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GEOLOGY AND GROUNDWATER RESOURCES OF THE MILK RIVER SANDSTONE IN SOUTHERN ALBERTA

by
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Edmonton
Printed by L. S. Wall, Queen's Printer for Alberta
1960

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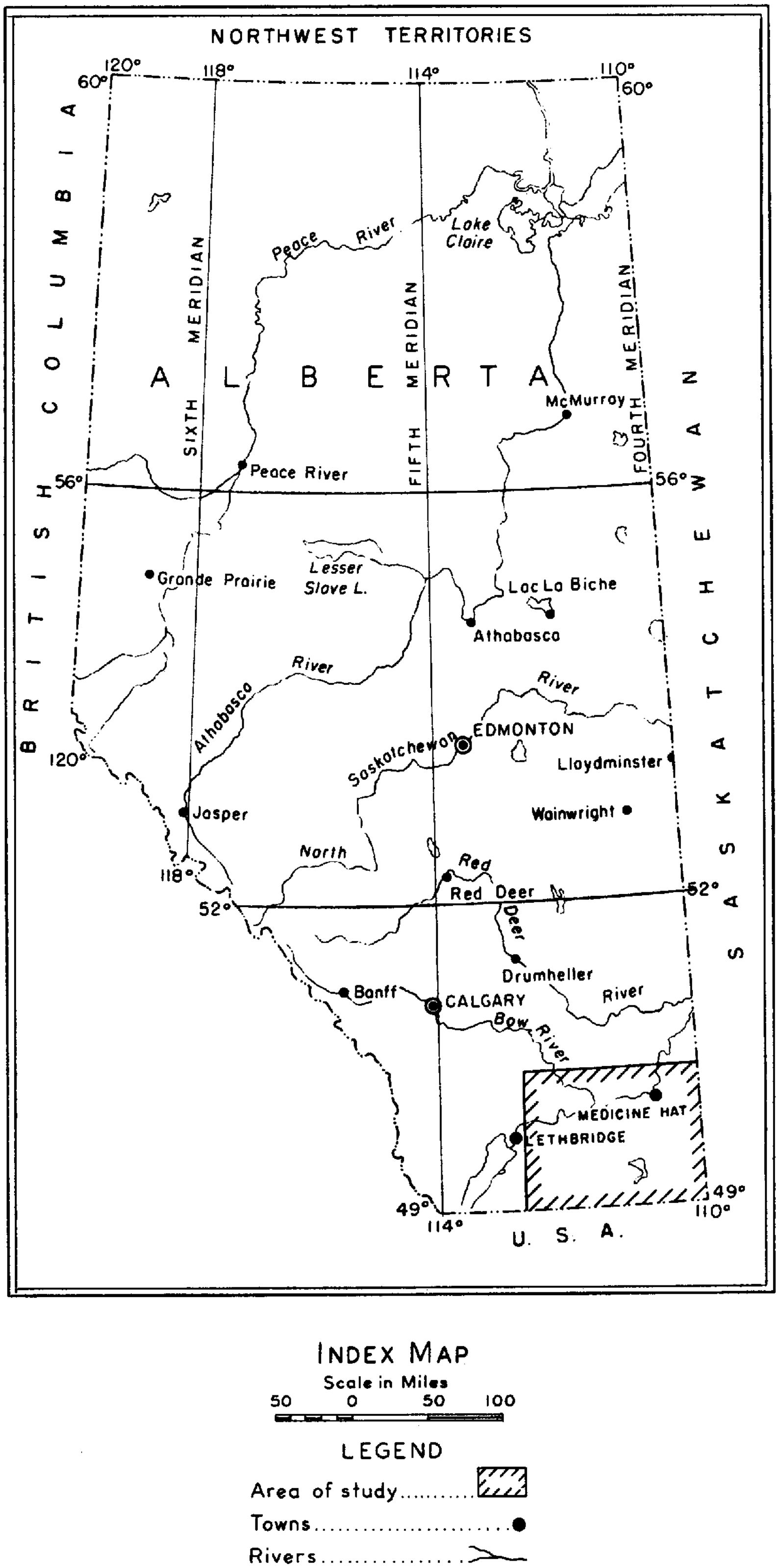


FIGURE 1. Map showing location of the area

Introduction

PURPOSE AND SCOPE OF INVESTIGATION

When the general decline of water levels in many of the deep wells in southern Alberta warned of a serious future problem, the Alberta Federation of Agriculture requested the Research Council of Alberta to investigate the groundwater conditions in this part of the Province. Such an investigation was carried out during 1958 and 1959 on the Milk River sandstone, which is an extensive artesian aquifer in southern Alberta. The results of the study are presented in this report.

During the investigation data were recorded pertaining to the depths of the wells drilled into the Milk River sandstone, the depths to water and the quality of the water; in addition, field tests were conducted on many of the wells to establish transmissibility values. Adequate control from electrologs, samples and drillers' reports, together with a study of the outcrop area, supplied the necessary information to show the relationship between the geology and the hydrology of the Milk River sandstone. Short interviews with well owners gave a better understanding of the actual demand for water and of the way in which the water from this particular aquifer is used.

LOCATION OF THE AREA AND PHYSIOGRAPHY

The area in which the investigation was conducted lies in the southern part of the Province of Alberta between the 49th and 50th parallels of north latitude and the 110th and 113th meridians of west longitude. The area consists of townships 1 to 12 inclusive, within ranges 1 to 19 inclusive, west of the Fourth Meridian (Fig. 1). This area comprises approximately 7,500 square miles.

Maps 72E and 82H of the National Topographic Series (scale 1:250,000, issued by Canada Department of Mines and Technical Surveys) and the corresponding planimetric sheets (scale 1 inch to 1 mile, issued by the Alberta Department of Lands and Forests) provide reliable topographic coverage.

The physical features of southern Alberta are well described by Russell and Landes (1940) and Wyatt and Newton (1941). However, a general description is necessary in order to stress the importance of water in the southern Alberta prairie regions.

Southern Alberta is traversed by the Saskatchewan River-Missouri River divide, which reaches considerable heights in the Milk River Ridge to the west (4,100 feet), and the Cypress Hills in the east (4,700 feet) (Fig. 2). The average elevation of the intervening plains is 3,000 feet in the south and 2,500 feet in the north. The surface of this area is gently rolling and is cut by some deeply-eroded

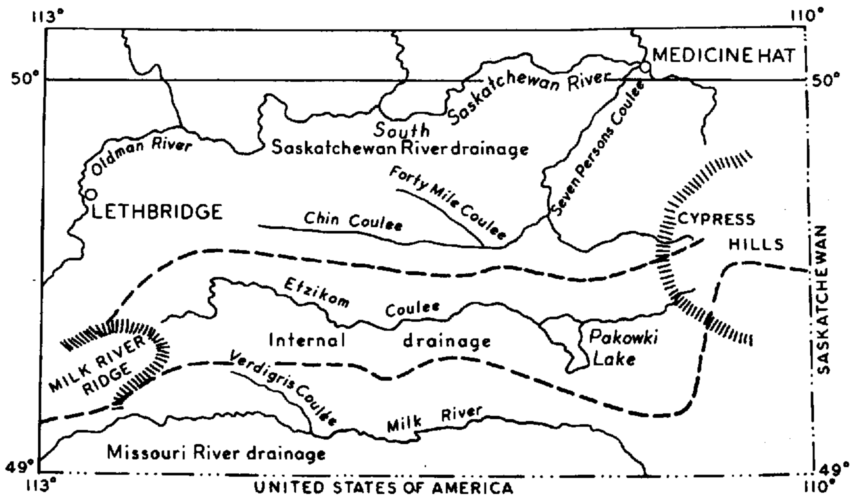


FIGURE 2. Drainage systems in southern Alberta

gullies, known as coulees. The regional surface slope is from the west and south to the north and east.

Several streams run eastward from the Milk River Ridge and westward from the Cypress Hills. The creeks from the Milk River Ridge discharge into the Milk River, whereas those from the Cypress Hills drain into Pakowki Lake (an internal drainage basin), into the South Saskatchewan River or into the Milk River (Fig. 2). These drainage systems also include the coulees which are considered to be relicts of post-glacial drainage, but have since been largely abandoned by streams. Their positions are believed to mark the successive positions of the retreating ice front. Verdigris Coulee, Pendant d'Oreille Coulee, and Lost River Coulee enter the Milk River Valley from the north, Etzikom Coulee is the main channel of the internal drainage system, and Chin Coulee and Forty Mile Coulee, which join to form the Seven Persons Coulee, drain into the South Saskatchewan River (Fig. 2).

CLIMATE AND VEGETATION

The climate on the prairie is semi-arid, and is characterized by long hot summer days and bright cold winter weather. Although lying a considerable distance east of the Rocky Mountains, the area is influenced by warm chinook winds during the winter. These mild winds often replace the cold polar air at irregular intervals, which makes the character of the winter period variable from year to year.

The mean annual temperature is 43°F. The mean annual precipitation is 13 inches, and rainfall is less on the central prairie than on the adjacent uplands.

Southern Alberta has a frost-free period of only 100 days. This strongly affects the character of the plants which grow and can be grown in the area. Thus coarse grains, which can withstand light frosts, are the principal crops and 77 per cent of the fieldcrop is wheat. The non cultivated parts of the area are covered by a typical prairie flora consisting of grasses and sagebrush. Trees do not thrive here, except along some of the coulees, although some farmers have planted shelter belts.

HISTORY AND PREVIOUS INVESTIGATIONS

Southern Alberta was the favorite hunting ground of the Blackfoot Indians, and trappers and rumrunners were the early immigrants.

Captain Palliser visited the area in 1859 while preparing a report on the Western Prairies for the British Parliament. He described the area lying between the Cypress Hills and the Rocky Mountains as an unpromising stretch of arid country. Nevertheless the region became settled and the first agricultural activity was ranching. In 1892 the Bar $\overline{\text{N}}$ Bar ranch was operating on the Pakowki Flats, south of Manyberries.

Construction of the railroad from Medicine Hat to Lethbridge in 1895, followed soon after by the construction of the Lethbridge-Coutts-Montana line, gave easier access to southern Alberta. Thus more settlers arrived in the area in the fall of 1906, and during the next few years the flow of settlers developed into a land rush which lasted until 1910. Encouraged by a series of good crops, the population continued to grow during World War I; then due to the depression and crop failures, many homesteads were abandoned. However, some of the homesteaders persevered and after the depression of the Thirties—and more recently since World War II —a new influx of immigrants has again populated the prairies and many of the abandoned homesteads have become inhabited once more. Many new and comfortable farms have been built during the last few years.

The first geologist to visit the prairie was Sir James Hector, who was a member of the Palliser Expedition spent some time in the "Blackfoot Country". Hector's report, however, deals mainly with central Alberta. The first geological description was given by Dawson, in his "Report on the geology and resources of the region in the vicinity of the forty-ninth parallel from the Lake of the Woods to the Rocky Mountains" (Dawson, 1875). D. B. Dowling conducted an excellent study of the southern Alberta plains, of which the most important contribution was the indication of the Milk River sandstone as a possible artesian aquifer (Dowling, 1915). Fifteen years later, in 1930, Williams and Dyer published the "Geology of Southern

Alberta and Southwestern Saskatchewan"; their most important contribution was a detailed geological map of the Calgary area.

In 1937 the Geological Survey of Canada started a groundwater survey in southern Alberta but results have not been published. Information obtained from this survey is filed in Ottawa and part of it was used for the present study.

In 1940 Russell and Landes published a detailed geologic and stratigraphic study of the "Geology of the Southern Alberta Plains", a firm basis for subsequent work in the area.

In recent years, studies have been carried out by several oil companies. The results of their work were filed at the Alberta Oil and Gas Conservation Board in Calgary, and these reports also were used during the present study.

ACKNOWLEDGEMENTS

The author wishes to express his grateful thanks to Professor Dr. R. W. van Bemmelen (State University Utrecht, Netherlands) for his valuable advice and great help.

Moreover, the author wants to thank J. R. Pow, chief geologist, and M. Fuglem, geologist, of the Provincial Oil and Gas Conservation Board, who have been helpful in providing advice during the preparation of this report.

The author expresses his appreciation to Ir. B. van Nes and Ir. G. Santing, members of the staff of the State Institute for Drinking Water Supply (The Hague, Netherlands) who read critically the chapter on Hydrology; Dr. V. K. Prest, of the Geological Survey of Canada, who generously provided the chemical data that were collected during the 1937 survey; Mr. C. E. Noble, Provincial Analyst, who carried out the analyses of samples taken during the present study; Mr. J. Maynard and Mr. J. McQuillan, from the Medicine Hat and Coaldale Health Units, who supplied many chemical data; the members of the geological staff of the Alberta Oil and Gas Conservation Board in Medicine Hat; the members of the Prairie Farm Rehabilitation activities in Medicine Hat; and the members of the Water Resources Branch in Edmonton for their help and co-operation.

The author is very thankful for the aid and hospitality shown by the ranchers and farmers, without which this study would have been far more difficult.

Geology

STRATIGRAPHY

Cretaceous

The southern Alberta plains are underlain mainly by rocks of Cretaceous age. The Cretaceous strata consist of a complex series of interbedded sandstones and shales which have been subdivided into a number of rock units. The basal Cretaceous strata consist predominantly of a sandy sequence, overlain by a thick shale unit (the Colorado formation), above which lies the Milk River sandstone and a succession of sandstone and shale units (Fig. 3).

For a clear understanding of the stratigraphic position of the Milk River sandstone it is sufficient to give a brief description of the stratigraphic section from the Colorado formation upward.

1. *Colorado Formation.* This important formation underlies the entire southern plains region. A small outcrop of the upper beds of the formation is present in township 1, range 12, but the rest of the formation is known only from drilling records. The Colorado formation is composed of 1,700 feet of dark shale and some sandstone units, which are given in ascending order.

(a) *Basal Colorado sandstone* is a fine-to medium-grained "salt and pepper sandstone", interbedded with silty shale. Its thickness is approximately 10 feet. It lies at the base of the formation and is often called "Colorado water sand", because of its (salt) water content.

(b) *Bow Island sandstone,* 75 feet thick, lies 350 feet above the base of the formation and consists of a series of fine-grained "salt and pepper sandstones", commonly topped by a pebble bed. The Bow Island sandstone is the producing zone of several gas fields in southern Alberta.

(c) *Fish Scale sandstone* is also a "salt and pepper sandstone", only a few feet thick. It is considered to be the top of the Lower Cretaceous (Stelck, Wall, and Wetter, 1958) and because of its distinctive curve on electrologs is commonly used for subsurface mapping.

(d) *Medicine Hat sandstone* is the only important sand occurrence in the upper part of the Colorado formation. The sandstone lies about 100 feet below the top of the formation and was formerly mistaken for the Milk River sandstone. It is a fine- to medium grained "salt and pepper sandstone" and is the producing zone of the Medicine Hat gas field.

The upper boundary of the Colorado formation is commonly taken at the *first white speckled shale,* a dark-grey shale with minute white specks of calcareous material. Above this zone the shale grades into sandy shale and eventually into sandstone. This transitional zone may occupy a vertical interval of 50 feet (Russell and Landes, 1940).

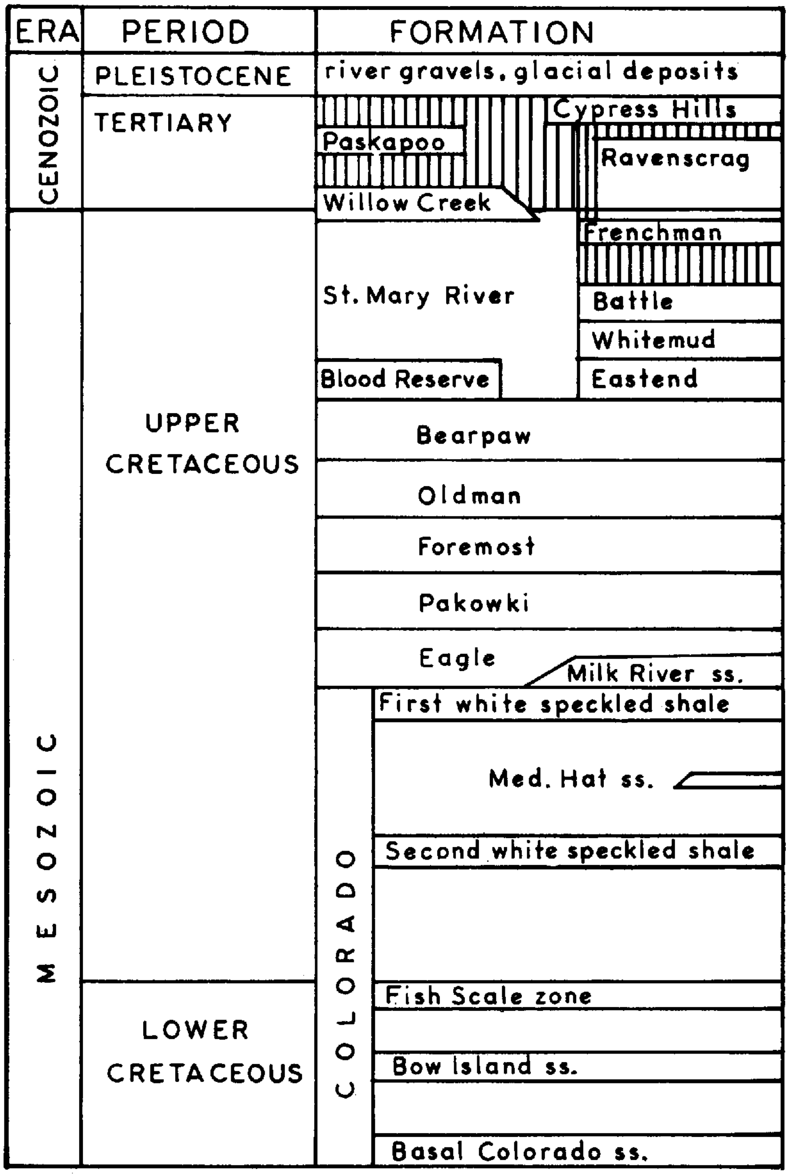


FIGURE 3. Stratigraphic column of southern Alberta

For the purpose of the present study, the upper boundary of the Colorado formation was taken at the bottom of the first definite sandstone appearance on the electrologs.

2. *Eagle Formation.* Until now, this name has been restricted to usage in Montana, but for reasons which will be discussed below, the name Eagle formation is introduced in the stratigraphic terminology of Alberta also. The Milk River sandstone is the basal member of this formation.

Dowling (1915) was the first to use the name Milk River sandstone, which he defined as the "sandstones exposed along Milk River". In the description of this new formation, he stated:

> The Milk River sandstones are only slightly consolidated and several beds near the top of the formation in their exposure along the Milk River are roughly sculptured into castellated shapes and have been referred to by G. M. Dawson as "castellated sandstones". This name not being distinctive has not been continued as a formational name. . . . The sands form a minimum thickness of 5 feet at Medicine Hat to 200 feet at Foremost. The formation is cut through along the top of an anticline by the valley of the Milk River.

It is obvious from this description that Dowling assigned the name Milk River sandstone to the sandstones along Milk River because they constitute a mappable rock-unit.

In a later paper (1916) Dowling elaborated this definition with the statement that "The Milk River sandstone dips under the Pakowki shale". However, he admitted inability to give a clear definition of the stratigraphic boundary because "the line between the clay and shale formation above the sandstone is somewhat indefinite".

Evans (1930) noted and described the occurrence of a chert-pebble conglomerate in the overlying Pakowki shales. He designated this "bed of grey calcareous sandstone containing black chert pebbles" as the base of the Pakowki formation. But as this conglomerate lies stratigraphically a considerable distance above the top of the Milk River sandstones as defined by Dowling, it became necessary to name this stratigraphic interval, consisting of shales, sandy shales and interbedded sandstones. Evans introduced the name "Upper Milk River" for this succession, and he gave the following description (Evans, 1930, p. 15):

> 20-30 feet of grey and yellowish shales and sandy shales, some bentonite and selenite.
>
> 8-24 feet of coarse and medium grained sandstone.
>
> 45 feet of shales, carbonaceous and sandy, with thin sandstone beds and layers of nodules of iron carbonate and greenish sandstone cemented with iron carbonate. These layers and nodules weather dark brown.
>
> 8-22 feet of medium-coarse grained yellowish sandstone.
>
> 45-50 feet of grey, greenish grey, and dark grey sandy shale, with white or yellowish sandstone, top of Lower Milk River.

Evans did not designate a type section for this newly-named member, however, and he retained the name Milk River sandstone to indicate both the Milk River sandstone as defined by Dowling, plus the newly-described shale sequence. The Milk River sandstone as defined by Dowling had thus lost its formational status and became the lower part of a larger stratigraphic unit bearing the same name. To distinguish the upper and lower parts of the formation, Evans applied the names "Upper Milk River" and "Lower Milk River" without lithologic specification. The name Milk River sandstone was extended to indicate both members, thus entirely changing the original definition of this name.

Russell and Landes (1940) essentially followed Evans' stratigraphic nomenclature, but with a slight modification in terminology; they described the Milk River formation as consisting of:

(1) the lower Milk River sandstone;
(2) the upper Milk River beds.

Thus they tried to restore the original definition of Dowling without rejecting Evans' stratigraphic contribution. Until now this vague and ambiguous terminology has been in common usage.

As neither Evans (1930, p. 15) nor Russell and Landes (1940, p. 31) gave a type section for the "Upper Milk River", this name has no formal significance.

Russell and Landes (1940, p. 28) designated Police Creek (NW. 1/4, Sec. 23, Tp. 1, R. 13) as the type section of the Milk River sandstone, this section being one of the localities mentioned in Dowling's report. They gave the following description:

Shale, grey, friable, plastic, with yellow sandstone beds near the base. Basal beds of upper Milk River formation	5 feet
Sandstone, indurated, rather thin bedded in places, brown, very reddish in some parts, a few thin clay streaks	5 feet
Sandstone, light grey and buff, moderately to very hard, massive, cliff-forming, intricately weathered	50 feet
Sandstone as above, becoming progressively somewhat softer	30 feet
Sandstone, moderately hard, brown and bluish grey, rusty weathering, with shaly streaks	5 feet
Sandstone as above, without shaly streaks	5 feet
Alternating sandstone, soft, brown, and shale, grey and light-grey banded, the shale becoming progressively more predominant	15 feet
Shale, very sandy, grey to light-grey, brown banded with numerous rather hard yellowish sandstone beds	15 feet
Shale as above, but sandstone beds less numerous	15 feet
Total exposed thickness	140 feet

The sandstone weathers in steep cliffs and pillars which are commonly protected at the top by a layer of ironstone nodules. Small-scale cross-bedding is common, especially in the upper part of the section.

In northwest Montana the stratigraphic interval between Colorado shale and Clagget (=Pakowki) shale is also occupied by a basal sandstone overlain by a series of interbedded shales, sandy shales, and thin sandstones, and these beds form a continuous natural unit from Montana into Alberta. Weed (1899) named this interval the *Eagle formation,* after the type exposure along the Missouri River near the mouth of Eagle Creek. One year before Dowling's study appeared, Stebinger (1914) reported the presence of a basal sandstone member in the Eagle formation, which he called *Virgelle sandstone,* after the type section along the Missouri River near the town of Virgelle. The Virgelle sandstone is generally recognized as the stratigraphic equivalent of the Milk River sandstone of Dowling (1915). The upper (shaly) part of the Eagle formation was not designated as a separate member.

Although the name Virgelle sandstone (Stebinger, 1914) has priority over Milk River sandstone (Dowling, 1915), wide usage in Canada of the name Milk River sandstone renders it impracticable to reject this name. Another justification for retaining this name is the lithological difference between the Virgelle sandstone and the Milk River sandstone, the latter being finer grained and more argillaceous than the Virgelle sandstone. Therefore the term Milk River sandstone is retained for use in the original sense of Dowling (1915) and the usages of this term by Evans (1930), and Russell and Landes (1940) are rejected as invalid.

As stated above, the term Eagle formation covers the stratigraphic interval between the top of the Colorado formation and the base of the Clagget (Pakowki) formation, which is the interval to which Evans, and Russell and Landes, applied the term Milk River. Thus it seems justified to modify the present southern Alberta terminology so that the name Eagle formation is recognized to indicate the stratigraphic interval between the top of the Colorado formation, which is taken at the first white speckled shale, and the base of the Pakowki formation, which is taken at the chert-pebble conglomerate.

The Milk River sandstone is then defined to be the basal sandstone member of the Eagle formation in southern Alberta and is thus stratigraphically equivalent to the Virgelle sandstone member in Montana, but differs from it lithologically as is apparent from descriptions of the respective type sections.

The question may be raised whether the shale overlying the Milk River sandstone should be included in the Lea Park formation, rather than in the Eagle formation. However, this possibility is ruled out by Shaw and Harding (1954, p. 302, Fig. 2) who clearly demonstrate that the southern equivalents of the Lea Park formation include the Pakowki shale, the micro-micaceous marine shales of which differ considerably from the brackish-water, silty shales overlying the Milk River sandstone.

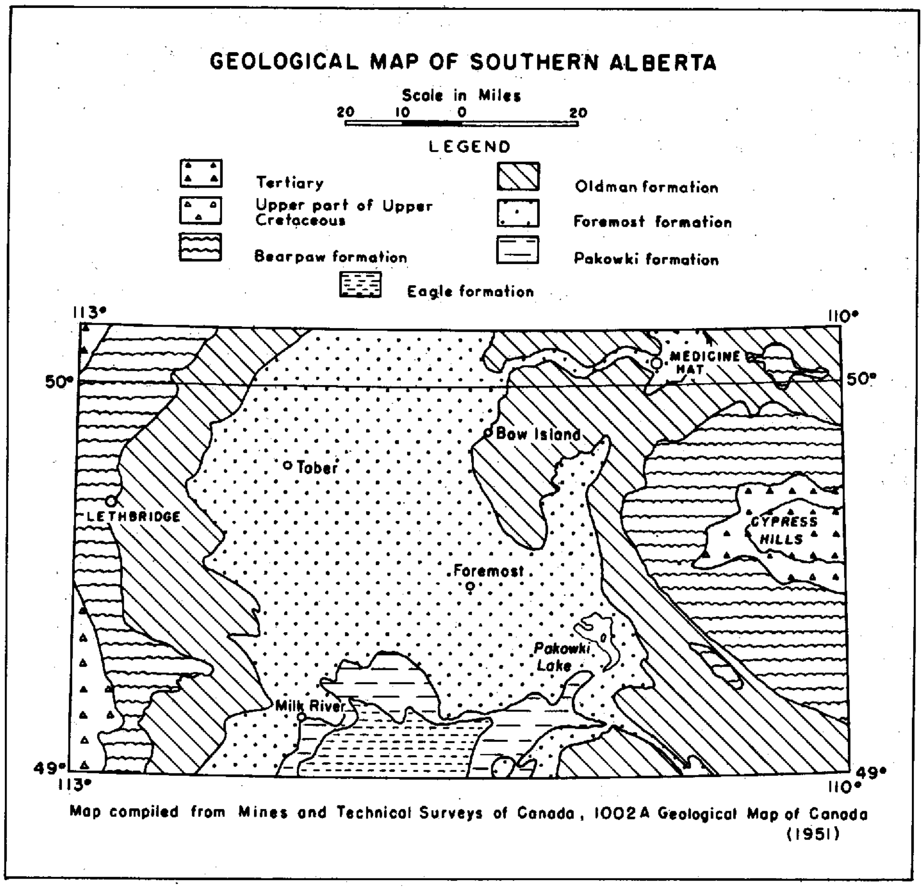

GEOLOGICAL MAP OF SOUTHERN ALBERTA
Scale in Miles
20 10 0 20
LEGEND
Tertiary
Upper part of Upper Cretaceous
Bearpaw formation
Oldman formation
Foremost formation
Pakowki formation
Eagle formation
113°
110°
50°
50°
49°
113°
110°
49°
MEDICINE HAT
Bow Island
Taber
LETHBRIDGE
CYPRESS HILLS
Foremost
Pakowki Lake
Milk River
Map compiled from Mines and Technical Surveys of Canada, 1002A Geological Map of Canada (1951)

FIGURE 4.

Above the Eagle formation is a series of sandstones and shales, which are described for the purpose of completeness.

3. *Pakowki Formation.* This formation consists of grey shale interbedded with thin layers of ironstone, silty shale and bentonite. The formation reaches a maximum thickness of 900 feet in the northeast of the area. The position of the top of the formation is commonly difficult to determine, because of the resemblance of the shales to those of the lower beds of the Foremost formation (Russell and Landes, 1940).

4. *Foremost Formation.* This formation is composed of grey and dark-grey shales, coal seams, thin sandstone beds and some shell-bearing beds. The thickness is about 180 feet.

5. *Oldman Formation.* The typical rocks of this formation are light-colored shales and sandy shales with some coal seams in the upper part, of which the Lethbridge coal member is an example. The thickness varies from 200 to 600 feet.

6. *Bearpaw Formation.* This formation is almost exclusively shale, interbedded with thin layers of bentonite, and it contains zones of ironstone nodules.

The highlands adjacent to the plains are composed of still younger Cretaceous strata. The Bearpaw formation in the Cypress Hills is overlain by a series of shale, sandstone, bentonite and coal beds, which comprise the Eastend, Whitemud, Battle, and Frenchman formations. Their stratigraphic equivalents, the Blood Reserve and St. Mary River formations, also consisting of shales and thin sandstones, are present on the flanks of the Milk River Ridge.

Tertiary

The Tertiary deposits in the area have been removed by erosion, except on the Cypress Hills, which are topped by a thick conglomerate of Oligocene (?) age, overlying the Ravenscrag formation which consists of sandstones and shales of Paleocene (?) age.

The areal distributions of the several formations are shown on the accompanying geological map (Fig. 4).

Pleistocene

Most of the area is covered by glacial drift of varying thickness, except for the Cypress Hills, which were not affected by glacial activity. In the coulees, which already have been described as being ice-marginal drainage channels, the drift cover has been removed, thus exposing the several Cretaceous formations discussed above.

STRUCTURAL GEOLOGY

General Statement

The southern Alberta plains region is situated on a broad northerly-plunging anticlinorium known as the Sweet Grass arch. This arch extends from Montana into Alberta and consists of three

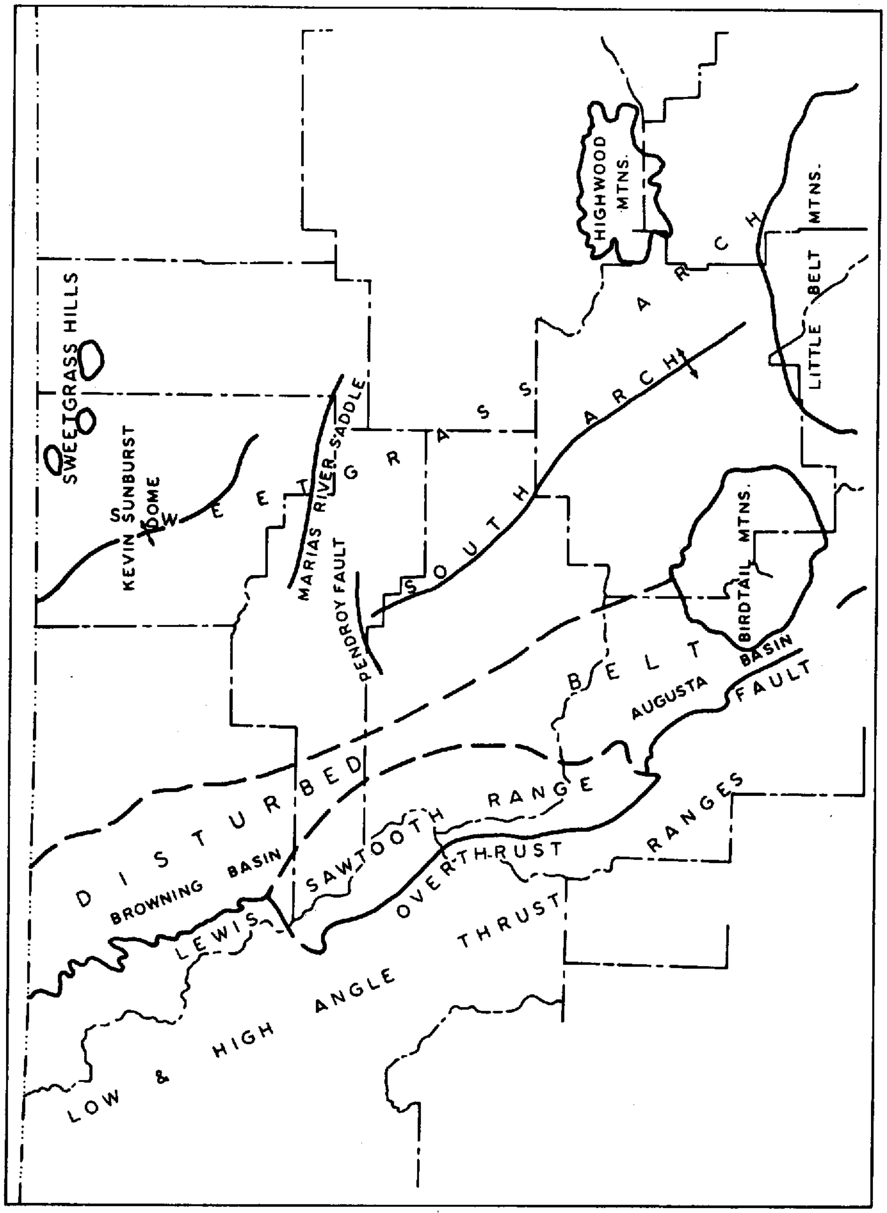


FIGURE 5. Major structural elements of north central Montana (A. G. Alpha, 1955)

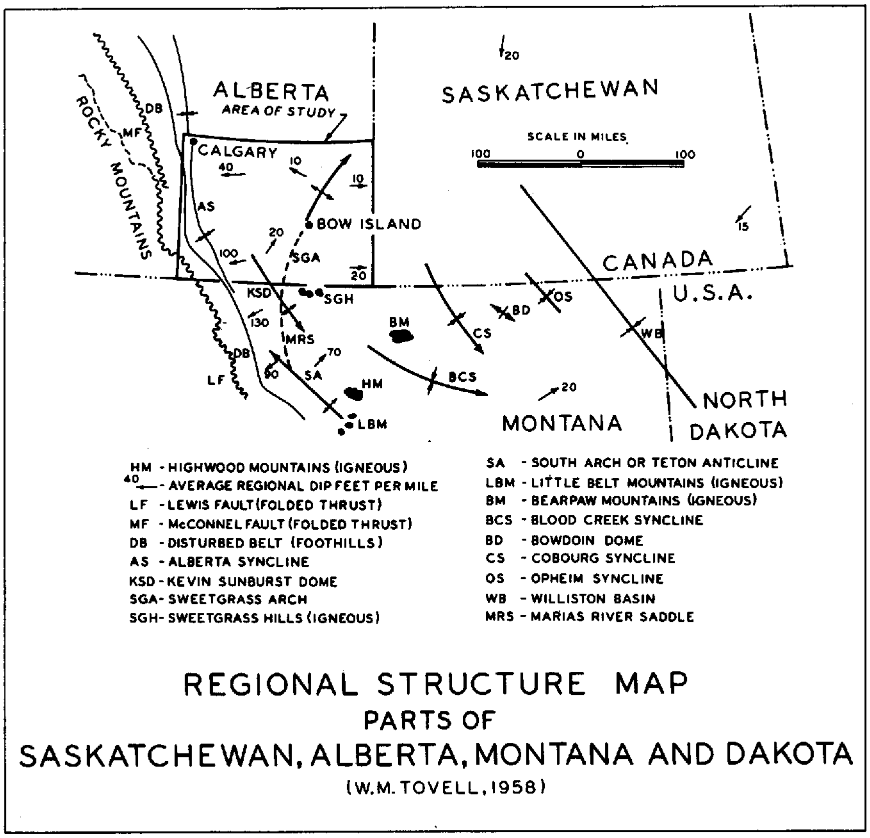

ALBERTA
AREA OF STUDY
SASKATCHEWAN
SCALE IN MILES
100 0 100
ROCKY MOUNTAINS
CALGARY
BOW ISLAND
CANADA
U.S.A.
MONTANA
NORTH DAKOTA
HM - HIGHWOOD MOUNTAINS (IGNEOUS)
40 - AVERAGE REGIONAL DIP FEET PER MILE
LF - LEWIS FAULT (FOLDED THRUST)
MF - McCONNEL FAULT (FOLDED THRUST)
DB - DISTURBED BELT (FOOTHILLS)
AS - ALBERTA SYNCLINE
KSD - KEVIN SUNBURST DOME
SGA - SWEETGRASS ARCH
SGH - SWEETGRASS HILLS (IGNEOUS)
SA - SOUTH ARCH OR TETON ANTICLINE
LBM - LITTLE BELT MOUNTAINS (IGNEOUS)
BM - BEARPAW MOUNTAINS (IGNEOUS)
BCS - BLOOD CREEK SYNCLINE
BD - BOWDOIN DOME
CS - COBOURG SYNCLINE
OS - OPHEIM SYNCLINE
WB - WILLISTON BASIN
MRS - MARIAS RIVER SADDLE
REGIONAL STRUCTURE MAP
PARTS OF
SASKATCHEWAN, ALBERTA, MONTANA AND DAKOTA
(W.M. TOVELL, 1958)

FIGURE 6.

major tectonic elements and a series of subsidiary folds. The strata are gently dipping to the east, north and west. The major tectonic elements in Montana are the South arch and the Kevin Sunburst dome, both trending northwest and separated by the Marias River saddle (Alpha, 1955) (Fig. 5). In Alberta the major tectonic elements are the northwest extension of the Kevin Sunburst dome and the northeast-plunging Bow Island arch (Tovell, 1958) (Fig. 6).

In addition to the above-mentioned structures, there is a series of igneous intrusions on the east flank of the Sweet Grass arch, which form the Sweet Grass Hills in northern Montana. Around these hills nose- and dome-like structures are developed, several of which radiate into Alberta.

Structure

The structure contour map of the Milk River sandstone reveals a fan-like pattern of subsidiary folds associated with the two major tectonic elements and the Sweet Grass Hills intrusions (Fig. 7).

The following structures are distinguished:*

1. *Kevin Sunburst Dome,* located in township 1, range 17; described by Alpha (1955), and Erdman and Schwabrow (1941). This structure is a broad anticline, plunging northwestward.

2. *Red Coulee Structure,* located in township 1, range 16; described by Evans (1930), and Erdman and Schwabrow (1941). This structure is known as the Borderfield structure in Montana. Erdman and Schwabrow suggest that this northeast-plunging anticline "extends from the principal fold (Kevin Sunburst dome) somewhat in the manner than fingers extend from the hand".

   Toward the west similar structures are present, of which the Twin River structure (Tp. 1, R. 20) is the most important in Alberta.

3. *Ericson Coulee Structure,* located in township 1, range 12; described by Russell (1936). This structure is an asymmetrical anticline, tending somewhat west of north. Its axis points in the direction of West Butte, one of the Sweet Grass Hills in Montana. To the north the fold broadens and flattens.

4. *Dead Horse Coulee Structure,* located in township 1, range 11; described by Russell (1936). This is a northward-plunging anticline with closure to the south. Its axis makes a slight angle with the axis of the Ericson Coulee structure, and also points toward West Butte.

5. *Pinhorn Structure,* located in township 1, range 9; described by Russell (1936). The structure is a steep-flanked anticline, trending somewhat east of north. There is closure to the

*The numbers and letters are those shown in Fig. 7.

FIGURE 7. Structure contour map on top of Milk River sandstone

north, but not to the south. Its axis points toward East Butte in Montana.

6. *Black Butte Structure,* located in township 1, range 8; described by McCord (1957). This structure is quite similar to the Pinhorn structure, being a steep anticline with closure to the north. Its axis trends northeast.

7. *Comrey Structure,* located in township 1, range 5; described by Russell (1936). The Comrey structure appears to be a dome, with a slightly steeper dip than the regional dip.

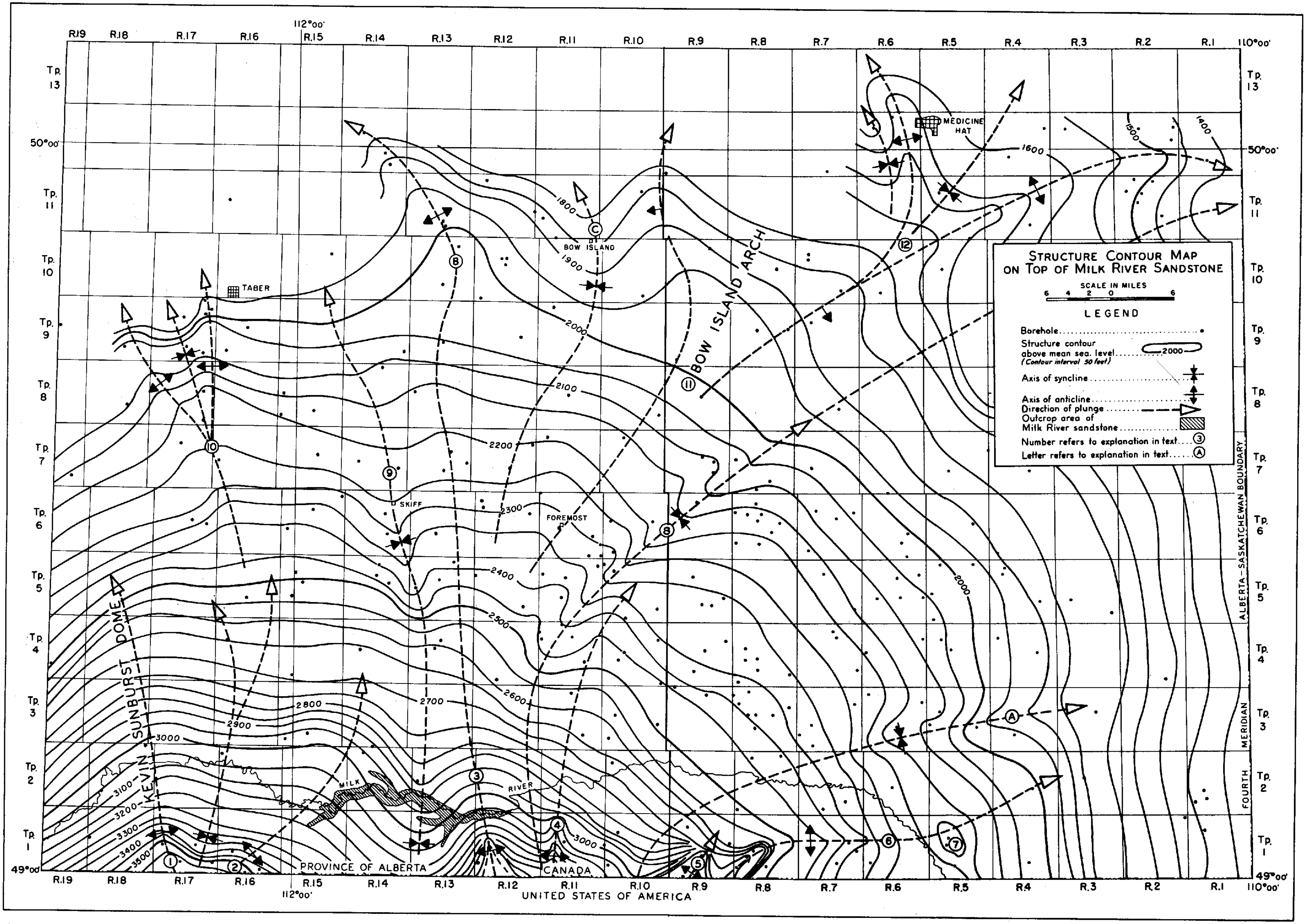
8. *Foremost Structure,* located in townships 4, 5, and 6, ranges 9, 10, 11; described by Howells (1936) and Slipper (1935). Slipper interpreted the structure as an eastward-dipping monocline, but additional information on the area east of Foremost, which was used in the present study, indicates a northeast-trending syncline east of Foremost, the flanks of which have a moderate dip of 30 feet per mile.

   This structure is not an isolated unit, but from the structure contour map (Fig. 7) it appears to be connected with the syncline between Ericson Coulee (3) and Dead Horse Coulee structure (4). Its northward continuation seems to be part of the Medicine Hat structure, which will be discussed later.

9. *Skiff Structure,* located in townships 5 and 6, ranges 13 and 14; described by Howells (1936). Howells obtained his information from scattered water-well borings, and he described the structure as an anticlinal nose, trending north, which was closed in the south by a syncline. However, the Skiff structure is very similar to the Foremost structure, being a broad syncline with moderate dips. In the direction of strike, however, this structure trends somewhat west of north, whereas the Foremost structure trends somewhat east of north. The southern continuation of both of these structures can be followed into township 1, where connection exists of the Skiff structure with the syncline west of the Ericson Coulee structure (3).

10. *Taber Structure,* located in townships 8 and 9, range 17; described by Russell (Russell and Landes, 1940). In determining this structure, Russell obtained his data from the top of the Taber coal seam (Foremost formation). He interpreted the structure as a dome, located southwest of Taber.

    On top of the Milk River sandstone this structure is less pronounced, but characteristic features are still recognizable. There are two anticlines, diverging to the north and joining in township 6, range 16. The eastern fold forms a nose southwest of Taber and the western one trends northwest.



STRUCTURE CONTOUR MAP ON TOP OF MILK RIVER SANDSTONE
SCALE IN MILES
6 4 2 0 6
LEGEND
Borehole
Structure contour above mean sea level (Contour interval 50 feet) 2000
Axis of syncline
Axis of anticline
Direction of plunge
Outcrop area of Milk River sandstone
Number refers to explanation in text
Letter refers to explanation in text
MEDICINE HAT
BOW ISLAND
TABER
SKIFF
FOREMOST
BOW ISLAND ARCH
SUNBURST DOME
KEVIN
MILK RIVER
PROVINCE OF ALBERTA
CANADA
UNITED STATES OF AMERICA
ALBERTA-SASKATCHEWAN BOUNDARY
FOURTH MERIDIAN
112°00'
110°00'
50°00'
49°00'
R.19 R.18 R.17 R.16 R.15 R.14 R.13 R.12 R.11 R.10 R.9 R.8 R.7 R.6 R.5 R.4 R.3 R.2 R.1
Tp. 13 Tp. 11 Tp. 10 Tp. 9 Tp. 8 Tp. 7 Tp. 6 Tp. 5 Tp. 4 Tp. 3 Tp. 2 Tp. 1
1400 1500 1600 1800 1900 2000 2100 2200 2300 2400 2500 2600 2700 2800 2900 3000 3100 3200 3300 3400 3500

11. *Bow Island Arch,* located in townships 10 and 11, ranges 6, 7 and 8; described by Slipper (1935) and Tovell (1958). Slipper described this structure first, under the name Bow Island arch, but he considered it to be restricted to the immediate vicinity of Bow Island only. Tovell recognized the more regional character of the structure and he therefore designated the name Bow Island arch to the broad uplift, plunging northeast toward the central Alberta plains, and disappearing toward the south between Foremost and Skiff structures. In this report the name Bow Island arch is used in the sense of Tovell.

12. *Medicine Hat Structure,* located in townships 11 and 12, ranges 4, 5 and 6; described by McCord (1957). This structure consists of a steep asymmetrical anticline tending north in range 6 and a broader east-trending anticline in townships 11 and 12. The features join in township 10, range 6.

    McCord described this structure as a saddle between the southwest-plunging North Battleford high in Saskatchewan, and the northeast-plunging Bow Island arch.

In addition to these structures several other structural features which became apparent are considered sufficiently large to be discussed. They are indicated in figure 7 by the letters A, B, and C.

A. *Lost River Structure,* located in township 3, ranges 4, 5 and 6. This is a broad syncline, trending east. Its flanks have a moderate dip of 30 feet per mile and from the structure contour map (Fig. 7) there seems to be a relationship between the Lost River structure and the syncline between Dead Horse Coulee (4) and Pinhorn structure (5).

B. A pronounced anticlinal nose is located in townships 6 to 11, ranges 13 and 14. Although this structure trends northwest, it seems to be the northward continuation of the structural high that was described as Ericson Coulee structure (3) in township 1. Because of this continuation there does not seem to be justification for assigning a different name to it, but this anticline can be referred to as the *Grassy Lake portion of the Ericson Coulee structure.*

C. *Bow Island Syncline,* located in townships 9, 10 and 11, range 11, This syncline lies between the Grassy Lake portion of the Ericson Coulee structure and the Bow Island arch. From figure 7 it appears to be a rather broad feature, its flanks dipping 30 feet per mile. It is not possible to follow this syncline far to the south, because it disappears between the converging axes of the adjoining structures.

The over-all picture of the structure map (Fig. 7) reveals a radiating pattern of closely connected folds. The prominent direction of fold axes in the western part of the area is to the west and northwest, whereas the folds in the eastern part all trend east and northeast.

Origin of the Sweet Grass Arch

According to several authors (Alpha, 1955; Wells, 1957) the present Sweet Grass arch had earlier counterparts, at least as far as Mississippian time, for thinning of Mississippian strata over the arch indicates areas of slight tilting on the Alberta shelf. Tovell (1958) demonstrated that an ancestral Bow Island arch was already in existence during early Devonian time. More detailed studies of the Jurassic in Montana (Cobban, 1945) and in Alberta (Weir, 1949) showed that both the south arch and Kevin Sunburst dome, and probably the Bow Island arch, were distinct positive elements during late Jurassic time. In early Tertiary time these ancestral trends were subject to rejuvenating forces which produced the present forms. About the cause and character of these forces, several theories exist.

Alpha (1955) suggested an eastward migration of a mobile belt which caused compression and attendant folding along inherited lines of weakness. Wells (1957) pointed out that the eastward-directed forces of the Rocky Mountain uplift and the opposing forces forces of the Williston basin downwarp resulted in compressional forces which caused the uplift of the intervening Sweet Grass arch. Tovell (1958) ascribed the origin of the Sweet Grass arch to compressional forces due to subsidence of the Williston basin in the east and the Cordilleran geosyncline in the west.

A strong objection against Cretaceous or Tertiary subsidence, or both, of the Williston basin was brought up by Sloss (1956) who pointed out that the Williston basin had ceased to behave like an interior basin by middle Jurassic time. From that date the area became part of a complex of marginal basins, and did not undergo further subsidence. Therefore it could not have contributed to the formation of the Sweet Grass arch, since this structure proper has been shown to be of post-Jurassic age.

However, crustal compressional forces are not necessarily the cause of a fold pattern in an uplifted area. Van Bemmelen (1954) suggested that differential vertical movements of the basal complex, called primary tectogenesis, may be related to mass displacements or expansions and contractions of the substratum underneath. This theory can be applied to give an explanation of the origin of the Sweet Grass arch.

The uplift of the three major tectonic elements of the Sweet Grass arch was caused by vertical movements of the basement complex, and the structural pattern on top of the Milk River sandstone is believed to be a reflection of these deeper movements through the sediment cover. Strong evidence for deeply-seated vertical movements was given by Sikabonyi (1957). His structure contour map of the surface of the Precambrian basement clearly shows the Sweet Grass arch as an outstanding structural feature.

The plutonic activity associated with the primary tectogenesis produced the Sweet Grass Hills intrustions. These intrusions, probably together with more deeply-seated intrusions, disturbed the regional dip in the area and created a radiating pattern of nose- and dome-like structures extending from Montana into Alberta.

The fan-like structural pattern of the Milk River sandstone is caused by both the diverging axes of the Kevin Sunburst dome and Bow Island arch, and the Sweet Grass Hills intrusions.

Conclusions

1. The Sweet Grass arch is believed to be not the result of crustal compressional forces, but rather of primary tectogenesis which has caused vertical movements in the basement complex, which in turn are reflected by the overlying mantle of sediments. The Kevin Sunburst dome and Bow Island arch are the products of this process.
2. Plutonic activity, associated with primary tectogenesis, produced the Sweet Grass Hills intrusions.
3. The fan-like structure pattern is related to the diverging axes of the Kevin Sunburst dome and Bow Island arch, as well as to the Sweet Grass Hills intrusions.
4. The actual age of the Sweet Grass arch is difficult to determine, because of erosional removal of Tertiary and Cretaceous strata. Russell and Landes (1940) report secondary folds in strata of the St. Mary River formation, which suggests early Tertiary tectonism.

SEDIMENTOLOGY

General Statement

The purpose of the sedimentological investigation was to establish the areal and vertical extent and the lithologic variation of the Milk River sandstone. The information for this study was obtained from electrologs, drill cuttings from a large number of wildcat wells, and examination of the outcrop area.

It is possible to distinguish sandstones and shales on electrologs of wells by means of differences in the resistivity and self-potential curves (Krumbein and Sloss, 1956, p. 272), and this method was used successfully to determine the amounts of sandstone in those parts of the electrologs that showed the Milk River sandstone. Borehole samples aided in correlating the lithology with electrolog data.

The Milk River sandstone appears to consist of one or several sandstone beds interbedded with shale. The positions, lithologies and thicknesses of these beds show distinct variations throughout the area.

Descriptions of Analytical and Graphical Techniques

A conventional facies map showing the areal variations of sand percentages within the Milk River sandstone does not give any

FIGURE 8. Centre of gravity map of Milk River sandstone

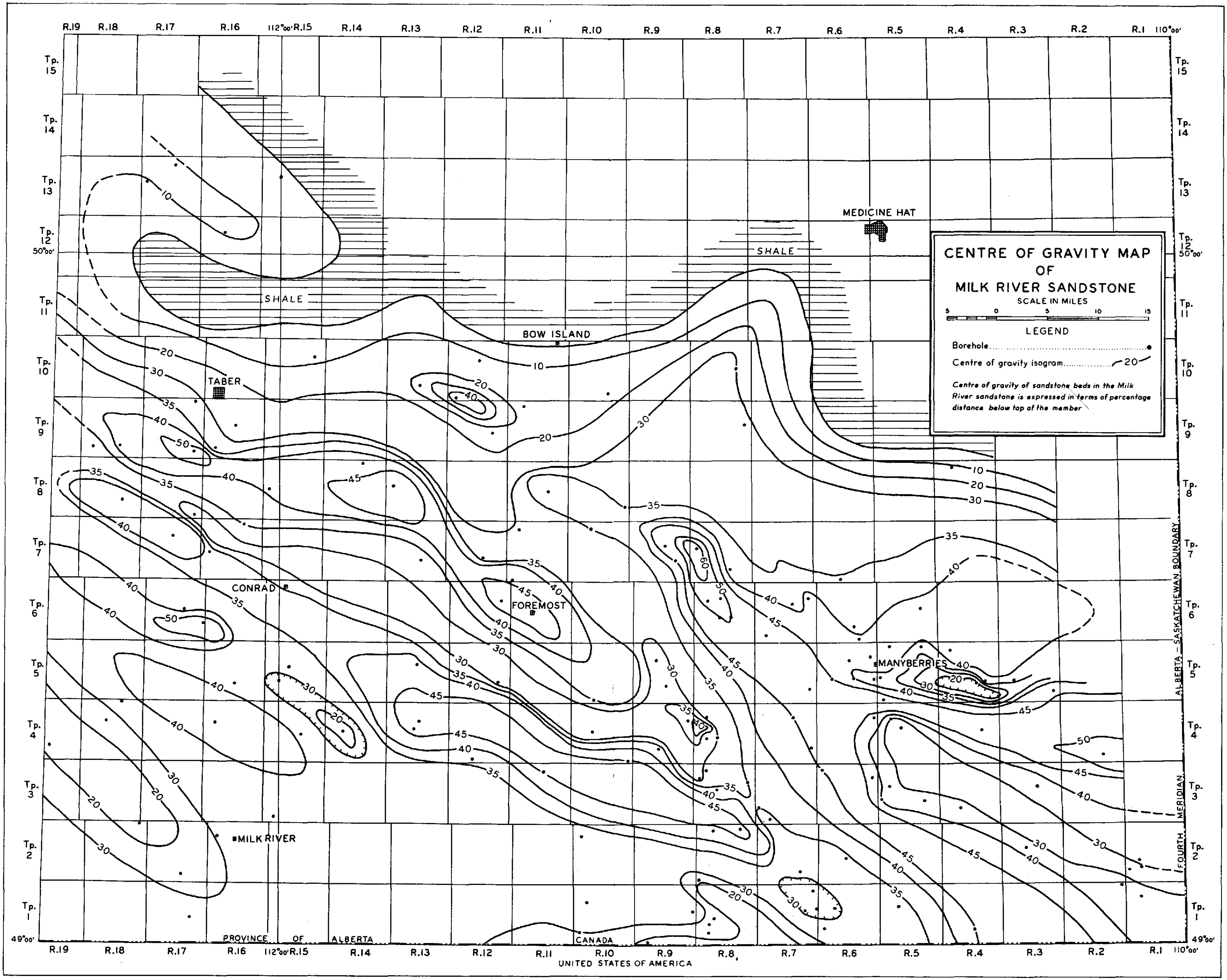

CENTRE OF GRAVITY MAP
OF
MILK RIVER SANDSTONE
SCALE IN MILES
5 0 5 10 15
LEGEND
Borehole
Centre of gravity isogram 20
Centre of gravity of sandstone beds in the Milk River sandstone is expressed in terms of percentage distance below top of the member
MEDICINE HAT
BOW ISLAND
TABER
CONRAD
FOREMOST
MANYBERRIES
MILK RIVER
SHALE
SHALE
PROVINCE OF ALBERTA
CANADA
UNITED STATES OF AMERICA
ALBERTA - SASKATCHEWAN BOUNDARY
FOURTH MERIDIAN
R.19
R.18
R.17
R.16
112°00' R.15
R.14
R.13
R.12
R.11
R.10
R.9
R.8
R.7
R.6
R.5
R.4
R.3
R.2
R.1 110°00'
Tp. 15
Tp. 14
Tp. 13
Tp. 12
50°00'
Tp. 11
Tp. 10
Tp. 9
Tp. 8
Tp. 7
Tp. 6
Tp. 5
Tp. 4
Tp. 3
Tp. 2
Tp. 1
49°00'

FIGURE 9. Standard deviation map of Milk River sandstone

information on whether the sand occurs near the top or near the bottom of the section, a feature which is important in hydrological as well as in sedimentological interpretation. Thus the approach used here is the application of computed variables to express the vertical variability of the sandstone beds, a method described by Krumbein and Libby (1957). Two characteristic variables which describe the variations in gross lithology of each stratigraphic section have been calculated.

The first variable—*the relative centre of gravity*—expresses the average position of the sandstone beds in the section, either as a distance in feet from the top, or as a percentage of the total thickness of the section, also measured from the top. The values for this variable, expressed as percentages, have been plotted on a base map and contoured. The relative centre of gravity map of the Milk River sandstone is given in figure 8. (A relative centre of gravity of 60 per cent means that the centre of the main sand development lies two-thirds of the way down from the top of the section.) The second variable is the *relative standard deviation* which indicates the distribution or *spread* of the several sandstone beds within the section, expressed as a percentage of the total thickness of the section. The value of the relative standard deviation added to and subtracted from the relative centre of gravity provides the range which is occupied by at least two-thirds of the total number of sandstone beds in the section. (A relative standard deviation of 25 per cent means that one-quarter of the total length of the section should be added to and subtracted from the relative centre of gravity to obtain the range occupied by two-thirds of the total number of sandstone beds. A small value for the relative standard deviation denotes a more or less uninterrupted sand sequence.) These values have been plotted and contoured on a second base map. Figure 9 shows the spread of the sandstone beds within the Milk River sandstone.

For a detailed description of this method the interested reader is referred to the paper of Krumbein and Libby (1957).

The maps obtained from the two variables can be combined by means of superposition. The resultinm map is called a *vertical variability pattern* map. In order to compile this map, the relative centre of gravity and the spread are each grouped into three classes:

Relative Centre of Gravity	Relative Standard Deviation
0 - 20% . . . high position	0 - 20% . . . small spread
20 - 40% . . . medium position	20 - 40% . . . moderate spread
40 - 60% . . . low position	40 - 60% . . . large spread

Thus nine possible combinations occur, each of which is given a certain symbol (Fig. 10), and each is called a class.

As one thick sandstone bed lying in the middle of the section will have the same relative centre of gravity (50%) and the same spread (0%) as one thin sandstone lying in the middle of the section,

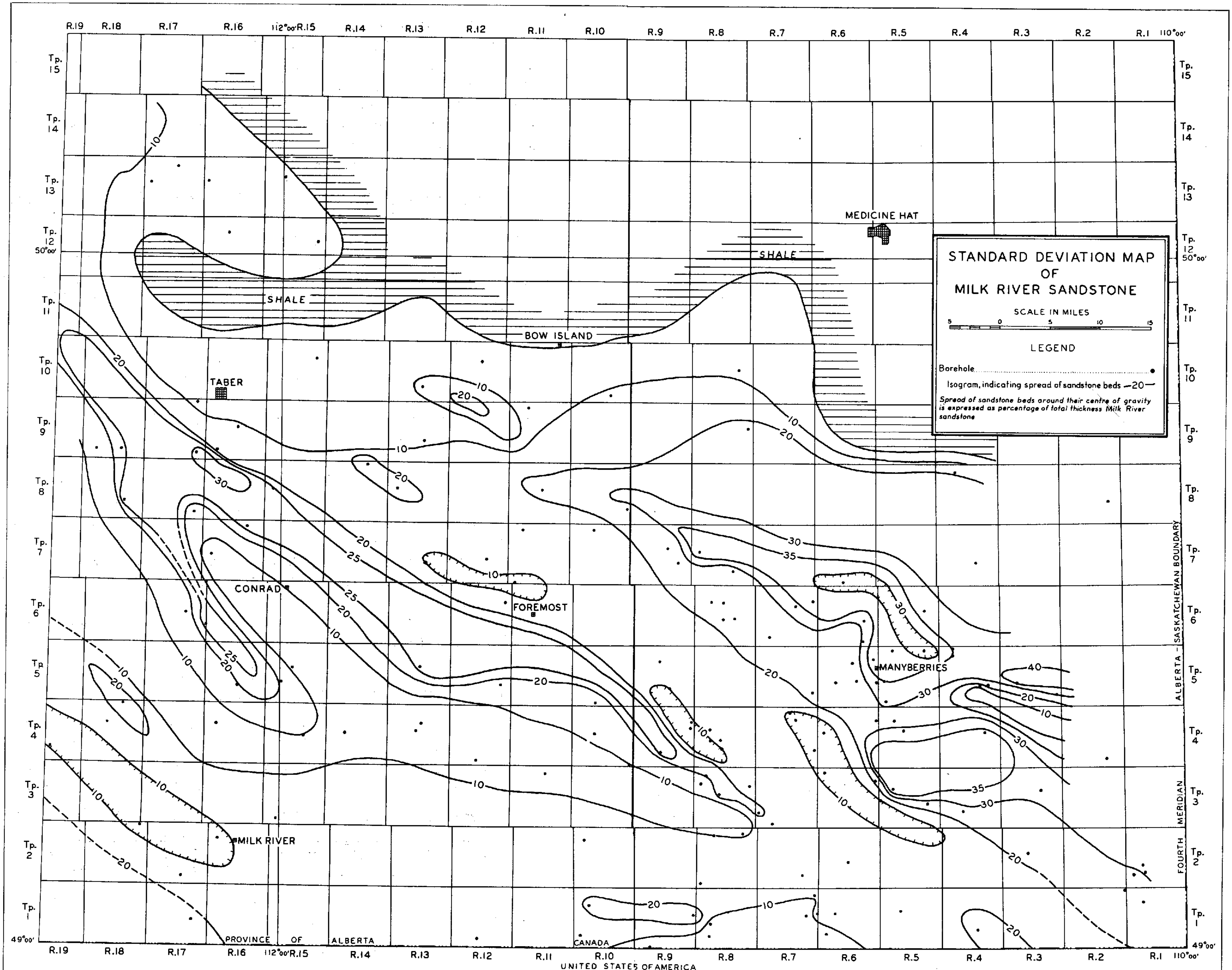

STANDARD DEVIATION MAP OF MILK RIVER SANDSTONE
SCALE IN MILES
LEGEND
Borehole
Isogram, indicating spread of sandstone beds —20—
Spread of sandstone beds around their centre of gravity is expressed as percentage of total thickness Milk River sandstone
MEDICINE HAT
SHALE
BOW ISLAND
TABER
CONRAD
FOREMOST
MANYBERRIES
MILK RIVER
PROVINCE OF ALBERTA
CANADA
UNITED STATES OF AMERICA
ALBERTA - SASKATCHEWAN BOUNDARY
FOURTH MERIDIAN
112°00'
110°00'
50°00'
49°00'

FIGURE 10. Vertical variability pattern map of Milk River sandstone

it is necessary to supplement the vertical variability pattern map with sand to shale ratio values, in order to show not only the positions of the sandstone beds, but also the nature of the section at any particular locality. There appears to be good correlation between the nine classes and the sand to shale ratios. The two variables and the sand to shale ratios for the Milk River sandstone were calculated for 160 electrologs and the results are shown in figure 10.

Description of Classes

Class I.

Characteristics:

Relative centre of gravity: high (0 - 20%)
Spread: small (0 - 20%)
Average sand-shale ratio: 0.3

Description: The main sand development occurs in the upper part of the section, and generally consists of one sand bed varying in thickness from 0 to 50 feet.

Lithology: The sandstone consists of 50 per cent mainly clear quartz grains, 5 per cent chert debris, 15 per cent micaceous minerals, and 30 per cent argillaceous matrix. Probably because of authigenic overgrowths, the quartz grains are subangular to poorly-rounded; the chert grains are generally well-rounded. The color is dark-grey and the cementation is poor. In some of the samples the matrix was found to be calcareous.

Occurrence: The beds of this class are considered to comprise the transitional beds from the Milk River sandstone to its shale equivalent of the central Alberta plains, the Lea Park formation. The beds occur as a fringe along the northern edge of the area, ranging from ranges 1 to 19 in townships 10, 11 and 12. A few isolated patches occur scattered through the area.

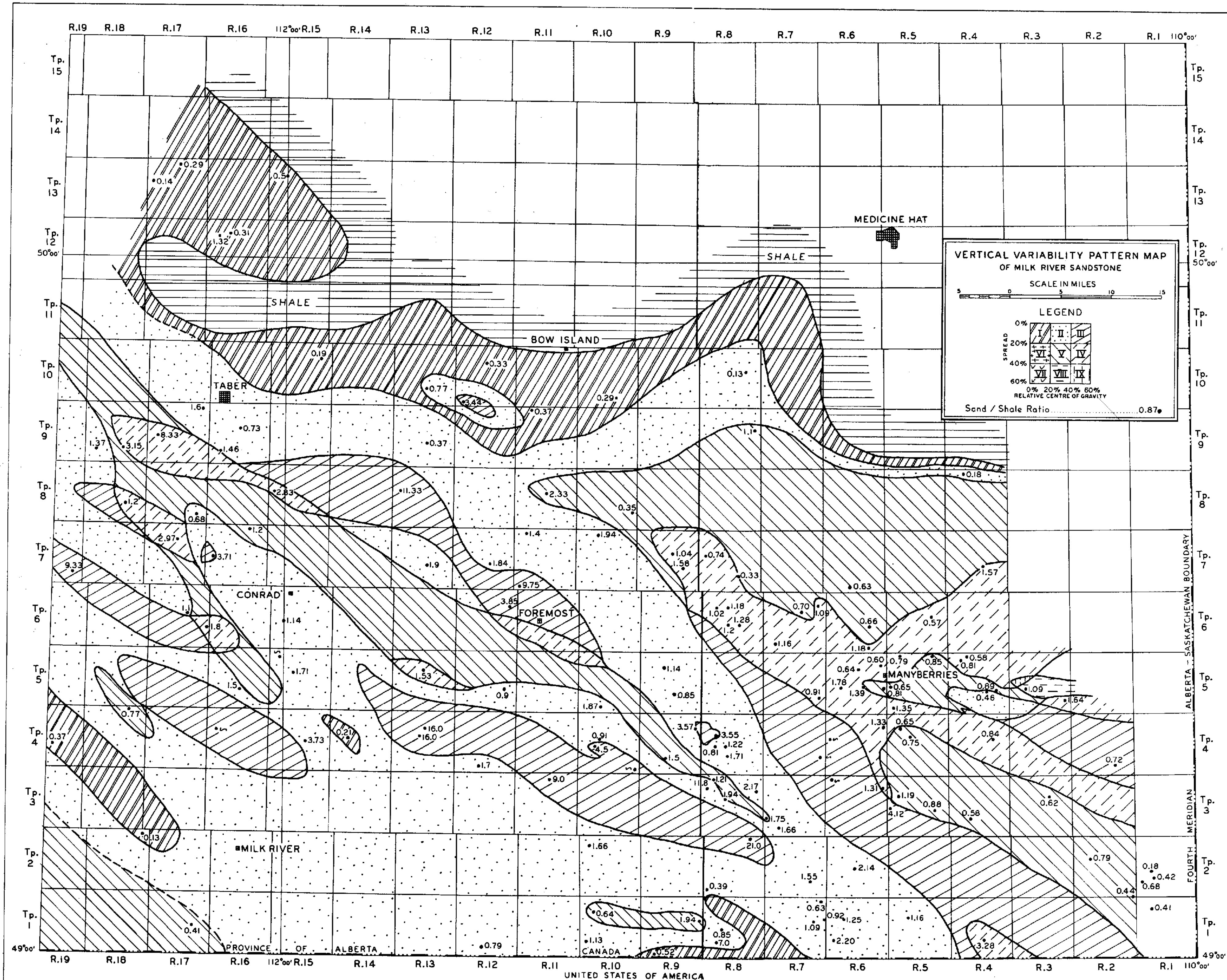
Class II.

Characteristics:

Relative centre of gravity: medium (20 - 40%)
Spread: small (0 - 20%)
Average sand-shale ratio: 1.25

Description: More than 50 per cent of a class II section consists of sandstone. The small spread indicates a more or less uninterrupted sand sequence which is 100 to 150 feet thick.

Lithology: The sandstone consists of 50 per cent to 70 per cent clear quartz grains, 10 per cent to 20 per cent rock fragments (mainly chert), weathered feldspar and a small amount of micaceous minerals. The color is white to grey.



VERTICAL VARIABILITY PATTERN MAP
OF MILK RIVER SANDSTONE
SCALE IN MILES
5 0 5 10 15
LEGEND
SPREAD
0%
20%
40%
60%
I II III
VI V IV
VII VIII IX
0% 20% 40% 60%
RELATIVE CENTRE OF GRAVITY
Sand / Shale Ratio 0.87
R.19 R.18 R.17 R.16 112°00' R.15 R.14 R.13 R.12 R.11 R.10 R.9 R.8 R.7 R.6 R.5 R.4 R.3 R.2 R.1 110°00'
Tp. 15
Tp. 14
Tp. 13
Tp. 12
50°00'
Tp. 11
Tp. 10
Tp. 9
Tp. 8
Tp. 7
Tp. 6
Tp. 5
Tp. 4
Tp. 3
Tp. 2
Tp. 1
49°00'
MEDICINE HAT
SHALE
SHALE
BOW ISLAND
TABER
CONRAD
FOREMOST
MANYBERRIES
MILK RIVER
PROVINCE OF ALBERTA
CANADA
UNITED STATES OF AMERICA
ALBERTA - SASKATCHEWAN BOUNDARY
FOURTH MERIDIAN

The rock is generally fine- to very fine-grained (Wentworth grain classification), with moderate sorting (sorting coefficient of Trask: 2) and poor to fair cementation.

The associated shales vary from silty clay to clay. Plant fragments are common, and the color of the shales is dark-brown to black.

Occurrence: The beds of this class are believed to be typical of the Milk River sandstone. They occur predominantly in the southern part of the area, but some elongated stretches of this class occur farther north, transitional between other classes. This class is virtually absent in the eastern part of the area.

Class III.

Characteristics:

Relative centre of gravity: low (40 - 60%)
Spread: small (0 - 20%)
Average sand-shale ratio: 9

Description: As is indicated by the sand to shale ratio, this class is predominantly sand. The spread is commonly very small which indicates an almost uninterupted sand sequence. It appears to be one sandstone bed, ranging in thickness from 150 to 200 feet, without major shale intervals.

Lithology: The sandstone consists of 50 per cent to 75 per cent clear, poorly-rounded quartz grains, 0 per cent to 20 per cent well-rounded chert grains and small amounts of micaceous minerals. The color is grey and cementation is poor to fair. The argillaceous matrix constitutes 25 per cent to 50 per cent of the rock, commonly giving it a dirty appearance.

Occurrence: Class III strata occur as several elongated stringers through the area. The lengths of these stringers are approximately 40 miles, the breadths vary from 1 to 8 miles. They all have a cigar-like form and run parallel to one another in a northwest direction.

Class IV.

Characteristics:

Relative centre of gravity: low (40 - 60%)
Spread: moderate (20 - 40%)
Average sand-shale ratio: 1.30

Description: Judging by the sand to shale ratio, there is a close resemblance to the typical lower Milk River sandstone (class II). However, the positions of the sand beds in the section are quite different. The section can be divided into an upper and lower sand portion, which are separated by shale. Both sand portions may or may not be split up by thin shale layers. The low centre of gravity indicates that the main sand development occurs in the lower sand portion.

Lithology: Relatively clean sandstone is scarce in this class. The rock consists of 50 per cent very fine quartz grains, 5 per cent chert fragments, 5 per cent micaceous minerals and 40 per cent argillaceous matrix, which gives it a dirty appearance. The color is grey and brown, the sorting is moderate, and the cementation is fair. The most striking difference between class IV strata and those of classes I to III is the larger amount of argillaceous matrix.

The underlying and interbedded shale is dark and and dense; plant remains are common.

Occurrence: Strata of this class play an important role in the eastern part of the area, and they are present in isolated patches in the central and western parts.

Class V.

Characteristics:

Relative centre of gravity: medium (20 - 40%)
Spread: moderate (20 - 40%)
Average sand-shale ratio: 1

Description: This class can also be divided into an upper and a lower sand portion separated by shale. In contrast to the previous class, however, the upper part of the section contains the main sand development. As in class IV, both upper and lower sand portions may be split up by thin shale layers.

Lithology: The sandstone contains 60 per cent very fine quartz grains, 5 per cent chert fragments, 5 per cent mica and 30 per cent argillaceous matrix, which is generally calcareous. The color is dark-brown and grey, cementation is fair. The quartz grains are generally poorly-rounded, in contrast with the well-rounded chert grains.

The interbedded shale varies from very silty clay to dense, plastic bentonite shale. Plant remains and mica-flakes are common.

Occurrence: Class V strata form a narrow band extending northwest through the area, and they cover a considerable part of the northeast corner.

The Milk River sandstone, as it is developed in southern Alberta, is composed mainly of these five classes of strata. Others of the nine possible classes occur in the eastern part of the area, but

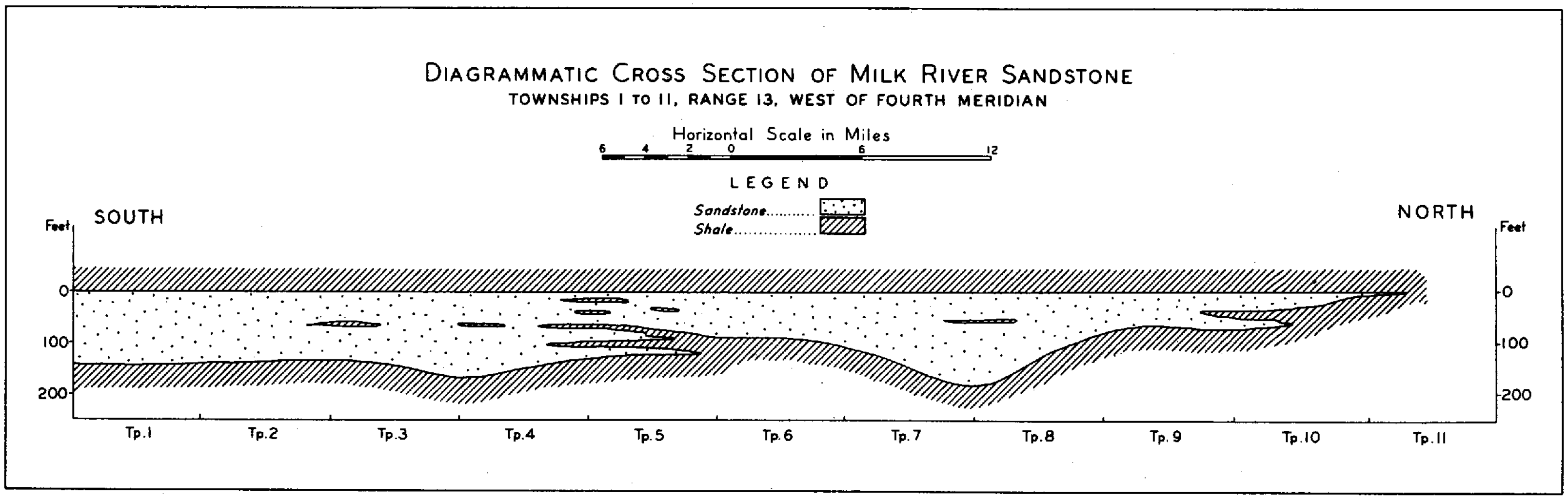

DIAGRAMMATIC CROSS SECTION OF MILK RIVER SANDSTONE
TOWNSHIPS 1 TO 11, RANGE 13, WEST OF FOURTH MERIDIAN
Horizontal Scale in Miles
6 4 2 0 6 12
LEGEND
Sandstone
Shale
SOUTH
NORTH
Feet
0
100
200
Feet
0
100
200
Tp.1
Tp.2
Tp.3
Tp.4
Tp.5
Tp.6
Tp.7
Tp.8
Tp.9
Tp.10
Tp.11

FIGURE 11.

because these play only a minor role, they will not be discussed in detail.

The mutual relations between the predominant classes are as follows:

The thick sand belts of class III grade laterally into thinner sand sequences, in which some shale lenses may be present (class II). These in turn pass into the more shaly sequences of classes I, IV and V. Locally, and especially in the eastern part of the area, the class III sand stringers grade directly into class IV or V beds. Towards the north the shale gradually occupies a larger portion of the section and north of township 11 sandstone is no longer present. This relationship is illustrated by means of a diagrammatic cross section (Fig. 11).

Such a lateral transition from relative massive sandstone to sandstone and shale is observed in the outcrop area also. In the west half of Sec. 16, Tp. 2, R. 14, the massive sandstone passes laterally into a sandstone and shale sequence which continues for several hundred feet, beyond which the massive character of the sandstone is resumed. This exposure was first described by Evans (1930).

Not only the position of the sand beds shows an areal variation but the composition of the sandstone also changes. The typical Milk River sandstone, as it is present in the outcrop area, can be described in terms of:

Mineral Composition: The rock consists of 60 per cent mainly clear quartz grains, 10 per cent chert fragments, 5 per cent cent weathered feldspar and micaceous minerals, 25 per cent matrix.

Gross Character: The color is light-grey and buff. Bedding is obscure in thin sections, but small-scale cross-bedding is observed in hand specimens.

Texture: The rock is fine- to very fine-grained. The maximum grain size is 0.5 mm, the average grain size between 0.125 and 0.062 mm. More than 80 per cent of the weight of the sample is larger than 0.05 mm. The sorting is moderate to good (Trask sorting coefficient: 1.5 - 3). The quartz grains are subangular to poorly-rounded, probably because of authigenic overgrowths. The chert fragments are generally well-rounded.

Matrix: 25 per cent of the rock consists of argillaceous material, which is in places calcareous. The sandstone is friable to poorly-cemented.

Fossils: The strata are unfossiliferous.

Samples of the Milk River sandstone and the associated shale were taken at the type section and a histrogram of the grain-size distribution in the sandstone is shown in figure 12.

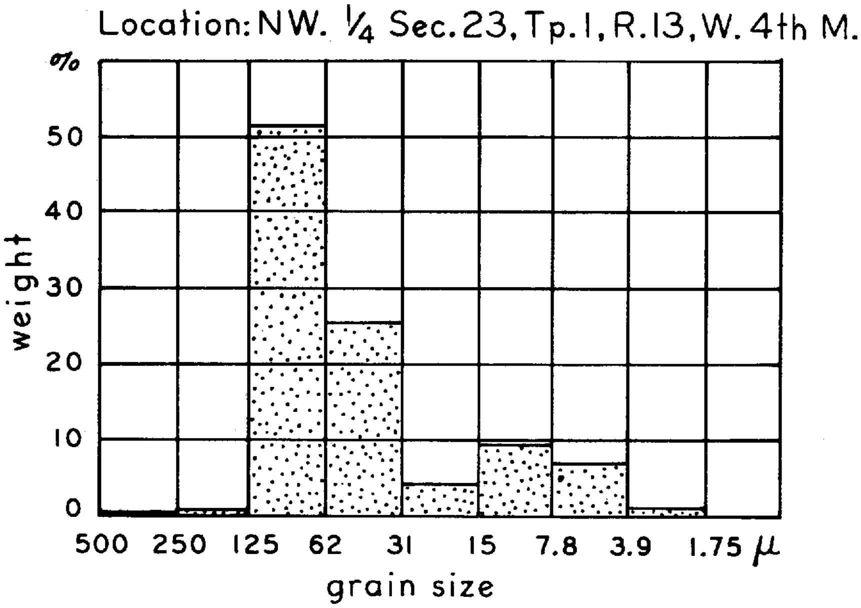


FIGURE 12. Histogram showing grain-size distribution of typical Milk River sandstone

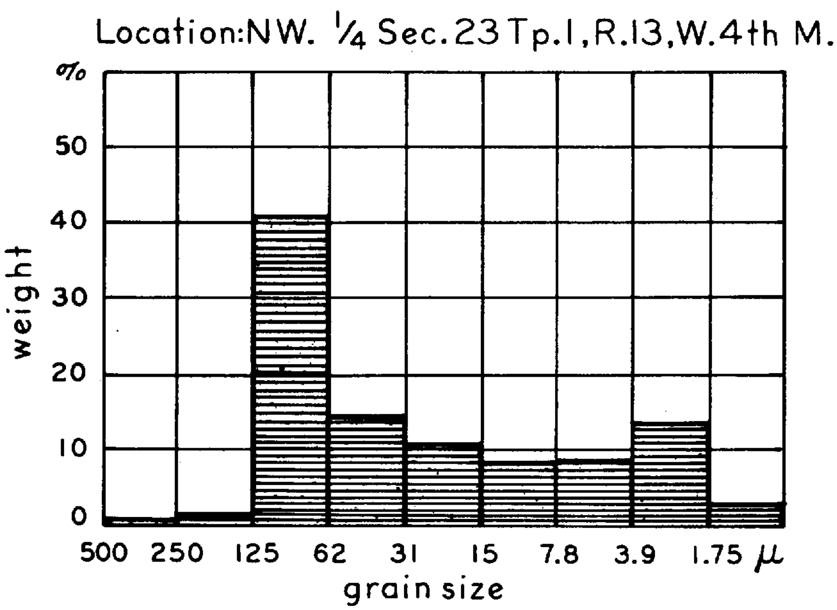


FIGURE 13. Histogram showing grain-size distribution of shale underlying Milk River sandstone

A sediment of this type of composition is often called a "salt and pepper sandstone". According to the classification of Krumbein and Sloss (1956) the sandstones can be classified as subgreywackes. As shales predominate in the Cretaceous sediments in Alberta, every sediment which is slightly coarser is called a sandstone. For the sake of convenience this usage will be maintained.

The shale associated with the Milk River sandstone ranges from very argillaceous sand to pure clay. Micaceous minerals, small chert fragments and plant remains are common. The maximum grain size is 0.5 mm and the average grain size is between 0.08 and 0.05 mm. More than 50 per cent of the total weight of the sample is larger than 0.05 mm. A histogram of this grain-size distribution is given in figure 13.

Toward the north and east there is a definite change in the composition of the sandstone as well as of the shale: the argillaceous matrix increases (up to 50%) giving the rock a more dirty appearance; the proportion of chert fragments decreases and mica flakes become more common. In the shale more lignite and plant remains are found. Bentonite, absent in the south, was commonly observed in northern samples.

Origin of the Milk River Sandstone

In order to establish the source area and the sedimentary environment in which the Milk River sandstone was deposited, it is necessary to analyze the tectonic setting of the area during late Cretaceous time. During this time, southern Alberta was part of an extensive shelf-area lying between the cratonic platform to the east and the Cordilleran geanticline in the west. The Cordilleran geanticline, a result of the late Jurassic Nevadan orogeny, was located on the site of the present Selkirk Mountains (Webb, 1954; Goodman, 1954). The following rock types probably were exposed in this mountain range: Paleozoic limestones, dolomites, quartzites, chert beds and acidic intrusions of Triassic and Jurassic age; these provided the sediments which filled the marginal basin to the east. Judging by the thick lower Cretaceous deposits in the Foothills and Front Ranges of the Rocky Mountains, this trough underwent great subsidence during early Cretaceous time (Glaister, 1959).

During late Cretaceous time the rate of subsidence of the marginal basin was less than the rate of deposition. This resulted in an eastward shifting of the shoreline and a more eastward extension of freshwater and transitional sediments. This type of environment was described by Sloss (1956) in a general discussion of basins.

Because of the rapid uplift of the Cordilleran geanticline, great volumes of poorly-weathered and poorly-sorted debris were carried toward the eastern margin of the basin, building up a large sedimentation platform consisting of rather coarse material. The finer fractions were transported over this platform to quieter offshore waters. Some of the sands were taken up by currents moving parallel to the coast, and were deposited in linear bodies along certain definite trends. Changes in the volume of sediment supplied affected the seaward extent of the sedimentation platform and also the relative distribution of the sediments, resulting in the lenticular interfingering lithologic units which are characteristic of the Milk River sandstone. A large part of the clay is of volcanic origin, for it has been established that most montmorillonite clays in the Cretaceous sediments of Alberta have been derived from the decomposition of volcanic ash (Byrne, 1955).

Conclusions

The Milk River sandstone in southern Alberta represents the seaward margin of a littoral environment. The sediments are fine- to very fine-grained, and moderately well sorted. The quartz, chert, feldspar and micaceous minerals are derived from the Upper Cretaceous Selkirk Mountains, where Paleozoic sediments and Jurassic and Triassic intrusions were exposed. A large percentage of the clay in the sediments is of volcanic origin.

Some of the sand was deposited by streams or currents, running parallel to the coastline, resulting in linear sand belts. The lenticular shapes of the sediment bodies is a function of fluctuations in the supply of sediments and local variations in the environment of deposition.

The mainland may have been separated by a broad coastal plain from this area, but the shoreline in this particular region probably extended in that same north-westerly direction that is indicated by the sand stringers and the shale boundary.

Hydrology

"Water is the best of all things"
(Pindar, Olympian Odes I, 475 B.C.)

GENERAL STATEMENT

Dowling (1915) concluded that the Milk River sandstone might be an artesian aquifer in a large area of southern Alberta. In 1916 the Federal Government drilled three wells to test this theory. The results were successful and soon thereafter large-scale development began. In 1937 a survey carried out by the Geological Survey of Canada showed that 250 water wells were producing from the Milk River sandstone. Many of these older wells are abandoned now, and have been replaced by new ones. During the present investigation 409 wells in the Milk River sandstone were found. These wells can be classified into two classes, flowing and nonflowing.

A. *Nonflowing*: in this class are 217 wells, of which
  154 never flowed, and
  63 have stopped flowing in recent years.

B. *Flowing*: in this class are 192 wells, of which
  72 are used in corrals and pastures,
  49 are used for domestic gas and water supply, and
  71 are used for domestic water supply only.

The majority of the wells are located in the central part of the area, lying approximately between townships 1 and 11, within ranges 5 to 15 inclusive. The total daily production is estimated at 700,000 gallons.

HYDROLOGIC PROPERTIES OF THE MILK RIVER SANDSTONE

Definitions

In dealing with quantitative groundwater investigations two physical properties of the aquifer are of great interest.

(i) *Coefficient of transmissibility,* which is defined as the rate of flow of water, in gallons per day, at the prevailing temperature, through a vertical strip of the aquifer one foot wide, extending the full saturated thickness of the aquifer, under a hydraulic gradient of 100 per cent (1 foot per foot).

(ii) *Coefficient of storage,* which is defined as the volume of water that is released from storage, from a vertical prism of the aquifer, one foot square and of the height of the saturated thickness of the aquifer, when the hydrostatic head on the column is reduced one foot.

The coefficient of transmissibility was determined both in the field and in the laboratory, whereas the coefficient of storage was deduced from other data.

Research Council of Alberta, Memoir 2, Geology and Groundwater Resources of the Milk River Sandstone in Southern Alberta, by P. Meyboom.

ERRATA

(1) Page 33, equation 2 should read:

$$s^1 = \frac{114.6\,Q}{T}\left[\int_{1.56\,r^2S/Tt}^{\infty} \frac{e^{-u}}{u}\,du - \int_{1.56\,r^2S/Tt^1}^{\infty} \frac{e^{-u}}{u}\,du\right]$$

(2) Page 67, equation 15 should read:

$$T°_{(800)^1} = 43° + (800 \times 0.02°F./ft.) = 59°F.\ (15°C.)$$

(3) Page 67, the line below equation 16 should read:

2.0×10^7 cu. ft.

Field Tests

Theis (1935) devised a modification for his nonequilibrium formula, which can be applied to the analysis of the recovery of a pumped or flowing well.

$$T = \frac{264\ Q}{s^1} \log t/t^1 \quad \text{.......} \quad (1)$$

T = coefficient of transmissibility in imperial gallons per day foot (gpdf.)
Q = rate of discharge in imperial gallons per minute (gpm.)
s^1 = residual drawdown in feet (recovery in feet)
t = time since pumping began, in minutes
t^1 = time since pumping stopped, in minutes.

The residual drawdown (s^1) at any time during the recovery period is the difference between the observed water level and the nonpumping level, and can be written as:

$$s^1 = \frac{114.6\ Q}{T} \int_{1.56\ r^2S/Tt}^{\infty} \frac{e^{-u}}{u}\, du - \int_{1.56\ r^2S/Tt^1}^{\infty} \frac{e^{-u}}{u}\, du \quad \text{.....} (2)$$

in which T, Q, s^1, t and t^1 are as previously defined (Theis, 1935).

$$u = 1.56\ r^2S/Tt \quad \text{.......} \quad (3)$$

in which

S = coefficient of storage
r = effective radius of pumping well, or distance to observation well.

The exponential integral is generally written symbolically as W(u), which is called "well function of u". Values of W(u) for values of u, are given in Wenzel tables (Wenzel, 1942, p. 88).

The quantity of 1.56 r^2S/Tt^1 will be very small as soon as t^1 ceases to be small, then all but the first two terms of the series (2) may be neglected and the recovery formula (1) results. The effective radius of a well is extremely difficult to determine, and as no observation wells were available, it was impossible to determine the storage coefficient by this method. It was possible, however, to determine it by other means.

For a more simple mathematical treatment, recovery of a well is considered to be the result of an image well which is recharging at the same rate as the flowing well was pumping. The afore-mentioned recovery formula (1) is only applicable when the well has been flowing sufficiently long so that no significant drawdown occurs in the pumping image well during the recovery test.

The most convenient method for application of the modified nonequilibrium formula is to plot the data of the recovery test on semilogarithmic paper, where values of the recovery are plotted on the linear scale and the corresponding values of t/t^1 on the logarithmic scale. The observed data should fall on a straight line, if the conditions in the aquifer meet the assumptions of the mathematical model. These assumptions are that: (1) the transmissibility is constant at all times and in all places; (2) the aquifer is homogenic, isotropic, and of infinite areal extent; (3) the well penetrates the entire aquifer; (4) the flow is laminar; and (5) water removed from storage is discharged instantaneously with decline in head. The real aquifer never fully meets these requirements of the mathematical model, but despite these restrictions the method is applied successfully.

Both assumptions 1 and 2 are not realized in the Milk River sandstone, but recovery tests were supposed to be representative for the vicinity of the well only, where constant conditions do exist.

In order to obtain recovery data, flowing wells were shut in and each was fitted with a pressure gauge. The pressure build-up was measured in pounds per square inch, and converted to feet of water thus giving the recovery. This method has certain disadvantages, as early measurements may be in error, but in general the results were quite satisfactory.

Depending on the time a flowing well could be left shut in, two types of recovery tests were made, long-period tests (12 hours) and short-period tests (15 - 60 minutes). Despite the difference in time the results of the two methods correlated very closely. Fifty-two recovery tests were carried out, and four different types of graphs resulted which are discussed below. Examples of each type are shown in figure 14.

Type 1: *Straight Line*—If the hydrologic conditions of the aquifer satisfy the assumptions of the mathematical model, the plotted data of s^1 versus t/t^1 form a straight line. This type occurred both with high (Fig. 14A) and low (Fig. 14B) transmissibility values. Observations of 15 tests resulted in straight lines.

Type 2: *Deviation from Straight Line*—In this type of recovery curve the first part of the semilogarithmic plot of s^1 versus t/t^1 forms either (a) a curve, which after some time (= increasing t^1 and thus decreasing t/t^1) gradually changes into a straight line (Fig. 14C) or (b) a straight line, the angle of which changes abruptly after some time (Fig. 14D). This break usually occurs during the first few moments of the test; long-period tests have shown that no second change in slope occurs.

Six cases of type 2a occurred and 12 cases of type 2b. Both phenomena are essentially the same, but differ in degree. Possible explanations are:

1. The aquifer is not homogeneous, and therefore T is not constant throughout the aquifer. Such situation is commonly referred to as a hydrologic boundary. If this was the case, however, a repeated change of slope should be expected during the long-period tests because of the lenticular character of the sediment.

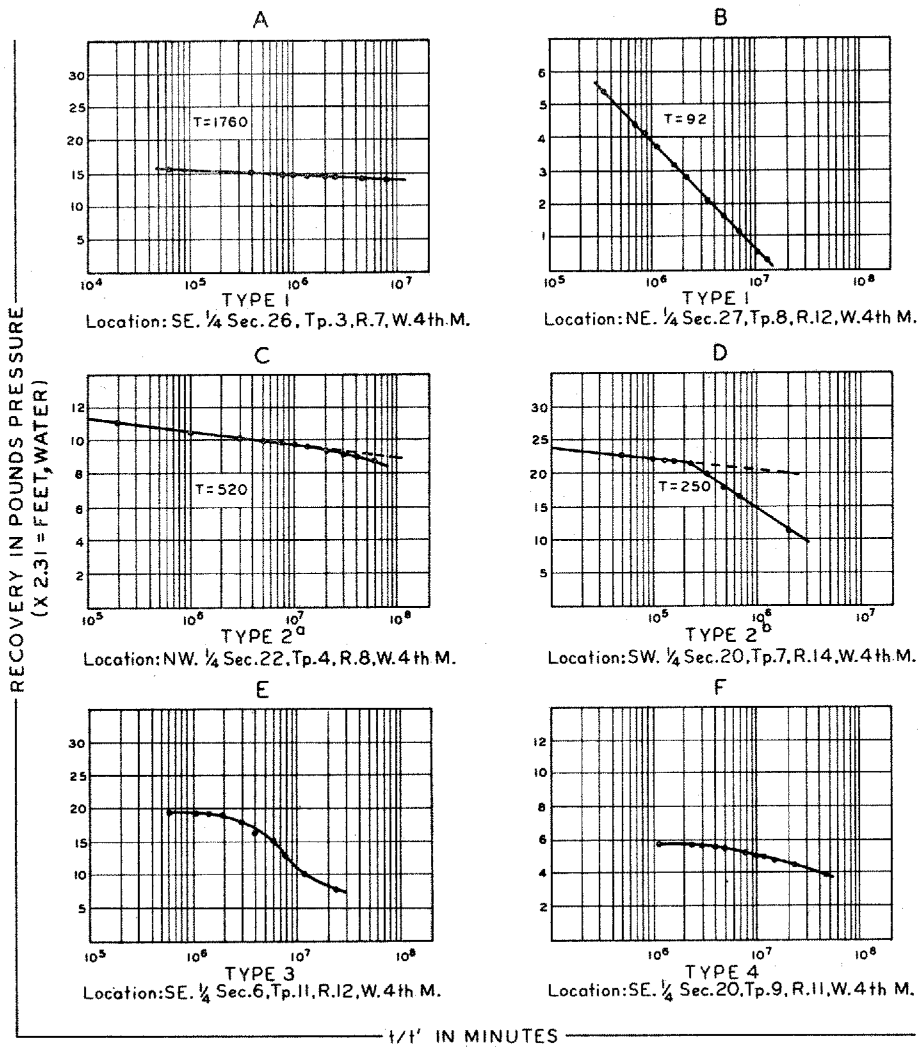


FIGURE 14. Recovery curves of flowing wells

If boundary conditions were the cause, both negative and positive boundaries—indicated by steeper or more gentle slopes, respectively—should be expected to occur in about equal numbers. However, all tests except one showed a decrease in slope, which would indicate the presence of a positive boundary only. This, however, is very unlikely.

Although the aquifer is certainly not homogeneous at all places, boundary conditions do not offer a good explanation for the sudden or gradual changes in slope of the recovery curves.

2. During the very first moments, when the rise in pressure is extremely fast, readings are taken every 15 seconds. Due to the fast rise, however, a certain lag between the observed value and the real value may exist, resulting in a deviation from a straight line during the first moments. Figure 14C may thus be explained.
3. In using the modified nonequilibrium formula (p. 33), it is assumed that the quantity 1.56 r^2S/Tt^1 is small enough to permit neglect of all but the first two terms of the series (2). In some cases this may not be true, and the recovery does not follow the abbreviated form (1). With increasing t^1, however, 1.56 r^2S/Tt^1 becomes sufficiently small and the observed data form a straight line. This explanation may hold for the graph shown in figure 14D.
4. Due to a pressure differential between the inside and the outside of a well, known as "well loss", the first moments of a recovery test tend to give higher values, as this pressure differential is eliminated before true recovery begins.

Type 3: *S Curve*—In this type, the plotted data form a sigmoid curve (Fig. 14E). This curve may originate from a combination of all reasons offered to explain the second type. However, S curves were not used for the interpretation of the results. Eight cases occurred.

Type 4: *Parabolic Curve*—This situation occurred four times (Fig. 14F). A possible reason for this type of curve is that the well only partially penetrates the saturated portion of the aquifer. This type of curve was not used for the final interpretation either. The results of the recovery tests are given in table 1.

Table 1: Transmissibility Values, Obtained from Field Tests

Location ¼	Sec.	Tp.	R.	Transmissibility, gpdf.	Length of test, minutes	Yield, gpm.	Type of Curve
SE.	26	1	14	737	100	12	2a
NW.	31	2	8	425	30	8	1
SE.	33	3	7	1584	11	12	1
SE.	26	3	7	1760	60	20	1
SW.	18	3	8	3000	30	30	1
NW.	10	4	6	178	10	2.50	1
SW.	18	4	7	570	10	5	2b
NE.	36	4	7	146	10	1	2b
NW.	22	4	8	520	720	4	2a
NE.	24	5	9	377	10	5	1
SE.	23	5	11	688	10	3	1
NW.	6	6	8	170	10	2	1
SE.	20	6	8	159	720	1.50	2b
NW.	21	6	11	—	—	0.25	3
SE.	29	6	11	352	30	8	1
NE.	28	6	11	407	720	2.50	2a
SE.	17	7	8	65	10	1	2b
SE.	18	7	8	425	10	3.50	1
SE.	12	7	9	30	10	0.50	2b
SW.	20	7	14	250 or 60	10	5	2b
SE.	22	7	14	253	10	3	1
SE.	23	7	15	118	15	3	1
SE.	9	8	8	—	10	5	3
SW.	19	8	8	36	720	1.50	2b
SE.	21	8	8	34	10	4.50	1
SE.	7	8	9	280 or 31	10	1.50	2b
SE.	23	8	11	—	10	—	3
NE.	27	8	12	92	10	2	1
NE.	22	8	13	34	10	0.75	2b
SE.	29	8	13	—	—	—	3
SW.	31	8	13	8	30	0.25	2b
SW.	15	8	15	22	10	0.50	2a
NW.	29	8	16	—	—	—	3
NE.	32	8	16	—	—	—	4
SE.	20	9	8	—	—	—	3
SE.	14	9	11	190	10	1	2a
NE.	17	9	11	44	10	0.25	2b
NW.	20	9	11	—	—	—	4
SE.	14	9	12	—	—	—	3
NW.	17	9	12	34	15	0.50	2b
SE.	2	9	13	176	10	1	1
SE.	28	9	13	—	—	—	4
SW.	16	9	15	31	10	4.50	4
SW.	25	10	11	10	60	0.50	2a
SE.	6	11	12	21	10	3	3

Laboratory Tests

Laboratory tests were undertaken in order to compare the transmissibility values obtained from the field tests with conventional permeability values. The results show a good correlation with the field tests.

At Writing on Stone (Sec. 35, Tp. 1, R. 13) approximately 100 feet of the Milk River sandstone are exposed, consisting entirely of massive sandstone. From this section eight samples were taken, the descriptions and locations of which are given in table 2.

Table 2:
Locations and Descriptions of Samples from Writing on Stone

Sample No.	Location and Description
1	10 feet below the top of the section. Yellowish-brown; brittle, soft sandstone; bedding irregular, small-scale cross-bedding.
2	8 feet below #1, grey "salt and pepper sandstone", somewhat indurated, small-scale cross-bedding. This layer acts as a protective cap on several hoodoos.
3	10 feet below #2, dark-brown, indurated sandstone; hard, massive, bedding irregular.
4	12 feet below #3, grey "salt and pepper sandstone"; rather soft; well bedded.
5	15 feet below #4, yellowish-grey, massive, well-bedded sandstone.
6	10 feet below #5, yellowish-grey, massive, well-bedded sandstone.
7	20 feet below #6, grey "salt and pepper sandstone"; soft, bedding irregular.
8	20 feet below #7, yellowish-grey, massive, well-bedded sandstone.

From each of these samples two cores were taken, one parallel to the bedding plane and one perpendicular to the bedding plane. Horizontal and vertical permeability were determined with a standard permeameter. Several determinations were made from each core, a different orifice and a different pressure being applied for each measurement. The permeability was obtained from the following formula:

$$k = \frac{uQL}{A\,p} \qquad (4)$$

k = permeability in darcies
u = viscosity of air in centipoises
L = length of core in centimeters
Q = flow of air through core, in cubic centimeters per second
A = area of core in square centimeters
p = downstream pressure (applied pressure) in atmospheres

The applied pressure ranged from 0.25 atm. to 2.5 atm.. The results of the test are given in table 3.

Table 3: Permeability Values Obtained from Laboratory Tests

Sample No.	Horizontal Permeability, millidarcies	Vertical Permeability, millidarcies
1	145	126.96
2	20.6	6.17
3	14.79	4.90
4	865.50	502.85
5	364.10	455.24
6	540.40	473.90
7	523.60	426
8	520.69	491.62
Average Permeability:	374 md.	311 md.

In order to compare transmissibility values, which are generally expressed in flow of water in gallons per day, with conventional permeability values which are expressed in flow of water in cubic centimeters per second, it is necessary to convert the darcy unit into its equivalent flow of water in gallons per day:

> A porous medium with a permeability of one darcy will allow a flow of 21 imperial gallons of single-phase fluid, with one centipoise viscosity, at a rate of one foot per day per square foot of cross-sectional area, under a hydraulic gradient of one foot per foot.

Therefore one millidarcy equals a transmissibility of 0.021 gallons per day per foot thickness of an aquifer. As is shown in table 3, the average permeability of the Writing on Stone section equals 374 millidarcies. The average thickness of the Milk River sandstone in this area is 150 feet, which would result in a coefficient of transmissibility of $374 \times 0.021 \times 150 = 1177$ gpdf.. Although it is recognized that the actual transmissibility may be somewhat lower, this value agrees very well with the values obtained from recovery tests in the southern townships.

Although the laboratory tests show a significant difference between the horizontal and vertical permeabilities, it is believed that this difference is not sufficiently large to cause great differences between vertical and horizontal water movements.

Evaluation of Results

As the coeffficient of transmissibility equals the product of the coefficient of permeability and the height of the saturated portion of the aquifer, any changes in those properties will be reflected in the transmissibility.

Both permeability and thickness of the Milk River sandstone decrease toward the east and north. Figure 15 shows how the trans-

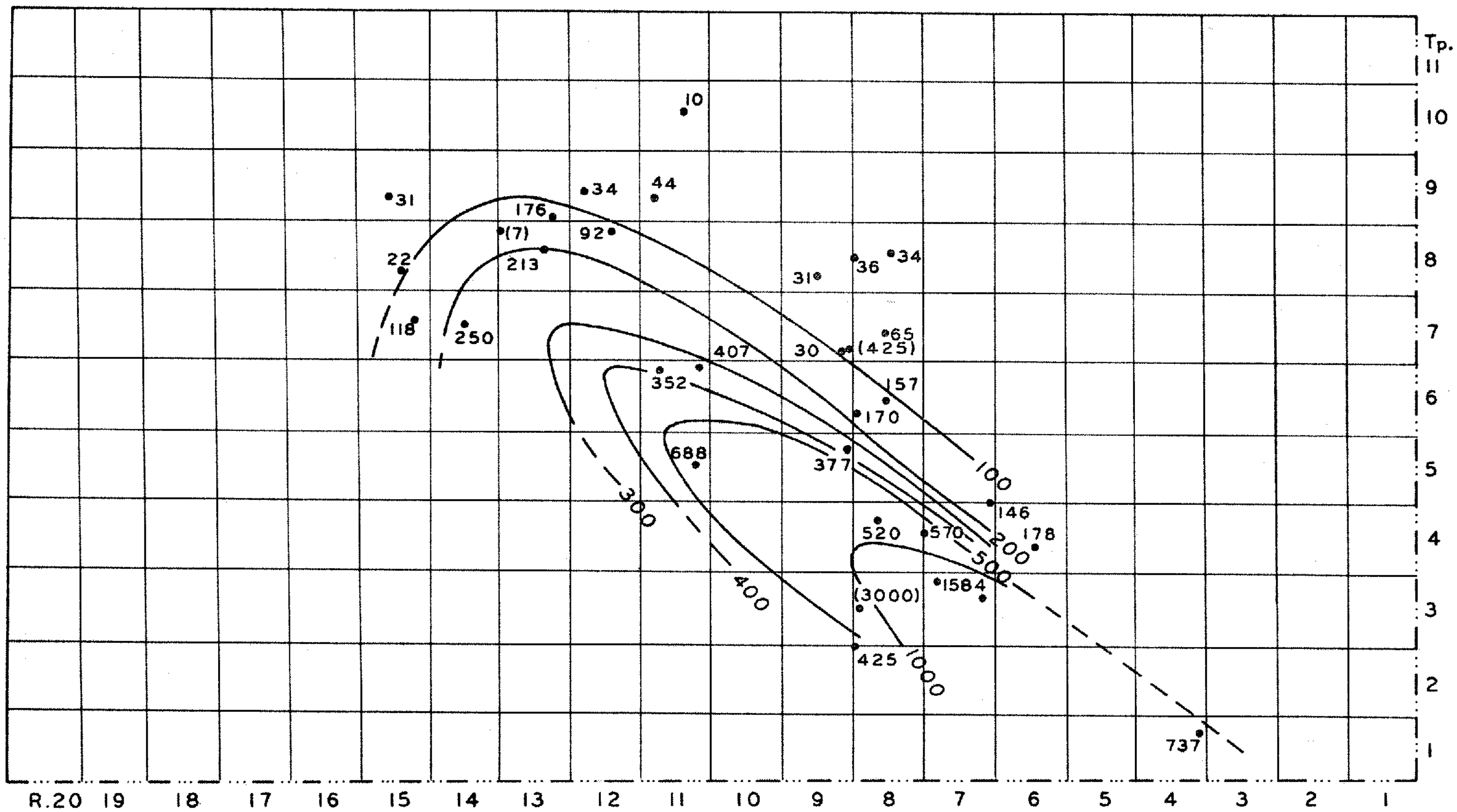


FIGURE 15. Transmissibility pattern of Milk River sandstone

missibility pattern closely follows these sedimentological trends. A northwest-trending zone of high transmissibility values, extending from township 1, range 2, toward township 8, range 13 coincides with a similar zone consisting of thick sand deposits that is shown on the vertical variability pattern map (Fig. 10).

Although no field tests could be carried out in the southwest part of the area, similar conditions may occur along the other sand belts.

PIEZOMETRIC SURFACE AND DIRECTION OF GROUNDWATER MOVEMENT

Definitions

The piezometric surface is defined as an imaginary surface that everywhere coincides with the head of water in the aquifer (Meinzer, 1932). The configuration of this surface gives valuable information as to the direction and rate of groundwater movement.

As is pointed out by Hubbert (1940), the piezometric surface is the projection of a three-dimensional flow field upon an arbitrary two-dimensional surface through that field. It is assumed that the groundwater gradient is proportional to the slope of the piezometric surface and it is also assumed that the confining beds are entirely impermeable, so that the normal flow component across the boundary surface is negligible and that the tangential flow component represents the total flow.

The hydraulic gradient can only be considered as proportional to the slope of the piezometric surface if the dip of the aquifer is less than about 3 degrees, or 276 feet per mile. The dips of the Milk River sandstone are considerably lower than 3 degrees except in the vicinity of the Sweet Grass Hills, where dips of 400 feet per mile occur. The extreme southern part of the piezometric map may therefore not reflect the true situation.

No attempt was made to fit the piezometric surface to a flow-net, as quantitative information could be obtained from other sources.

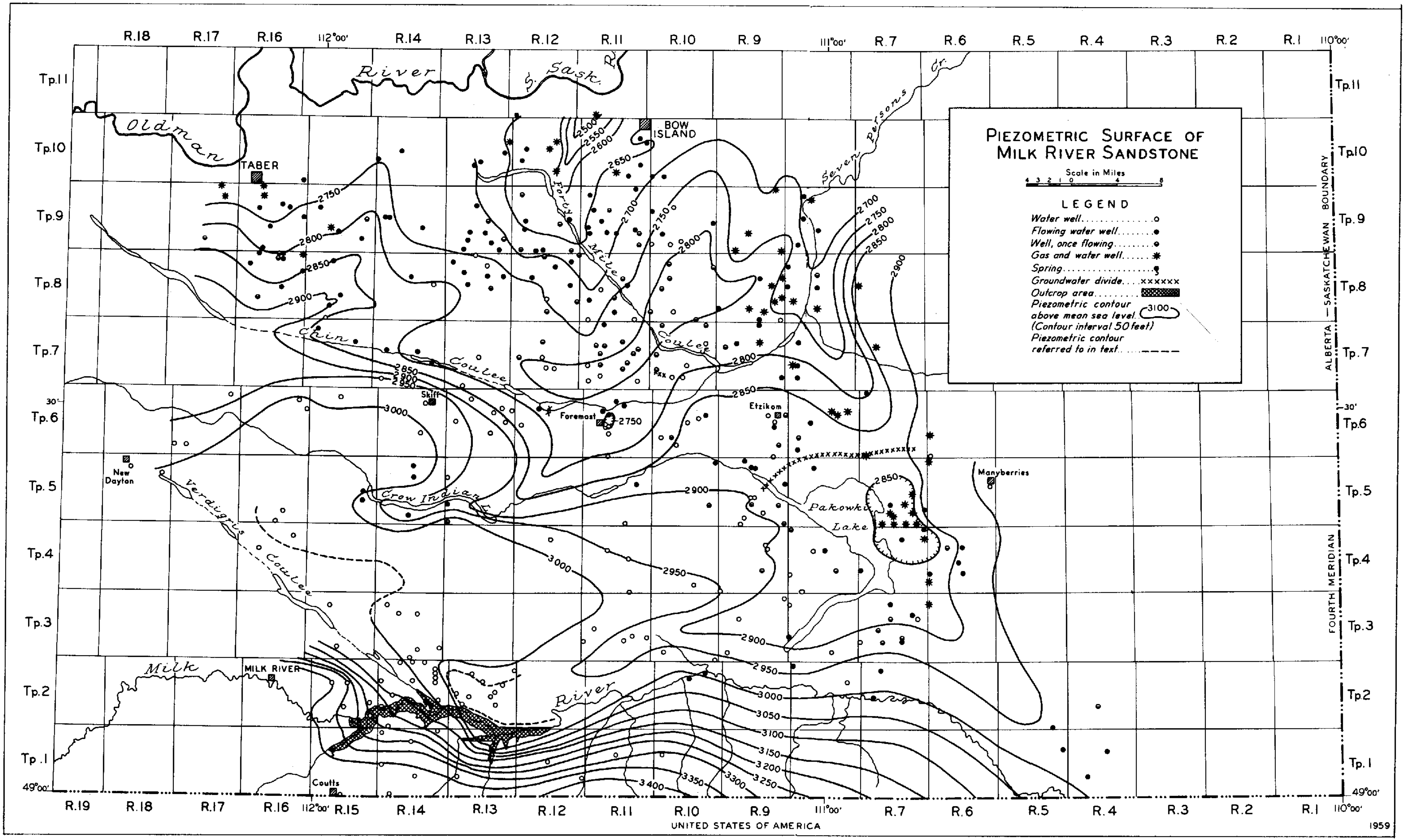
Water levels were measured with pressure gauges, an electric tape, and a steel tape. The elevations of the wells were determined with a survey altimeter, or were taken from the topographic maps.

A map showing the piezometric surface of the Milk River sandstone is given in figure 16.

Development of the Present Piezometric Surface

Before any water was pumped from the aquifer, the configuration of the piezometric surface was determined by the amount of natural discharge, the rate of recharge and the permeability of the aquifer. The small amount of natural discharge and the decreasing permeability to the north and east probably produced a high head and a very low hydraulic gradient, so that consequently the

FIGURE 16 Piezometric surface of Milk River sandstone



PIEZOMETRIC SURFACE OF MILK RIVER SANDSTONE
Scale in Miles
LEGEND
Water well
Flowing water well
Well, once flowing
Gas and water well
Spring
Groundwater divide
Outcrop area
Piezometric contour above mean sea level. (Contour interval 50 feet)
Piezometric contour referred to in text
ALBERTA — SASKATCHEWAN BOUNDARY
FOURTH MERIDIAN
UNITED STATES OF AMERICA
1959
TABER
BOW ISLAND
Skiff
Foremost
Etzikom
New Dayton
Manyberries
MILK RIVER
Coutts
Oldman
S. Sask. River
Seven Persons Cr.
Forty Mile Coulee
Chin Coulee
Crow Indian L.
Pakowki Lake
Verdigris Coulee
Milk River

rate of movement was extremely small. Nevertheless some movement certainly took place, and the connate water in the Milk River sandstone was replaced and freshened by downward-seeping meteoric water. This process took considerable time, since the rate of movement is believed to have been in the order of 0.5 to 5 feet per year, the greatest speed being along the northwestward path of high transmissibilities.

This hydraulic system was disturbed during post-glacial time, when the Milk River cut its present valley and intersected the Milk River sandstone in townships 1 and 2, ranges 12 to 15. The natural discharge then strongly increased by means of newly-formed springs along the southern bank of the river. These springs contributed to the formation of the deep and steep-sided canyons south of the outcrop area (Fig. 17). This post-glacial disturbance was accompanied by and followed by an adjustment of the hydraulic system. Since it is unlikely that the amount of natural recharge increased during this period of adjustment, the restoration of the dynamic equilibrium was accomplished by a lowering of the piezometric surface over a large area. It is believed that these changes are reflected by the 3,000-foot contour of the present-day piezometric surface, which still indicates places where the water from the Milk River sandstone rises above the lowest river level in the outcrop area.

In the outcrop area, these changes resulted in a change from artesian to water-table conditions in the aquifer. However, this situation only exists for a short distance north of the river, because of the northward dip of the strata and the overlying confining beds.

The recent development of the aquifer again disturbed the dynamic equilibrium. Prior to pumping from the Milk River sandstone, the over-all gradient was to the north, east, and west. The most definite changes brought about by the development of the aquifer have been the steepening of the gradient to the north and the reversal of the gradients to the east and west. Whereas the water previously moved toward the north, east, and west in response to the original gradient, it now moves from all directions to cones of depression caused by heavy pumping. The areas between the cones of depression, which may first appear to be areas of local recharge, are actually areas where the original piezometric surface has been lowered to a lesser extent, or they may even represent remnants of the original piezometric surface. During the recent development the discharge increased again without increase in recharge, and the piezometric surface was lowered anew.

Areas of Discharge

The most notable lowering of the piezometric surface occurs in heavily-pumped areas.

Pumping from a confined aquifer such as the Milk River sandstone causes a cone of pressure relief to expand in all directions.

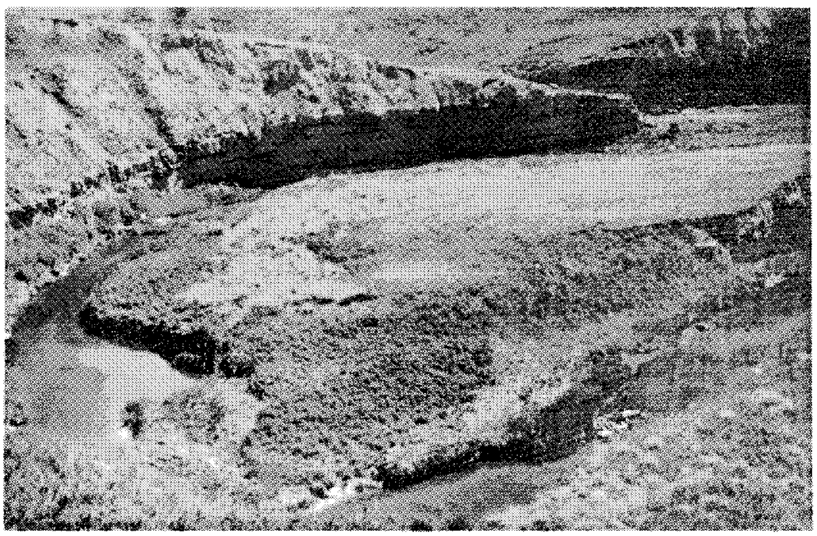


FIGURE 17. Red Creek Canyon

The transfer of pressure changes takes place quite rapidly and even small pumping rates will have a large and widespread effect upon the piezometric surface. The same effect on a larger scale can be obtained by several wells producing from the same aquifer. The individual cones of depression will interfere, producing one large cone of depression extending in all directions from the pumped area. This situation exists in several places in southern Alberta, and the following areas are of particular interest:

1. *Chin Coulee, Etzikom Coulee, Seven Persons Coulee, and Forty Mile Coulee.* The piezometric surface shows pressure anomalies over the several coulees, resulting in a striking similarity in directions of groundwater flow and surface drainage. The narrow depressions in the piezometric surface (Fig. 16) are caused by the large number of strongly-flowing wells in the coulees. Because of their lower elevation their flow is considerably larger than that from wells which are located on the adjacent uplands. The wells in the coulees are characterized by a deeper cone of pressure relief because of the difference in discharge.

Most of the wells are located in pastures, and the water is used for stock watering.

2. *Pakowki Lake Area.* In 1937 all wells around Pakowki Lake were reported to be flowing (Geological Survey of Canada, 1937) with an average flow of 15 gpm. The pressure has declined since then and the average flow has been reduced to 4 to 7 gpm., with an accompanying drop in hydrostatic head of 20 to 30 feet. The greatest decline of pressure as indicated by the 2,850-foot contour (Fig. 16), is caused by 13 strongly-flowing wells, very closely spaced. The asymetrical cone of depression around these wells is characterized by a steep eastern slope and a more gently-dipping western slope. This reflects the changing transmissibility in the area.

Darcy's law can be expressed as

$$Q = TIL \qquad (5)$$

where: Q = total amount of flow in gallons per day
T = transmissibility
I = hydrostatic gradient in feet per mile
L = length in miles of cross-sectional area, through which the water moves, normal to the flow direction.

The gradient on the west side of the 2,850-foot contour is 5 feet per mile, whereas the gradient at the eastern side is as much as 50 feet per mile. However, since the transmissibility changes from 50 gpdf. in range 6, to 500 gpdf. in range 8, there is still the same amount of water moving across each mile of the cone depression.

The average transmissibility around Pakowki Lake is 250 gpdf. and the average gradient is 12 feet per mile. The circumference of the cone of pressure relief, which is given by the 2,850-foot contour, is approximately 20 miles. Equation (5) can be used to calculate an approximate value of the daily influx across the 2,850-foot contour, namely 250 × 12 × 20 is 60,000 gallons. The average flow of the wells in the area is 5 gpm., resulting in a daily output of 93,000 gallons. From this total daily production only 60,000 gallons are estimated to be transmitted through the aquifer, the remaining 33,000 gallons being obtained from storage, indicating a steady depletion of the aquifer. This value may be inaccurate but it is believed to show the magnitude of the amount drawn from storage under present conditions. Before equilibrium between natural recharge and discharge will be reached, the flow of many wells will be curtailed severely.

3. *Foremost Area.* A detailed map of the piezometric surface around Foremost was difficult to construct, because of a lack of well control. It is certain, however, that a deep cone of pressure relief exists in the area, the circumference of which around the 2,750-foot contour is estimated at three miles. The regional northward gradient is reversed and the water flows toward Foremost from all directions.

North of Foremost an isolated mound exists on the piezometric surface, indicated by the 2,850-foot contour (Fig. 16). As was pointed out earlier (p. 43), this may be either a result of differential depletion or a remnant of the original piezometric surface. Many of the wells on this high were drilled early in the history of development and almost all once flowed. Due to many additional wells, the pressure declined gradually and wells are reported to have stopped flowing first in 1940. In later years some strongly-flowing wells were drilled in the Chin and Forty Mile Coulees, and since 1954 the village of Foremost has withdrawn its entire water supply from the Milk River sandstone. In the meantime, some of the older wells north of Foremost were abandoned. As a result of the steady increase in production in township 6 and the contemporaneous decrease in production in townships 7 and 8, the hydraulic gradient in the area was reversed from northward to southward.

The Foremost discharge area is separated from the Pakowki Lake discharge area, as well as from the rest of southern Alberta, by a groundwater divide which runs from township 3, range 13 through township 4, range 10 toward township 6, range 7 (Fig. 16). This ridge probably also results from differential depletion in a similar manner to the other groundwater divides already discussed. Compared with water levels reported in 1937, the average drop of the piezometric surface in the Foremost area is 70 feet. A maximum drop of 100 feet has taken place south of Foremost, whereas the pressure decline to the north has amounted to 30 to 50 feet.

Within the area enclosed by townships 5, 6 and 7, within ranges 10, 11, and 12, fifty water wells have been producing for 25 years, with an average production of 2 gpm. each, amounting to a total

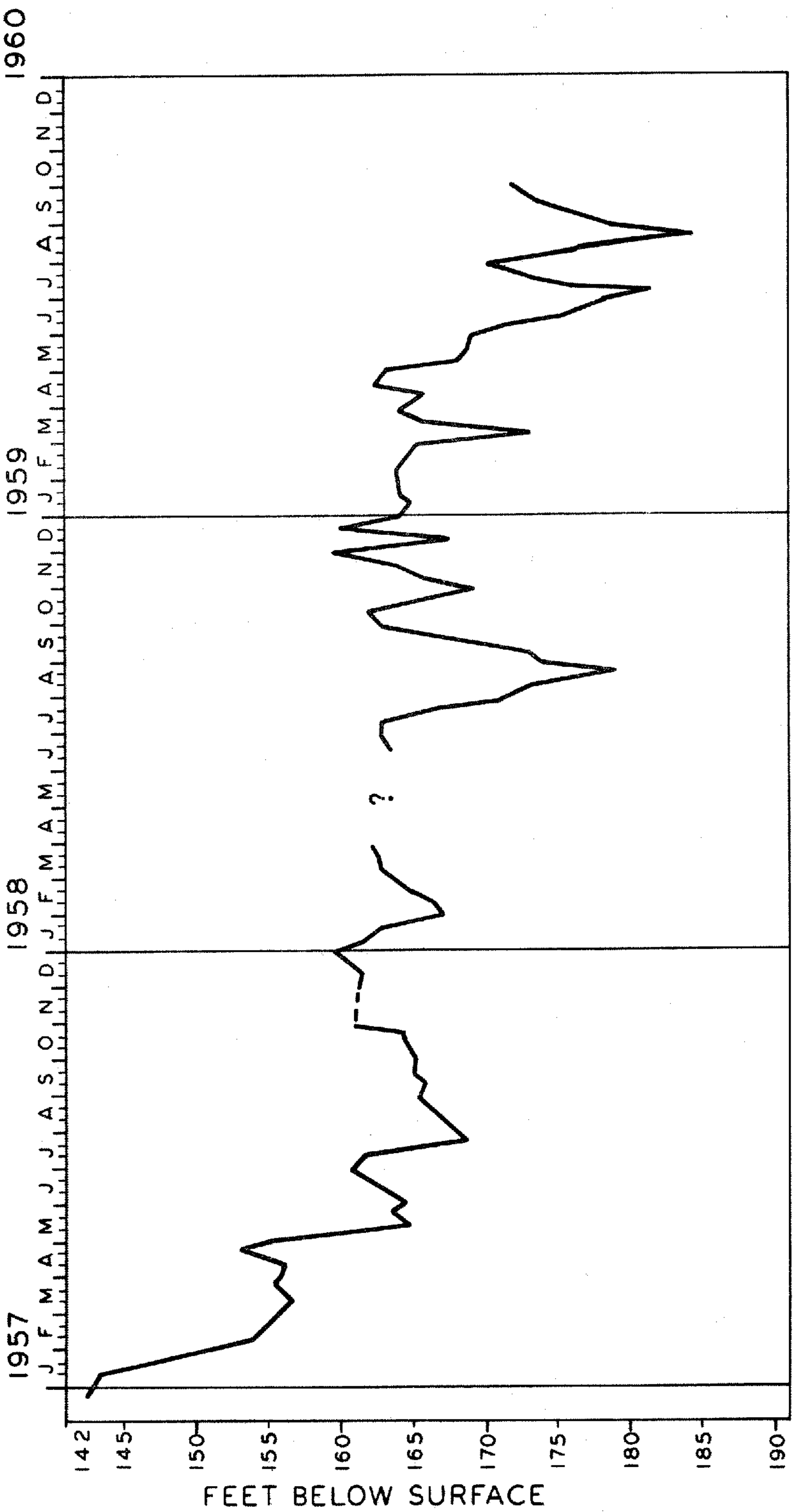


FIGURE 18. Foremost hydrograph, 1957 - 1959

output of 0.2×10^9 cubic feet of water during the past 25 years. During the same time the piezometric surface has been lowered 70 feet over an area of 324 square miles.

The storage coefficient of the aquifer may be calculated by dividing the total volume of water released by the product of head change and the area of aquifer surface over which the lowering was effective. Therefore:

$$S = \frac{0.2 \times 10^9}{7.0 \times 10 \times 9.0 \times 10^9} = 0.0003 \qquad (6)$$

This figure may not be very accurate, but is believed to give the magnitude of the true value, and is therefore worthwhile presenting.

Since 1956 the history of the declining piezometric surface around Foremost has been recorded by means of a Leupold Stevens type FM recorder, which was installed on an abandoned well at the Foremost school. The village draws considerable amounts of water from the Milk River sandstone by means of two town wells and a privately-owned hotel well. The average daily production is 20,000 gallons. When the recorder was installed, the static water level in the observation well was 128 feet below surface. In the summer of 1959 the static level was approximately 180 feet below surface. The hydrograph obtained from this observation well is shown in figure 18.

It is possible to predict future water levels by means of a time-series analysis of such hydrographs. This technique has been used in a similar study by Remson and Randolph (1958) and the general procedure is discussed by Arkin and Colton (1950, p.65-75) and Moroney (1956, p. 321-33).

The difference between the mean water level over a period of three months (equal to one quarter year: Q) and the datum level of 128 feet below the surface was taken as a measure of the decline in water level.

The mean drop in successive three-month periods was plotted on an arithmetic scale (Fig. 19) and shows both a clearly defined secular (long-term) trend and seasonal variations. The latter result from changes in pumping rates.

To analyze the secular trend, the ratio-to-trend method was used (Arkin and Colton, 1950). The secular trend is expressed by the general equation:

$$L^1 = K_1 + K_2 \ln t \qquad (7)$$

L^1 = expected difference between mean seasonal water level and datum level (trend value), in feet

K_1 = constant

K_2 = constant

$\ln t$ = natural logarithm of elapsed time (t) since pumping began, measured in periods of three months.

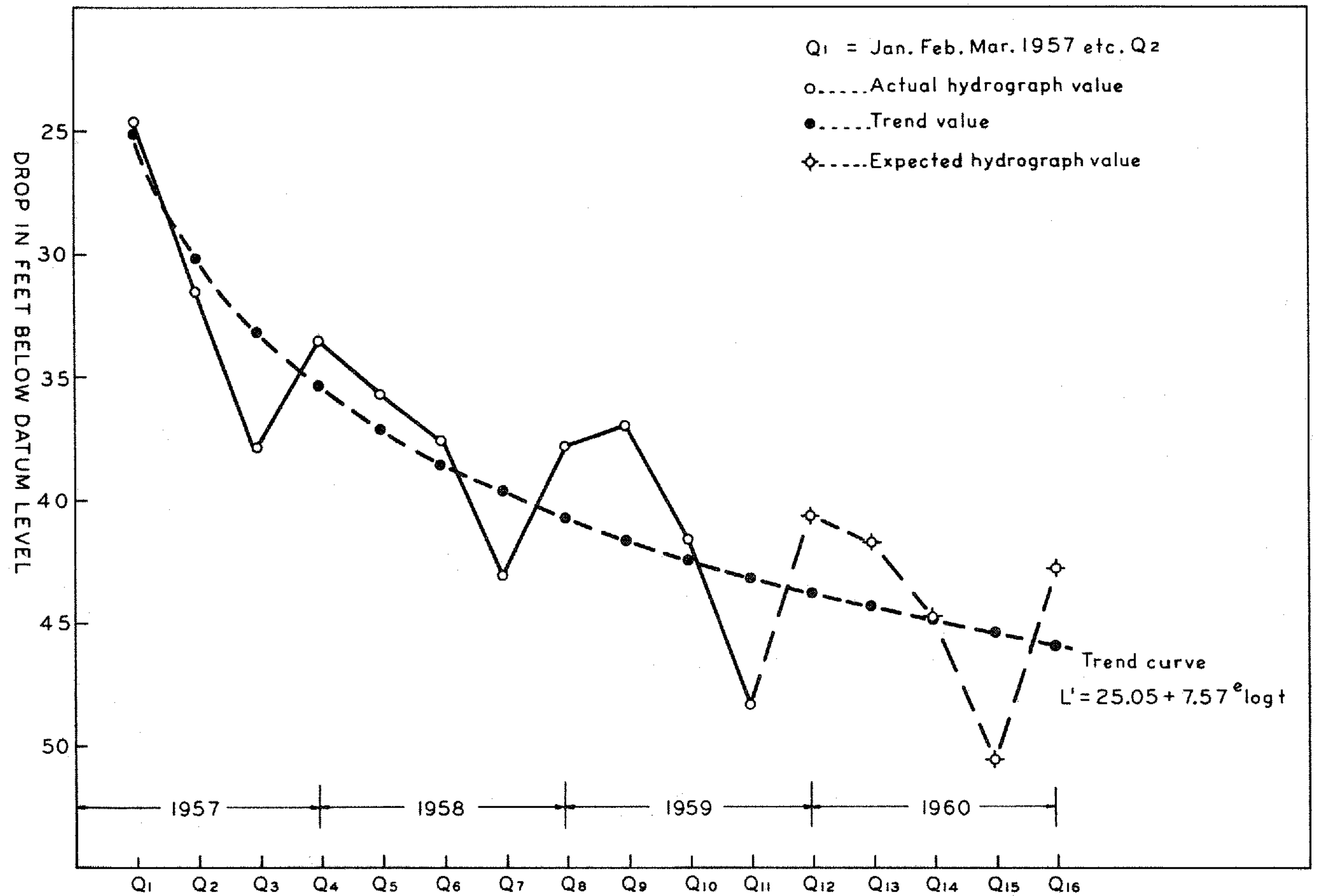


FIGURE 19. Time-series analysis of Foremost hydrograph

The trend equation was obtained by fitting the curve of equation (7) to the hydrograph data, using the principles of the least squares. The least squares were determined by the normal forms:

$$\Sigma\, L = NK_1 + K_2\, \Sigma \ln t \qquad (8)$$

$$\Sigma\, (L. \ln t) = K_1\, \Sigma \ln t + K_2\, \Sigma\, (\ln t)^2 \qquad (9)$$

N = number of periods

L = observed difference between mean seasonal water level and datum level (trend value), in feet

From these equations K_1 and K_2 were found to be 25.05 and 7.57, respectively, and thus the secular trend equation becomes:

$$L^1 = 25.05 + 7.57 \ln t \qquad (10)$$

This equation was obtained from hydrograph data from January, 1957 to October, 1959, which are shown in table 4.

Table 4: Time-series Analysis of Foremost Hydrograph

Time (t)	L	ln t	L ln t	$(\ln t)^2$	L^1	$L - L^1$	$\frac{L - L^1}{L} \times 100$
1	24.6	0	0	0	25.05	—0.45	—1.7%
2	31.5	0.69	21.73	0.47	30.27	1.23	4%
3	37.9	1.09	41.31	1.18	33.30	4.60	14%
4	33.6	1.38	46.36	1.90	35.49	—1.89	—5%
5	35.7	1.61	57.48	2.59	37.23	—1.53	—4%
6	37.6	1.79	67.30	3.20	38.60	—1	—2%
7	43.1	1.94	83.61	3.76	39.73	3.37	8%
8	37.8	2.07	78.24	4.28	40.71	—3.71	—9%
9	37	2.19	81.03	4.79	41.61	—4.61	—11%
10	41.7	2.30	95.90	5.29	42.46	—0.76	—1%
11	48.3	2.39	115.43	5.71	43.14	5.16	12%
N=11	408.8	17.45	688.38	33.18			

There is considerable deviation among the computed trend values (L^1) and the observed hydrograph values (L). For this reason it is necessary to take seasonal variations into account, in order to predict future water levels more precisely. The average seasonal variation for:

January, February, March	(Q_1, Q_5, Q_9):	—5.5%
April, May, June	(Q_2, Q_6, Q_{10}):	—0.3%
July, August, September	(Q_3, Q_7, Q_{11}):	11.3%
October, November, December	(Q_4, Q_8, —):	—7%

The seasonal factors given as a percentage of the secular trend become

January, February, March	94.50%
April, May, June	99.70%
July, August, September	111.30%
October, November, December	93.00%

The average range per season is 6.25 per cent and the standard deviation of the average range is:

$$\frac{\text{average range}}{\sqrt{N}} = 3.12\% \qquad (11)$$

If no unforeseen factors such as changes in pumping rate cause major changes in the long-term trend, the observed values should lie within two standard deviations of the expected values in at least 95 per cent of the cases. The expected values are shown in figure 19 and table 5.

Table 5: Expected Water Levels in Foremost, 1960

	Time	Trend Value	Seasonal Factor	Expected
Q_{12}	October, November, December, 1959	43.82	×0.93	= 40.75
Q_{13}	January, February, March, 1960	44.42	×0.945	= 41.97
Q_{14}	April, May, June, 1960	44.94	×0.997	= 44.81
Q_{15}	July, August, Septmber, 1960	45.48	×1.113	= 50.65
Q_{16}	October, November, December, 1960	46.01	×0.93	= 42.78

In January, 1959, this same method was applied to the data that were available at that time. The trend curve was calculated to be: $L^1 = 25.97 + 7 \ln t$, and the levels that were predicted are compared with the actual values observed during 1959. This comparison is given in table 6.

Table 6: Comparison of Calculated and Observed Water Levels in Foremost, 1959

	Expected	Observed
Q_9	39.44 ± 1.38	37 feet below datum level
Q_{10}	41.85 ± 1.41	41.76 feet below datum level
Q_{11}	46.97 ± 1.43	48.30 feet below datum level
Q_{12}	40.94 ± 1.45	42.30 feet below datum level

The trend equation of January, 1959, underwent some modification to fit the 1959 observations, but except for Q_9, all observed levels were within the expected limits.

This method might well be a very useful tool in making short-range predictions which would enable those concerned to take the necessary precautions in time. Furthermore, the method will give an answer to the question of whether or not flow reduction in the nearby Chin Coulee will have a great effect upon the water levels in the Foremost wells.

Decline of Head and Aquifer Compressibility

It is possible now to give some quantitative values concerning the reduction of storage water in the Milk River sandstone. Similar calculations were carried out by Meinzer and Hard (1925) and Meinzer (1928) for the Dakota sandstone in North Dakota.

Since the survey of the Geological Survey of Canada in 1937, many new wells have been drilled into the Milk River sandstone and during the present investigation 409 wells were found. The total daily production of these wells is 700,000 gallons which is slightly over one gallon per minute per well. Jones (1960) mentioned the same production of water wells in the Beaverlodge district, and this seems to be a reasonable estimate for the average production of a farm well in Alberta.

The average decline of head in the past 22 years is 20 feet, or 0.9 feet per year.

The average depth of the Milk River sandstone is 700 feet; the pressure exerted by 700 feet of overlying shale, with a specific gravity of 2, will equal to $700 \times 2 = 1400$ feet of water, or $1400 \times 0.43 = 600$ pounds per square inch.

The pressure that is borne by the aquifer skeleton is:

formation pressure (P_f) — artesian buoyance (P_a) .... (12)

which is 297 pounds per square inch for the Milk River aquifer.

A pressure decline of 0.9 foot per year equals 0.38 pounds per square inch, which is an increase in overburden pressure (P_f) of 0.127 per cent. Since 1937 the overburden pressure on the Milk River sandstone therefore increased by 2.97 per cent or 8.28 Psi.

According to compressibility tests carried out by Terzhagi (1925), the porosity of sandstone decreases 0.013 per cent per 1 per cent load increase. The decrease in porosity of the Milk River sandstone thus amounted to 0.036 per cent since 1937.

Over the past 22 years, the Milk River aquifer has yielded approximately 500,000 gallons per day, which equals a total production of 6.4×10^8 cubic feet. The main discharge occurred between townships 2 and 11, within ranges 6 to 16. The Milk River sandstone in this area can be considered to be a wedge, 200 feet high in the south, 54 miles long and 60 miles broad. The total volume of the wedge is 9×10^{12} cubic feet. The original pore space of this body is approximately 10 per cent, or 9×10^{11} cubic feet. This volume was reduced 0.036 per cent during the past 22 years, which means a total reduction of 3.2×10^8 cubic feet of pore space.

As pointed out above, 6.4×10^8 cubic feet of water were released since 1937. During the same time the pore space was reduced by 3.2×10^8 cubic feet. It is obvious now that only 50 per cent of the total water production could have been transmitted through the aquifer and the remaining 50 per cent was obtained from storage.

Again it is possible to calculate the coefficient of storage using equation (6). The total amount of water released is 6.4×10^8 cubic feet over 9×10^{10} square feet of aquifer area; the accompanying head change was 20 feet.

$$S = \frac{6.4 \times 10^{8}}{2 \times 10 \times 9 \times 10^{10}} = 0.00035 \quad (13)$$

The amount of water that is drawn from storage clearly demonstrates that the Milk River sandstone is barely a functional reservoir, for according to the definition given by Kazmann (1958) a functional reservoir must admit water, store water, and permit water to be withdrawn economically.

The true nature of the Milk River sandstone as a groundwater reservoir is best illustrated by the extremely low velocities at which the water is moving. The rate of groundwater movement is expressed by:

$$V = \frac{P\,I}{5280\,p} \quad (14)$$

V = velocity in feet per day
P = permeability in cubic feet of flow per square foot of cross-sectional area (transmissibility divided by aquifer thickness)
I = hydraulic gradient in feet per mile
p = porosity in decimal fraction

The hydraulic gradient in the central portion of southern Alberta does not exceed 25 feet per mile, the average permeability is 0.40 cubic feet per square foot (average transmissibility of 350) and the average porosity is 10 per cent. Therefore the maximum possible velocity is:

$$V = \frac{0.40 \times 25}{0.10 \times 5280} = 0.018 \text{ foot per day, which equals } \mathbf{6.57 \text{ feet per year.}}$$

In the southeastern part of the area, where the transmissibilties are somewhat higher, the rate of groundwater movement is:

$$V = \frac{0.90 \times 25}{0.10 \times 5280} = 0.042 \text{ foot per day, which equals } \mathbf{15.33 \text{ feet per year.}}$$

The significance of these values with regard to proper exploitation of the Milk River groundwater resources will be discussed in conjunction with areas of recharge.

Areas of Recharge

Since not all water that is pumped from the aquifer comes from storage, recharge must take place. The first opinion on recharge of the Milk River sandstone was expressed by Dowling (1915); the conclusion of his excellent study was that the outcrop area along the Milk River was responsible for the replenishment of the aquifer. Evidence has been found to show that this is only partially true.

The Milk River sandstone is exposed for a distance of 20 miles along the Milk River. As is shown on the piezometric map, discharge from the aquifer into the river takes place in ranges 14 and 15, over a distance of 10 miles. Red Creek which flows into the Milk River from the south is fed entirely by a spring issuing from the Milk River sandstone (Figs. 16 and 17). Several springs also exist along the west side of Verdigris Coulee, on the north side of the Milk River.

During its course through Canada, the Milk River almost doubles in flow, according to stream-flow measurments conducted by the Department of Northern Affairs and Natural Resources (Surface Water Supply of Canada, Water Supply Papers 109 - 19). Table 7 gives a comparison between the average flow at Milk River (Station 11AA 5, Tp. 2, R. 16) and at the Eastern Crossing (Station 11AA 0, 2; NE. ¼ Sec. 6, Tp. 37 N., R. 9 E, Montana). The difference between the means of the yearly records are statistically significant.

Table 7: Stream-flow Measurements of the Milk River, 1947 to 1957

(discharge in cubic feet per second)
(extracted from Surface Water Supply of Canada, Water Supply Papers, 109-19)

Year	Station 11AA 5	Station 11AA O, 2
1946 - 1947	360	613
1947 - 1948	431	663
1948 - 1949	304	426
1949 - 1950	331	486
1950 - 1951	482	779
1951 - 1952	370	625
1952 - 1953	489	794
1953 - 1954	368	524
1954 - 1955	334	552
1955 - 1956	390	574
1956 - 1957	369	580
Average	384	601

From 1910 to 1915 when Writing on Stone was still a police post, additional gauging stations existed along the Milk River. The observations of these stations are given in table 8. The station at Writing on Stone was located in SW. ¼ Sec. 35, Tp. 1, R. 13 and the Pendant d'Oreille station was located in SW. ¼ Sec. 21, Tp. 2, R. 8.

Table 8: Stream-flow Measurements of the Milk River, 1910 to 1915

(discharge in cubic feet per second)
(Extracted from Surface Water Supply of Canada; Water Supply Papers 73-78)

Year	Milk River	Writing on Stone	Pendant d'Oreille
1911	206	255	279
1912	148	105	153
1913	155	231	291
1914	94	111	121
1915	175	282	316
Average	155*	196	232

* The difference in stream volume during the periods 1910 to 1915 and 1947 to 1957 is a result of the irrigation development in the United States. The flow of the Milk River is augmented during the

irrigation season by water flowing into the north branch of the Milk River from the St. Mary Canal.

As is shown, the flow increases from range 16 to range 8, but since 31 major creeks discharge into the river along this stretch, it is difficult to determine exactly the contribution of springs from the Milk River sandstone. It is possible, however, to determine the order of magnitude of flow from such springs, assuming that discharge into the river takes place along the entire southern bank of the outcrop area. Using equation (5) (p. 45), the following values are substituted: the transmissibility is 1100 gpdf., the length of the cross-sectional area through which discharge takes place is 20 miles and the gradient toward the river is 50 feet per mile. The total flow of groundwater discharging into the river is then

$1100 \times 20 \times 50 = 1.1 \times 10^6$ gallons per day, which equals 1.76×10^5 cu. ft. per day, or 2 second-feet.

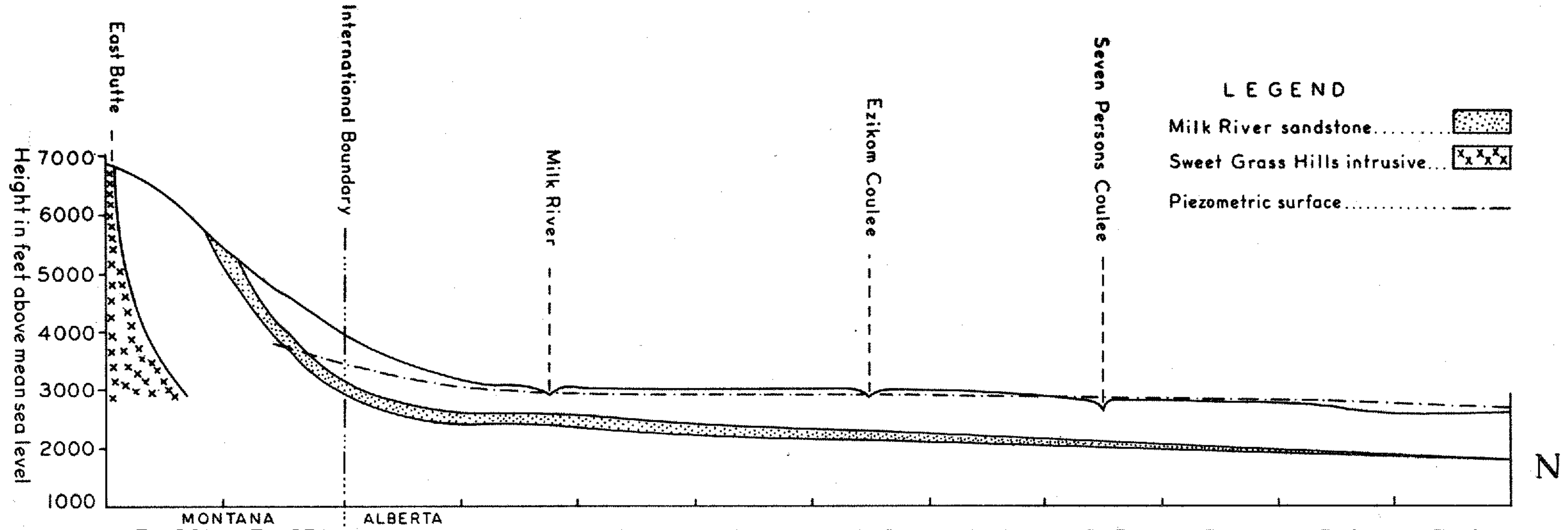
It is obvious from this calculation that, even if discharge took place along the entire length of the outcrop, springs from the Milk River sandstone should contribute only 0.3 per cent of the total stream flow.

East of Verdigris Coulee some infiltration from the river into the exposed aquifer takes place along the northern bank of the Milk River; but since only 50 per cent of the Milk River sandstone is below river level, the infiltration capacity is reduced considerably. The transmissibility at Writing on Stone can be assumed to be 1100 gpdf., the average gradient is 8 feet per mile and the length of the intake area across the 2,890-foot contour (dashed line in figure 16) is 13 miles, then, according to equation (5), the daily influx is 57,000 gallons which is less than 10 per cent of the total daily production from the aquifer.

The outcrop area of the Milk River sandstone along the Milk River is therefore only a very limited source of recharge, and perhaps even this small amount of infiltration in induced by heavy pumping in township 2, range 13.

According to the piezometric map (Fig. 16), the Sweet Grass Hills are the main intake area of the Milk River sandstone. This sandstone, together with older Cretaceous and Jurassic strata, has been uplifted by the Sweet Grass Hills intrusions and is exposed in circular outcrops around these hills. A cross section of this situation is given in figure 20.

The strata dip steeply away from the intrusive nuclei by as much as 400 feet per mile and the outcrop area of the Milk River sandstone in the Sweet Grass Hills behaves like a water-table aquifer. The boundary between the water-table aquifer and artesian aquifer is given by the piezometric surface in figure 20. The fountainhead is



CROSS SECTION OF MILK RIVER SANDSTONE AQUIFER FROM MONTANA INTO CANADA
THROUGH RANGE 9, W.4th M.

Horizontal Scale in Miles
6 0 6 12 18

FIGURE 20

at approximately 3,700 feet above mean sea-level. More evidence to support this hypothesis will be offered in the discussion of the chemical data (p. 62).

Since transmissibility values appear to change over short distances it is difficult to give a quantitative estimate of the total influx from the Sweet Grass Hills into Alberta, but it is likely that this influx is sufficient to replenish the major part of the water withdrawn around Pakowki Lake. The groundwater divide north of Pakowki Lake prevents further natural recharge northward, and consequently the water that is produced north of the divide is drawn mainly from storage, and the remainder is transmitted from the Crow Indian Lake area to the west. This contribution, however, is probably very small because of the decreasing transmissibility in that direction. The situation will continue to exist until further decline of the piezometric surface has eliminated the divide, unless the heavy production near Pakowki Lake maintains a depression in the piezometric surface and thus maintains the divide.

As has been pointed out previously, the extremely low rate of groundwater movement limits the amount of water that can ultimately be produced from the aquifer. For example, if the water level at Foremost were lowered another 400 feet, then a maximum gradient of 38 feet per mile could be established between the Sweet Grass Hills and Foremost, provided that no discharge took place in between. According to equation (14) (p. 53), the groundwater velocity in the aquifer should then be

$$V = \frac{0.50 \times 38}{0.10 \times 5280} = 0.035$$ foot per day, assuming an average transmissibility of 465 gpdf.

This means that it would take more than 15,000 years to move water from the intake area to Foremost.

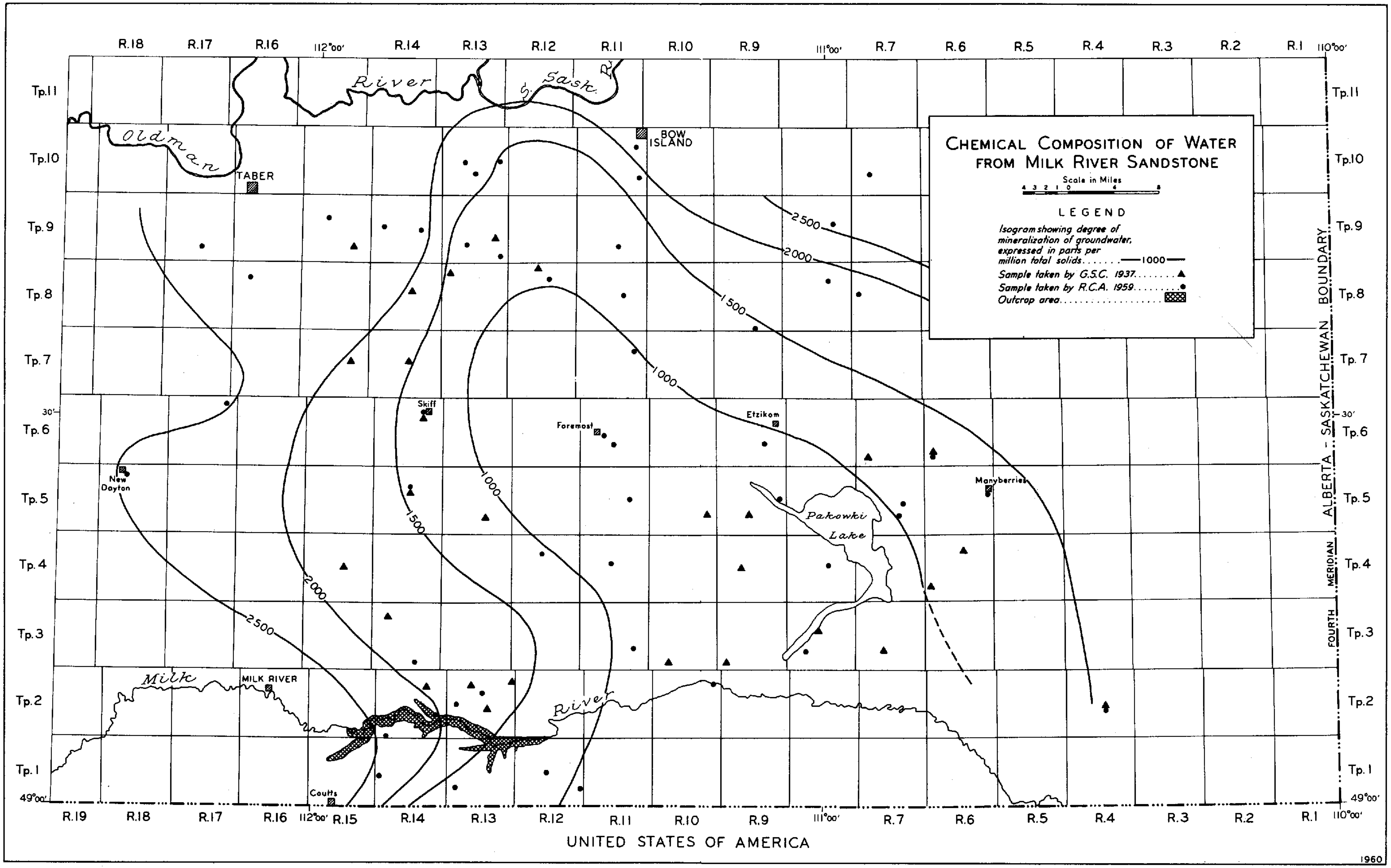
CHEMICAL QUALITY OF WATER FROM THE MILK RIVER SANDSTONE

General Statement

Water from the Milk River sandstone has certain definite chemical characteristics and if ordinary standards of quality were used, only a limited portion of the total output would be considered suitable for human consumption.

As has been pointed out previously, the connate water of the Milk River sandstone has been replaced and freshened by meteoric water. The degree to which this process has proceeded is shown in figures 21 and 22. The degree of mineralization is given in parts per million total dissolved solids (Fig. 21). Since sodium bicarbonate

FIGURE 21. Chemical composition of water from Milk River sandstone



CHEMICAL COMPOSITION OF WATER FROM MILK RIVER SANDSTONE
Scale in Miles
LEGEND
Isogram showing degree of mineralization of groundwater, expressed in parts per million total solids 1000
Sample taken by G.S.C. 1937........
Sample taken by R.C.A. 1959.........
Outcrop area..................
BOW ISLAND
TABER
Skiff
Foremost
Etzikom
New Dayton
Manyberries
MILK RIVER
Coutts
Pakowki Lake
Oldman
River
S. Sask. R.
Milk
River
2500
2000
1500
1000
ALBERTA - SASKATCHEWAN BOUNDARY
FOURTH MERIDIAN
UNITED STATES OF AMERICA
1960

FIGURE 22. Chemical composition of water from Milk River sandstone

and sodium chloride are the chief constituents of the water, their concentration in parts per million are shown on a separate map (Fig. 22).

The increasing degree of mineralization to the north, east and west from the Sweet Grass Hills is clearly demonstrated by figure 21. Both the mineralization map and the alkalinity and salinity map show a central zone of lower concentrations, extending northwest from township 2, range 9 toward township 8, range 12. This fresher zone is the result of higher water velocities through the more permeable part of the formation, as was shown in figure 15.

Types of Water

Four types of water from the Milk River sandstone are distinguished.

Type A. This type occurs in the area north of township 3, within the 1000 ppm. alkalinity isogram (Fig. 22). A typical analysis is shown graphically in figure 23A, and the corresponding data are set out in table 9.

The water is characterized by a moderate degree of mineralization (up to 1000 ppm.), caused almost entirely by sodium bicarbonate. Hardness is generally nil, but can be as high as 20 ppm. calcium carbonate. Chlorides and sulfates are of secondary importance, and do not exceed 70 and 10 ppm., respectively.

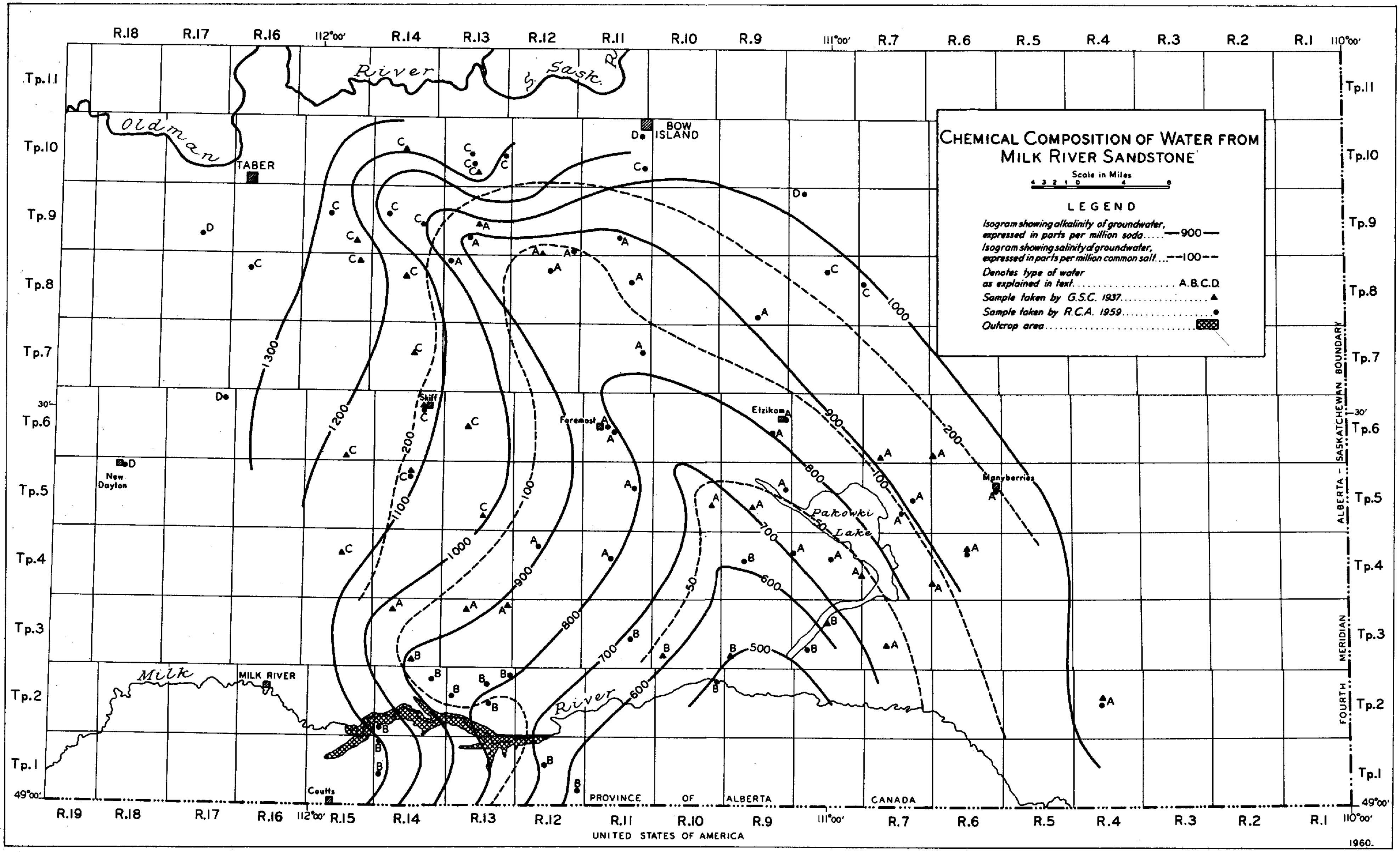
Type B. South of the area in which type A water occurs, the degree of mineralization decreases and the second type of Milk River groundwater is found in the area enclosed by the 50 ppm. salinity isogram (Fig. 22). A typical analysis is shown in figure 23 B and in table 9.

The most notable change from type A to type B water is an increase in sulfates. In township 1, the sulfate concentration may reach 500 ppm., and the increase in total dissolved solids in townships 1 and 2, ranges 13 and 14, is directly related to this high sulfate concentration (table 9).

Outside the area where waters of types A and B occur, the quality changes quite rapidly.

Type C. This type of water is produced in a narrow zone between the 1000 and 1200 ppm. alkalinity isogram (Fig. 22), and marks the transition to more strongly mineralized waters in the west. Along the eastern edge of the area, this transition zone is almost absent, and type A water is in immediate contact with connate type water. An analysis of type C water is given in figure 23C and table 9.

Both the degree of mineralization and the salinity are shown to have increased, compared to those of types A and B. Some sulfates



CHEMICAL COMPOSITION OF WATER FROM MILK RIVER SANDSTONE
Scale in Miles
LEGEND
Isogram showing alkalinity of groundwater, expressed in parts per million soda 900
Isogram showing salinity of groundwater, expressed in parts per million common salt ... 100
Denotes type of water as explained in text .... A.B.C.D.
Sample taken by G.S.C. 1937 ....
Sample taken by R.C.A. 1959 ....
Outcrop area ....
R.18
R.17
R.16
112°00'
R.14
R.13
R.12
R.11
R.10
R.9
111°00'
R.7
R.6
R.5
R.4
R.3
R.2
R.1
110°00'
Tp.11
Tp.10
Tp.9
Tp.8
Tp.7
Tp.6
Tp.5
Tp.4
Tp.3
Tp.2
Tp.1
30'
49°00'
R.19
R.15
Oldman
River
S. Sask. R.
TABER
BOW ISLAND
Shiff
Foremost
Etzikom
Manyberries
New Dayton
Pakowki Lake
MILK RIVER
Milk
River
Coutts
PROVINCE OF ALBERTA
CANADA
UNITED STATES OF AMERICA
ALBERTA - SASKATCHEWAN BOUNDARY
FOURTH MERIDIAN
1960.

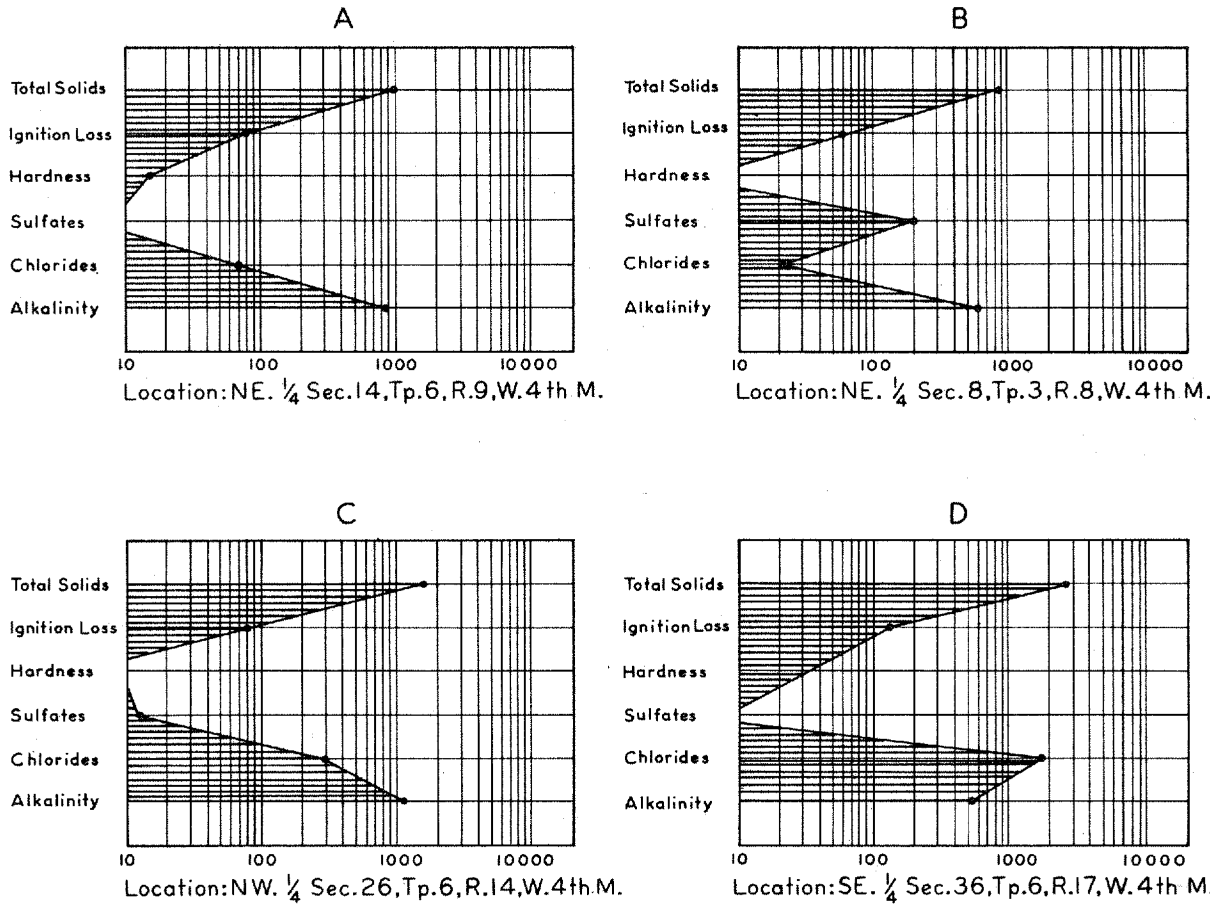


FIGURE 23. Chemical composition of water from Milk River sandstone

may occur, especially to the west, but their concentration does not exceed 20 ppm. This type of water represents a mixture of connate water and type A water.

Type D. Outside the 1200 ppm. alkalinity isogram in the west and the 1000 ppm. alkalinity isogram in the east, only highly mineralized water occurs, which is believed to be unaltered connate water, designated here as type D. An analysis is shown in figure 23D and in table 9.

In this type of water, the salt content (up to 2000 ppm.) exceeds the sodium content by almost four times.

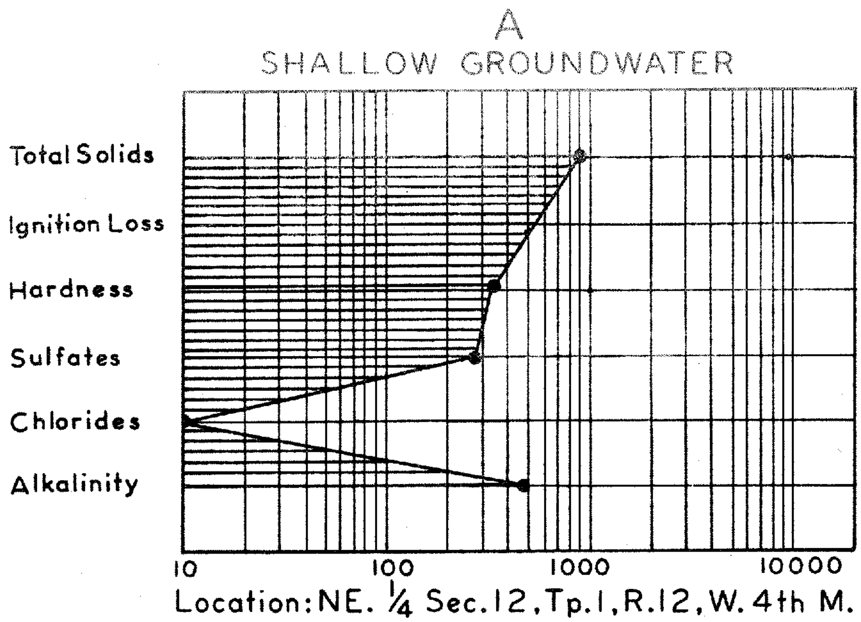
As the chemical composition of water from the Milk River sandstone is believed to be the result of a slow and prolonged process of freshening and replacing of connate water by meteoric water, no notable changes could be brought about in the relatively short time that elapsed since the first well tapped the aquifer. Nothwithstanding the small increase in water velocity since development began, because of an increase in gradient, it is believed that the contours in figures 21 and 22 closely approximate to the original (prepumping) situation. It is noteworthy that the samples taken by the Geological Survey of Canada in 1937 fit in the pattern obtained from recent anlayses, indicating that no significant changes in composition have occurred during the past 20 years.

Shallow groundwater of the plains region is characterized by a hardness of up to 1200 ppm. calcium carbonate and magnesium carbonate, and a rather high sulfate concentration. This is likely a result of insufficient leaching of the soil (Riffenburg, 1925; Hem, 1959). A typical analysis of water from a shallow well (less than 100 feet) in southern Alberta is given in figure 24A and table 9. Although no sample was available, the water in the Milk River sandstone near the outcrop area in the Sweet Grass Hills is expected to be of similar composition.

Table 9: Chemical composition of Waters from the Milk River Sandstone

(constituents are expressed in parts per million)
(Analyses by Provincial Analyst, Edmonton)

Location Constituents	NE. 14-6-9 Type A	NE. 8-3-8 Type B	NW. 26-6-14 Type C	SE. 36-6-17 Type D	Shallow well	NE. 34-1-13 Milk River surface water
Total solids	982	872	1464	3680	900	204
Ignition loss	78	54	74	140	—	96
Hardness	15	—	—	35	350	105
Sulfates	—	120	15	—	295	10
Chlorides	68	120	129	1835	10	—
Alkalinity	820	545	1085	500	420	135
Nature of alkalinity	bicarb., Na, Ca	bicarb., Na, Mg, Ca	bicarb., Na	bicarb., Na	bicarb., Ca, Mg	bicarb., Na, Ca, Mg
Nitrites	—	—	—	—	—	—
Nitrates	—	—	—	—	—	—
Iron	0.3	—	0.2	0.2	—	1.2



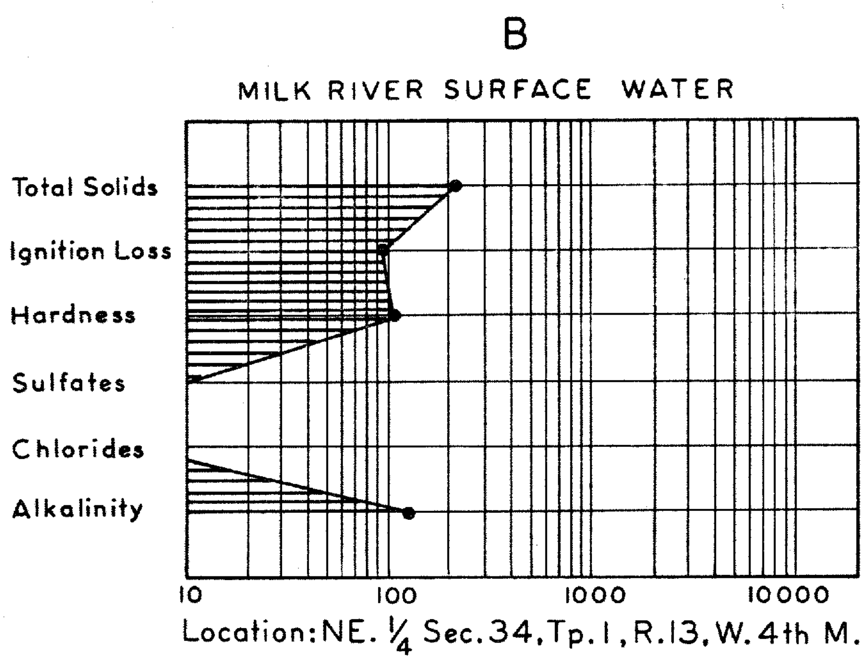


FIGURE 24. Comparison between chemical composition of shallow groundwater and surface water

Distinct chemical changes take place in the water while it is moving deeper into the formation. The hardness is greatly decreased by natural softening which begins as soon as the water comes into contact with materials containing natural zeolites (sodium and potassium aluminum silicates); this process has been described by Renick (1924). The softening takes place when the calcium and magnesium ions of the carbonates and bicarbonates are replaced by sodium and potassium ions from the zeolites. By this process of base exchange, the calcium and magnesium are removed from the solution and are fixed with the silicates. Bentonite, which is common in Cretaceous sediments of Alberta, acts in many respects like a zeolite in that the sodium cations of the montmorillonite are easily exchanged for calcium cations of the water (Byrne, 1955).

With increasing distance from the outcrop area, all calcium and magnesium will be replaced by sodium, which causes the increasing alkalinity to the north, east and west. This process is represented by the equation $2NaX + Ca \leftrightarrows CaX_2 + 2Na$, where X represents a unit of exchange capacity in the solid phase material (Hem, 1959).

The calcium sulfates in the water also contribute to increasing alkalinity, but by a slightly different process. As has been pointed out previously (p. 60), the sulfate concentration decreases to the northwest, north and east. This is a result of a reduction process that takes place when the water comes into contact with methane, which is the principal constituent of the natural gas occurring in the Milk River sandstone. The following reaction is given by Renick (1924) and Hem (1959):

$$CaSO_4 + CH_4 = CaS + CO_2 + 2H_20$$
$$CaS + 2CO_2 + 2H_2O = H_2S + Ca(HCO_3)_2$$

The calcium in the resulting bicarbonate will also be changed for sodium, thus producing a still higher soda-alkalinity.

The sulfate content of water from the Milk River sandstone is another strong indication that the amount of river infiltration in the outcrop area is extremely small and was virtually nonexistent when Milk River groundwater originated in its present form. As is shown in table 10, no difference in sulfate concentration exist north and south of the Milk River. For comparison, the sulfate content of the river is given in the same table. The fact that springs from the Milk River sandstone discharge into the river is reflected by the rise in sulfate content between SW. ¼, Sec. 12, Tp. 2, R. 15 and S.W. ¼, Sec. 3, Tp. 2, R. 12. A complete analysis of river water is given in figure 24B and table 9.

Table 10: Sulfate Contents of Waters from Milk River Sandstone North and South of Outcrop Area, Compared with Sulfate Contents of Milk River Surface Waters

(Analyses by Provincial Analyst, Edmonton)

Location ¼	Sec.	Tp.	R.	Sulfates, ppm.
South of outcrop:				
NW.	18	1	14	1124
NE.	12	1	12	295
SE.	21	1	12	511
NE.	6	2	14	500
North of outcrop:				
SE.	19	2	13	537
SW.	27	2	13	755
SW.	13	2	14	640
NE.	3	3	14	745
Milk River surface water:				
SW.	12	2	15	0
NE.	34	1	13	10
SW.	3	2	12	13

In the northern part of the area, fluoride is reported to be present in greater quantities than 1.5 ppm. which is the limit permitted by ordinary standards of quality (table 11).

Table 11: Fluoride Contents of Waters from Milk River Sandstone

(Analyses by Provincial Analyst, Edmonton)

Location ¼	Sec.	Tp.	R.	fluoride, ppm.
NE.	16	10	13	3.6
NW.	13	10	13	2.9
—	9	10	13	3.8
NE.	17	6	11	2.1
—	16	6	11	2.5

Considerable amounts of fluoride are found in soft sodium bicarbonate waters in many places throughout the United States (Sinnott and Whetstone, 1950). The relation between soft water and fluorides is also discussed by Cederstrom (1945), who concludes that the fluoride is probably derived from some widely-distributed clay mineral or from some muscovite or sericite mica. Goldschmidt (1954) points out that in some hydroxy silicates and hydroxy-alumino-silicates the hydroxyl ions may be largely replaced by fluoride. The fluoride content in such silicates may even greatly exceed the amount fixed in apatite. Phosphate beds, which are a common source of fluoride, are known neither in the Milk River sandstone nor in any of the other Cretaceous formations in this part of the Province, and it is unlikely that the fluoride has been derived from phosphate beds which were exposed in the Cretaceous Selkirk Mountains, as apatite and fluorite are soluble in water and susceptible to ion exchange processes during transport. As far as the present data permit interpretation, there seems to be a certain relationship between the increasing fluoride content in the water and the increasing clay and mica percentages in the aquifer.

In summary there appear to be three, and perhaps four, factors controlling the chemical composition of water from the Milk River sandstone:

1. Degree of mineralization or replacement of connate water by meteoric water;
2. Base exchange, resulting in natural softening of the water;
3. Sulfate reduction by methane, which occurs in natural gas;
4. The amount of clay or mica in the aquifer may bear some relation to the fluoride content of the water.

Occurrence of Natural Gas

Natural gas occurs in the Milk River sandstone in varying amounts. Within the water-producing area, no free gas wells are known, but north of the sandstone pinch-out gas wells produce from silty strata at the same horizon in the Lea Park formation. Almost all flowing wells at the periphery of the area produce water together with gas. In many cases the gas is present in large enough quantities to be used for domestic purposes. The gas consists mainly of methane and has a gross heating value of 955 British thermal units per standard cubic foot. An analysis is shown in table 12.

Table 12: Analysis of Natural Gas from Milk River Sandstone Equivalent

(Analysis by Alberta Oil and Gas Conservation Board)

NW. ¼ Sec. 11, Tp. 15, R. 9		
Methane	94.65	volume %
Ethane	0.07	"
Propane	0.07	"
Isobutane	0.05	"
n Butane	0.02	"
Pentane plus	0.20	"
Nitrogen	4.27	"
Helium	0.10	"
Carbon dioxide	0.57	"
Hydrogen sulfide	0.00	"

It is believed that the gas discharged by some of the farm wells is present in solution in the water, and when the pressure is reduced, the gas is released. Since the gas is dissolved in the water, it acts as part of the water and it therefore has not escaped to the outcrop area. Where gas is known to occur as free gas, it is held back from moving up-dip by the water-wet sandstone. The small amounts of natural gas that will have a sufficiently high entry pressure to overcome the resistance of the water-wet sand and move up-dip into the aquifer, will be dissolved in the water.

Some quantitative data concerning the occurrence of gas in the Milk River sandstone are presented below:

The mean annual temperature in southern Alberta is 43°F. (6°C.), and according to the Oil and Gas Conservation Board, the average geothermal gradient in Alberta equals 0.02°F. per foot. The average temperature of the Milk River sandstone at a depth of 800 feet is therefore:

$$T^{\circ}_{(800)'} = 43.6^{\circ} + (800 \times 0.02^{\circ}\text{F./ft.}) = 59.6^{\circ}\text{F. } (15^{\circ}\text{C.}) \ldots\ldots (15)$$

The bottom-hole pressure in those parts of the Milk River sandstone where gas-producing wells occur ranges from 238 pounds per square inch to 319 pounds per square inch with an average value of 300 pounds per square inch. Interpolating the pressure, volume, temperature, and solubility relations for natural gas and water mixtures (Dodson and Standing, 1944), the solubility of natural gas in water under an absolute pressure of 300 pounds per square inch and 60°F. temperature is 3.34 cubic feet per barrel.

A farm well, producing 7 gallons of water per minute, can thus have a maximum output of 0.75 Mcf. of natural gas per day. According to information given by Northwestern Utilities Limited, the average daily domestic consumption in Edmonton is 0.64 Mcf. Since most Milk River wells produce less than 7 gallons per minute, only a few farms have an adequate gas supply for the entire house, but in most cases the amount of gas produced is sufficient for cooking purposes.

RECOVERABLE GROUNDWATER RESOURCES

The total amount of groundwater stored in the Milk River sandstone can be calculated by multiplying the volume between the top of the aquifer and the piezometric surface by the coefficient of storage. This volume can be approximated by a prism, 700 feet high, 54 miles long, and 60 miles broad, which has a volume of 3.1×10^{13} cubic feet. The total amount of water stored in the aquifer is:

$$S \times 3.1 \times 10^{13} = 3 \times 10^{-4} \times 3.1 \times 10^{13} = 9.3 \times 10^{9} \text{ cu. ft.} \ldots (16)$$

At the present rate of withdrawal, approximately 0.2×17^{7} cu. ft. are drawn from storage annually. The groundwater resources of the Milk River sandstone should therefore last 465 years, assuming that the recovery is 100 per cent. It will take considerable care, however, to recover 40 per cent, in which case the total groundwater resources will last less than 200 years.

In local cases the situation is even worse, and if no conservation measures are taken, total depletion will be reached sooner because of increasing production from the aquifer. It is reasonable to believe that, without conservation, within 5 to 10 years all flowing wells in the area will have stopped flowing. Local heavy withdrawal is expected to create severe water shortages around Foremost, Bow Island, and the Pakowki Lake area within this generation.

Economy

UTILIZATION OF GROUNDWATER

General Statement

That area of southern Alberta where the Milk River sandstone serves as the main source of fresh groundwater is in one of the least densely populated regions in the Province. The total population in the investigated area amounts to 15,085 persons, of whom 58 per cent are rural residents. The rural population density is 1.35 persons per square mile.

Water from the Milk River sandstone is used almost exclusively for domestic purposes and livestock supplies.

Domestic Supplies

One quarter of the rural population obtains its water from the Milk River sandstone, and likely consumes a total of 4×10^7 gallons per year, assuming a per-capita consumption of 50 gallons per day. Since a suitable water supply is an extremely important factor on the prairie, most farmers are inclined to spend a considerable amount of money to develop and assure a reliable supply. The average total capital investment on each farm or ranch in southern Alberta is $40,000.00, 5 per cent of which ($2,000.00) is the average investment devoted to the development of a water supply.

Many of the older farms have been modernized, and the installation of new appliances necessitates larger quantities of water. It is believed that the present total investment of approximately $800,000.00 in domestic water supplies will increase to $1 million in 1975. This figure is based on a comparison with the results of a recent survey in the United States (Picton, 1959).

Livestock Supplies

On the prairie where cattle are the main source of income, livestock water supplies are as important as domestic supplies.

An estimated 16,000 head of cattle, representing a net value of $3.2 million, are dependent on water from the Milk River sandstone, and will probably consume an estimated 1.46×10^8 gallons of water annually.

A total of 72 flowing wells are located in pastures and are used for stock watering. Many of the flowing domestic wells are also a source of drinking water for cattle. Moreover, most ranchers believe it to be essential to have a flowing well both in the corral and in the pasture. In many cases the lowering of the piezometric surface threatens to limit the number of stock that can be raised in the area.

Public Waterworks

As has been mentioned earlier, Foremost (population 456) is the only community left that obtains its entire water supply from the Milk River sandstone. The annual consumption is estimated at 7×10^6 gallons.

Other communities in southern Alberta obtain their water either from a surface source (Taber, 3,688; Bow Island, 1,001; Milk River, 642), or do not have a water system at all (Purple Springs, 282; Grassy Lake, 225; Etzikom, 160; Skiff, 100; Manyberries, 97). The people living in these communities either haul water from the town well, or have individual wells. The town wells of Skiff and Etzikom are tapping the Milk River sandstone. Originally both Taber and Purple Springs had town wells producing from the Milk River sandstone, but as a result of poor construction, they were abandoned soon after having been drilled.

Industrial Supplies

An old railway well in Foremost, drilled by the Canadian Pacific Railways, was the first and only industrial water well that produced from the Milk River sandstone. The water was used to refill the steam locomotives but since the advent of modern diesel engines the well has been abandoned.

The transmissibility of the aquifer is too low to be able to yield large industrial supplies.

Irrigation Supplies

As a result of the large amounts of sodium bicarbonate or sodium chloride the water is unfit for irrigation purposes. However, throughout the area many gardens are irrigated with water from the Milk River sandstone, and although in most parts of the area the safety limit for vegetation (700 ppm. soda) is exceeded, harmful effects are absent. Around Taber some complaints were filed about soil contamination resulting from water from a flowing well.

VALUE OF GROUNDWATER

According to a recent investigation in the United States, the value of water is estimated at $0.75 per 1,000 gallons.

In southern Alberta the value of water is close to $1.00 per 1,000 gallons, provided that the water is obtained from a public water system. If this is not the case, and the water is obtained from a town well, farmers pay considerably more. The price of water that is hauled by farmers who do not possess a well varies from place to place, but exceeds in all cases $1.00 per 1,000 gallons. Several examples are given in table 13.

Table 13: Prices of Water in Several Southern Alberta Communities

Community	Water Source	Price, per 1,000 gal.	Remarks
Coutts	CPR tank wagon from Lethbridge	\$4.00	Delivered home
Etzikom	Milk River sandstone	\$5.55	Wellhead price
Milk River	Milk River (surface)	\$1.20	Wellhead price; 50 farmers haul water
Taber	Oldman River	\$3.30	Wellhead price; 300 farmers haul water
Warner	Foremost formation	\$1.37	Wellhead price
Average		\$3.08 per 1,000 gallons	

The estimated annual water consumption in the area is 1.93×10^8 gallons. The total cash farm income in the area is \$2.3 million. Thus, if the Milk River sandstone were not a source of fresh water, many people in southern Alberta would be forced to purchase water for \$3.08 per 1,000 gallons at the nearest watering point, which would amount to a cost of \$594,000.00 per year—25 per cent of the total annual farm income. This amount is not spent now and the Milk River sandstone enables farming, and especially ranching, operations to be carried on without excessive water costs.

The total annual water production from the Milk River sandstone is as much as 2.55×10^8 gallons, which indicates an annual wastage of 6.4×10^7 gallons. It might be said that the quantity wasted represents an annual sum of \$25,000.00, because every gallon that is wasted now will have to be hauled sometime in the near future and will cost at least \$3.08 per 1,000 gallons.

CONSERVATION OF GROUNDWATER

General Conservation Principles

It is generally understood that the conservation of groundwater aims at the intelligent use of a renewable resource. However, it is obvious from the conclusions derived from the hydrological investigation that water in the Milk River sandstone is a non-renewable resource, because the Milk River sandstone is a reservoir which is slowly being depleted. It is further shown that the water in this reservoir is of great economic importance to southern Alberta, and it should therefore be developed properly without undue waste. Conservation of the water supply from the Milk River sandstone has two aspects:

1. *Quantitative conservation* which tries to establish the most economical way of development of the aquifer. A quantitative conservation should therefore be based on hydrological investigations.
2. *Qualitative conservation* which protects the groundwater resource against contamination, pollution and degradation. Contamination is generally chemical, resulting from dissolved minerals.

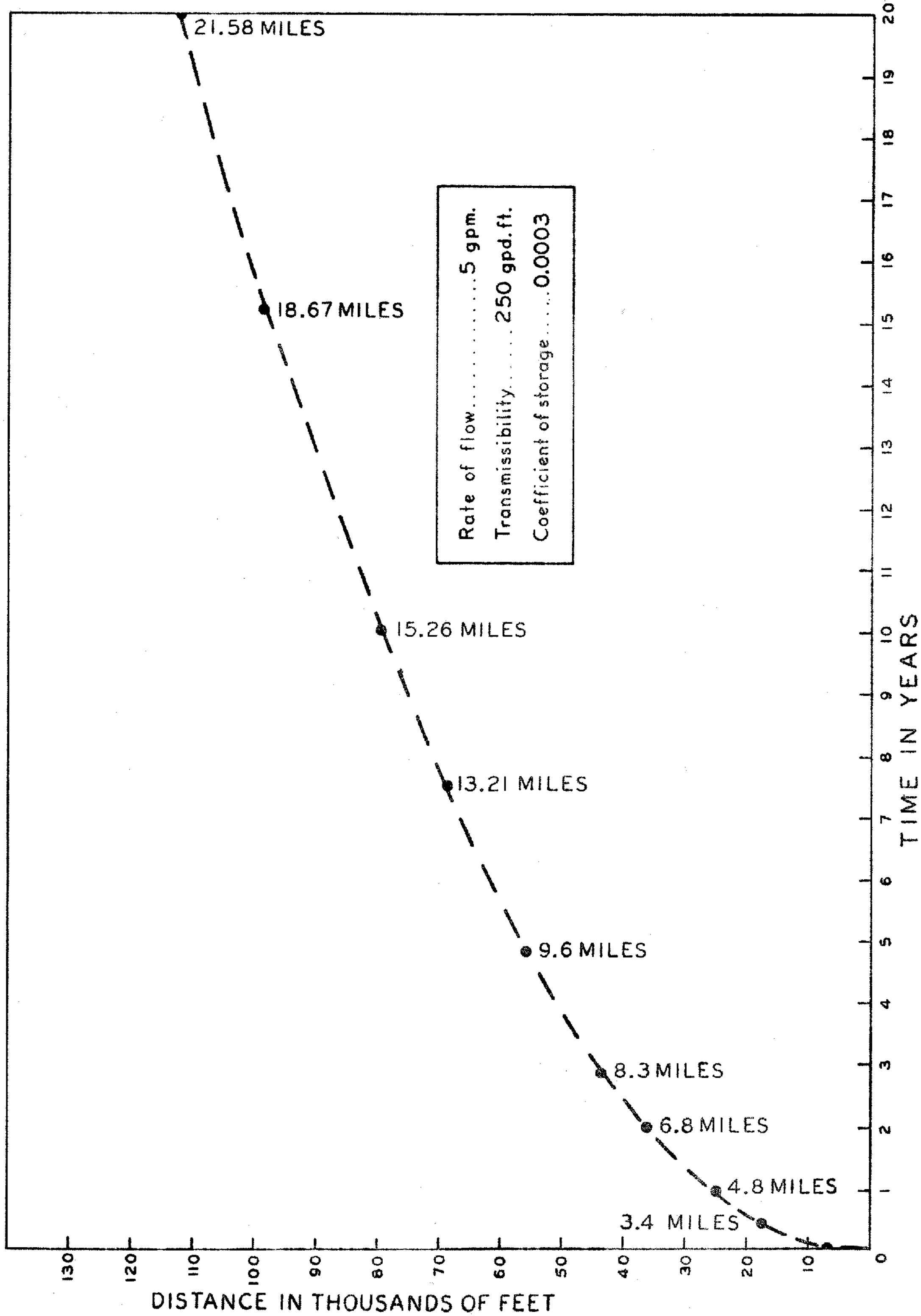


FIGURE 25. Extent of cone of pressure relief around flowing well

Pollution is caused by man or animals and is commonly of a bacteriological character, whereas degradation is defined as an impairment of water quality caused by man's development, use or re-use of the water (Groff, 1958).

It is of prime importance to know which various hydrologic factors govern the groundwater conditions in an aquifer before suggesting conservation measures designed to obtain maximum benefit from the water supply. However, "the difficulty arises whenever one attempts to translate a guiding scientific principle into an effective administrative mechanism" (Thomas, 1951, p. 279). In many cases the public considers conservation measures to be hindering and limiting factors in further development, whereas they are intended to be regulations that ensure proper use of groundwater supplies.

Present Situation in Southern Alberta

The Alberta Ground Water Control Act was passed 38 years after the first well was sunk into the Milk River sandstone. The present situation is therefore a precarious one, resulting from overuse of the groundwater resources before adequate legislation existed. Both aspects of present-day groundwater conservation in southern Alberta will be discussed below.

1. *Quantitative Conservation.* Of the 192 wells flowing from the Milk River sandstone, 189 are in violation of The Ground Water Control Act, for according to chapter 48, section 10, sub 4; ". . . every owner . . . shall provide the necessary valves and plugs to control the flow of water from such (artesian) wells".

No attempt has been made to maintain this conservation policy. As has been pointed out earlier, the Milk River sandstone has been depleted since development started and this process will accelerate with the increasing number of wells.

The widespread influence of a flowing well is demonstrated in figure 25. This graphical method of summarizing well-field history is given by Cooper and Jacob (1946). The curve is based on:

$$s = -(2.303\, Q/4\pi T)\,[\log (r^2/t) - \log (2.25\, T/S)] \qquad (17)$$

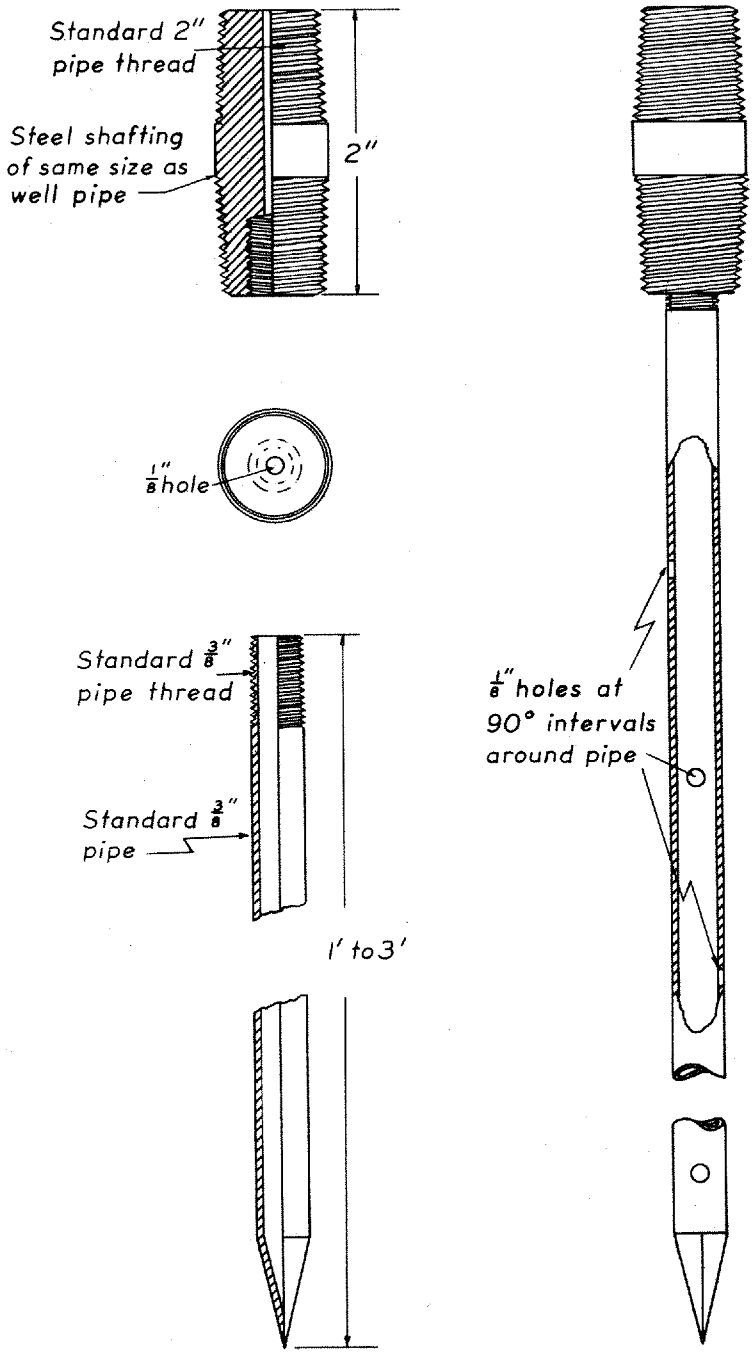
s = drawdown in feet
Q = quantity of flow in gallons per minute
T = coefficient of transmissibility
r = distance in feet from well
t = time elapsed since flowing began, in days
S = coefficient of storage

The limit of the radius of influence is the point of zero-drawdown and this has been calculated for the period of 1 to 25 years. The large radius of the cone of pressure relief after a relatively short time is characteristic for confined aquifers. In calculating the curve of figure 25, the transmissibility is assumed to be 250 gpdf., the storage coefficient is taken at 0.0003, and the amount of flow is assumed to be 5 gpm.

Some quantitative conservation measures have been established by the Alberta Oil and Gas Conservation Board, but only with regard to the natural gas that is produced from some of the water wells. Only those wells which produce 0.75 Mcf. or more per day are affected by these regulations. The regulations are extremely useful, because some of the strongest water flows are thus confined within reasonable limits.

The prospects for large-scale quantitative conservation are not very promising. Virtually all wells are poorly constructed; most water wells in the Milk River sandstone have a 2- or 4-inch casing, set loosely in the hole; none of the wells is provided with a screen and none of the wells is cemented. It has been common practice to complete the wells, using gunny-sack packing in the annulus. If this type of well should be provided with "the necessary valves and plugs", it is obvious that the water will escape outside the casing, since gunny sacks are insufficient packing. In such cases it will be necessary to abandon the well and replace it by a new one, which should be constructed properly. This type of quantitative conservation could be prohibitively expensive for the average farmer. In many cases, however, the water wastage of a flowing well can be reduced considerably by an *inside reducer*. This type of reducer can be installed into any size of well pipe, provided that the well casing is not leaking. Because of its low cost—$2.50 to $5.00 each—and because of its easy installation, this type of reducer is expected to be a valuable tool for groundwater conservation in southern Alberta. The following description—and figure 26, illustrating this reducer—are copied from a paper by Simpson (1932) who, as State Groundwater Geologist for the North Dakota Geological Survey, successfully introduced this method in North Dakota.

> A cylindrical piece of steel shafting two or more inches in length and of the same diameter as the well pipe to be fitted, is threaded with standard threads on each end, leaving about one-half inch not threaded. A one-eighth inch hole is drilled through the centre of the shafting and one end is drilled and tapered to insert a three-eighths-inch pipe. A piece of standard three-eighths inch pipe one foot to four feet in length is welded and tapered at one end. On the other end is cut a standard three-eighths inch pipe thread and a dozen or more one-eighth inch holes are drilled through the side of the pipe at well spaced intervals or an equal number of slots may be cut. The three-eighths inch pipe is then screwed into the shafting and the reducer is complete.
>
> This reducer may be fitted into the pipe leading from the well either vertically or horizintally, the tapered end of the pipe inserted first and the inner end of the reducer used as a plug, added lengths of well pipe being screwed to the outer end of the reducer. The reducer thus becomes an inside unit in the well pipe. By this method the flow is greatly reduced, the pressure is also reduced through friction on the walls of the small holes and any particle of sand or gravel which enters the reducer may pass entirely through it and out without danger of clogging. The flow from a well thus reduced is uniform, constant



REDUCER FOR ARTESIAN WELL
(H.E. Simpson, 1932)
FIGURE 26.

> and without great force. In case of emergency the reducer may be removed by a small pipe wrench and again replaced with the emergency is passed. The flow is kept open to prevent it from freezing and the amount is sufficient for the stock of an ordinary farm if used with an ample storage tank. If placed at the tank outlet of a looped line of pipe passing through the house, it will maintain sufficient back pressure to give a good flow at the house tap. If all pipes are properly buried one foot underground and the exposed loops covered in winter, there will be ample flow to prevent freezing through a considerable line of pipe and abundant water may be furnished to both house and stock, cool in summer and moderately warm in winter.
>
> (Simpson, 1932, p. 5-6.)

2. *Qualitative Conservation.* With respect to qualitative conservation, the situation is much better. The most likely source of groundwater contamination in southern Alberta is the penetration of salt water into the aquifer from nearby oil and gas wells. However, all necessary precautions to assure that no contamination occurs are taken by the Oil and Gas Conservation Board, and no cases of brine contamination are known.

It is believed that with increasing development of the aquifer, salt-water encroachment may occur from the east and west, where the piezometric surface shows inwardly directed gradients. Further development will increase these gradients and connate water will be drawn toward the central area. This will, however, be an extremely slow process.

Salt-water contamination other than oil-well disposal or encroaching connate water within the formation does occur, for the casing of some of the older wells has been corroded to a considerable extent, and water from formations other than the Milk River sandstone can thus penetrate into the fresh water zone.

Except for occasional cases, neither pollution nor degradation are known in the area. Through the activities of the local Health Units, a close watch is kept on these possibilities by means of regular water analyses.

THE LAW OF GROUNDWATER

General Principles

According to Stone (1958), three principal views concerning groundwater exist on the American continent.

1. The *English rule,* according to which the man who owns the land can develop a well and use the water for any purpose he chooses.
2. the law of *reasonable use,* by which the landowner is restricted to uses "common to, or reasonable in the locality". The difference between this concept and the first one is mainly one of attitude.
3. the concept of *correlative rights,* in which case the groundwater is prorated among the landowners and no priority exists.

The Alberta Ground Water Control Act

Most Canadian laws are derived from the English Common Law. The original view concerning groundwater was therefore also based on the English Common Law and essentially The Alberta Ground Water Act has not developed beyond this stage (Foster and Farvolden, 1958). The Alberta Ground Water Control Act was passed in 1953 and specifically prohibits groundwater wastage. By this law an attempt was made to dilute the original English rule to the concept of reasonable use.

The beneficial effects of a groundwater conservation policy have not been brought sufficiently to the fore, with the result that the public may consider such a policy willful restriction of their personal freedom. The Alberta Water Well Drilling Association has not been sufficiently informed about the quantitative aspects of groundwater conservation, or stronger co-operation could be expected from this organization.

Ample evidence exists that the declining piezometric surface has had disastrous effects on some ranching operations. Groundwater conservation is of utmost importance for the continuation of ranching in southern Alberta.

For the communities which derive municipal supplies from this aquifer, conservation measures will likely have immediate beneficial effects. Serious efforts should be made to improve the existing situation and to assure a continuing water supply from the Milk River sandstone. The present situation fully justifies an extensive conservation program.

Summary

A great number of artesian wells in southern Alberta obtain their water from the Milk River sandstone, which is the largest sandstone aquifer in the Province. This study was initiated because of a serious decline of water levels in many of the wells.

The area of investigation is located between townships 1 and 12, within ranges 1 to 19 inclusive, west of the Fourth Meridian.

The major structural elements in the area are the northwest-trending Kevin Sunburst dome and the northeast-trending Bow Island arch, which were formerly grouped as a single structural unit, called the Sweet Grass arch. Late Tertiary intrusions seated in the Sweet Grass Hills in northern Montana have disturbed the regional features to a certain extent, creating a radial pattern of steep folds, several of which extend into Alberta. The geologic structure of southern Alberta was determined mainly by vertical movements of the basement complex, which are reflected by the overlying younger strata.

The Milk River sandstone is the basal member of the Upper Cretaceous Eagle formation. The member consists of fine-grained sandstones and shales, interbedded in lenticular fashion. A study of the vertical variability of the sandstone beds revealed the presence of some northwest-trending belts of relatively clean thick sandstone. The Milk River sandstone is believed to have originated on the seaward margin of a littoral environment.

The member is characterized by relatively low transmissibilities ranging from 2,000 gpdf. in the south, to less than 10 gpdf. near the sand pinch-out in the north. A path of high transmissibility values coincide with one of the northwest-trending sand belts.

The piezometric surface has an average gradient of 20 feet per mile, in a northerly direction. Along the eastern and western edges of the area the downward gradient is directed inward. Due to the low permeability, the rate of groundwater movement does not exceed 20 feet per year. The mean production from the water wells is 1 gallon per minute. The total daily water production from the Milk River sandstone is estimated at 700,000 gallons.

There has been depletion of the aquifer since development began and approximately 50 per cent of the amount of water produced is drawn from storage. On the average, the piezometric surface has been lowered 20 feet since 1937. In some areas of heavy withdrawal (Pakowki Lake, Foremost) this value is as high as 100 feet. Areas of lesser depletion which consequently stand out as ridges on the piezometric surface, act as groundwater divides. The groundwater divide between Pakowki Lake and Foremost prevents water movements to the north, making the northern part of the area mainly

dependent on storage water; a small amount, however, is transmitted from the west. The storage coefficient of the aquifer is 0.0003.

Natural replenishment of the aquifer occurs in the Sweet Grass Hills, where the Milk River sandstone has been uplifted by the intrusions and is exposed. Infiltration of river water along the outcrop area is not a substantial form of recharge.

The chemical quality of the groundwater near the outcrop area is characterized by a high sulfate content (more than 500 ppm.) and a moderate hardness (100 ppm.). As it moves deeper into the formation the water is softened by base exchange and the sulfate concentration is reduced by methane, the chief constituent of natural gas occurring in the Milk River sandstone. The water of the central part of the area is characterized by a moderate content of sodium bicarbonate (1,000 ppm.) and a moderate degree of mineralization (1,000 ppm. total dissolved solids). Towards the north, east and west, connate water has not yet been replaced by infiltrating meteoric water and the chemical quality is poor.

Natural gas, which is produced together with the water in some wells, is believed to occur in solution in the water. Maximum gas production from a well producing 7 gallons per minute of water is 750 cubic feet per day.

Water from the Milk River sandstone is used mainly for domestic purposes and livestock watering. Foremost (population 456) depends on the Milk River sandstone for its public water supply. Water from the Milk River sandstone cannot be used for industrial or irrigation purposes because of its poor quality.

The total recoverable groundwater resources of the Milk River sandstone are calculated to be 9.3×10^9 cu. ft. At the present rate of withdrawal from storage and with very careful development, this reserve should last 200 years. In local cases total depletion will be reached sooner. Heavy withdrawal is expected to create a severe water shortage around Foremost, Bow Island and Pakowki Lake within this generation.

The average investment in groundwater development from the Milk River sandstone amounts to 5 per cent of the total farm investment, or $2,000.00 per farm. A total of $800,000.00 is invested in the development of the aquifer and this value is expected to increase to $1 million by 1975.

The value of water to prairie residents lies between $1 and $3 per 1,000 gallons,, depending on the locality. Farmers who do not own a well pay up to $5 per 1,000 gallons.

Because of principles set out by the English Common Law, virtually no groundwater conservation exists in southern Alberta. However, the present situation justifies an extensive conservation program.

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Appendix

CONVERSION TABLES

LENGTH

UNIT		EQUIVALENT							
		Centimetres	Inches	Feet	Yards	Metres	Rods	Kilometres	Miles
1 Centimetre	=	ONE	.3937	.0328	.01093	.01	.00199	.00001	.00000621
1 Inch	=	2.54	ONE	.0833	.0278	.02540	.00505	.0000254	.0000158
1 Foot	=	30.48	12	ONE	.33333	.30480	.0606	.000305	.000189
1 Yard	=	91.44	36	3.	ONE	.91440	.18181	.000915	.000568
1 Metre	=	100	39.37	3.2808	1.0936	ONE	.1988	.001	.000621
1 Rod	=	502.9	198	16.5	5.5	5.0292	ONE	.00503	.00312
1 Kilometre	=	100,000	39,370	3280.8	1093.6	1000	198.83	ONE	.621137
1 Mile	=	160,936	63,360	5280	1760	1609.3	320	16093	ONE

AREA

UNIT		EQUIVALENT							
		Square Centimetres	Square Inches	Square Feet	Square Yards	Square Metres	Square Rods	Acres	Square Miles
1 Sq. Centimetre	=	ONE	.155	.001076	.0001196	.0001	.000003953	—	—
1 Sq. Inch	=	6.452	ONE	.00694	.0007716	.0006452	.00002551	—	—
1 Sq. Foot	=	929	144	ONE	.1111	.0929	.003673	.00002296	—
1 Sq. Yard	=	8361	1296	9	ONE	.8361	.05306	.0002066	—
1 Sq. Metre	=	10,000	1550	10.76	1.196	ONE	.0595	.0002471	—
1 Sq. Rod	=	252,908	39,204	272.25	30.25	25.29	ONE	.00625	.000009766
1 Acre	=	40,465,284	6,272,640	43,560	4840	4047	160	ONE	.001563
1 Sq. Mile	=	—	—	27,878,400	3,097,600	2,589,998	102,400	640	ONE

FLOW

UNIT	EQUIVALENT						
	U.S. Gallon per Day	Imp. Gallon per Day	Cubic Feet per Day	U.S. Gallon per Minute	Imp. Gallon per Minute	Acre Feet per Day	Cubic Feet per Second
1 U.S. Gallon per Day =	ONE	.8333	.1337	.0006944	.0005787	.000003069	.000001548
1 Imp. Gallon per Day =	1.200	ONE	.1606	.0008333	.0006944	.000003683	.000001856
1 Cubic Foot per Day =	7.4805	6.233	ONE	.005195	.004327	.00002296	.00001157
1 U.S. Gallon per Minute=	1440	1200	192.50	ONE	.8333	.00442	.00223
1 Imp. Gallon per Minute=	1728	1440	231.12	1.200	ONE	.00530	.00267
1 Acre Foot per Day =	325,850	271,542	43,560	226.28	188.57	ONE	.5042
1 Cubic Foot per Second=	646,323	538,860	86,400	448.83	374.03	1.9835	ONE

VOLUME

UNIT	EQUIVALENT							
	Cubic Centimetres	Cubic Inches	Litres	U.S. Gallons	Imp. Gallons	Cubic Feet	Cubic Yards	Cubic Metres
1 Cu. Centimetre =	ONE	.06102	.001	.0002642	.0002201	.0000531	.000001308	.000001
1 Cu. Inch =	16.39	ONE	.016387	.004329	.003607	.0005787	.00002143	.00001639
1 Litre =	1000	61.0234	ONE	.26417	.22008	.03531	.001308	.001
1 U.S. Gallon =	3785.4	231	3.7854	ONE	.83311	.13368	.00495	.005786
1 Imp. Gallon =	4542.5	277.274	4.5425	1.2000	ONE	.16046	.00594	.00454
1 Cubic Foot =	28,317	1728	28.317	7.4805	6.2321	ONE	.03704	.02832
1 Cubic Yard =	764,560	46,656	764.56	201.974	168.267	27	ONE	.76456
1 Cubic Metre =	1,000,000	61,023	1000	264.17	220.083	35.3145	1.30794	ONE

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