

RESEARCH COUNCIL OF ALBERTA

REPORT 69-1

GROUNDWATER CHEMISTRY AND HYDROLOGY
OF THE
HANDHILLS LAKE AREA, ALBERTA

by

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Research Council of Alberta
Edmonton, Alberta
1969

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GROUNDWATER CHEMISTRY AND HYDROLOGY OF THE HANDHILLS LAKE AREA, ALBERTA

Abstract

This report describes the groundwater chemistry and hydrology in an area of 275 square miles between the crest of the Hand Hills and Bullpound Creek and attempts to correlate chemical properties of the groundwater with position in the flow system and chemical nature of the sedimentary rocks.

The bedrock formations found at or near the surface in the study area are the Bearpaw and Edmonton Formations of late Cretaceous age, and the Paskapoo and later beds of Tertiary age. The Bearpaw Formation, a relatively impermeable marine shale, completely underlies the area and is considered to form a very effective, although not necessarily complete, barrier to the downward movement of meteoric water. The Edmonton Formation, a series of alternating lenticular beds of argillaceous sandstone, shale, and coal which immediately overlies the Bearpaw Formation, is found throughout most of the area and forms the greater part of the framework through which groundwater moves from its recharge area in the Hand Hills toward the discharge area in the lowlands surrounding Bullpound Creek. The permeability of this formation is generally extremely low because of the high clay content but the coal beds are sufficiently permeable to supply local farm needs. Most farm wells in the study area pump water from these beds but yields are commonly less than 5 gallons per minute.

The Tertiary strata are restricted to the elevated regions of the Hand Hills. The Paskapoo Formation commonly resembles the Edmonton Formation but is locally developed as thick sandstone beds of better permeability. Locally overlying the Paskapoo Formation are beds of marl, gravel, sand, and conglomerate.

The surficial deposits are varied in nature but are primarily of glacial or glaciofluvial origin. The buried gravels of the preglacial Hanna channel and the lake and outwash sands to the south of Watts and Hanna have above-average permeabilities and hence have some hydrologic significance as well as some water-supply potential. An aquifer test for the channel gravels resulted in an estimated single-well safe yield of 60 imperial gallons per minute; the lake and outwash sands have reported yields which are much lower but these deposits have significance because meteoric water can infiltrate them readily.

Hydrologically, the study area can be subdivided into four parts: (1) a high-level recharge area in the elevated region of the Hand Hills, (2) an area of "active discharge" through springs and seepages forming a band along the steep northern and western flanks of the Hand Hills, (3) a

lowland area of "hidden discharge" through evapotranspiration, and (4) a lowland recharge area south of the town of Hanna where the presence of near-surface permeable deposits facilitates infiltration of precipitation.

Water-level measurements and calculated vertical components of the hydraulic gradient revealed (1) a strong horizontal component of flow in the Paskapoo sandstones, (2) a distortion in the regional flow system in the lowland area, possibly caused by the Hanna channel deflecting groundwater flow in its vicinity, and (3) near stagnant or essentially horizontal flow conditions in the lowland area north of the Hand Hills.

Chemically the groundwater ranges from hard bicarbonate water with less than 500 parts per million total dissolved solids in the Hand Hills to soft sulfate water with more than 3,000 parts per million total dissolved solids in the low area surrounding Bullpound Creek. Maps of the concentration of total anions and of selected ratios of various dissolved constituents illustrate the two basic types of areal variation in groundwater composition: (1) those due to simple aging of the groundwater as it moves through the subsurface and (2) those due to inhomogeneities in the flow medium. Maps illustrating the first type are characterized by lines of equal concentration which tend to be oriented transversely to the directions of groundwater flow; those illustrating the second type are characterized by lines of equal concentration which tend to be oriented along the directions of groundwater flow. To the first type belong the total solids, percentage sodium, and the percentage bicarbonate plus carbonate in those areas where sulfate reduction is not a factor. The calcium:magnesium ratio is the outstanding example of the second type from the present study but attempts to correlate the calcium:magnesium ratio map with measured calcium and magnesium contents for various formation samples met with only partial success. The percentage chloride and chloride:sulfate ratio show areal variations of both types. Except for the presence of the lowland recharge area, interpretation of the hydrologic and chemical data strongly favors the classical picture of recharge in the uplands and discharge in the lowlands.

INTRODUCTION

Purpose and Scope of Investigation

The purpose of this investigation was to map regional variations in near-surface groundwater chemistry in the study area, to determine the nature and extent of near-surface underground flow systems, and to assess the influence of flow path and position along the flow path on various characteristic chemical parameters. For the purposes of the study, "near-surface groundwater" was defined as groundwater of probable meteoric origin found within a few hundred feet of the surface.

The area chosen for this purpose was selected to satisfy a number of conditions. The most important are listed below.

- (1) The geology should be simple and the rock units comprising the groundwater flow medium of relatively uniform composition, at least on the large scale, to minimize the possibility of local variations in composition of the groundwater environment giving rise to local changes in groundwater composition large enough to obscure regional trends.
- (2) Total topographic relief should be pronounced, so that hydrologic head differences and hence groundwater flow rates would be relatively large. Under these conditions, chemical changes should be strongly influenced by position in the flow system, even in the case of relatively homogeneous sediments.
- (3) The topographic surface should deviate sufficiently from a uniform slope to provide for the existence and observation of intermediate or local flow systems.

As will be seen, the second and third conditions were probably fulfilled satisfactorily whereas the first was only partially satisfied.

Water samples were obtained from practically all farm wells in the area and from as many springs and seepages as could be located, and additional information on wells was gathered wherever possible. However, drillers' logs and water-level measurements could seldom be obtained; in most instances well depth at the time of installation was the only information available.

Aerial photographs were found to be very helpful in locating springs and seepage areas, which are commonly made quite noticeable by white salt precipitates or abundant vegetation.

Test holes 64-1 to 64-12 were drilled with a rotary machine during the fall of 1964. The primary aim of these test holes was to determine calcium:magnesium ratios for carbonates in the deposits in an effort to throw some light on "anomalous" features of the calcium:magnesium ratio groundwater map. Hole 64-7 had to be abandoned without reaching the projected depth because coarse gravel was encountered near the surface.

Test holes 65-1 to 65-4 were drilled with a cable-tool machine during the fall of 1965; holes 65-1 and 65-2 were drilled primarily to obtain information on variation of chemical quality and fluid potential with depth; holes 65-3 and 65-4 were drilled for and paid for by the village of Craigmyle and Mr. N. Nelson, respectively. Test holes 65-1, 65-1A, and 65-2 were completed as piezometers to permit permanent recording of water levels.

Location and Extent of Area

The area studied is bounded by parallels of latitude $51^{\circ}20'$ and $51^{\circ}40'$ north and meridians of longitude $111^{\circ}50'$ and $112^{\circ}21'$ west (Fig. 1). On the basis of the Dominion Land System of Survey, it lies within townships 28 to 31, ranges 14 to 17, west of the 4th meridian. The total area is about 275 square miles.

Topography and Drainage

The study area (Fig. 2) is part of the plains region of Alberta and, apart from a small area of internal drainage centered on Handhills Lake, is drained entirely by Bullpound Creek. Handhills Lake occupies the lowest part of a depression separating the eastern and western lobes of the Hand Hills, which form the major physiographic feature of the area. The divide between the drainage basins of the Bullpound Creek and the Red Deer River lies along the crest of the western lobe and is taken as the western boundary of the area. Elevations along the divide reach values in excess of 3,400 feet above sea level. The lowest elevations in the study area – less than 2,600 feet – are found in the southeast.

Acknowledgments

The author would like to express his appreciation to the drilling contractors – R. McDonald and G. L. Doering – who participated in the test-drilling programs in the study area, and to L. King-Hunter, Public Health Inspector of the Big Country Health Unit, who introduced him to the study area.

Costs of the test-drilling programs were shared equally between the Federal and Provincial Governments under the terms of the Federal Agricultural and Rural Development Act (ARDA) through ARDA projects 9023 and 28011. This assistance is gratefully acknowledged.

GEOLOGY

The bedrock strata of interest in a study of shallow groundwater in the area consists of the late Cretaceous and Paleocene Bearpaw, Edmonton and Paskapoo Formations, and later Tertiary unconsolidated strata. They are covered by glacial drift in most of the area, but outcrops are found along the steep flanks of the Hand Hills and in the southern part of the Bullpound Creek valley, west of Coleman Lake (Fig. 3).

The bedrock of the area was described in some detail by Allan and Sanderson (1945). Subsequently, several regional stratigraphic studies (Owen, 1960; Elliott, 1960; Campbell, 1962) have considered the Edmonton-

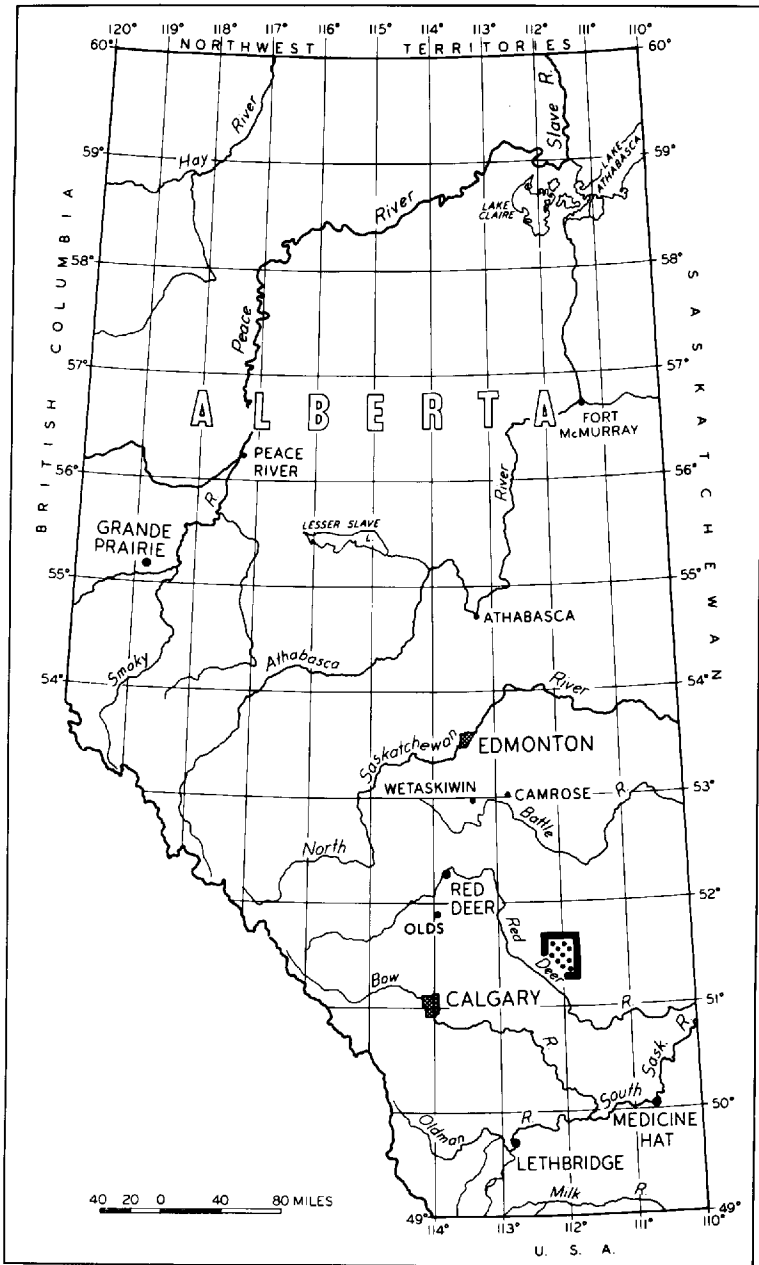


Figure 1. Location of Handhills Lake area.

Paskapoo succession in the Hand Hills area. Most recently Irish (1967a, b) has published more accurate geological maps of the area, which serve as the principal basis for the bedrock geology map illustrated in figure 4. During the course of test-drilling, some supplementary information on local stratigraphy was obtained, most of which is specifically mentioned in the text.

Bearpaw Formation

The Bearpaw Formation is the lowermost bedrock formation to outcrop in the study area; it subcrops in the valley of the Bullpound Creek in townships 28 and 29 and is exposed in this valley south of Coleman Lake. It is typically a monotonous sequence of brownish and grey marine shales with a few sandstone lenses and ironstone nodules.

Edmonton Formation

The Bearpaw Formation is overlain by the Edmonton Formation, which forms the bedrock surface over most of the study area. Several attempts have been made to subdivide this unit into members (Allan and Sanderson, 1945; Owen, 1960; Elliott, 1960), but none has been fully satisfactory. Irish (1967b) divides the Edmonton Formation into upper and lower parts, using the "Kneehills Tuff Zone" — a distinctive 35-foot unit of dark shale and white-weathering sandstone — as the divisor. This subdivision is satisfactory for the purposes of this report.

The lower part of the Edmonton Formation, roughly 700 feet thick, consists of grey and brown shale with local grey sandstones and discontinuous coal seams. Hard bands of siderite are common, and thin beds of calcareous shale grading into marl or limestone are also present. Montmorillonite is common throughout the formation, in places occurring as more or less pure beds of bentonite.

The "Kneehills Zone" consists of a lower grey, white-weathering bentonitic sandstone, up to 20 feet thick, overlain by 15 to 30 feet of mauve, highly montmorillonitic shale — essentially a bentonite bed. The combination of these strata is distinctive, and the beds form a widespread essentially isochronous marker.

The upper Edmonton consists of 200 to 300 feet of green and grey shales, siltstones and fine- to medium-grained sandstones with local coal seams.

Paskapoo Formation

The Paskapoo Formation forms the bedrock on the higher parts of the Hand Hills — mainly above elevations of 3,200 feet. It is described by Irish (1967b) as consisting of "buff to brown - grey weathering, medium to

coarse-grained, 'pepper-and-salt' sandstones interbedded with beds of grey and greenish-grey siltstone and clay shale. There are some calcareous beds containing fresh water or terrestrial gastropods in the succession. The sandstones are well sorted and contain little clay."

During the present investigation the typical buff-colored sandstone was encountered in test holes 64-5 and 65-1 only. Sandstone was absent from holes 64-6 and 64-8, where younger Tertiary beds were found to lie directly over beds of Edmonton-type shale. In both test holes where it was uncovered, the sandstone had a thickness of 98 feet. The grain size ranged from fine to medium and varying amounts of argillaceous and silty matrix and calcareous cement were present. The lowermost 28 feet were fairly porous.

Tertiary Strata

Allan and Sanderson (1945) described a sequence of Tertiary strata, lying unconformably on the Paskapoo Formation, on the west side of the Hand Hills. They reported yellowish and light grey marl beds of uncertain thickness overlain by 27 feet of gravel, sand, and conglomerate and underlain by 40 feet of black freshwater shale. During the present investigation, marl, gravel, sand, and black shale were recorded in the test holes of cross section AA' (Figs. 2, 5) but the layering sequence not only varied from hole to hole but also differed from Allan and Sanderson's description. Where observed, the gravel and sand deposits were at the top of the sequence, as observed by Allan and Sanderson, but black shale was found within the marl deposits in hole 64-8 and overlying them in hole 64-6. No shale was observed in test hole 65-1.

Gravel deposits are generally more widespread throughout the area at all elevations than is indicated by Irish (1967b) (Fig. 3) or by Craig (1957) (Fig. 3). Some of the gravel deposits, — particularly those in townships 29 and 30, range 15 — are doubtless of the same age as those described by Allan and Sanderson farther west. In the study area they are found on the hill crests although at an elevation (3,200 feet) some 200 feet below that of the gravels farther west, thus indicating an eastward slope of the depositional surface of approximately 20 feet per mile. Other gravel deposits in the area are found at much lower elevations and must be of younger, age, representing a later depositional phase or lag deposits of preglacial erosion of the Hand Hills area.

Buried Channel Deposits

An important buried bedrock channel, previously reported by Farvolden (1963) and by Kunkle (1962), runs through the area. Figure 6 indicates an average thickness for till and other surficial deposits of about 50 feet over most of the area, compared to a thickness of 170 feet in the deepest part of the channel. According to Kunkle (1962), gravel deposits

are found in pockets at the base of the channel. Figure 7 is a detailed map of the bedrock topography near the town of Hanna. It shows a bedrock-surface relief of about 250 feet in the vicinity of the channel.

Glacial Deposits

The glacial deposits for most of the study area were mapped by Craig (1957). His mapping covers that portion lying to the west of 112° west longitude. Some modifications were made to Craig's map as a result of the present study during which the area to the east of 112° was also mapped (Fig. 3).

The glacial deposits of interest for this report are the lake and outwash sands covering the areas south of Watts and Hanna. These deposits are extensive and thick enough to be of some interest as water-table aquifers. The remainder of the area is covered mainly by ground moraine and hummocky moraine.

HYDROLOGY

Water-Supply Potential of Bedrock and Surficial Deposits

In general, the bedrock strata in the area consist of alternating beds of shale and argillaceous or bentonitic sandstone, with thin coal seams throughout the section. Hard bands of ironstone and limestone are found in some places.

Both the shale and the sandstone have low permeabilities and are in general unsuitable for the development of satisfactory farm wells. Where water is obtained from the bedrock, it is generally being drawn from highly fractured coal seams. The hard ironstone bands and limestone stringers are in places sufficiently fractured to yield enough water for farm use. In general, it can be said that no well completed in bedrock is capable of yielding over 5 imperial gallons per minute (igpm).

No pump tests have been carried out on wells completed in the shallow sand and gravel deposits in the area. Their saturated thickness, however, is only a few feet and is subject to seasonal fluctuations so that only limited quantities of water can be withdrawn from wells completed in these deposits. Typical yields are possibly 1 igpm or less.

The buried gravels in the Hanna bedrock channel were pump tested by Kunkle (1962). Although the calculated transmissibility was 5,700 imperial gallons per day per foot (igpd/ft) and the hydraulic conductivity 285 imperial gallons per day per square foot (igpd/ft²), the limited extent of the gravel deposit led to an estimated safe yield of only

60 igpm.

Water-Level Measurements

Water levels were measured in a few farm wells but in most it was not possible to obtain a measurement without removing the pump from the well. The few measurements obtained were inconclusive.

Water levels were also measured for different water-bearing zones during the drilling of test holes 65-1, 65-2, and 65-3. These are listed in table 1. For each measurement, total drilled depth and length of the cased interval are also given, so that the open interval to which the measurement applies is readily derived. The water levels in the table probably represent true hydraulic heads, with some accuracy in the case of long recovery periods; similarly, where recorded water-level differences between two zones are appreciable, these must represent real head differences.

Table 1. Change of Fluid Potentials with Depth

RCA test hole No.	Drilled depth (ft)	Depth to water (ft)	Depth of casing from surface (ft)	Recovery period (hrs)
65-1	125	118.44	50	1
	127	116.00	50	85
	133	117.05	117	167
	136	117.44	136	135
	190	146.48	173	14
	222	197.50	208	13
	295	157.40	208	65
	308	232.88	208	13
	308	263.65	301	168
65-2	26	23.90	0	1/2
	52	43.68	30	13
	72.5	flowing	63	2
65-3	50	27.22	0	13
	100	27.75	0	13
	157	28.42	0	13
	196	28.50	0	13

The water-level data of table 1 may be used to estimate vertical components of the hydraulic gradient and to draw some inferences concerning groundwater flow and its relation to geology at the three test hole sites. It should be noted, first of all, that a number of depth intervals listed in the table overlap. It is convenient to replace measured water levels for the

overlapping intervals by a new set of water levels – some measured, some computed – which apply to a set of discrete depth intervals. Consider the depth interval from z_0 to z_2 containing the intermediate depth point z_1 and let h_1 , h_2 , and h be the average hydraulic heads over the intervals z_0 to z_1 , z_1 to z_2 , and z_0 to z_2 , respectively. Then, if it can be assumed that head variation with depth in each of the two subintervals is linear, the relation among h_1 , h_2 , and h is given by

$$h = \frac{(z_1 - z_0)}{(z_2 - z_0)} h_1 + \frac{(z_2 - z_1)}{(z_2 - z_0)} h_2 \quad (1)$$

Head variation with depth, of course, is almost certainly not linear but, for the discussion which follows, the errors introduced by assuming it to be so must be of little consequence, since the argument eventually involves consideration of hydraulic gradients which differ by amounts approaching two orders of magnitude. Introduction of a more precise substitute for (1) or of other refinements to the calculations is most unlikely to alter such a difference substantially.

Equation (1) may be rewritten in a more suitable form by employing substitutions of the type $h = e - d$, where e is elevation of the well head above the same standard datum used for the measurement of h , and d is depth to water:

$$d = \frac{(z_1 - z_0)}{(z_2 - z_0)} d_1 + \frac{(z_2 - z_1)}{(z_2 - z_0)} d_2 \quad (2)$$

As an example of the application of equation (2), consider the calculation of depth to water for the depth interval from 295 to 308 feet in test hole 65-1. The data in table 1 give $z_0 = 208$ feet, $z_1 = 295$ feet, $z_2 = 308$ feet, $d_1 = 157.40$ feet, and $d = 232.88$ feet; substitution into (2) gives $d_2 = 738$ feet. This result must be erroneous since it gives such an abnormally low water level and it suggests that some of the original data were in error. Examination of table 1 indicates that value of 157.40 feet may be questionable because it introduces a significant reversal into the otherwise persistent trend of declining water level with depth for test hole 65-1. Thus, this measurement is suspect on two counts and it was not used in any of the subsequent calculations. All other water levels computed from data for overlapping depth intervals appeared to be consistent with measured water levels.

Measured and computed water levels for discrete depth intervals in the three test holes are given in table 2, which also summarizes the calculations of vertical components of the hydraulic gradient. Each gradient is determined as the ratio of the water-level difference between successive depth intervals to the vertical distance between the midpoints of the intervals.

Table 2. Estimated Vertical Components of the Hydraulic Gradient

RCA test hole No.	Depth interval No. (n)	Interval range (ft)	Depth to water (ft)	Interval midpoint (ft)	Comparison of nth and (n+1)th depth intervals		
					Water-level difference (ft)	Midpoint difference (ft)	Estimated gradient component (ft/ft)
65-1	1a	50-125	118.44	87.5	- 1.39	37.5	-0.04
	1b	50-127	116.00	88.5	1.05	36.5	0.03
	2	117-133	117.05	125.0	0.39	11.0	0.04
	3	136	117.44	136.0	29.04	45.5	0.64
	4	173-190	146.48	181.5	51.02	33.5	1.52
	5	208-222	197.50	215.0	41.14	50.0	0.82
	6	222-308	238.64*	265.0	25.01	39.5	0.63
	7	301-308	263.65	304.5			
65-2	1	0-26	23.90	13.0	19.78	26.0	0.76
	2	26-52	43.68	39.0	-43.68	23.2	-1.88
	3	52-72.5	flowing	62.2			
65-3	1	0-50	27.22	25.0	1.06	50.0	0.02
	2	50-100	28.28*	75.0	1.37	53.5	0.03
	3	100-157	29.65*	128.5	- 0.80	48.0	-0.02
	4	157-196	28.85*	176.5			

* Computed using equation (2).

The calculated hydraulic gradients for test hole 65-1 can be placed in two categories: (1) those for the depth interval from 50 to 136 feet which range several hundredths of a foot per foot above and below zero and (2) those for the depth interval from 136 to 308 feet which vary from 0.63 to 1.52 ft/ft. The observed variation for those in the first category is probably indicative, for the most part, of errors associated with the gradient determination. This follows from a comparison of the first two calculated gradients in table 2: consideration of the depth intervals involved suggests these two gradients must be the same or very nearly the same but the calculated values differ by 0.07 ft/ft. With this result in mind, it is probably reasonable to assume that the calculated gradients of table 2 are only accurate to the first decimal place at best.

The two categories of calculated hydraulic gradients in test hole 65-1 have an interesting correlation with lithology: the near-zero gradients found between 50 and 136 feet are associated with a lithologic sequence which contains about 87 per cent of relatively permeable materials, such as sandstone and coal, whereas the larger gradients between 136 and 308 feet are associated with a sequence which contains only about 24 per cent of these materials (Appendix A). On cross section AA' (Fig. 5) the near-surface, more permeable group of materials are considered part of the Paskapoo Formation and the deeper, less permeable materials part of the Edmonton Formation.

If natural groundwater flow at the site of test hole 65-1 is wholly in the vertical direction, the observed vertical gradients must obviously reflect only the permeability (or hydraulic conductivity) changes between the two formations. That is, since the product of gradient and hydraulic conductivity must remain constant under these conditions, the conductivity in the Edmonton Formation must decline in value from that in the Paskapoo in the same proportion as the gradient increases. Average calculated gradients for the 50- to 136-foot and 136- to 308-foot intervals are 0.01 and 0.90 ft/ft respectively, which suggests that vertical hydraulic conductivity in the Paskapoo strata is some two orders of magnitude greater than that in the Edmonton strata, provided natural flow can be assumed to be vertical. It is likely, however, that there is some horizontal component to the flow, even at the site of test hole 65-1. Consideration of the effects of horizontal components in both formations, and of the variability and possible errors in the gradient determinations, suggest that the difference between hydraulic conductivities in the two formations might be less than that calculated on the basis of the average gradients. Nevertheless, even a cautious estimate of this difference indicates that it should be at least an order of magnitude.

Where the hydraulic conductivity in the Paskapoo strata is consistently an order of magnitude or more greater than that in the underlying Edmonton Formation, observation of hydrologic field phenomena may provide a useful means of mapping the Edmonton-Paskapoo contact. With such a

difference in conductivities there should be a pronounced tendency for recharging water to flow preferentially approximately parallel to the land surface through the Paskapoo to eventual discharge at springs and seepage areas wherever the Edmonton-Paskapoo contact outcrops or subcrops along the flank of the Hand Hills. As drift cover thickens, of course, or where unconsolidated Tertiary deposits lie above, spring and seepage areas will tend to become more diffuse and may disappear. Nevertheless, consideration of the available evidence concerning spring and seepage locations may prove to be geologically rewarding, not only in the Hand Hills area but elsewhere in Alberta where the position of rock unit contacts is still open to question and where adequate hydraulic conductivity contrast exists between the two adjacent units.

Calculated vertical components of the hydraulic gradient in test hole 65-2 (Table 2) are of the same order of magnitude as those observed for the Edmonton Formation in test hole 65-1. This hole, however, demonstrates a reversal in flow direction: flow is downward between the upper two depth intervals and upward between the lower two. This reversal is believed to be real and not related in any way to possible errors originating in the measurement techniques. It could be caused by the presence of a permeable body "downstream" of the test hole (Tóth, 1962), possibly at about the same level as the second depth interval (26-52 feet). Such permeable bodies are undoubtedly present in the nearby Hanna channel. Moreover, the channel deposits as a whole are probably more permeable than the bedrock or till. Thus, the gradient reversal in hole 65-2 may result from (a) local distortions in the groundwater flow system produced by a nearby localized permeable zone or (b) a major distortion caused by the channel acting as a drain and deflecting groundwater flow in its vicinity into a direction generally parallel to the channel. Meyboom, Van Everdingen, and Freeze (1966) describe similar effects on groundwater flow systems in the vicinity of and due to drainage by Saskatchewan rivers.

Calculated vertical components of the gradient in test hole 65-3 (Table 2) are small and not significantly different from zero. In this area groundwater probably moves either very slowly or essentially horizontally or both.

Recharge and Discharge Areas

During the present survey over sixty springs were mapped in the area. Spring locations are shown on all of the hydrochemical maps (Figs. 11-16). The spring with the largest flow was encountered in the northwest quarter of section 34, township 28, range 15, west of the 4th meridian where a flow of 10 igpm was measured. Other springs have flows ranging down to a mere trickle, and in many cases water slowly discharges over an extended area of boggy soils instead of from a definite localized source. "Soap holes" (Tóth, 1966b) were commonly found at the bottom of coulees wherever soil conditions were favorable and an upward component of

groundwater flow presumably existed.

Recharge Areas

Two of the areas designated as recharge areas (Fig. 8) occupy all of the higher parts of both lobes of the Hand Hills. No evidence of groundwater discharge was found in these areas and, as evidenced by test hole 65-1, water levels are quite low. The same data suggest that groundwater movement within the relatively permeable Paskapoo deposits has a major component parallel to the stratification, whereas the major component of flow in the underlying Edmonton deposits is in the vertical direction. Despite these changes in flow characteristics between the two formations, movement within these two recharge areas is generally away from the surface and does not impede infiltration of rainwater or snowmelt, some of which will reach the water table and become part of the groundwater regime; from then on its movement is dependent on the distribution of fluid potential and permeability within the regime.

A third recharge area lies to the south of the town of Hanna. It was identified primarily from the chemical data and is discussed in the section on chemistry.

Area of Active Discharge

Figure 8 shows the general distribution of springs and seepages in the Hand Hills area. They are found in three bands averaging some 2 to 3 miles in width: the longest fringes the east side of the eastern lobe of the Hand Hills, a similar but shorter band fringes the western lobe, and the two join a third and slightly wider band running along the north side of the Hand Hills. Together they define the "area of active discharge."

The bands fringing the western lobe and the north side of the Hand Hills are of particular interest because of their probable relation to the Edmonton-Paskapoo contact, a point which was raised in the section on water-level measurements. Comparison of the bedrock geology map with figure 8 indicates a reasonable correlation in the western lobe of the Hand Hills. However, it should be kept in mind that the favorable hydraulic conductivity contrast between the two formations inferred for the site of test hole 65-1 is not characteristic of conditions at the position of this contact everywhere else in the area. Some of the information available tends to support this belief, such as the fact that the bedrock outcrops from which springs and seepages emerge are of Edmonton-type lithology rather than Paskapoo.

In the main, therefore, it is believed that the existence of springs and seepages in the narrow bands of the "area of active discharge" is due to either or both of two reasons: (1) the deep erosional surface incisions into the bedrock and (2) the presence of a presumed strong component

of upward flow in this area. Although a great number of springs issue from horizontal permeable layers exposed in steep coulee walls and can be considered as interceptions of horizontally flowing groundwater, there are numerous springs and other discharge points located on gentle regional slopes, at the bottom of coulees, or at the very heads of coulees; in other words, at points where an upward component of flow is necessary to bring the water to the surface.

Another interesting feature about the location of these springs in and around the coulees is that they are practically always found either in the bottom of the coulee or on the side which is towards the regional high (the Hand Hills in this case). Figure 9 shows several typical cases.

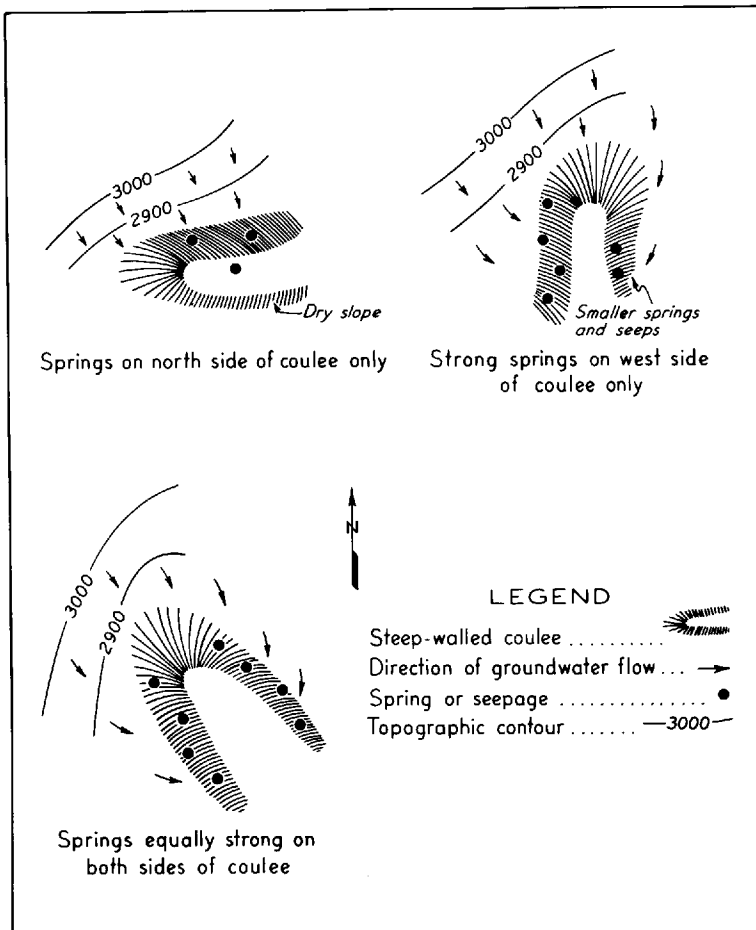


Figure 9. Influence of coulee orientation and regional flow pattern on spring and seepage locations.

Area of Hidden Discharge

This area, which includes the lower parts of the study area (Fig. 8) was so designated because, although generally no springs or seepages are found within it, discharge is nevertheless occurring, as is clearly shown by the salty deposits commonly encountered on the soil and the presence of halophytes – notably salt grass. Wells in this area have a tendency to flow, although this may not always be an indication of natural groundwater discharge, as is evident from the water-level measurements in test hole 65-2 (Tables 1, 2). Such flow-reversed conditions, however, are probably local or confined to a narrow strip alongside of and overlying the permeable deposits of the Hanna channel.

GROUNDWATER CHEMISTRY

Introduction

During the course of the investigation 194 groundwater samples were analyzed. The complete analyses of these samples are compiled in appendix B. Locations of the sampling points are shown on figures 11 to 16. Samples were analyzed for the following constituents: sodium (Na^+), potassium (K^+), calcium (Ca^{++}), magnesium (Mg^{++}), sulfate (SO_4^{--}), chloride (Cl^-), carbonate (CO_3^{--}), bicarbonate (HCO_3^-), nitrate (NO_3^-), and iron (Fe^{++}). For a number of samples the sum of sodium and potassium, the sum of calcium and magnesium, and the sum of carbonate and bicarbonate replaced the individual determinations of these constituents. Total dissolved solids were determined as dry residue as well as calculated from the sum of all constituents. Values of pH were measured in the laboratory; specific conductance was measured in the field.

Analytical Procedures

The analytical procedures were taken exclusively from "Standard Methods for the Examination of Water, Sewage and Industrial Wastes," prepared by the American Public Health Association and others (1955). In those cases where more than one procedure is listed the following were adopted:

Na^+, K^+	: flame photometric method
$\text{Ca}^{++}, \text{Mg}^{++}$: compleximetric method
SO_4^{--}	: turbidimetric method
Cl^-	: Mohr method
NO_3^-	: phenoldisulfonic acid method
Fe^{++}	: phenanthroline method.

A number of analyses reported by the Provincial Analyst were obtained through the Alberta Department of Public Health. The analytical

procedures used by the Provincial Analyst are described by Le Breton and Vanden Berg (1965).

Range of Concentration of Major Constituents

A common characteristic of the groundwater of the area at shallow depth (less than 400 feet) is the near absence of chloride and potassium; all other constituents are present in a wide range of concentrations (Fig. 10).

The concentration range is widest for sodium; 90 per cent of the samples have concentrations less than 32 equivalents per million (epm) sodium. Except for peaks from 0 to 5 and from 10 to 15 epm, the histogram shows a relatively even distribution of samples between 0 and 30 epm.

Both calcium and magnesium have much narrower concentration distributions. In more than 90 per cent of all samples the concentration of either is less than 6.0 epm. The modal group – that is, the group containing the greatest number of observations – covers the range 2 to 3 epm for calcium and 1 to 2 epm for magnesium.

Ninety-three per cent of all samples have potassium concentrations of less than 0.3 epm and 83 per cent have less than 0.2 epm. Because of their uniformity, the potassium data are not shown on figure 10.

Of the anions, chloride has the least variation in concentration, with 90 per cent of the samples having concentrations of less than 0.7 epm and 50 per cent having less than 0.3 epm. The modal group comprises the range 0.1 to 0.2 epm.

The greatest number of sulfate concentrations fall in the range 0 to 5 epm. More than 90 per cent of the samples have sulfate concentrations of less than 20 epm.

Bicarbonate plus carbonate concentrations have the distribution most resembling the normal distribution. The modal group covers the range 10 to 15 epm and more than 90 per cent of the samples contain less than 22 epm.

The distribution of total dissolved solids concentration has no obvious modal value; more than 90 per cent of the samples have total dissolved solids concentrations of between 10 and 80 epm.

Processes Causing Changes in Groundwater Composition

Solution

Even in a relatively small area, concentration and composition of groundwater may vary greatly if water movement is slow enough so that

the period of time during which the water has been underground varies sufficiently for different locations. Fresh groundwater is generally an indication of a short period of residence underground, and a high dissolved-solids concentration of a long period. Within the boundaries of a single essentially homogeneous groundwater flow system, changes in dissolved solids concentration are generally gradual; the farther the water moves away from the area where it infiltrated into the soil as rain water or snowmelt (the recharge area), the greater the amounts of soluble constituents it will acquire by continuous reaction with its environment. Where it finally leaves the underground regime, either through springs and seepages or through slow evapotranspiration, it will have acquired its maximum concentration of dissolved substances. On a regional map of total dissolved solids, the lines of equal concentration will therefore tend to be aligned transversely to the flow directions.

A number of processes — apart from the simple dissolution in water of soluble rock materials — tend, first of all, to increase total dissolved solids concentration and, secondly, to change the relative amounts of the dissolved constituents. A particularly important process is the combination of carbon dioxide (CO_2) from the atmosphere or from the respiration of soil organisms with water to form carbonic acid (H_2CO_3) which subsequently dissociates, freeing hydrogen (H^+) ions to react with the calcium and magnesium carbonates of the earth materials and produce calcium (Ca^{++}), magnesium (Mg^{++}), and bicarbonate (HCO_3^-) ions (Hem, 1959). In the case of calcium carbonate, this series of reactions can be simplified as follows:



The solubility of calcium or magnesium carbonate in pure water is relatively low, so that this process turns out to be the primary mechanism for getting calcium and magnesium into solution.

From the equation above it is apparent that the addition of a molecule of carbon dioxide to the water can lead to the eventual formation of a single calcium or magnesium ion and two bicarbonate ions. The partial pressure of carbon dioxide in air is 3×10^{-4} atmospheres and its solubility coefficient at 10°C is 1.194 liters per liter (Schoeller, 1962). Thus, during the summer season when recharge is not prevented by frozen-ground conditions, the concentration of carbon dioxide in rain water averages about 0.016 millimoles per liter. If rain water is the only source of carbon dioxide and all the carbon dioxide in the rain water is used up to form bicarbonates of calcium and magnesium, the bicarbonate content of the groundwater will average only about 0.032 epm. Respiration of organisms living in the soil increases carbon dioxide concentrations enormously so that partial carbon dioxide pressures can range from 0.001 to 0.1 atmospheres (Schoeller, 1962). Resulting bicarbonate concentrations may then exceed 10 epm.

In comparison to other processes by which groundwater acquires soluble solids, the solution of calcium and magnesium carbonate is a very rapid process, and therefore in groundwater near the recharge area the predominant constituents are calcium, magnesium, and bicarbonate. Their total concentration depends primarily on the partial pressure of carbon dioxide in the soil of the recharge area, and therefore on the activity of soil life, as well as on the availability of calcium and magnesium carbonates in the soil and underlying rock.

As soon as the available carbon dioxide has been depleted, further increase in the bicarbonate content will be extremely slow; on the other hand, processes like the dissolution of gypsum (CaSO_4) – which is present in small amounts in the rock – and the oxidation of pyrite (FeS) continue to add sulfate ions (SO_4^{--}) to the water. Chloride (Cl^-) may be added by slow attack on a number of chloride-containing silicates (biotite, muscovite, hornblende). Therefore an increase in the ratio of sulfate and chloride to bicarbonate ions must take place as the groundwater travels farther away from its recharge area; consequently, a map of bicarbonate as a percentage of total anions must show a steady decrease from the recharge to the discharge end of a single flow system, and lines of equal percentage must be aligned transversely to the flow directions.

Evaporation and Transpiration

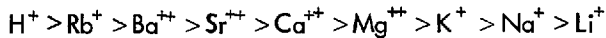
At the discharge end of a flow system the groundwater again comes into contact with the air. The water level at the discharge end is an equilibrium level which may be above or below the surface. Where the water level is above the surface, springs and seepages occur which may result in ponded surface water or runoff if the rate of groundwater discharge is greater than the rate of evapotranspiration. More commonly there will be a water table at some depth below the surface; for this level, the rate of groundwater flow to the surface is exactly balanced by the rate of loss of water to the atmosphere by evapotranspiration. Since both evaporation and transpiration by plants proceed most vigorously at the surface and decline in importance with depth, it is apparent that, under otherwise identical conditions, relatively deep water tables will tend to be associated with relatively slow-moving groundwaters, and relatively shallow water tables with relatively fast-moving groundwaters.

Evaporation from the water table will result in a more mineralized residual water. Eventually the groundwater may become saturated with respect to a certain salt and the salt may be precipitated. Such highly mineralized waters were indeed found at a number of locations during the present study. For example, a sample was taken from a dugout (Lsd. 4, Sec. 3, Tp. 28, R. 14, W. 4th Mer.), the day after construction had been completed; the analysis (Appendix B) shows that the water contains 1.63 grams of calcium sulfate per liter, which compares very closely to the solubility of gypsum in pure water at 0°C , which is 1.76 gram $\frac{1}{2}$ per liter.

That the water was actually saturated with regard to calcium sulfate was indicated by the numerous large gypsum crystals found in the excavated clay and shale.

Base Exchange

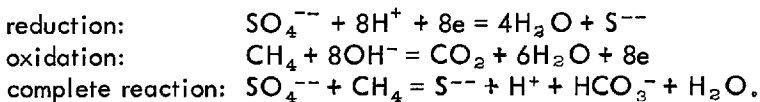
Once a compound has gone into solution in the groundwater it may enter into further reactions with the environment resulting in further modifications of water composition. Modification as a result of ionic exchange with clay minerals is a widely occurring process. Clay minerals, especially montmorillonite, in contact with a salt solution are able to exchange cations contained in the crystal lattice for other cations contained in the solution. The higher the valency of the ion in solution and the less it is hydrated, the more it is inclined to take up a position in the crystal lattice. Schoeller (1962) gives the following order in which cations tend to become fixed in clay minerals, stating, however, that the order is of a general nature and depends to some extent on the particular clay mineral:



For example, if water with a high calcium concentration comes in contact with sodium-rich montmorillonite, exchange will generally take place and the calcium in the water will be partially replaced by sodium from the montmorillonite. The degree of replacement will depend on an equilibrium position determined by the concentrations of the exchanging cations, both in the solution and in the mineral.

Sulfate Reduction

In the presence of organic material (such as natural gas, oil, coal, or carbonaceous shale) sulfate ions in groundwater can be reduced to sulfide ions by the action of certain anaerobic bacteria. For example:



Combination of the hydrogen and bicarbonate ions leads to the production of carbonic acid, which in turn can dissolve any calcium or magnesium carbonate present in the sediment.

Usually then, in areas where sulfate reduction is occurring, groundwater will be characterized by above-normal concentrations of bicarbonate and below-normal concentrations of sulfate (Meyboom, 1960). In areas where the bedrock is devoid of carbonates, sulfate reduction must result in a more acidic water.

Processes Involving Deep Groundwater

Although this report is limited to a discussion of relatively shallow groundwater, a full understanding of its chemistry involves consideration of those chemical and physical processes that play a role in the zone between the regional flow system and the higher-order system underlying it. Although depth of penetration of the water in the regional flow system originating in the Hand Hills cannot be ascertained, it may be large. If so, it is possible, for example, that the process of membrane selective filtration, which is of great importance in the chemistry of deep formation waters (Bredehoeft, Blyth, White and Maxey, 1963; Back and Hanshaw, 1965; Billings, Hitchon and Shaw, in preparation), affects the composition of the regional groundwater in its deeper reaches. Briefly, this process is an ultrafiltration through shales in which water molecules pass freely through the shale, while electrically charged ions are inhibited by electric forces in the pore spaces. The process requires a high degree of compaction and therefore only takes place at greater depths. If a flow line of the regional system passes through such a shale membrane, the total solids content of water moving along it decreases in the direction of flow.

On the other hand, water in the higher-order system, owing to its longer residence time underground, will generally have an appreciably higher total solids content than water of the regional system. Although the dividing line between the two systems forms an effective impermeable boundary to groundwater flow (Tóth, 1963) there is not necessarily a barrier preventing the diffusive flow of ions and molecules. Theoretically, therefore, there must be diffusive motion of ions from the higher-order into the regional system resulting in an enrichment in total solids in the latter. In their paper on the mechanism for concentration of brines in the Illinois basin, Bredehoeft *et al.* (1963) show that the effect of diffusive motion is extremely small in comparison to the effects of the filtration process described above.

Back and Hanshaw (1965), however, point out that shale strata in the regional flow regime, because of their high porosity and low permeability, will be very slow in the release of the large quantities of formation water that they contain and will retain a high salt concentration long after the surrounding more permeable strata have been flushed out by recharge water.

Afterwards, slow release of ions by diffusion into the more permeable beds will continue until concentrations are equalized. Large differences in composition of waters from adjacent sampling points are an indication that this process may still be continuing at the present time.

Variation in Chemical Composition with Depth

Water samples were taken during the test-drilling program of 1965; complete analyses of these samples are contained in appendix B; a

Table 3. Vertical Variation in Groundwater Composition

RCA test hole No.	Drilled depth (ft)	Sum of anions (epm)	% $\text{HCO}_3^- +$ CO_3	% Cl	Cl/SO_4	% Na	Ca/Mg
65-1	125	6.89	96	3.0	3.800	31	0.5
	135	7.17	88	3.8	0.560	27	0.6
	165	10.64	85	0.7	0.048	87	1.6
	172	11.59	85	0.7	0.041	94	1.4
	200	11.53	89	0.9	0.100	92	1.5
	220	13.25	91	2.1	0.300	96	1.8
	305	11.12	97	3.0	∞	98	4.2
	315	10.86	97	3.0	∞	-	6.5
65-2	25	21.51	58	9.6	0.300	84	2.2
	40	30.02	57	4.3	0.110	79	1.5
	70	33.35	58	1.5	0.040	71	1.0
65-3	50	48.18	15	5.6	0.078	44	1.2
	100	49.17	18	5.5	0.076	45	1.1
	120	50.72	17	5.3	0.072	46	1.0
65-4	40	36.59	32	13.7	0.246	68	1.4
	80	32.16	43	1.7	0.032	84	1.6
	100	31.25	44	1.4	0.026	84	1.6
	120	30.64	50	1.6	0.034	80	2.0

summary of some characteristic ratios is given in table 3.

In hole 65-1 three chemically distinct zones exist: (1) from 125 to 135 feet, (2) from 165 to 220 feet, and (3) from 305 to 315 feet. These zones correspond to the main geologic units, the Paskapoo beds and the upper and lower parts of the Edmonton Formation. The waters in the Paskapoo and the upper Edmonton differ markedly in all characteristics with the exception of the percentage bicarbonate plus carbonate; the differences between the waters in the upper and lower parts of the Edmonton are less pronounced, and are limited to the percentage chloride, the chloride:sulfate ratio and the calcium:magnesium ratio. The large difference in composition between the waters of the Paskapoo and Edmonton reflects the difference in hydraulic conductivity between these units, which causes the more permeable Paskapoo to be flushed by meteoric water at a faster rate than the relatively impermeable Edmonton and a difference in the chemical composition of these units.

In hole 65-2 there is a noticeable increase in the sum of anions with increasing depth, as well as decreases in percentage chloride, the chloride:sulfate ratio, the percentage sodium and the calcium:magnesium ratio. As discussed in the section on hydrology, a local recharge area is superimposed on the regional discharge area in the vicinity of this hole. The chemical analyses here illustrate the large differences in composition that may exist between adjacent groundwaters belonging to separate flow systems.

The waters from hole 65-3 are all very similar, as are those from hole 65-4, except for the shallowest sample. In general it can be concluded that, within the depth interval studied, major vertical chemical compositional differences exist only where major geologic boundaries or boundaries between flow systems are crossed.

Groundwater Chemistry Maps

Generally, in order to show clearly the variations in chemical composition for groundwaters in a given area, various chemical characteristics must be selected and presented separately, preferably on three-dimensional plots, so that changes in composition with depth, as well as in the horizontal plane, can be detected and interpreted. In the case of the present study, which was limited to the upper 300 feet, in which all private water wells of the area are completed, observed changes in composition, with a few exceptions, were predominantly in the horizontal direction. Thus, for most of the ensuing discussion, mapping of chemical characteristics of groundwater on the sole basis of geographical location, regardless of depth, is sufficient.

Differences in chemical composition between groundwaters in the area are of two kinds: (1) a result of the aging of water as it moves through the subsoil, and thus continually subjected to the processes described

in the previous section; (2) a result of differences in composition of the rocks through which the waters move and, therefore, controlled by the geology of the area. Differences of type (1) tend to be greatest in the direction of groundwater movement and lines of equal composition will therefore tend to be aligned transversely to the directions of groundwater flow. Differences of (2) will be greatest where major lithologic or other geologic boundaries are crossed, as in the case of the calcium:magnesium ratio which, due to the important role of carbon dioxide in the solution of calcium and magnesium carbonate, is determined by the calcium:magnesium ratio of the carbonates in the sediments of the recharge area. In this case lines of equal composition will tend to parallel the directions of groundwater flow.

Where all these influences are at work in one area, the resultant patterns showing chemical variations can become rather complicated and will be even more so if waters from more than one flow system are sampled. In any area where the topography, and therefore the water table, can be described as a regional slope on which local sinusoidal deviations are superimposed, short local and longer intermediate flow systems will generally be superimposed on the system of regional groundwater flow (Tóth, 1963) so that two groundwater samples, taken from adjacent points in the subsurface may have entirely different origins, ages, and therefore compositions.

The least complicated pattern will evidently be shown by a map representing total dissolved solids for which the trend, without exception, will be one of an increase with increasing age of the water. Any "anomalous" regions of a total solids map that do not seem to conform to this rule must be due to the unrecognized sampling of some flow system or systems other than the main regional one. Also, the trend of an aging water must finally, disregarding local disturbances, be an increase in those components showing the greatest propensity for the dissolved state. This is the principle behind Chebotarev's (1955) rule, according to which the trend in the metamorphism of a groundwater is always toward a water with chloride and sodium as the dominant ions.

Total Solids

Figure 11 shows the distribution of total anions, expressed in equivalents per million (epm)*. The two main low total anion areas clearly coincide with the two topographic highs to the northwest and northeast of Handhills Lake; in these areas the sum of the anions does not exceed 10 epm (approximately 600 parts per million total dissolved solids). Most of the topographically low areas, on the other hand, are associated with high total-solids concentrations; in these areas the sum of the anions is generally

* The total anion content, in epm, represents approximately one half of the total solids content, in epm. Generally, total anions in $\text{epm} \times 60 = \text{total solids content, in parts per million}$.

over 30 and commonly over 40 epm (approximately 1,800 and 2,400 ppm total dissolved solids, respectively). Thus, the total-solids distribution over most of the study area supports the concept that natural groundwater movement is from elevated to low-lying areas.

One low-lying area, however, presents total-solids results that are "anomalous", at least in the sense that they seem to contradict this basic concept. Within this area, which lies 2 miles south of the town of Hanna in the northeast part of the study area, total-anion content ranges downward to values below 10 epm. Except for one well (Lsd. 16, Sec. 36, Tp. 30, R. 15) completed in a gravel deposit in the Hanna channel at a depth of 176 feet, all wells in this area obtain water from depths not exceeding 15 feet in the sands and gravels of near-surface glacial lake and outwash deposits. The low anion content in an area that should be at the discharge end of the regional flow system is noteworthy; this feature is doubtless related to the high infiltration capacity of these permeable deposits which permits rapid direct recharge and temporary near-surface storage of fresh groundwater from snowmelt and rainfall. Within these lake and outwash and outwash deposits, each period of recharge should lead to the creation or augmentation of a shallow mound of fresh water over-lying the more mineralized water in the regional flow system. Such a mound represents an unstable hydrologic situation and would tend to dissipate during the intervals between recharge periods. Production from shallow wells would be a dissipating influence, as would the tendency for water to migrate laterally away from the central portion of the mound. Another factor that might assume considerable importance is subsurface drainage of water through the permeable deposits of the Hanna channel, a possibility already mentioned in connection with the discussion of test-hole water-level measurements. Such drainage could cause the fresh waters in the lake and outwash deposits to move downward toward the channel deposits which lie generally beneath them. If this situation exists, then at least some of the groundwaters in the channel deposits should be relatively fresh and, indeed, the one sample taken from the channel gravels (Lsd. 16, Sec. 36, Tp. 30, R. 15) contained 18.6 epm total anions – substantially less than that expected if the gravels received only water discharging from the bedrock. Unfortunately, no water-level measurement was possible in this well, and this could have provided fairly conclusive evidence for the existence of downward flow.

The available total-solids information supports the hypothesis that there is a fairly extensive recharge area coinciding with the low-lying area of lake and outwash deposits to the south of Hanna. The information is not adequate to establish whether the resulting subsurface freshwater body is seasonal and shallow or whether it eventually feeds the permeable deposits in the Hanna channel; there is, however, some suggestion that the second alternative is correct. Additional chemical and water-level data, plus possibly the observation of seasonal variations in these parameters should help to resolve the question.

Percentage Bicarbonate plus Carbonate

Probably the groundwater characteristic next in importance to total-solids concentration is the relative amount of bicarbonate plus carbonate. Bicarbonate and carbonate are both derived from the same sources, the carbon dioxide of the soil water and the solid carbonates (usually of lime and magnesia) of the rock through which the water has passed. Figure 12 shows the variation in relative bicarbonate plus carbonate content expressed as a percentage of the total anions:

$$\frac{\text{HCO}_3^- + \text{CO}_3^{--}}{\text{HCO}_3^- + \text{CO}_3^{--} + \text{SO}_4^{--} + \text{Cl}^- + \text{NO}_3^-} \times 100$$

where all constituents are expressed in epm.

The general trend is one of decreasing bicarbonate plus carbonate with increasing distance from the Hand Hills, with values of over 80 per cent in the highest areas of the Hand Hills decreasing to less than 40 per cent in the plains areas near Craigmyle and Hanna in the northwest and northeast, respectively, and in the extreme southeast corner of the mapped area.

In the southeast part of the study area this trend is fairly uniform, but in the remainder of the area the pattern is much more complicated. Particularly anomalous are the three areas in the northeast quadrant of the map enclosed by the 80 per cent contours; complications here must be ascribed primarily to the effects of a sulfate-reduction process. To clarify this, figure 12 shows those areas where total concentration of bicarbonate plus carbonate exceeds 50 ppm, as well as those areas where total sulfate is less than 200 ppm. As shown in the earlier discussion of this phenomenon, the characteristics of a groundwater undergoing sulfate reduction are a low sulfate content, an anomalously high bicarbonate plus carbonate content, and consequently a high percentage bicarbonate plus carbonate; in the three areas in question there is a reasonable correlation among these properties.

Another unusual feature is the low bicarbonate plus carbonate area over the south half of township 30, range 16, showing a decrease to less than 40 from nearly 100 per cent in the adjoining high area (wells in sections 27 and 28, township 30, range 16). Although the cause of this feature is not certain, it may be that water in this area has not encountered sufficient solid carbonates in the rock to be able to reach saturation, or else that soil water in the recharge area is abnormally low in carbon dioxide. The few water samples that could be obtained in the adjacent Hand Hills recharge area to the southwest suggest that absolute values of bicarbonate plus carbonate concentration are low, as are the pH values. These observations tend to support the proposition of undersaturation with respect to calcium carbonate as the more likely reason for this bicarbonate

plus carbonate low.

Percentage Chloride and Chloride:Sulfate Ratio

Maps of the percentage chloride* and the chloride:sulfate ratio are presented in figures 13 and 14, respectively. The constituents involved in the calculation of these parameters are measured in epm.

Owing to the small amounts of chloride present in the groundwaters of the area, the relative errors in the determination of total chloride and hence in the determination of the two ratios are large. Therefore, although the broad features of the map should be considered significant, both ratios are apt to be erratic in detail.

In general, both ratios increase with increasing distance from the Hand Hills, that is, with increasing age of the groundwater, indicating that groundwater movement is generally outward from the Hand Hills. On both maps there appears, however, an anomalously high trend from the northwest quarter of township 29 to the southeast quarter of township 30, range 16, west 4th meridian, and a similar but narrower trend approximately 3 miles to the west. The first trend partly coincides with the area of abnormally low bicarbonate plus carbonate concentrations, and both trends are probably indicative of differences in the chemical composition of the rocks in this area or of the composition of the connate water still retained in the shale section of the formations and slowly released into the surrounding more permeable beds. In other words, the percentage chloride and chloride:sulfate ratio maps, although generally displaying the characteristics of chemical maps of type (1), have in some areas the characteristics of type (2).

Percentage Sodium

The map of percentage sodium** is presented in figure 15. All constituents are in epm. It is markedly similar to the map of total dissolved solids, showing a gradual increase from the recharge to the discharge area, with values ranging from less than 20 per cent in the former to over 80 per cent in the latter. The area south of Hanna, where percentage sodium is low, corresponds to the area where shallow wells produce from surficial sand, as discussed under total solids.

Base exchange between the groundwater originally rich in

$$* \text{ percentage chloride} = \frac{\text{Cl}^-}{\text{HCO}_3^- + \text{CO}_3^{--} + \text{SO}_4^{--} + \text{Cl}^- + \text{NO}_3^-} \times 100$$

$$** \text{ percentage sodium} = \frac{\text{Na}^+}{(\text{Na}^+ + \text{K}^+ + \text{Ca}^{++} + \text{Mg}^+)} \times 100$$

calcium and magnesium and the clay minerals in the rock is the mechanism causing this areal variation. As the calcium-magnesium water moves outward from the recharge area the calcium and magnesium ions are partially replaced by sodium ions until equilibrium is established between the minerals and the solution. Early in the history of a flow system, the exchange capacity of the clay and shale near the recharge area will be large and the groundwater will be "softened," that is, its "hard" ions — calcium and magnesium — will be exchanged for the "soft" sodium ions as soon as it comes into contact with the clay minerals. As time goes on, however, the clay minerals will become saturated with calcium and magnesium at increasing distances from the recharge area and consequently the groundwater will remain hard for a longer period and over a larger area.

Active base exchange is probably limited to a narrow "front"; behind this front no base exchange will take place owing to calcium and magnesium saturation of the clay minerals; ahead of the front no exchange will occur because the softening process has reached equilibrium. With time, however, the front will move steadily outward.

It is tempting to interpret the zone of rapid compositional change between the 40 per cent and 80 per cent contours in figure 15 as the front along which base exchange occurs; comparison with the bedrock-geology map (Fig. 3) indicates a close coincidence of this zone with the subcrop of the highly bentonitic Kneehills Zone. It seems reasonable, therefore, to assume that the Kneehills Zone is the primary agent in the base exchange process that determines the location of the zone of rapid compositional change. A notable example is the group of two springs and one well in section 32, township 29, range 15, located practically on the subcrop of the Kneehills Zone; percentage sodium is very low in both springs, which presumably discharge from the section above the Kneehills Zone, and very high in the well at a depth of 115 feet.

In the generally bentonitic strata of the Edmonton Formation, permeable sandstone bodies (Paskapoo-type sandstones) are more extensively developed above the Kneehills Zone than lower in the formation. Consequently, considerable groundwater flow is induced towards and through these permeable units. Groundwaters in these sandstones tend to have low sodium contents, both because of their relatively short residence time and because of calcium and magnesium saturation of the clay minerals along their flow paths. However, where more shaly and bentonitic strata are developed, as in holes 64-8, 64-6, and part of 65-1, base exchange with the more abundant available sodium in the clay minerals has produced more sodium-rich groundwaters. The abundant montmorillonite content of the Kneehills Zone also ensures that all groundwaters moving through these beds become sodium-rich, and as the large amount of exchangeable sodium in the Kneehills bentonites has not been depleted at present, the base-exchange front in the Hand Hills nowhere extends below this zone.

Calcium:Magnesium Ratio

The calcium:magnesium ratio map (Fig. 16) has an entirely different character than the maps described in the foregoing sections. In this case the lines of equal concentration appear to make up two distinct sets: the first extends to the northeast from the main or western limb of the Hand Hills, the second radiates outward from a center on the east limb of the Hand Hills in section 28, township 29, range 15. For all other chemical maps (Figs. 11-15), the lines of equal concentration tend to form a pattern of roughly parallel elliptical arcs converging on the western limb of the Hand Hills as center. Thus the calcium:magnesium ratio lines are aligned more or less transversely to the lines of concentration for other chemical parameters.

The calcium:magnesium pattern again is evidence that groundwater moves radially outward from the Hand Hills toward the lowlands around Bullpound Creek to the north and east. The calcium:magnesium ratios vary normally between 1.0 and 3.0, with the exception of two zones in which the ratio is less than 1.0. The smaller of these zones, in the northwest corner of the study area, coincides with an abnormal trend in both percentage chloride and chloride:sulfate ratio. Within the larger zone, four individual narrow strips are outlined in which the ratio is less than 0.5. Three of these appear to originate in the high area east of Handhills Lake and do not have their counterparts on the maps of percentage chloride and chloride:sulfate ratio; the fourth strip is poorly defined: the 0.5 contour is based only on the samples from the Paskapoo sandstone in hole 65-1 (Table 3) and the domestic well 1 mile to the east. However, the data from hole 65-1 strongly suggest a correlation between the low calcium:magnesium ratio and the presence of Paskapoo sandstone; furthermore, this strip coincides with a high trend in percentage chloride and chloride:sulfate ratio.

It is likely that the low calcium:magnesium ratio encountered in hole 65-1 will persist at least for a short distance in the direction of flow, which, theoretically, must extend towards the low area north of Handhills Lake; there, the shallower water will discharge, while the deeper portion will continue to flow underground in the direction of the surface gradient, which is towards the valley of Bullpound Creek to the north.

Determination of Calcium:Magnesium Ratios for Rock Samples

In order to determine the origin of the low calcium:magnesium ratios in the groundwater a number of test holes were drilled and samples of drill cuttings taken at 5-foot intervals. In an attempt to simulate the process of solution by water containing carbon dioxide a measured quantity of each sample was acidified with a sufficient amount of 0.02 normal hydrochloric acid to extract the calcium and magnesium contained in the carbonates present in the rock and easily available at exchange sites in the clay minerals. The resulting acid solution was then analyzed for calcium

and magnesium. The results are presented in figure 17. The total amount of calcium and magnesium recovered is shown to the left of each stratigraphic column as milligrams (mg) of calcium carbonate per gram of rock. The calcium:magnesium ratio is shown to the right of the stratigraphic column.

Five of the test holes (Fig. 3) were drilled along the strip with low calcium:magnesium ratios extending from section 33, township 29, range 16, to section 30, township 30, range 14, west of the 4th meridian (Fig. 16). Test hole 64-5 was in the recharge area and the ratios obtained for samples from this hole are noticeably lower than those for test holes 64-1, -2, -3, and -4. Total amounts of calcium and magnesium recovered per gram of sample were also noticeably lower. However, the results for test holes 64-6 and 64-8 on the recharge end of the low calcium:magnesium ratio strip in the northwest of the mapped area (Fig. 3) indicate no correlation between ratios for the groundwater in this strip and for the rock in the recharge area. Here a 40-foot thick section of marl overlies calcareous shales and high ratios predominate. Results from test holes 64-9 and 64-10 are inconclusive, although ratios from test hole 64-9 at the recharge end of the southernmost strip of low calcium:magnesium ratios in the groundwater are predominantly less than two and hence slightly less than average.

On the whole, the correlation of calcium:magnesium ratios for groundwater with those for bedrock carbonates was not proven. In view of the uncertainty about the exact locations of the recharge areas for the "low calcium magnesium strips" it is possible that a denser distribution of test holes might show a more positive correlation.

It appears, nevertheless, that the relationship between calcium-magnesium contents of bedrock and groundwaters is complex and deserving of further study. For instance, in the Olds area, west of the Hand Hills (Fig. 1), the calcium:magnesium ratio in the near-surface bedrock (Porcupine Hills Formation) is approximately 6 (M. A. Carrigy, personal communication) whereas that of groundwaters averages approximately 1 (Tóth, 1966a). Groundwaters from areas where the Edmonton Formation is the near-surface bedrock generally have calcium:magnesium ratios of well over 1, whereas Edmonton Formation sandstones have an average ratio of approximately 3 (M. A. Carrigy, personal communication).

Summary

Variations in chemical composition of groundwater in the study area are of two kinds: (1) those for which the contours are aligned transversely to the direction of groundwater flow and which indicate relative groundwater age and (2) those for which the contours are aligned in the direction of groundwater flow and which reflect differences in composition of the rocks through which the waters have passed. Differences of the first kind are clearly evident on the contour maps of total solids and percentage sodium. A comparison of these maps indicates that areas of low total solids tend to coincide with those

of low percentage sodium. Since both these properties are generally characteristic of recharge area groundwaters, they have been used to outline the three recharge areas shown on figure 8.

Two of the recharge areas, in the elevated regions of the eastern and western lobes of the Hand Hills, are located in agreement with the classical picture of groundwater flow from elevated to low-lying areas. The third, on the other hand, coincides with a low-lying area of near-surface sands and gravels lying to the south of the town of Hanna. Here, rapid infiltration of precipitation forms a groundwater mound which tends to dissipate by pumpage, radial outward flow, and possibly downward flow into the permeable deposits of the underlying preglacial Hanna channel. In the latter case, the water is then presumably drained out of the study area through these deposits, and relatively fresh groundwaters should be found within them. The one sample available for testing this hypothesis contained only 18.6 epm total anions; although the percentage sodium was high, the low total-anion content is believed to have significance as far as the origin of this water is concerned.

The calcium:magnesium ratio map provides the best illustration of a chemical variation of the second kind. This ratio is considered to be determined primarily by the composition of the carbonates dissolved from rock material in the recharge area and to change little thereafter; consequently the contour lines radiate outward from the recharge areas in the Hand Hills with an alignment approximately parallel to the direction of groundwater flow. Their distribution presumably reflects significant lateral changes in the drift or bedrock materials in the recharge areas. The transition from Paskapoo sandstones to Edmonton-type sediments may be such a lateral change, as well as the discontinuous distribution of the Tertiary marl deposits. An attempt was made to provide a more positive correlation between formation chemistry and water chemistry by measuring calcium:magnesium ratios for a number of formation samples from the recharge areas in the Hand Hills and comparing them with ratios for water samples from points farther along in the flow system. The results were inconclusive, partly because the sampling density was far from adequate. The bulk of the available information is believed, however, to support the correlation between rock unit composition in the recharge areas and areal variation of the calcium:magnesium ratio for groundwaters.

The remainder of the chemical maps show features that are chemical variations of both kinds. These include the maps of percentage bicarbonate plus carbonate, percentage chloride, and chloride:sulfate ratio. In broad outline the contours on these maps form irregular arcs around the Hand Hills, showing dependence of these parameters on groundwater age. On the bicarbonate plus carbonate map, local highs can be explained as the result of sulfate reduction and local lows as the result of carbonate deficiency in the recharge area. On the maps of percentage chloride and chloride:sulfate ratio, a number of anomalies form elongated trends aligned

transversely to the general regional trend and possibly indicating differences in composition of the rock material in the recharge area, as in the case of the calcium:magnesium ratio.

Generally, with the exception of the data for the low-lying recharge area to the south of Hanna, the chemical evidence supports the usual concept of groundwater recharge in the highlands and discharge in the lowlands. It is noteworthy that the existence of the low-lying recharge area would almost certainly have been overlooked without the information provided by the chemical maps. Further study of these maps and supplementary field work, testing, and sampling might serve to clarify the nature of some of the observed chemical variations. The surface depression between the two lobes of the Hand Hills is a particularly promising area for such a supplementary investigation. It is characterized by local highs for total solids, percentage chloride, chloride:sulfate ratio, and percentage sodium and by a local low for percentage bicarbonate plus carbonate. The total-solids low has been interpreted as extensive whereas the other anomalies have been considered to be more localized. Data are sparse here, however, and additional data could result in considerable modification of the contours shown on the chemical maps. Even in the case of the present interpretation, all anomalies overlap or nearly overlap in section 3, township 30, range 16 so that a fairly conclusive case exists for at least a local discharge area in this location. Additional information could presumably lead to the outlining of a more extensive discharge area stretching to the southeast along the axis of the depression.

COMMENTS AND CONCLUSIONS

Hydrologically, the study area can be divided into four parts (Fig. 8): (1) a high-level recharge area in the elevated regions of the eastern and western lobes of the Hand Hills, (2) an area of "active discharge" through springs and seepages forming a band some 2 to 3 miles in width along the steep northern and western flanks of the Hand Hills, (3) a lowland area of "hidden discharge" where groundwater is discharged mainly through evapotranspiration, and (4) a lowland recharge area to the south of the town of Hanna where the presence of near-surface permeable deposits facilitates infiltration of precipitation and the creation of a mound of fresher groundwater overlying the more mineralized waters of the regional flow system. The existence of a highland recharge and lowland discharge area had been anticipated, and reveals the expected influence of topography on near-surface groundwater flow typical of the geologic environment of the Alberta plains. The existence of the band of "active discharge" and the lowland recharge area, on the other hand, had not been anticipated. The latter area is, beyond doubt, an expression of the modifying influences of geology, and the former may also be a similar expression.

Water-level measurements (Table 1) and hydraulic-gradient estimates (Table 2) for test hole 65-1, located in the recharge area covering the higher parts of the western lobe of the Hand Hills, revealed a large hydraulic conductivity contrast between a Paskapoo-type sandstone and the underlying Edmonton-type sediments. There thus must be a large component of horizontal flow in the more conductive Paskapoo sandstones, and both outcrops and subcrops should be characterized by local concentrations of groundwater outflow which, except in the case of thick drift cover, should be evident at the surface as springs or seepages. One may, therefore, expect a correlation of the observed 2- to 3-mile band of "active discharge" with the outcrop or subcrop of Paskapoo sandstones. However, correlation between the band location (Fig. 8) and the position of Paskapoo strata as given on the geologic map (Fig. 3) is almost nonexistent, thus raising questions concerning the validity of the two basic assumptions. This poor correlation may in part be indicative of the restricted development of Paskapoo sandstones in this area, and in part be due to the complex of near-surface permeable materials in the drift. Also, where no strong permeability contrast exists, the bands of "active discharge" are likely due to the effects of deep surface erosional incisions in the bedrock, or to strong surface ward flow components along the steep flanks of the Hand Hills.

In the case of the lowland recharge area south of Hanna, the obvious modifying geologic influence is provided by the near-surface deposits of sands and gravels which, as already remarked, permit rapid infiltration of precipitation and creation of a mound of relatively fresh groundwater. A less obvious geologic influence is quite possibly provided by the preglacial Hanna channel, which lies at some depth below these surficial sands and gravels. The channel deposits are suspected to be generally somewhat more permeable than the nearby bedrock deposits, and the sands and gravels found here and there along the channel floor will undoubtedly have a higher permeability still. The channel could, therefore, act as a drain to remove groundwater originating in both the highland and lowland recharge areas from the study area by a subsurface route. Evidence which can be used to support or refute this hypothesis is unfortunately sparse at the present time but what evidence is available does indicate that the preglacial Hanna channel does indeed act as a drain.

The study as a whole indicates that, although topography may be the major factor determining the characteristics of a regional flow system, the influence of geology can be important and can produce significant deviations from the results anticipated for supposedly homogeneous flow media. Observation and explanation of these deviations require careful field surveys, drilling, testing, sampling, and analysis, as well as painstaking correlation of the data collected. Chemical information is particularly useful in this respect and was instrumental in the identification and delineation of the lowland recharge area south of Hanna. Total solids and percentage sodium proved to be the chemical parameters most diagnostic of relative groundwater age and with the greatest application in the outlining of recharge

and discharge areas; percentage bicarbonate plus carbonate had some applicability for this purpose in those areas where sulfate reduction was not a factor. The calcium:magnesium ratio appeared to be useful as an indicator of flow directions where there was significant variation in carbonate rock composition in the recharge areas. Percentage chloride and the chloride:sulfate ratio, in contrast to the other chemical parameters, varied in a complicated way both with groundwater age and with composition of the rock material through which the water had passed and, as a result, maps of these parameters had limited utility.

Of the other types of data collected, test hole water-level data were particularly valuable. Their true value, however, only became apparent when they were used to derive estimates of vertical components of the hydraulic gradient in the test holes. They provided the evidence for the major hydraulic conductivity change in the vicinity of the Edmonton-Paskapoo contact with its possible implications for the regional groundwater flow regime. They also provided evidence for the existence of primarily vertical or primarily horizontal flow at other locations and in one case indicated the presence of a reversal in direction of the vertical flow component, a reversal that could only be the result of a distortion in the fluid potential field produced by a nearby permeable body. To obtain full value from water-level measurements, they should always be used for the estimation of the vertical components of the hydraulic gradient. This procedure unfortunately seems to be rare among groundwater hydrologists.

The field procedures utilized do not, of course, exhaust the possible methods of investigation. Another technique which might have served to clarify the regional flow picture is the mapping of surficial features related to groundwater recharge and discharge areas (Tóth, 1966b). This procedure is, however, expensive and time-consuming when applied systematically to an area as large as that covered by the Hand Hills study. Nevertheless, it could be extremely useful in resolving ambiguities in more localized areas and might, therefore, have been put to good use in dealing with some of the secondary questions which still remain unanswered in the Handhills Lake study area.

REFERENCES CITED

- Allan, J. A. and J. O. G. Sanderson (1945): *Geology of Red Deer and Rosebud sheets*; Res. Coun. Alberta Rept. 13, 109 pages.
- American Public Health Association, American Water Works Association, and Federation of Sewage and Industrial Wastes Associations (1955): *Standard methods for the examination of water, sewage and industrial wastes*; American Public Health Association, Inc., New York, 522 pages.

- Back, W. and B. B. Hanshaw (1965): Chemical Geohydrology; in *Advances in Hydrosience*, Vol. 2, p. 49-109; Academic Press, New York and London.
- Billings, Gale K., B. Hitchon, and D. R. Shaw: "Geochemistry and origin of formation waters in a large sedimentary basin. Part 2. Alkali metals,(in preparation).
- Bredehoeft, J. D., C. R. Blyth, W. A. White, and G. B. Maxey (1963): Possible mechanism for the concentration of brines in subsurface formations; *Am. Assoc. Petroleum Geol.* Vol. 47, No. 2, p. 257-269.
- Chebotarev, I. I. (1955): Metamorphism of natural waters in the crust of weathering: Part 3. *Geochim. et Cosmochim. Acta*, Vol. 8, p. 137-170.
- Craig, B. G. (1957): Surficial geology, Drumheller east-half, Alberta; *Geol. Surv. Can.*, Map 13-1957 (map with marginal notes).
- Farvolden, R. N. (1963): Bedrock channels of southern Alberta; in *Early contributions to the groundwater hydrology of Alberta*; *Res. Coun. Alberta Bull.* 12, p. 63-75.
- Hem, J. D. (1959): Study and interpretation of the chemical characteristics of natural water; *U. S. Geol. Surv. Water-Supply Paper* 1473, 269 pages.
- Irish, E. J. W. (1967a): Geology, Oyen, Alberta; *Geol. Surv. Can. Map* 21-1966 (Prelim. Series, 72M).
- (1967b): Geology, Drumheller, Alberta; *Geol. Surv. Can. Map* 5-1967 (Prelim. Series, 82P).
- Kunkle, G. R. (1962): Reconnaissance groundwater survey of the Oyen map-area, Alberta; *Res. Coun. Alberta Prelim. Rept.* 62-3, 23 pages.
- Le Breton, E. G., and A. Vanden Berg (1965): Chemical analyses of groundwaters of east-central Alberta; *Res. Coun. Alberta Prelim. Rept.* 65-2, 24 pages.
- Meyboom, P. (1960): Geology and groundwater resources of the Milk River Sandstone in Southern Alberta; *Res. Coun. Alberta Memoir* 2, 89 pages.
- Meyboom, P., R. O. Van Everdingen, and R. A. Freeze (1966): Patterns of groundwater flow in seven discharge areas in Saskatchewan

and Manitoba; Geol. Surv. Can. Bulletin 147, 57 pages.

Schoeller, H. (1962): Les eaux souterraines; Masson et Cie, Paris, 642 pages.

Tóth, J. (1962): A theory of groundwater motion in small drainage basins in central Alberta, Canada; Jour. of Geophys. Res., Vol. 67, No. 11, p. 4375-4387.

————— (1963): A theoretical analysis of groundwater flow in small drainage basins; Jour. of Geophys. Res., Vol. 68, No. 10, p. 4795-4812.

————— (1966a): Groundwater geology, movement, chemistry and resources near Olds, Alberta; Res. Coun. Alberta Bull. 17, 126 pages.

————— (1966b): Mapping and interpretation of field phenomena for groundwater reconnaissance in a prairie environment, Alberta, Canada; Bull. Int. Assoc. Sci. Hydrol., Vol. 11, No. 2, p. 20-68.

APPENDIX A.

LITHOLOGIC LOGS OF TEST HOLES

Test hole 64-1 Location: 0.6 miles north of NEC of 10-30-15 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 5	<u>Sand</u> and <u>clay</u>
5- 20	<u>Till</u> , sandy, brown
20- 50	<u>Till</u> , bluish grey
50- 52	<u>Sand</u>
52- 60	<u>Clay</u> , with <u>coal</u> fragments and fine <u>gravel</u>
60- 90	<u>Till</u> , sandy, grey
90-100	<u>Shale</u> , medium grey, bentonite
100-110	<u>Shale</u> , medium brownish grey and light grey, bentonitic
110-115	<u>Coal</u>
115-120	<u>Shale</u> , silty, carbonaceous, brown, grey and black
120-125	<u>Shale</u> , sandy, carbonaceous, grading to <u>sandstone</u>
125-145	<u>Sandstone</u> , very fine, argillaceous and bentonitic; light grey
145-150	<u>Sandstone</u> with bentonite layers
150-155	<u>Shale</u> , very sandy, bentonitic; medium brownish grey
155-165	<u>Sandstone</u> , very fine, bentonitic, argillaceous; 40% <u>coal</u>
165-205	<u>Sandstone</u> , very fine, bentonitic, argillaceous, light grey
205-210	<u>Sandstone</u> , fine, calcareous, porous; brownish grey; thin <u>coal</u> seams
210-245	<u>Sandstone</u> , very fine, bentonitic, argillaceous; light grey
245-250	<u>Sandstone</u> , very fine, calcareous, hard
250-300	<u>Shale</u> , brownish grey, carbonaceous

Test hole 64-2 Location: 0.5 miles south of NEC of 8-30-15 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 15	<u>Till</u> , brown
15- 70	<u>Till</u> , grey
70- 90	<u>Shale</u> , grey; trace of <u>coal</u>
90-100	<u>Shale</u> , slightly sandy; grey
100-105	<u>Shale</u> , grey
105-110	<u>Shale</u> , carbonaceous, dark grey
110-115	<u>Shale</u> , carbonaceous, dark grey; 30% <u>coal</u>

115-120	<u>Shale</u> , brownish grey; minor <u>coal</u>
120-125	<u>Shale</u> and thin <u>sandstone</u> layers
125-130	<u>Shale</u> , bentonitic and sandy
130-135	<u>Coal</u>
135-160	<u>Shale</u> , carbonaceous, bentonitic, medium grey
160-165	<u>Shale</u> , light grey, very bentonitic
165-170	<u>Shale</u> , carbonaceous, hard; brownish grey
170-180	<u>Sandstone</u> , bentonitic, salt and pepper
180-190	<u>Shale</u> , carbonaceous, bentonitic
190-200	<u>Sandstone</u> , very fine, argillaceous, light grey
200-205	<u>Shale</u> , carbonaceous, medium brown
205-210	<u>Sandstone</u> , very fine, argillaceous, light grey
210-215	<u>Shale</u> , carbonaceous, brown
215-220	<u>Shale</u> , carbonaceous, brown, 30% coal
220-240	<u>Shale</u> , carbonaceous, brown
240-250	<u>Sandstone</u> , very fine, bentonitic, light grey
250-255	50% <u>shale</u> , carbonaceous, brown; 20% coal; 30% <u>sandstone</u>
255-280	<u>Shale</u> , dark brownish grey, carbonaceous
280-285	<u>Shale</u> , as above, minor <u>coal</u>
285-300	<u>Shale</u> , carbonaceous, brown

Test hole 64-3 Location: 0.1 mile east of NEC of 31-29-15 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 15	<u>Sand</u> , medium size, predominantly quartz
15- 25	<u>Till</u> , sandy, with abundant <u>gravel</u>
25- 40	<u>Till</u> , grey
40- 50	<u>Shale</u> , carbonaceous, dark brown
50- 65	<u>Shale</u> , carbonaceous, slightly bentonitic, greyish brown
65- 90	<u>Shale</u> , bentonitic, sandy, grading to argillaceous <u>sandstone</u> ; light grey
90- 95	30% <u>coal</u> ; 60% <u>sandstone</u> , very fine, argillaceous, grey; 10% <u>shale</u> , sandy
95-110	<u>Sandstone</u> , as above; minor <u>coal</u>
110-115	<u>Shale</u> , silty, medium grey
115-120	<u>Shale</u> , carbonaceous, dark grey; 20% <u>coal</u>
120-125	<u>Shale</u> , silty, slightly carbonaceous, medium grey
125-130	No sample
130-135	<u>Sandstone</u> , fine, argillaceous and calcareous, light grey
135-140	No sample
140-155	<u>Shale</u> , silty, grey
155-175	<u>Shale</u> , silty, carbonaceous, greenish grey
175-220	<u>Shale</u> , sandy, greenish grey
220-225	<u>Shale</u> , as above, with minor <u>coal</u>
225-250	<u>Sandstone</u> , very fine, argillaceous, light grey
250-270	<u>Sandstone</u> , as above, and minor <u>limestone</u>

Test hole 64-4 Location: NEC of 26-29-16 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 12	<u>Sand</u> and fine <u>gravel</u>
12- 15	<u>Clay</u> , yellow
15- 30	<u>Till</u> , sandy, grey
30- 41	<u>Till</u> , sandy, yellow
41- 55	<u>Gravel</u>
55- 65	<u>Till</u> , sandy; minor <u>gravel</u>
65- 73	<u>Shale</u> , sandy, carbonaceous, light grey
73- 75	<u>Sandstone</u> , very fine, argillaceous
75- 85	<u>Shale</u> , sandy, grey
85- 90	<u>Shale</u> , sandy, very bentonitic, light grey
90-120	<u>Shale</u> , slightly carbonaceous, light grey
120-125	<u>Sandstone</u> , very fine, argillaceous, light grey
125-130	<u>Shale</u> , slightly carbonaceous, medium grey
130-145	<u>Sandstone</u> , argillaceous, very fine, light grey
145-160	<u>Shale</u> and sandstone, interbedded
160-170	<u>Shale</u> , sandy, light grey
170-185	<u>Shale</u> , medium grey, with thin <u>sandstone</u> stringers
185-190	<u>Shale</u> , very sandy, carbonaceous, light grey

Test Hole 64-5 Location: NEC of 17-29-16 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 25	<u>Sand</u> and <u>gravel</u> , in part very loosely cemented with <u>lime</u>
25- 35	<u>Clay</u> , sandy, yellow
35-131	<u>Sandstone</u> , fine to medium, friable, light brown
131-205	<u>Shale</u> , with thin <u>coal</u> seams

Test hole 64-6 Location: NEC of 36-29-17 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 5	<u>Clay</u> , sandy, light brown
5- 10	<u>Sand</u> and <u>gravel</u>
10- 20	<u>Gravel</u>
20- 25	<u>Shale</u> , hard, very dark grey
25- 50	<u>Marl</u> , light yellow
50- 75	<u>Shale</u> , medium grey and light brown
75- 95	<u>Shale</u> , bentonitic, plant fragments; bluish grey
95-120	<u>Shale</u> , light and medium grey; thin layers of <u>limestone</u> , argillaceous, medium grey
120-125	<u>Sandstone</u> , very fine, argillaceous, brownish grey
125-135	<u>Shale</u> , slightly calcareous, light grey

Test hole 64-7 Location: 0.2 miles south of NEC of 2-30-17 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 5	<u>Coarse gravel</u> Hole abandoned

Test hole 64-8 Location: 0.2 miles south of NEC of 2-30-17 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 25	<u>Marl</u> , light yellow
25- 30	<u>Shale</u> , hard, dark grey
30- 40	<u>Marl</u>
40- 45	<u>Coal</u>
45- 85	<u>Shale</u> , carbonaceous, medium grey and dark grey
85- 90	<u>Shale</u> , waxy, bentonitic, greenish grey
90-108	<u>Shale</u> , carbonaceous, light grey
108-135	<u>Sandstone</u> , very fine to fine, very calcareous, slightly argillaceous, friable, grey
135-160	<u>Shale</u> , carbonaceous, medium grey
160-165	<u>Shale</u> , bentonitic, waxy, greenish grey
165-207	<u>Shale</u> , calcareous
207-225	<u>Shale</u> , bentonitic, medium grey

Test hole 64-9 Location: NEC of 16-29-15 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 35	<u>Till</u> , sandy, brown
35- 45	<u>Till</u> , grey
45- 75	<u>Gravel</u>
75- 95	<u>Shale</u> , slightly sandy, bentonitic, light grey; minor bentonite, brown
95-100	<u>Shale</u> , sandy, yellowish brown
100-105	<u>Shale</u> , carbonaceous, yellowish grey; trace <u>coal</u>
105-115	<u>Sandstone</u> , very fine argillaceous, light yellowish grey, grading to <u>shale</u>
115-120	No sample
120-125	<u>Shale</u> , light grey
125-130	<u>Shale</u> , sandy, carbonaceous, light grey
130-135	<u>Shale</u> , carbonaceous, light grey
135-140	<u>Shale</u> , sandy, grey; grading to argillaceous <u>sandstone</u>

Test hole 64-10 Location: NEC of 4-29-15 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 26	<u>Till</u> , brown
26- 40	<u>Till</u> , bluish grey
40- 45	<u>Till</u> , with abundant <u>gravel</u>
45- 82	<u>Gravel</u>
82- 90	<u>Shale</u> , bentonitic, light greenish grey with thin bands of brown <u>shale</u> and bands with abundant <u>ironstone</u> nodules
90- 95	<u>Shale</u> , bentonitic, light grey; minor <u>sandstone</u> , very fine argillaceous, calcareous, light grey
95-100	<u>Shale</u> , bentonitic, greenish grey
100-118	<u>Shale</u> , light grey
118-125	<u>Sandstone</u> , very fine, argillaceous, bentonitic, carbonaceous, light grey
125-140	<u>Shale</u> , light grey

Test hole 64-11 Location: NEC of 9-28-15 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 22	<u>Till</u> , brown
22- 57	<u>Till</u> , blue
57- 90	<u>Shale</u> , carbonaceous, brown and greenish grey
90- 95	<u>Shale</u> , and <u>coal</u>
95-125	<u>Shale</u> , brown
125-130	<u>Sandstone</u> , very fine, argillaceous, light grey
130-135	<u>Coal</u> and <u>shale</u>
135-150	<u>Shale</u> , greenish grey, in part carbonaceous

Test hole 64-12 Location: NEC of 29-29-15 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 10	<u>Till</u> , sandy, yellow
10- 20	<u>Gravel</u> , fine
20- 60	<u>Till</u> and <u>gravel</u>
60- 70	<u>Shale</u> , carbonaceous, medium and dark grey
70- 80	<u>Shale</u> , sandy, bentonitic, white
80-100	<u>Shale</u> , carbonaceous, grey and dark brown
100-110	<u>Shale</u> , sandy, carbonaceous, bentonitic, grey
110-115	<u>Coal</u>
115-140	<u>Shale</u> , medium to light grey
140-145	<u>Sandstone</u> , very fine, argillaceous, light grey
145-155	<u>Shale</u> , sandy, grading to argillaceous <u>sandstone</u> , light grey
155-165	<u>Shale</u> , light grey
165-170	<u>Shale</u> and argillaceous <u>sandstone</u>

170-175 Shale, sandy light grey
 175-180 Sandstone, argillaceous, light grey

Test hole 65-1 Location: NEC of 20-29-16 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 28	<u>Gravel</u> , coarse
28- 30	<u>Marl</u> , sandy, yellowish brown
30- 40	<u>Sandstone</u> , fine, calcareous, argillaceous, yellowish grey
40- 45	No sample
45- 50	<u>Sandstone</u> , fine, slightly calcareous, yellowish grey
50- 57	<u>Sandstone</u> , medium size, slightly calcareous, yellowish grey
57- 87	<u>Sandstone</u> , fine to medium size, silty, calcareous and argillaceous matrix
87-116	<u>Sandstone</u> , fine to medium size, in part argillaceous or calcareous matrix, in part clean and porous
116-119	<u>Shale</u> , light greenish grey
119-128	<u>Sandstone</u> , medium size, in part silty, porous, yellowish grey
128-138	<u>Coal</u> and brown, carbonaceous <u>shale</u>
138-142	<u>Shale</u> , silty, grey
142-145	<u>Sandstone</u> , very fine, grey
145-150	<u>Shale</u> , silty, carbonaceous, light grey
150-152	<u>Shale</u> , carbonaceous, brownish grey
152-155	<u>Coal</u>
155-162	<u>Shale</u> , light grey
162-168	<u>Shale</u> , carbonaceous, thin <u>coal</u> seam
168-175	<u>Sandstone</u> , very fine, argillaceous, light grey
175-188	<u>Shale</u> , bentonitic, light grey and greenish grey
188-223	<u>Shale</u> , bentonitic, silty, carbonaceous
223-225	<u>Sandstone</u> , very fine, light grey
225-230	<u>Shale</u> , silty and sandy, light grey
230-240	<u>Shale</u> , carbonaceous, brown and grey, minor argillaceous <u>coal</u>
240-245	<u>Sandstone</u> very fine, light grey
245-255	<u>Shale</u> , sandy, bentonitic, light grey and medium brown
255-258	<u>Coal</u>
258-282	<u>Shale</u> , very bentonitic
282-295	<u>Sandstone</u> , soft, very bentonitic
295-303	<u>Shale</u> , carbonaceous
303-310	<u>Coal</u>
310-315	<u>Shale</u> , medium grey

Test hole 65-1A Location: NEC of 20-29-16 W. 4th Mer.
20 feet south of 65-1

No log

Test hole 65-2 Location: NE quarter of 6-30-14 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 20	<u>Till</u>
20- 22	<u>Clay</u> , sandy, brownish grey
22- 25	<u>Clay</u> with <u>gravel</u> and pieces of <u>coal</u> , <u>sandstone</u> and <u>shale</u>
25- 52	<u>Till</u> , sandy
52- 57.2	<u>Clay</u> , yellowish brown
57.2-62.5	<u>Shale</u> , yellowish brown
62.5-72.5	<u>Shale</u> , soft, grey

Test hole 65-3 Location: Lsd. 12-20-31-16 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 28	<u>Till</u> , brown
28- 40	<u>Till</u> , grey, abundant <u>gravel</u>
40- 42.5	<u>Shale</u> , light grey
42.5-50	<u>Sandstone</u> , very fine, argillaceous, light grey
50- 80	<u>Shale</u> , sandy, light grey; traces <u>coal</u>
80- 84	<u>Sandstone</u> , very fine, argillaceous, light grey
84-100	<u>Shale</u> , sandy
100-102.5	<u>Coal</u>
102.5-105	<u>Shale</u> , carbonaceous, dark brown
105-109	<u>Coal</u>
109-112.5	<u>Shale</u> , carbonaceous, dark brown
112.5-115	<u>Coal</u>
115-125	<u>Shale</u> , carbonaceous, dark brown
125-180	<u>Shale</u> , sandy, carbonaceous; minor <u>sandstone</u> stringers
180-187	<u>Coal</u>
187-194	<u>Shale</u> , dark grey
194-196	<u>Coal</u>
196-205	<u>Shale</u> , carbonaceous, dark grey and brownish grey

Test hole 65-4 Location: Lsd. 4-3-31-16 W. 4th Mer.

<u>Depth (feet)</u>	<u>Description</u>
0- 21	<u>Till</u> , brown
21- 31	<u>Shale</u> , light grey
31- 46	<u>Sandstone</u> , argillaceous, soft, light brown

46- 52.5	<u>Shale</u> , sandy, bentonitic, grey
52.5- 59	<u>Sandstone</u> , very fine, argillaceous, grey
59- 70	<u>Shale</u> , sandy, medium grey
70- 75	<u>Shale</u> , dark brown, carbonaceous
75- 80	<u>Coal</u>
80- 85	<u>Shale</u>
85- 88	<u>Coal</u>
88-100	<u>Shale</u> , sandy, minor <u>sandstone</u>
100-103	<u>Coal</u>
103-110	<u>Shale</u> with thin <u>sandstone</u> stringers

APPENDIX B.
CHEMICAL ANALYSES OF GROUNDWATER

APPENDIX B
CHEMICAL ANALYSES OF GROUNDWATER

Lad. 1/4	Sec.	Tr.	R.	Depth (ft)	Total solids (det.) (ppm)	Total solids (calc.) (ppm)	Specific conductance (microhms at 25°C)	Fe (ppm)	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	SO ₄ (ppm)	Cl (ppm)	CO ₃ (ppm)	HCO ₃ (ppm)	NO ₃ (ppm)	Sum anions (ppm)	pH					
NW	13	27	14	40	671				231	10.04*		2.50	49	1.03	6	0.17	339	11.30	2.5	0.04	12.54			
NE	24	27	14	50	4,541			4.5	583	26.36		18.60	984	20.50	34	0.96	675	22.50	0.0	0.00	43.96			
9	1	27	15	5	940	823	1,100	0.1	149	6.48	55	2.76	66	5.43	4	0.11	0	0.00	264	8.80	0.0	0.00	14.84	7.8
2	4	27	15	80	1,248				197	8.55		11.90	456	9.50	17	0.48	261	8.70	110.0	1.77	20.45			
4	15	27	15	100	1,277				371	16.11		5.00	488	10.17	19	0.54	312	10.40	0.0	0.00	21.11			
1	18	27	15	27	2,441				430	18.71		20.00	1,283	26.72	122	3.44	255	8.50	3.0	0.05	38.71			
12	35	27	15	70	1,650				399	17.35		9.00	716	14.92	25	0.73	321	10.70	0.0	0.00	26.35			
2	2	28	14	340	2,336	2,200		0.0	711	30.91	tr	tr	48	2.40	7	0.57	1,068	22.25	28	0.79	34.17	7.6		
3	3	28	14	175	1,670	1,610	2,250	0.0	450	19.56	tr	tr	72	3.60	41	3.37	636	13.25	63	1.78	26.63	7.9		
4	3	28	14	< 50	13,752	11,784	150,000	3.0	2,608	113.40	32	0.79	479	23.95	711	58.50	5,355	111.57	226	6.37	197.00	8.8		
11	4	28	14	50	974	759	940	0.0	147	6.40	43	1.07	91	4.55	17	1.40	318	6.62	32	0.89	11.21	7.2		
9	6	28	14	30	1,720	1,671	1,900	1.0	384	16.70	tr	tr	167	8.35	25	2.06	744	15.50	43	1.21	26.20	8.2		
8	11	28	14	5	5,026	5,049	5,300	5.0	1,445	62.83	26	0.64	125	6.25	57	4.69	3,010	62.70	51	1.44	75.14	8.5		
4	12	28	14	5	2,904	2,848	3,100	3.0	829	35.04	tr	tr	65	3.25	39	3.21	1,704	35.50	23	0.65	42.33	8.15		
13	13	28	14	100	1,608	1,572	2,050	0.3	532	23.13	tr	tr	31	1.56	14	1.13	541	11.28	29	0.80	26.05	7.6		
4	20	28	14	40	1,234	1,101	1,625	2.9	304	13.22	tr	tr	70	3.48	20	1.61	344	7.17	30	0.85	18.87	7.3		
23	28	28	14	Lake	658	574	800	0.7	157	6.83	tr	tr	43	2.16	10	0.92	237	4.93	13	0.37	9.98	7.4		
14	28	28	14	5	1,076	1,004	1,350	0.5	365	15.87	tr	tr	16	0.78	7	0.61	156	3.25	8	0.23	16.92	8.2		
5	30	28	14	5	1,020	964	1,350	0.0	364	15.83	tr	tr	12	0.60	4	0.30	179	3.72	18	0.51	19.18	7.6		
11	33	28	14	5	1,812	1,745		tr	635	27.61	tr	tr	22	1.08	4	0.32	535	11.15	25	0.70	30.13	7.5		
9	12	28	15	19	1,054	932	1,225	2.0	189	8.22	tr	tr	81	4.05	40	3.25	304	6.33	16	0.45	16.78	7.5		
5	14	28	15	80	922	856	1,250	5.0	339	14.76	tr	tr	12	0.60	0	0.00	94	1.95	25	0.70	15.35	7.85		
16	23	28	15	5	836	759	1,025	0.0	259	11.26	tr	tr	35	1.75	12	0.99	71	1.47	7	0.17	14.14	7.65		
10	25	28	15	5	2,274	2,180	2,600	0.0	826	35.91	tr	tr	29	1.44	2	0.16	523	10.90	20	0.56	37.46	8.4		
1	27	28	15	5	1,284	1,280	1,680	2.6	404	17.57	tr	tr	65	3.23	18	1.45	318	6.62	13	0.37	22.29	7.5		
16	28	28	15	5	1,026	995	1,380	3.0	309	13.43	tr	tr	48	2.40	16	1.30	274	5.70	12	0.34	17.14	7.8		
11	34	28	15	5	862	743	0.0	0.0	123	5.35	tr	tr	51	2.57	72	5.90	203	4.23	6	0.14	14.11	7.5		
13	4	29	14	5	1,020	941	0.0	0.0	239	10.40	tr	tr	48	2.40	53	4.33	296	6.17	5	0.14	16.31	7.7		
1	6	29	14	5	796	646	850	0.0	175	7.61	tr	tr	29	1.44	19	1.55	248	5.17	7	0.20	10.97	7.7		
7	18	29	14	5	1,314	1,213	1,550	tr	297	12.91	tr	tr	58	2.88	58	4.80	472	9.83	13	0.37	20.70	7.4		
9	18	29	14	5	1,768	1,627	2,000	10+	628	27.30	tr	tr	12	0.60	4	0.33	332	6.92	11	0.31	28.23	8.7		
11	18	29	14	100	1,438	1,394	1,750	1.6	509	22.13	tr	tr	29	1.44	4	0.36	349	7.28	6	0.17	24.04	7.5		
14	18	29	14	W	1,725	1,596	1,660		598	25.00	26.01		20	1.00	9	0.72	368	7.67	11	0.32	27.73			
1	20	29	14	S	3,185	2,965	3,000		1,018	44.25	44.25		31	1.56	21	1.74	1,242	25.87	14	0.39	47.55			
7	20	29	14	50	1,905	1,777	1,950		596	25.90	25.90		62	3.10	20	6.00	490	10.21	31	0.87	30.60			
9	20	29	14	5	2,225	2,200	2,100		686	29.84	29.84		75	3.76	31	2.54	846	17.43	37	1.04	36.14			
10	30	29	14	126	2,145	2,143	2,050		646	28.10	28.10		117	5.86	32	2.62	586	12.21	168	4.74	38.99			
16	1	29	15	5	2,500	2,388		2.8	844	36.70	tr	tr	26	1.28	9	0.72	888	18.50	19	0.53	36.58	7.6		
1	2	29	15	30	1,092	1,091	1,450	1.3	270	11.74	tr	tr	44	2.20	60	4.93	397	8.27	7	0.20	18.87	7.4		
5	2	29	15	5	956	902	1,325	0.2	128	5.57	tr	tr	29	1.44	113	9.33	329	6.85	6	0.18	16.73	7.4		
6	4	29	15	100	660	662	950	1.0	198	8.61	tr	tr	41	2.03	18	1.45	107	2.22	3	0.09	12.11	7.7		
5	5	29	15	150	962	892	1,240	4.1	219	9.52	tr	tr	60	3.00	41	3.40	233	4.85	8	0.28	15.98	7.8		
13	8	29	15	5	1,060	935	950		289	12.56	12.56		46	2.32	15	1.22	248	5.16	55	1.56	25.10			
15	10	29	15	160	1,395	1,341	1,230		253	11.01	11.01		148	7.40	55	4.56	517	10.77	11	0.30	14.07	7.6		
16	11	29	15	< 50	270	430	2.6	tr	tr	tr	tr		42	2.10	29	2.38	28	0.58	5	0.14	12.26	7.4		
5	12	29	15	110	974	772	1,300	1.8	236	10.27	10.27		33	1.66	26	2.14	139	2.90	6	0.17	16.26	7.7		
12	12	29	15	716	669	1,050	3.0	76	3.32	3.32		108	5.40	43	3.54	188	3.92	5	0.14	17.30	8.03			
1	13	29	15	100	1,020	940	1,400	0.0	237	10.30	0	0.00	72	3.60	28	2.29	304	6.33	8	0.23	18.79	7.40		
1	16	29	15	133	1,050	947	960		114	4.96	0	0.00	138	6.90	66	5.44	288	6.00	5	0.13	28.70	7.21		
8	22	29	15	150	1,075	1,089		15.0	198	8.62	5	0.13	58	2.90	87	7.14	428	8.92	5	0.13	24.59	7.26		
13	25	29	15	127	1,645	1,717		0.1	574	24.95	5	0.13	42	2.10	18	1.52	567	11.81	10	0.27	20.93	6.98		
13	26	29	15	189	1,435	1,434		0.1	324	14.09	7	0.18	101	5.06	64	5.26	531	11.07	7	0.21	14.64	7.60		
16	26	29	15	5	1,270	1,237		0.6	331	14.40	7	0.17	74	3.72	32	2.64	430	8.96	4	0.10				
13	28	29	15	875	875			0.1	263	11.44	4	0.11	15	0.76	27	2.20	335	6.97	7	0.21				

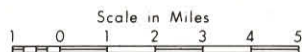
15	32	29	15	5	480	451	0.0	30	1.32	4	0.11	43	3.16	42	3.42	214	4.46	1	0.02	0	0.00	106	3.52	0.8	0.01	8.01	8.30		
16	32	29	15	115	925	966	0.6	311	13.51	4	0.09	20	1.02	20	1.64	326	6.80	3	0.08	0	0.00	281	9.38	0.7	0.01	16.27	7.45		
16	32	29	15	5	431	431	0.1	24	1.05	4	0.11	57	2.84	43	3.52	198	4.13	6	0.16	0	0.00	97	3.22	0.9	0.01	7.52	7.74		
15	33	29	15	80	1,925	1,928	0.1	637	27.69	5	0.13	25	1.26	43	3.50	356	11.59	23	0.64	0	0.00	584	19.45	5.5	0.00	32.58	7.39		
1	34	29	15	5	1,510	1,413	0.1	441	19.30	5	0.12	33	1.66	36	2.92	472	9.84	4	0.12	0	0.00	421	14.02	0.9	0.02	24.00	7.39		
3	34	29	15	5	680	766	7.5	124	5.38	8	0.19	81	4.06	23	1.92	460	9.58	0	0.00	0	0.00	57	1.90	4.8	0.08	11.56	5.73		
9	35	29	15	80	1,775	1,681	6.3	446	19.40	4	0.11	79	3.94	62	5.10	605	12.60	14	0.39	0	0.00	465	15.50	1.9	0.03	28.52	6.60		
14	35	29	15	5	1,610	1,580	0.5	514	22.35	20	0.49	34	1.70	26	2.10	486	10.12	13	0.37	0	0.00	463	16.10	2.7	0.05	26.64	6.60		
2	36	29	15	5	2,055	1,718	1,975	566	24.61	24.61	0.00	51	2.54	23	1.86	520	10.63	11	0.32	0	0.00	525	17.50	22.0	0.36	29.01	7.86		
4	36	29	15	5	1,410	1,355	0.1	422	18.33	6	0.14	25	1.24	40	3.26	456	9.50	9	0.26	0	0.00	395	13.18	2.1	0.03	22.97	7.25		
NE	16	29	16	120	1,456	1,456	1.7	232	10.10	10.10	0.00	16	0.33	389	10.97	381	12.70	12.70	0.00	0.00	149	4.96	2.0	0.03	24.00	6.97			
1	28	29	16	47	230	245	1.7	18	0.80	0.4	0.01	35	1.76	33	2.70	8	0.16	0	0.00	0	0.00	198	6.60	0.2	0.00	6.89			
A	4	28	29	16	125	318	425	50	2.16	6.0	0.14	31	1.53	37	3.01	3	0.06	8	0.23	0	0.00	163	5.44	4.1	0.07	7.17	8.60		
B	4	28	29	16	135	344	550	44	1.91	6.0	0.16	40	2.00	38	3.10	23	0.48	9	0.27	27	0.90	272	9.09	1.3	0.02	10.64	7.70		
C	4	28	29	16	165	574	950	212	9.22	4.0	0.11	9	0.44	3	0.28	70	1.46	3	0.07	0	0.00	267	8.93	1.3	0.02	11.59	8.65		
D	4	28	29	16	172	632	780	249	10.83	3.0	0.08	5	0.26	2	0.18	81	1.69	3	0.07	26	0.88	251	8.37	0.8	0.01	11.53	9.00		
E	4	28	29	16	200	585	800	245	10.65	7.0	0.17	7	0.32	2	0.22	53	1.10	4	0.11	58	1.94	301	10.04	0.85	0.01	13.25	9.04		
F	4	28	29	16	220	744	900	292	12.67	4.0	0.11	6	0.32	2	0.18	45	0.94	10	0.28	59	1.96	315	10.46	0.4	0.00	11.12			
G	4	28	29	16	305	612	597	253	10.96	3.0	0.08	3	0.17	1	0.04	0	0.00	12	0.34	14	0.47	301	10.05	0.4	0.00	10.86			
4	28	29	16	315	616	576	0.1	246	10.71	10.71	0.00	64	3.22	46	3.80	129	2.68	6	0.16	0	0.00	179	5.98	7.4	0.12	8.94	8.35		
7	32	29	16	5	477	479	1.4	45	1.94	3.0	0.07	108	5.82	90	7.42	101	2.10	99	2.78	0	0.00	377	12.58	1.9	0.03	11.49			
H	9	6	30	14	75	718	1.4	108	4.69	4.69	0.00	105	2.18	100	2.82	108	2.25	11	0.32	0	0.00	377	12.58	1.9	0.03	11.49			
J	9	6	30	14	25	1,245	1,256	417	18.11	18.11	0.00	46	2.32	13	1.08	330	6.87	73	2.06	0	0.00	517	17.24	1.5	0.02	30.02			
J	9	6	30	14	40	1,755	1,779	548	23.83	14.0	0.36	74	3.70	29	2.40	550	11.46	46	1.30	0	0.00	517	17.24	1.5	0.02	30.02			
K	9	6	30	14	70	1,955	1,939	547	23.78	8.0	0.20	86	4.29	54	4.42	640	13.33	19	0.53	0	0.00	584	19.45	2.5	0.04	33.33			
11	6	30	14	102	1,685	1,584	1,780	537	23.34	23.34	0.00	15	0.74	34	2.80	476	9.92	14	0.40	37	1.24	453	15.32	10.8	0.17	27.05			
SW	7	30	14	300	1,186	1,186	1.2	397	17.26	17.26	0.00	104	2.71	74	2.09	453	15.32	10.8	0.17	27.05	15.32	10.8	0.17	27.05					
10	7	30	14	12	1,160	1,055	1,210	273	11.87	11.87	0.00	79	3.96	36	2.98	265	5.52	16	0.45	0	0.00	385	12.82	1.0	0.02	18.81			
1	9	30	14	14	520	461	1,800	68	2.92	17.40	0.00	39	1.94	39	3.22	370	7.77	27	0.75	0	0.00	159	5.30	27.0	0.44	8.26			
1	18	30	14	70	1,680	1,685	1,800	569	24.73	24.73	0.00	39	1.94	39	3.22	370	7.77	27	0.75	0	0.00	159	5.30	27.0	0.44	8.26			
5	18	30	14	100	2,130	1,961	2,100	705	30.64	2	0.04	46	2.30	21	1.74	410	8.54	10	0.29	0	0.00	656	21.86	0.9	0.01	29.89			
4	22	30	14	11	1,630	1,532	1,600	286	12.44	12.44	0.00	172	8.58	62	5.10	315	6.56	215	6.05	0	0.00	334	11.12	148.0	2.39	26.12			
12	28	30	14	15	340	379	350	59	2.55	2.55	0.00	57	2.84	15	1.22	105	2.19	9	0.25	0	0.00	117	3.90	16.8	0.27	6.61			
1	32	30	14	12	1,060	1,038	1,030	172	7.47	7.47	0.00	92	4.60	75	6.14	235	4.90	100	2.82	0	0.00	269	8.96	96.0	1.53	18.21			
13	32	30	14	11	842	832	850	55	2.40	2.40	0.00	116	5.82	90	7.42	101	2.10	99	2.78	0	0.00	323	10.76	48.0	0.77	16.41			
13	1	30	15	170	1,975	1,674	0.1	677	29.43	5	0.12	8	0.42	12	1.02	108	2.25	11	0.32	0	0.00	852	28.41	0.7	0.01	30.99	7.57		
1	2	30	15	5	1,225	896	7.5	269	11.68	22	0.55	26	1.32	9	0.78	348	7.25	3	0.08	0	0.00	208	6.94	3.5	0.06	14.33	7.62		
6	3	30	15	5	1,735	1,541	0.1	529	23.01	7	0.17	7	0.36	39	3.23	410	8.54	9	0.26	0	0.00	539	17.95	1.0	0.02	26.77	7.49		
5	6	30	15	370	590	391	0.5	33	1.43	4	0.10	63	3.13	16	1.35	251	5.23	0	0.00	0	0.00	23	0.76	1.0	0.02	6.01	7.81		
5	6	30	15	15	485	479	0.1	35	1.51	4	0.10	58	2.92	49	4.02	127	2.65	7	0.19	0	0.00	146	4.86	53.0	0.85	8.55	7.20		
14	7	30	15	9	530	484	0.1	36	1.57	4	0.11	64	3.22	38	3.14	260	5.41	5	0.15	0	0.00	76	2.54	0.7	0.01	8.11	7.70		
4	8	30	15	5	900	831	0.4	251	10.91	10	0.26	30	1.50	26	2.14	163	3.40	6	0.17	0	0.00	343	11.44	1.5	0.02	15.03	7.66		
12	8	30	15	5	795	832	0.3	302	13.14	0	0.11	10	0.48	7	0.60	194	4.04	1	0.04	0	0.00	313	10.42	0.8	0.01	14.51	8.09		
9	30	15	16	396			0.4	14	0.59	0.59	0.00	14	0.59	6	0.50	39	0.82	6	0.17	183	6.10	0.0	0.00	77	2.56	3.7	0.06	38.20	5.83
14	10	30	15	90	2,565	2,509	10.0	318	13.84	9	0.23	236	11.80	152	12.50	1,690	35.20	13	0.38	0	0.00	77	2.56	3.7	0.06	38.20	5.83		
6	14	30	15	75	1,940	1,944	0.2	522	22.70	8	0.19	79	3.97	87	7.18	658	13.70	12	0.35	0	0.00	576	19.20	2.3	0.04	33.29	7.19		
16	14	30	15	110	1,580	1,421	1,700	487	21.16	21.16	0.00	19	0.94	35	2.86	340	7.08	11	0.31	64	2.12	462	15.40	2.8	0.05	24.96	8.48		
16	14	30	15	138	1,915	1,801	2,350	561	24.40	4	0.10	97	4.86	31	2.56	399	8.32	10	0.28	49	1.64	647	21.56	2.8	0.05	31.85	8.32		
5	15	30	15	2,340	2,154	2,038	7.5	840	36.52	9	0.23	4	0.22	5	0.44	450	9.37	9	0.25	174	5.80	658	21.94	4.6	0.08	37.44	9.03		
8	16	30	15	100	2,360	2,038	0.1	760	33.04	5	0.12	10	0.51	29	2.35	327	6.81	10	0.29	0	0.00	887	29.56	2.0	0.03	36.76	7.29		
2	20	30	15	100	2,330	2,095	2,300	640	27.81	27.81	0.00	100	5.02	23	1.92	753	15.69	23	0.65	22	0.72	523	17.44	15.6	0.25	34.75	8.34		
5	21	30	15	60	2,155	1,835	2,200	614	26.68	26.68	0.00	45	2.24	22	1.82	610	12.71	10	0.28	50	1.68	481	16.02	3.1	0.05	30.74	8.26		
5	21	30	15	100	2,250	2,001	2,300	675	29.35	29.35	0.00	58	2.92	15	1.22	656	13.66	10	0.28	0	0.00	586	19.54	0.8	0.01	33.49	8.03		
14	22	30	15	70	2,135	1,917	2,200	640	27.82	27.82	0.00	51																	

Lsd. or 1/4	Sec.	Tr.	R.	Depth (ft)	Total solids (det.) (ppm)	Total solids (calc.) (ppm)	Specific conductance (micromhos at 25°C)	Fe (ppm)	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	SO ₄ (ppm)	Cl (ppm)	CO ₃ (ppm)	HCO ₃ (ppm)	NO ₃ (ppm)	Sum anions (ppm)	pH									
16	6	30	16	30	640	522		0.1	41	1.77	4	0.09	74	3.72	42	3.47	210	4.37	54	1.52	0	0.00	93	3.10	3.6	0.06	9.05	6.55
16	6	30	16	60	440	439		0.1	16	0.71	3	0.08	97	4.88	34	2.81	84	1.75	3	0.09	0	0.00	193	6.44	9.3	0.15	8.43	7.33
9	7	30	16	15	1,745	1,389		0.1	283	12.30	7	0.17	117	5.86	59	4.82	576	12.00	10	0.28	0	0.00	324	10.81	12.8	0.21	23.30	7.40
8	8	30	16	30	645	616		0.0	74	3.22	3	0.07	78	3.92	39	3.20	297	6.18	0	0.00	0	0.00	109	3.62	16.0	0.26	10.06	7.30
14	9	30	16	28	475	487		0.0	59	2.56	3	0.07	57	2.86	33	2.74	233	4.85	0	0.00	0	0.00	101	3.36	1.2	0.02	8.23	7.66
1	10	30	16	< 50	720	643		0.0	31	1.36	4	0.11	94	4.70	54	4.46	340	7.50	33	0.94	0	0.00	66	2.20	0.7	0.01	10.65	7.63
8	11	30	16		600	531		0.6	21	0.93	5	0.12	62	3.08	50	4.12	250	5.20	8	0.22	0	0.00	39	1.30	95.0	1.53	9.37	7.43
13	12	30	16		825	842		2.0	223	9.67	10	0.26	41	2.04	29	2.38	275	5.73	11	0.30	0	0.00	250	8.32	0.7	0.01	14.36	7.63
15	12	30	16	S	855	854		0.0	322	14.02	2	0.05	7	0.34	4	0.30	206	4.30	3	0.09	0	0.00	309	10.30	1.1	0.02	14.71	7.99
9	13	30	16	S	355	286			29	1.21	1	0.02	60	3.00	15	1.24	40	0.83	0	0.00	0	0.00	139	4.62	2.9	0.05	5.50	8.30
10	14	30	16	23	600	573		0.2	99	4.31	4	0.10	61	3.07	27	2.19	325	6.77	7	0.20	0	0.00	49	1.62	1.1	0.02	8.61	7.25
10	14	30	16	S	557	554			103	4.48	5	0.13	69	3.46	24	2.00	140	2.92	4	0.12	1	0.00	209	6.96	0.3	0.00	10.00	8.30
4	17	30	16	18	420	363		0.1	33	1.42	28	0.69	56	2.82	18	1.52	91	1.90	0	0.00	0	0.00	124	4.12	13+	0.21	6.23	7.45
14	18	30	16	S	890	792			85	3.68	5	0.12	118	5.88	60	4.90	230	4.79	6	0.18	0	0.00	287	8.46	0.9	0.01	14.54	
16	18	30	16		1,380	1,308			132	5.74	5	0.13	159	7.94	101	8.32	370	7.71	67	1.89	0	0.00	254	8.56	220.0	3.55	21.61	8.13
13	20	30	16	63	1,365	1,295		0.1	324	14.10	6	0.15	33	1.66	73	6.02	530	11.04	8	0.22	0	0.00	315	10.49	5.8	0.09	21.84	7.98
13	21	30	16	S	1,800	1,682			431	18.74	17	0.43	48	2.38	97	7.98	600	12.50	0	0.00	0	0.00	488	16.26	1.0	0.02	28.78	7.89
16	21	30	16	S	1,105	1,077			329	14.32	5	0.13	42	2.08	14	1.16	285	5.94	4	0.11	0	0.00	397	13.24	0.6	0.01	19.30	8.14
4	22	30	16	S	1,842	1,813			689	29.95	8	0.21	31	1.56	18	1.50	310	6.45	1	0.03	22	0.72	738	24.60	0.75	0.01	31.81	8.80
4	22	30	16	S	900	874			308	12.41	3	0.07	19	0.96	10	0.80	240	5.00	6	0.18	0	0.00	285	9.52	2.3	0.01	14.74	8.30
16	22	30	16	S	1,082	1,033			288	12.52	7	0.17	81	4.06	15	1.22	255	5.31	9	0.26	0	0.00	371	12.38	6.5	0.10	18.05	7.88
12	23	30	16	S	787	768			235	10.20	10	0.20	35	1.74	17	1.36	215	4.47	5	0.14	0	0.00	172	5.74	63.0	1.02	9.11	8.00
8	24	30	16	< 50	675	505			26	1.11	1	0.01	110	5.54	30	2.50	80	1.67	24	0.68	0	0.00	370	11.70	1.6	0.02	22.73	8.40
8	24	30	16	S	1,415	1,236		1,550	490	21.31	10	0.48	3	0.24	190	3.96	3	0.08	38	1.28	501	16.70	0.9	0.01	63.0	1.02	9.11	8.00
14	24	30	16	S	1,490	1,284		1,600	487	21.19	21	1.04	6	0.50	230	4.79	3	0.08	12	0.40	523	17.44	1.6	0.02	22.03	8.51		
4	25	30	16	12	1,050	813		1,100	64	2.79	158	7.92	45	3.68	135	2.82	125	3.53	13	0.44	185	6.18	88.0	1.42	14.39	8.31		
4	25	30	16	70	1,500	1,193		1,500	470	20.44	10	0.52	4	0.32	180	3.75	5	0.13	58	1.92	463	15.44	2.6	0.04	21.28	8.72		
2	26	30	16	90	890	820			140	6.10	6	0.15	104	5.20	36	3.00	275	5.73	3	0.07	0	0.00	255	8.50	1.3	0.02	14.32	7.95
8	27	30	16	S	1,790	1,782			704	30.63	5	0.12	8	0.42	2	0.16	335	6.97	6	0.16	29	0.96	692	23.03	1.3	0.02	31.19	
15	28	30	16	S	1,207	1,194			401	17.45	4	0.11	14	0.72	14	1.12	475	9.90	0	0.00	0	0.00	100	3.34	1.1	0.02	4.87	8.10
3	29	30	16	30	540	266		0.1	33	1.42	0	0.00	39	1.93	20	1.61	72	1.50	0	0.00	0	0.00	275	9.16	0.7	0.01	19.35	7.83
1	30	30	16	92	1,565	1,464		8.0	308	13.40	6	0.16	137	6.86	49	4.04	575	11.98	21	0.60	0	0.00	359	11.96	1.8	0.03	4.87	8.10
1	31	30	16		2,305	2,177		15.0	708	30.80	4	0.11	44	2.21	22	1.84	910	18.96	12	0.34	0	0.00	461	15.37	1.1	0.02	24.56	7.63
10	32	30	16	S	2,802	2,898			962	41.81	7	0.17	50	2.50	22	1.84	1,280	26.57	13	0.37	0	0.00	563	18.76	1.3	0.02	34.69	7.90
10	32	30	16		2,602	2,580			851	37.00	5	0.13	41	2.06	28	2.28	1,125	23.44	17	0.46	0	0.00	505	16.84	7.7	0.12	40.86	8.30
4	33	30	16	43	1,755	1,751			609	26.47	4	0.09	21	1.06	11	0.88	675	14.06	10	0.28	0	0.00	418	13.92	3.2	0.05	28.31	8.26
4	33	30	16	S	1,980	1,965			724	31.49	4	0.09	12	0.60	8	0.68	660	13.76	6	0.17	46	1.52	505	16.82	0.45	0.01	32.28	
13	34	30	16		2,490	2,396			764	33.20	6	0.15	122	6.10	59	4.84	1,150	23.96	20	0.56	0	0.00	375	12.50	15.0	0.24	37.26	8.30
16	34	30	16	< 50	1,140	1,122			156	6.78	6	0.10	103	5.13	76	6.23	200	4.17	35	1.00	0	0.00	147	4.90	166.0	2.68	17.54	8.00
2	12	30	17	85	870	702		0.1	33	1.42	4	0.09	87	4.33	60	4.94	113	2.40	0	0.00	0	0.00	252	8.41	1.3	0.02	15.19	7.92
12	13	30	17	S	415	393		0.1	35	1.51	10	0.24	58	2.91	33	2.71	110	2.29	0	0.00	0	0.00	231	7.70	7.2	0.12	10.22	7.60
13	13	30	17	S	735	704		0.1	182	7.91	4	0.10	49	2.45	27	2.18	167	3.48	0	0.00	0	0.00	146	4.88	1.8	0.03	7.20	8.30
15	13	30	17	S	750	748		0.1	142	6.18	6	0.14	72	3.59	40	3.29	230	4.79	0	0.00	0	0.00	256	8.54	1.8	0.03	13.36	7.27
15	13	30	17	S	765	745		0.2	196	8.54	6	0.14	44	2.21	36	2.99	170	3.54	0	0.00	0	0.00	289	9.64	0.9	0.01	13.19	8.10
16	13	30	17	S	820	623		0.1	106	4.57	6	0.14	85	4.24	26	2.16	190	3.96	0	0.00	0	0.00	207	6.90	3.5	0.06	10.92	8.00
1	14	30	17	S	560	430		0.5	70	3.05	4	0.10	96	3.99	12	1.00	55	1.15	0	0.00	0	0.00	208	6.94	0.9	0.01	8.10	7.53
2	14	30	17	S	770	616		0.1	83	3.61	4	0.11	83	4.16	41	3.34	143	2.98	0	0.00	0	0.00	261	8.70	1.2	0.02	11.70	7.60
9	15	30	17	S	465	352		0.1	59	2.56	4	0.10	57	2.85	18	1.48	5	0.10	0	0.00	0	0.00	208	6.92	1.2	0.02	7.04	8.32
16	23	30	17	45	1,200	1,131		1,210	297	12.91	12	0.91	86	4.28	11	0.90	510	10.62	10	0.29	0	0.00	215	7.16	1.2	0.02	18.09	
9	25	30	17	S	885	865			232	10.10	9	0.23	64	3.22	26	2.14	200	4.17	3	0.09	0	0.00	328	10.94	0.4	0.01	15.21	
9	25	30	17	70	1,120	1,103			383	16.66	2	0.06	19	0.96	10	0.86	380	7.92	6	0.16	0	0.00	298	9.92	2.4	0.04	18.04	8.30
9	25	30	17	90	1,115	1,117			311	13.54	8	0.21	60	3.00	24	1.94	385	8.02	10	0.27	0	0.00	314	10.48	3.8	0.06	18.83	8.30
12	25	30	17	S	2,610	2,161		2,200	635	27																		

	1	8	31	15	215	1,500	1,368	1,600	574	-----	24.94	6	0.30	1	0.10	60	1.25	6	0.17	26	0.88	691	23.02	1.2	0.02	25.34	8.45	
	9	9	31	15	165	885	803	850	132	-----	5.75	82	4.12	60	4.96	220	4.58	4	0.12	0	0.00	304	10.12	0.6	0.01	14.83		
	1	16	31	15	180	1,440	1,347	1,570	484	-----	21.03	32	1.60	5	0.42	350	7.29	6	0.18	0	0.00	466	15.52	3.7	0.06	23.05	8.30	
	13	17	31	15	75	3,100	2,779	3,000	1,020	-----	44.36	34	1.70	5	0.42	850	17.71	59	1.67	36	1.20	776	25.88	1.2	0.02	46.48	8.44	
	2	22	31	15	5	685	610	640	47	-----	2.06	83	4.16	62	5.10	211	4.39	5	0.13	0	0.00	203	6.78	1.2	0.02	11.32	7.91	
P Q R	4	3	31	16	40	2,354	2,277		573	24.91	9	0.24	136	6.80	59	4.88	977	20.38	188	5.02	0	0.00	335	11.16	1.9	0.03	36.59	
	4	3	31	16	80	2,044	1,998		617	26.83	8	0.21	66	3.32	24	2.00	850	17.71	20	0.56	0	0.00	413	13.78	6.8	0.11	32.16	
	4	3	31	16	100	1,976	1,946		606	26.35	8	0.20	61	3.06	23	1.88	820	17.10	16	0.45	0	0.00	410	13.66	2.8	0.04	31.25	
	4	3	31	16	120	2,192	1,859		563	24.47	5	0.12	77	3.86	24	1.94	704	14.66	18	0.51	0	0.00	461	15.38	5.4	0.09	30.64	8.00
	15	10	31	16	70	1,590	1,492	1,720	495	-----	21.54	46	2.28	12	0.96	495	10.31	23	0.66	0	0.00	409	13.62	12.0	0.19	24.78	8.29	
	2	14	31	16	50	2,630	2,401	2,500	822	-----	35.77	57	2.84	10	0.80	860	17.92	26	0.74	0	0.00	620	20.66	5.6	0.09	39.41	8.30	
	5	20	31	16	150	4,218			1,175	-----	51.09	-----	20.00	0	0.00	1,923	54.23	0	0.00	0	0.00	321	10.70	382.0	6.16	71.09		
	5	20	31	16	130	3,630			880	-----	38.23	-----	16.40	1,380	28.76	215	6.07	387	-----	-----	-----	-----	12.90	428.0	6.90	54.63		
M	5	20	31	16	50	3,105	3,121		483	21.00	8	0.20	285	14.27	150	12.33	1,650	34.38	96	2.69	0	0.00	225	7.50	224.0	3.61	48.18	
N	5	20	31	16	100	3,195	3,169	3,400	510	22.17	10	0.25	288	14.40	150	12.60	1,695	35.28	96	2.69	0	0.00	261	8.70	155.0	2.50	49.17	
O	5	20	31	16	120	3,215	3,262	3,400	541	23.52	10	0.26	272	13.58	165	13.62	1,800	37.53	96	2.70	0	0.00	256	8.52	122.0	1.97	50.72	

* 23].....10.04 represents sum of the two cations (anions).

FIGURE 2. Topography and surface drainage of study area



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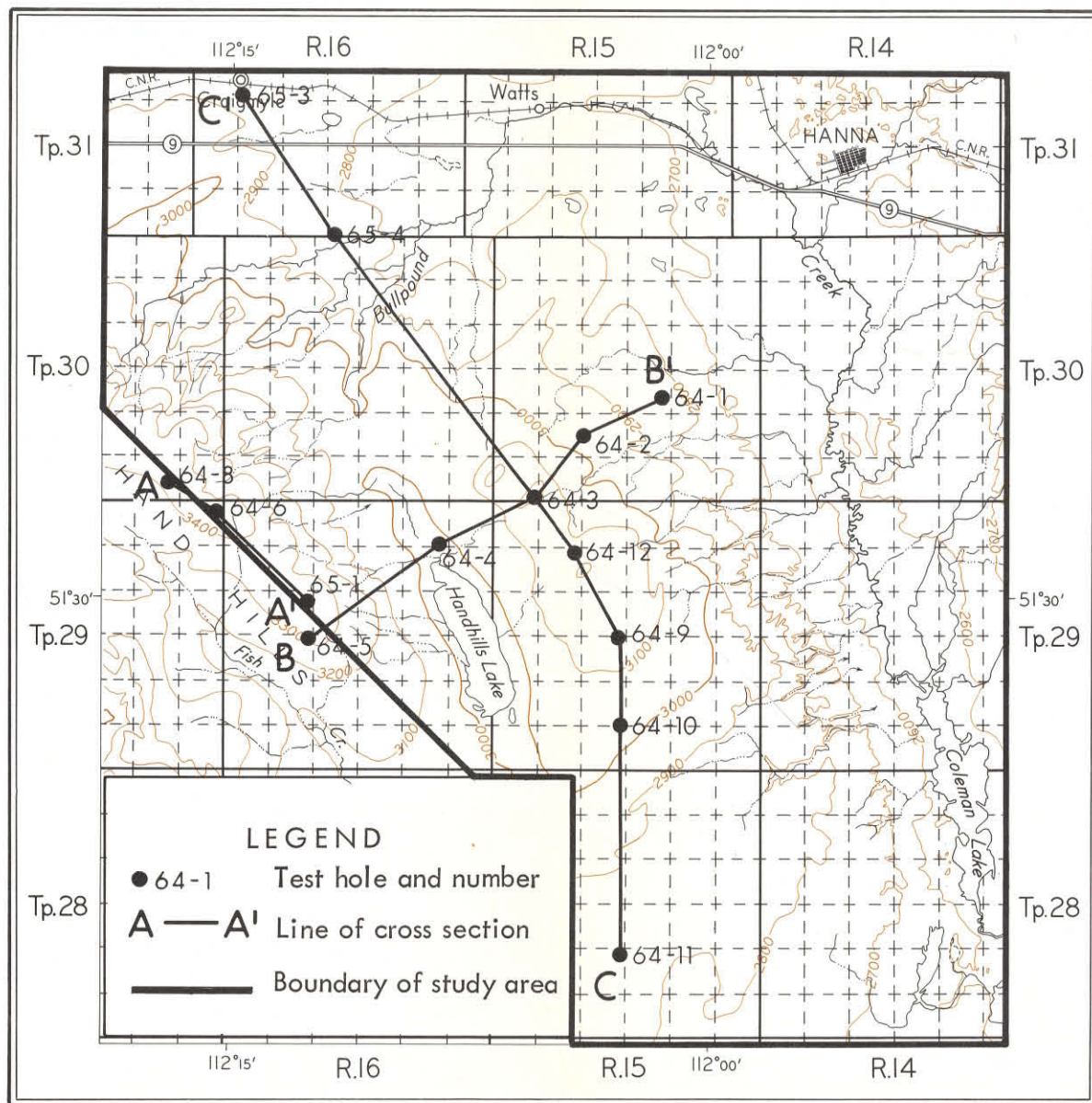
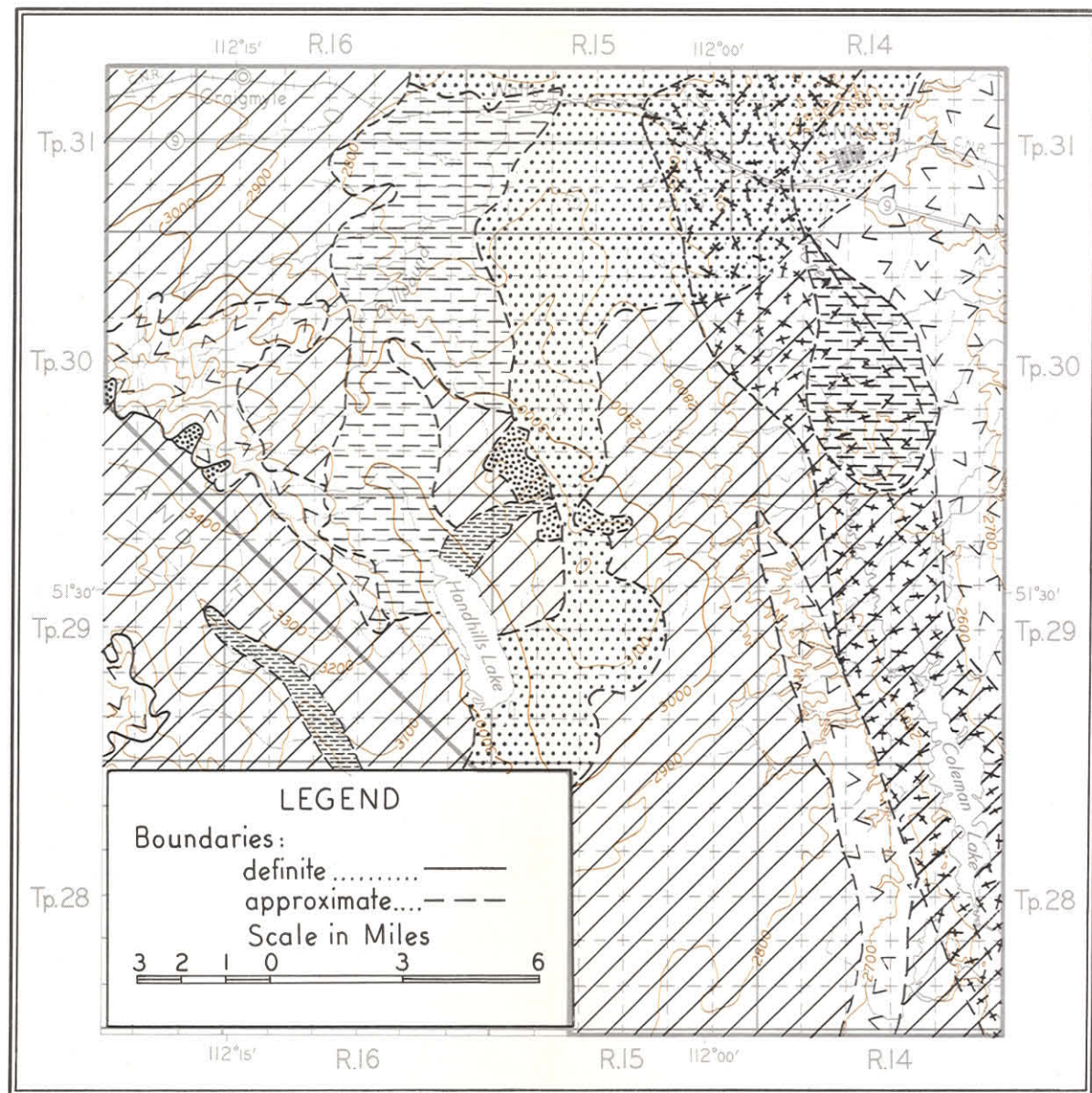
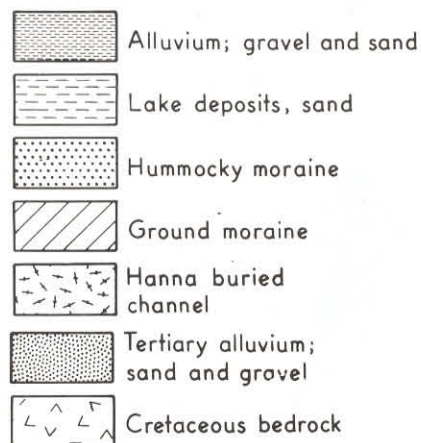


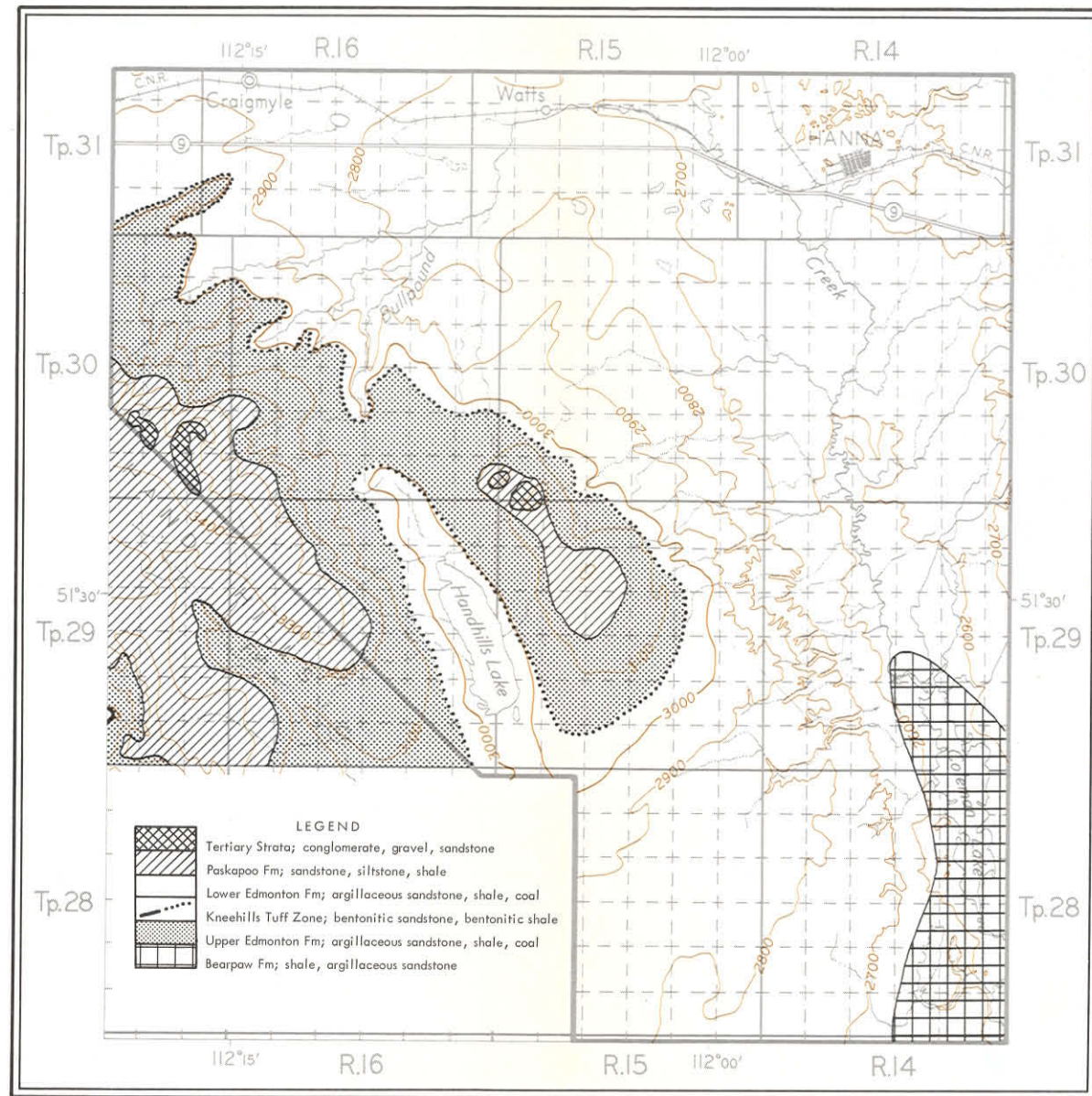
FIGURE 3. Surficial deposits of study area

LEGEND



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FIGURE 4. Bedrock geology of study area



Scale in Miles
1 0 1 2 3 4 5

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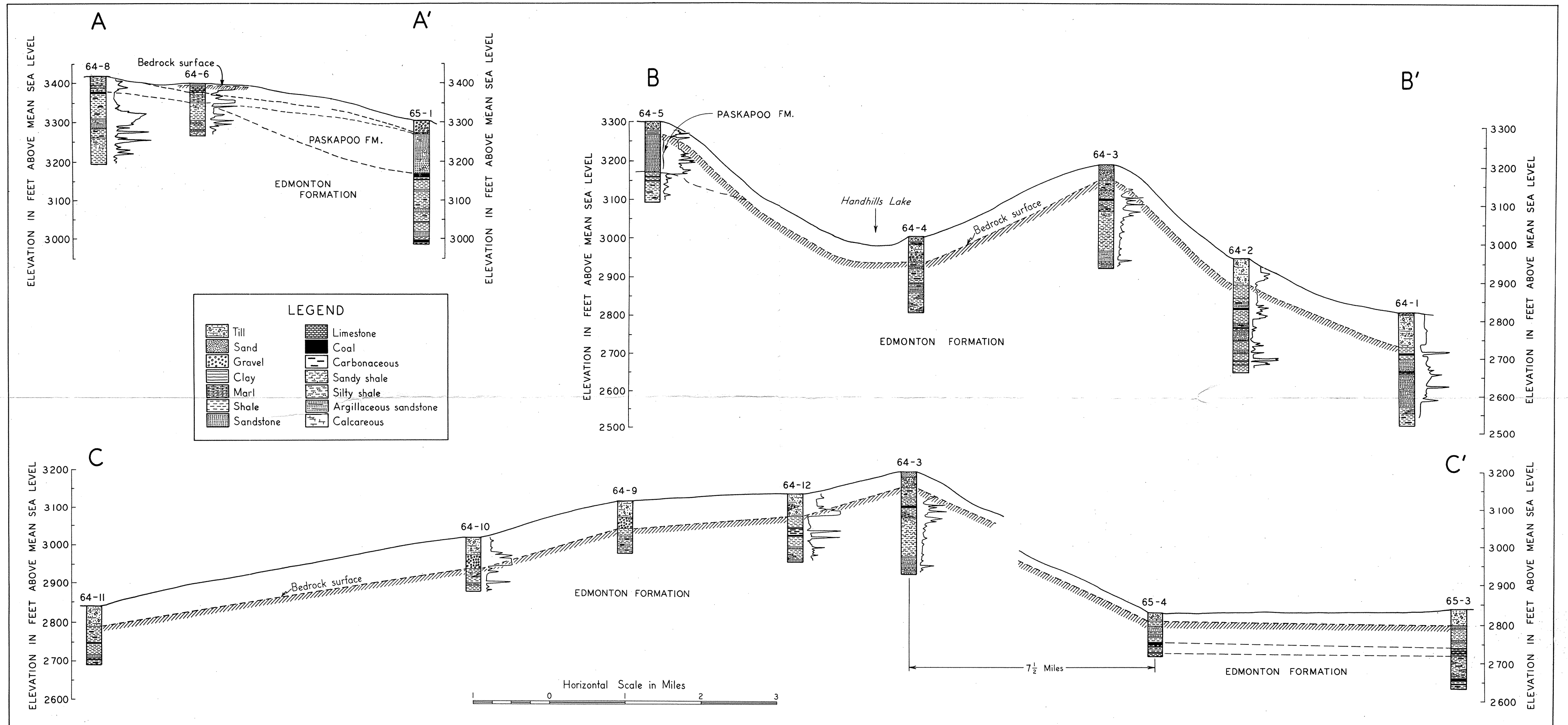
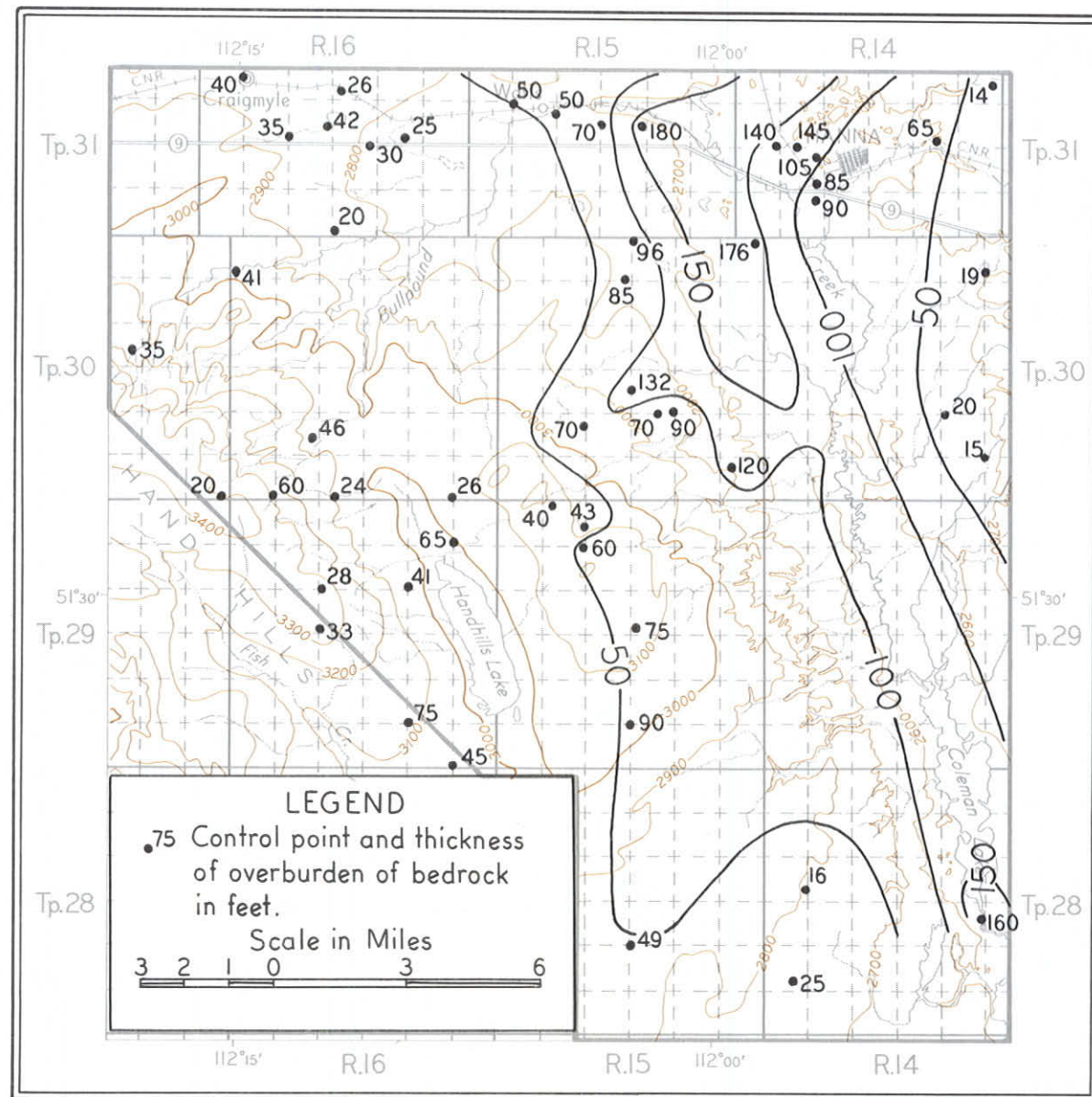


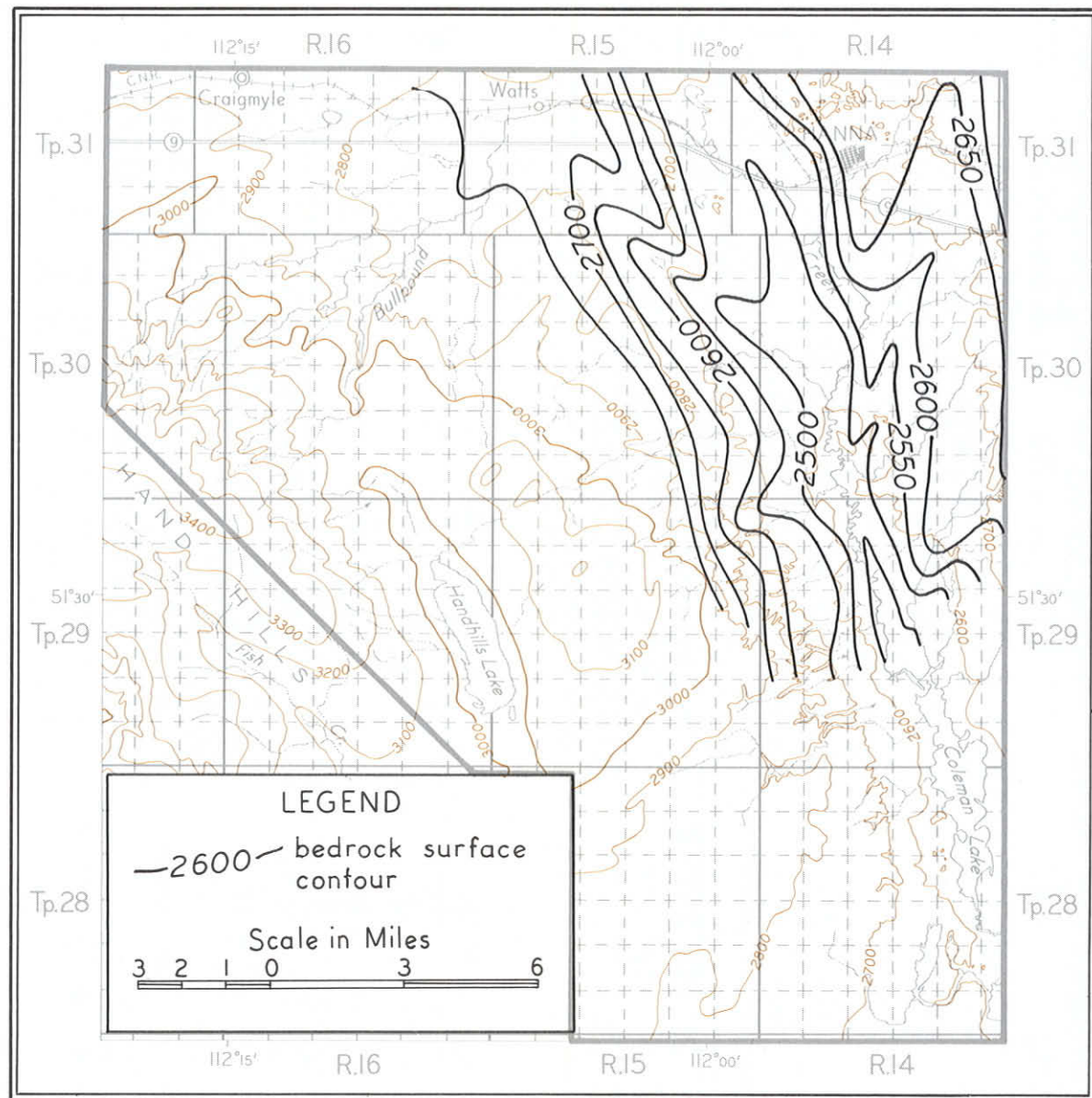
FIGURE 5. Geologic cross sections

FIGURE 6. Isopach map showing thickness of surficial deposits



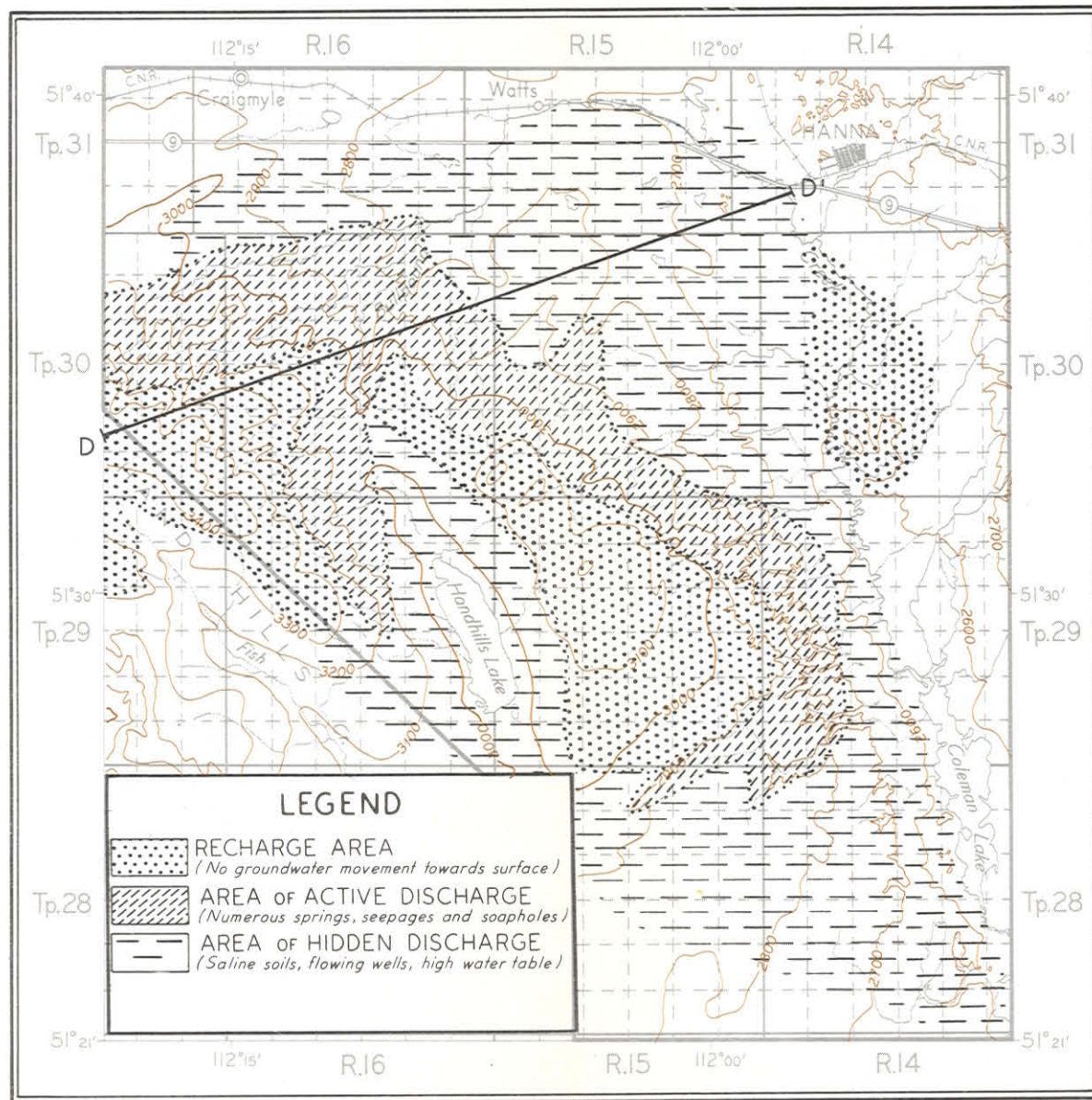
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FIGURE 7. Bedrock topography of Hanna buried valley and vicinity



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FIGURE 8. Discharge and recharge areas of study area



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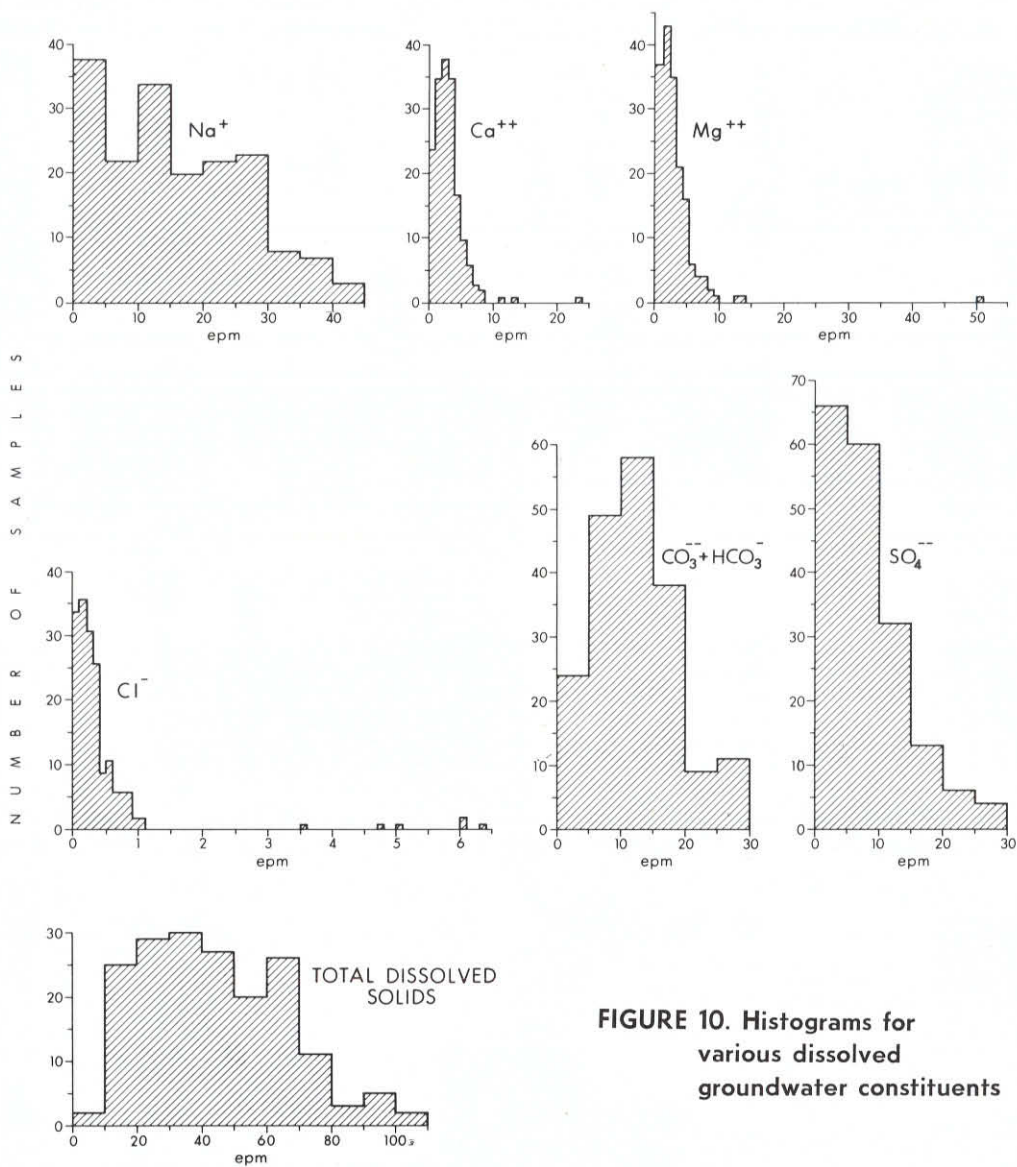
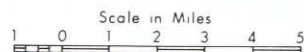


FIGURE 10. Histograms for various dissolved groundwater constituents

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FIGURE 11. Areal distribution of total anions content



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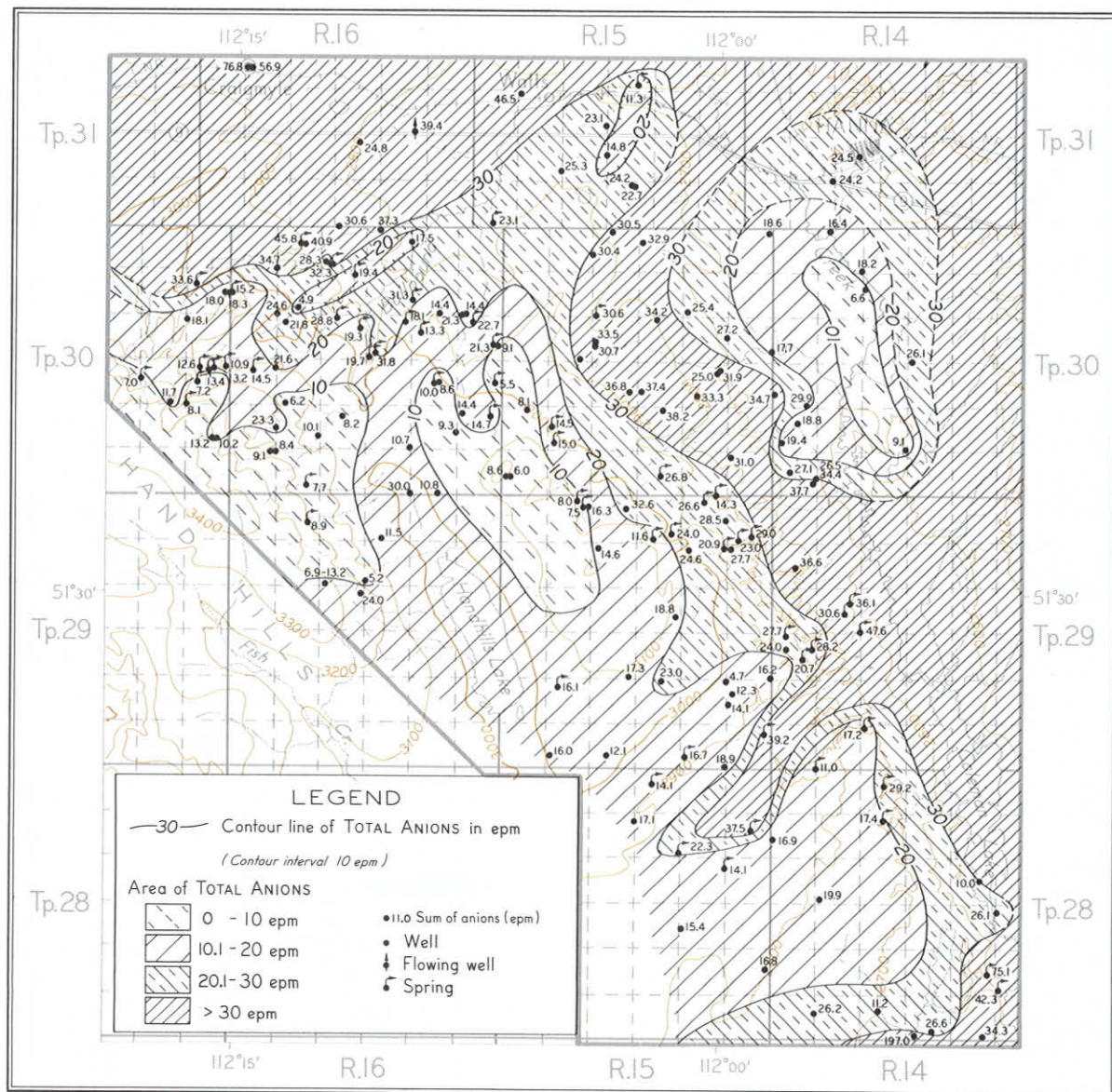


FIGURE 12. Areal distribution of carbonate plus bicarbonate as a percentage of total anions

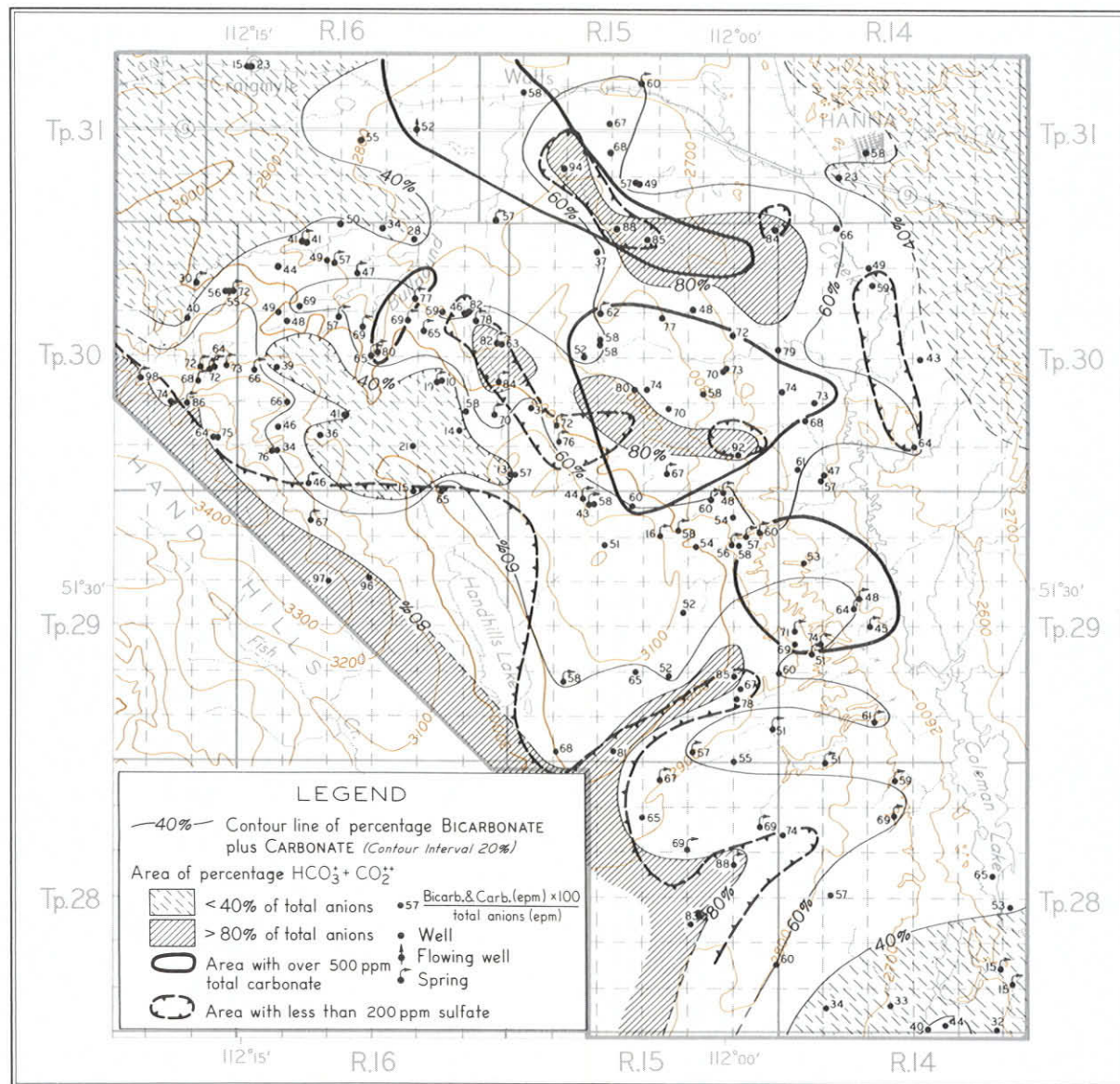


FIGURE 13. Areal distribution of chloride as a percentage of total anions

Scale in Miles
1 0 1 2 3 4 5

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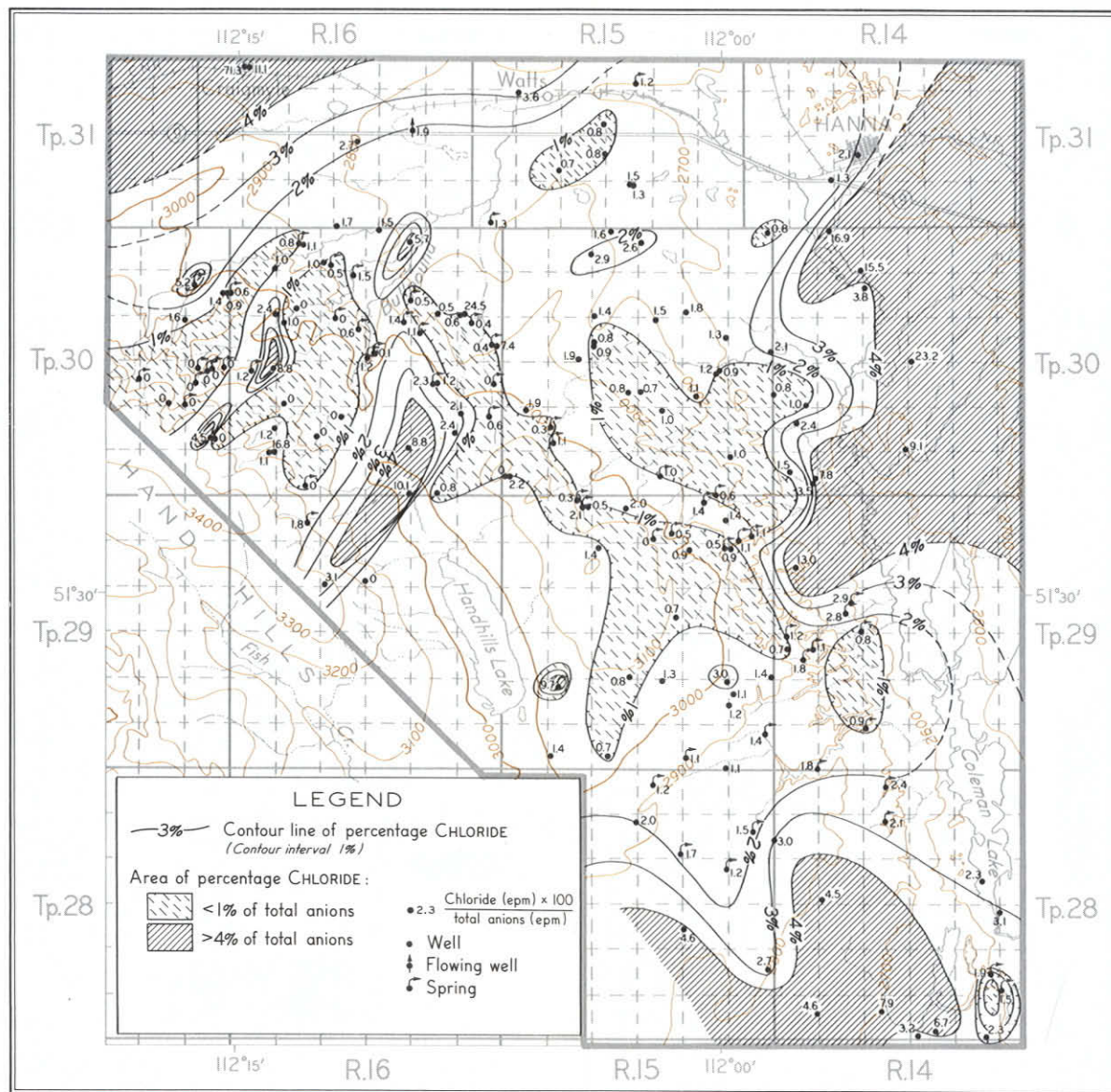
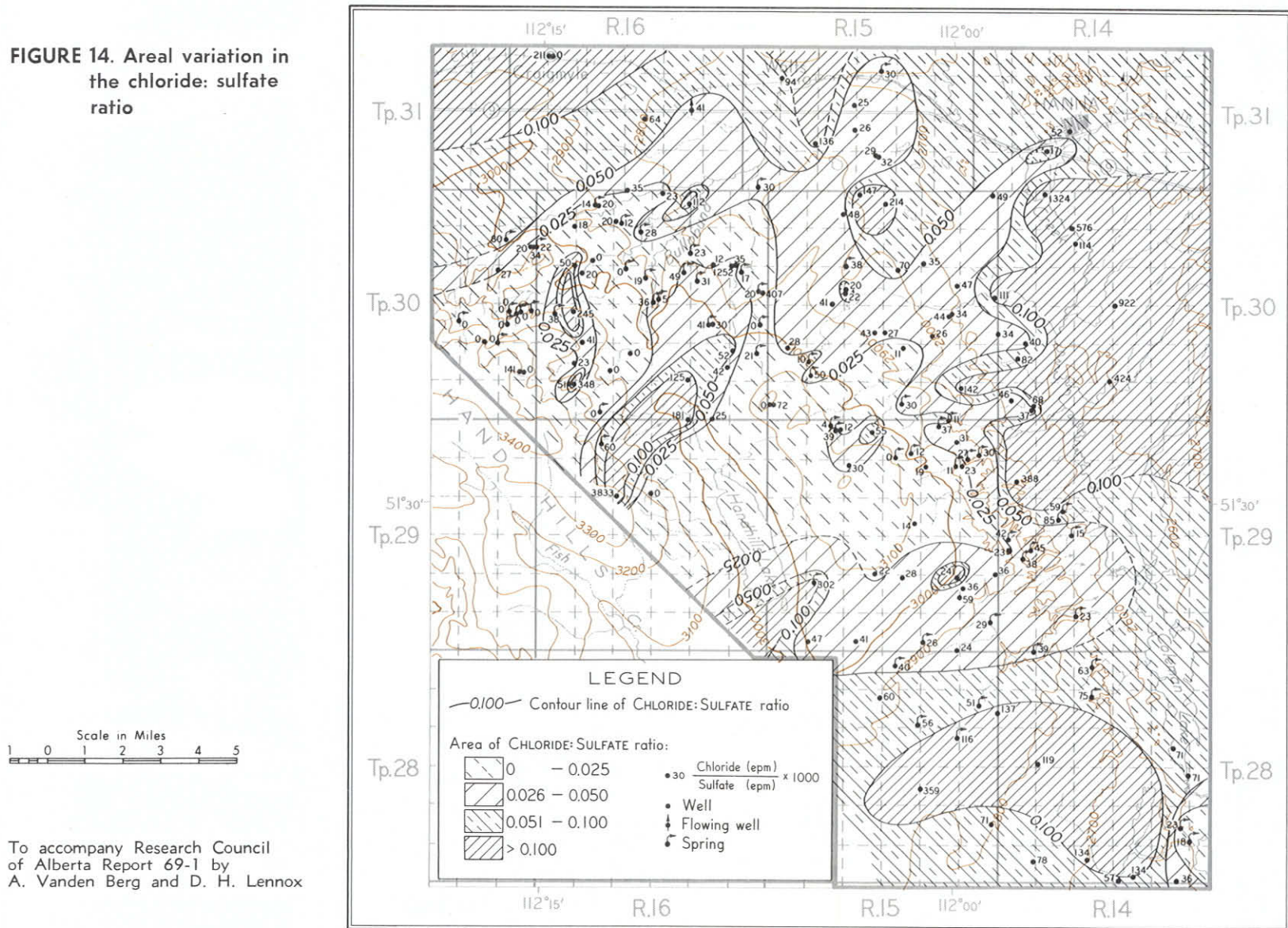
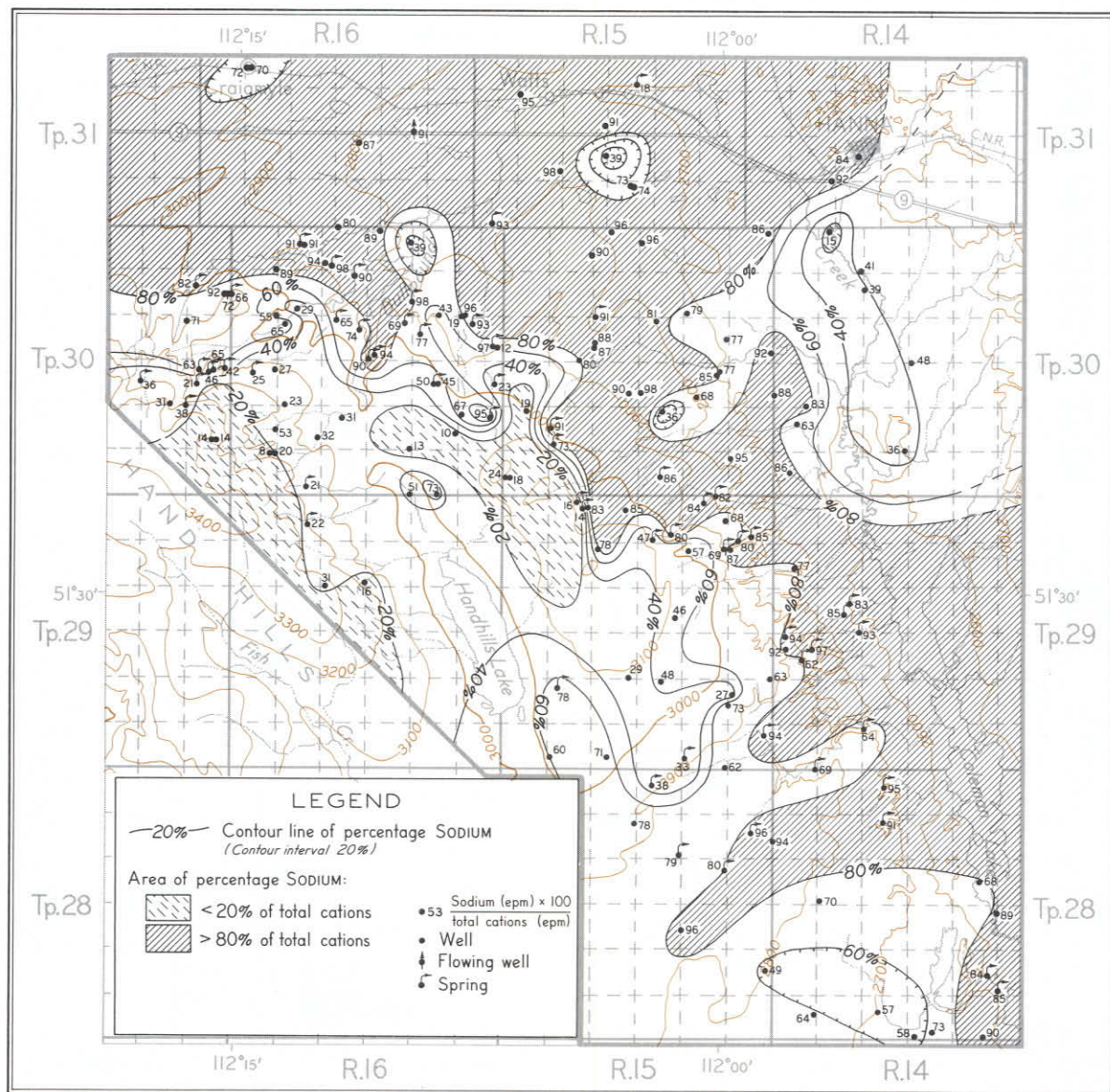


FIGURE 14. Areal variation in the chloride: sulfate ratio



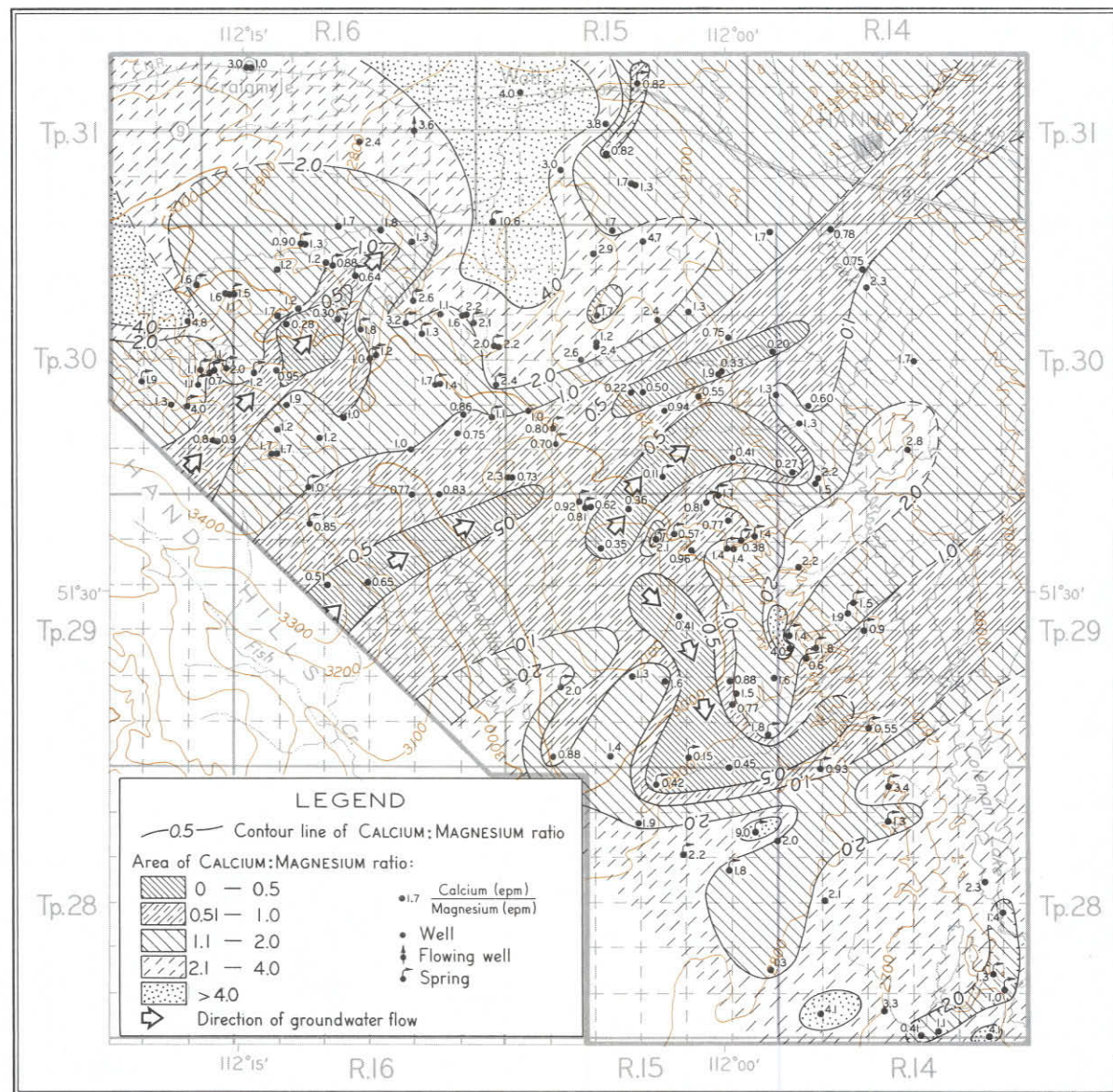
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FIGURE 15. Areal distribution of sodium as a percentage of total anions



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FIGURE 16. Areal variation in calcium: magnesium ratio



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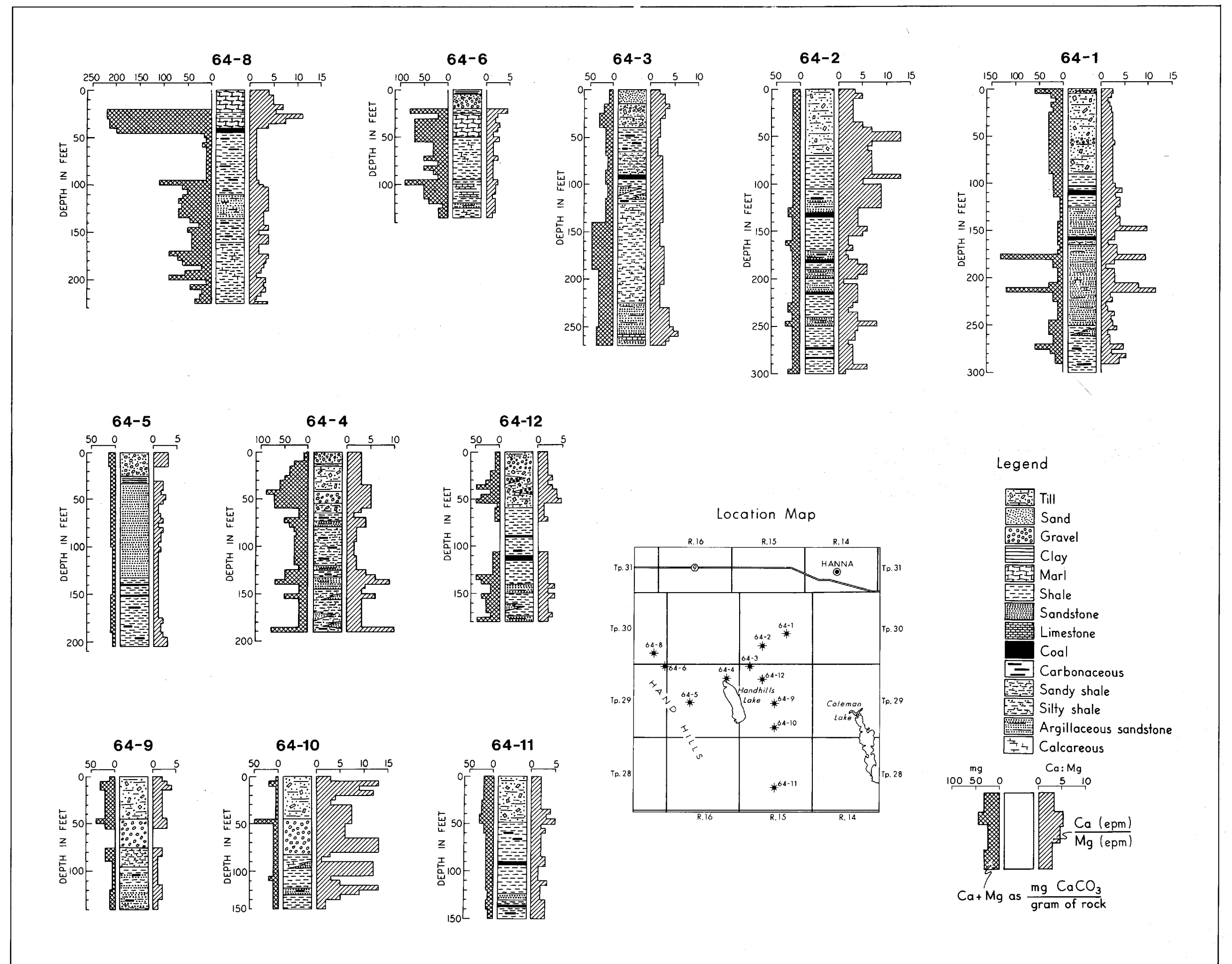


FIGURE 17. Test-hole logs showing occurrence of acid-soluble calcium and magnesium in sediments

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