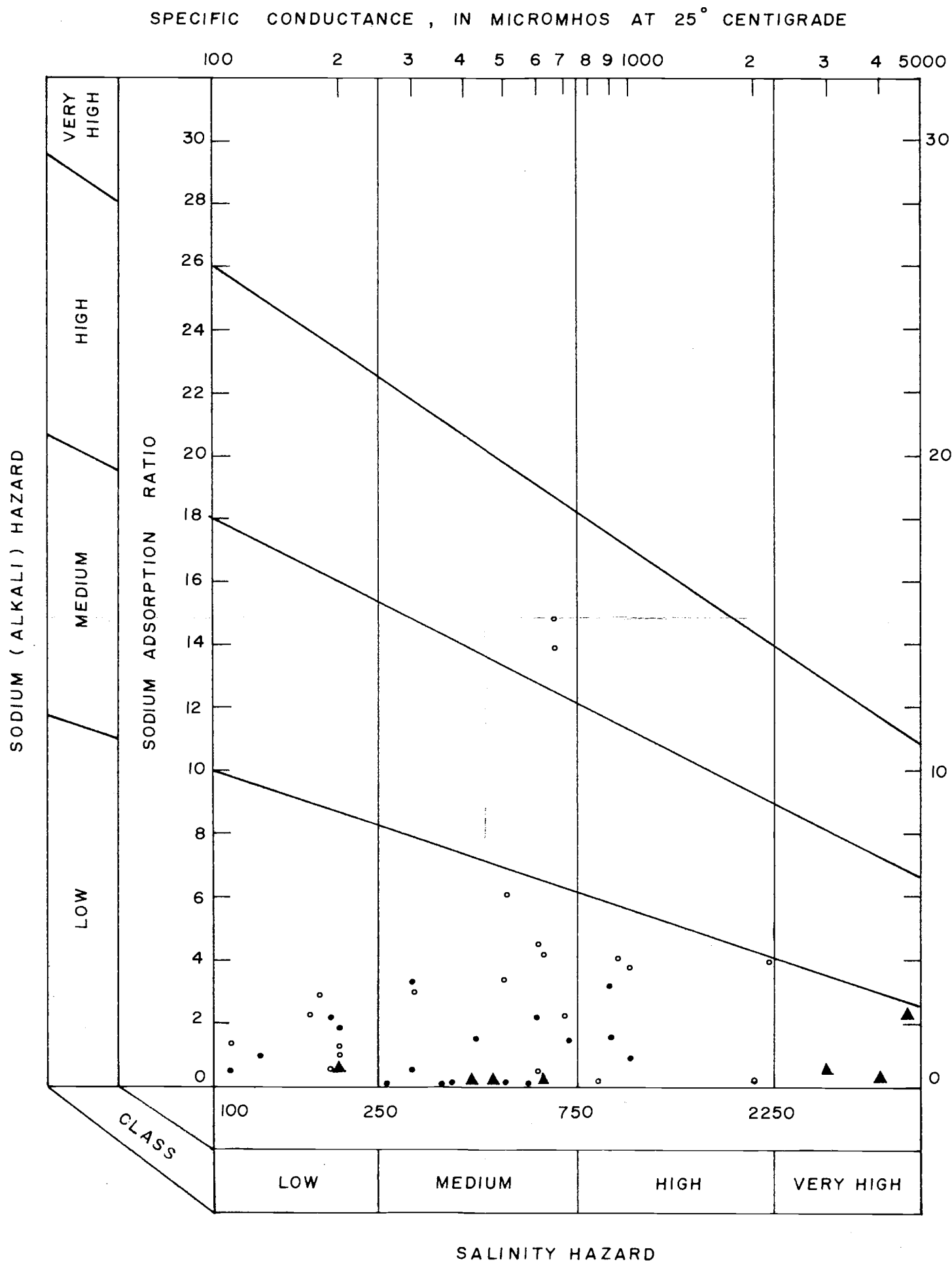
DATE:

JUNE 14, 1962

DRAWN BY:

CHAROEN

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1962  
131  
Plate V



Selected analysis from alluvial aquifer

Selected analysis from sandstone aquifers

Selected analysis from limestone aquifer

PLATE VI	
DIAGRAM SHOWING CLASSIFICATION OF IRRIGATED WATER	
DATE:	DRAWN BY:
JUNE 16, 1962	CHAROEN

E917  
1962  
131  
Plate V