A STUDY OF SOME URANIUM MINERALIZATION IN
ATHABASCA SANDSTONE, NEAR STONY RAPIDS,
NORTHERN SASKATCHEWAN, CANADA

A Thesis
Submitted to the Faculty of Graduate Studies
in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE
in the
DEPARTMENT OF GEOLOGY
University of Saskatchewan
by

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Written under the Supervision of .

Saskatoon, Saskatchewan May 5, 1955.

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Photograph taken looking northwest at location "B". The unconformity at the base of the Athabasca sandstone is indicated by a broken line. Note the crossbedding in the Athabasca sandstone and the bleached appearance of the highly weathered underlying granitic gneiss. Low radioactivity was detected just below the contact at this location.
ABSTRACT

The deposits were studied in the field by the writer in 1952. Later laboratory work was directed towards determining more of the nature, origin, and mode of deposition of this unique mineralization.

The chief uranium mineral is autunite, a calcium uranyl phosphate which occurs locally as a cementing material in nearly flat-lying beds of Athabasca sandstone, and disseminated in a clay-like regolith lying immediately below the unconformity at the base of the sandstone. The autunite occurs as aggregates of tiny, greasy-looking, platy, lemon-yellow crystals, which fluoresce a bright yellow green under ultra-violet light.

All known showings of this type, in the Middle Lake area are located along prominent scarps marking the eastern and northern limits of Athabasca rocks in the area. Usually the greatest concentration of uranium is on the unconformity, although it may occur in the sandstone anywhere to the top of the scarp, a vertical distance up to 70 or 80 feet.

Limited diamond drilling and surface sampling indicate that the grade is low; i.e. probably less than 0.05% $\text{U}_3\text{O}_8$ equivalent except in selected samples.

The origin is still much in doubt but results suggest that the uranium was derived from primary pitchblende deposits in pre-Athabasca rocks. Pre-Athabasca weathering of the pitchblende resulted in the accumulation of secondary deposits on the ancient surface of erosion.
Following deposition of the Athabasca series, groundwaters reworked some of these deposits and reprecipitated some of the uranium in the overlying sandstone.

Regardless of the origin, the unconformity at the base of the Athabasca appears to have had a major effect on localization of the autunite.
INTRODUCTION

Object and Nature of the Investigation

This report deals with a study of secondary uranium deposits at Middle Lake, near Stony Rapids, Northern Saskatchewan, Canada. The mineralization occurs locally as a cementing material in flat-lying, or gently dipping beds of Athabasca sandstone, and disseminated in a clay-like regolith lying on the unconformity at the base of the Athabasca series. The chief uranium mineral is autunite, with minor other secondary minerals. The deposits are unique in that none other of this type is known to exist in the Precambrian of Canada at least. It should be mentioned here, however, that autunite is common in minor amounts in different associations. For instance, it is common to most of the Colorado plateau type deposits in the United States, but seldom, if ever, forms an important part of the ore. In Madagascar, autunite and uranocircite are found in an ancient lake bed that presumably received drainage from weathering pegmatites that contained beta-fite and other complex uranium-columbium-tantalum minerals. Also, in the Rosemaneira region, Portugal, autunite is found along with tungsten and tin, in highly weathered, narrow pegmatite dikes.

The writer studied the Middle Lake deposits in the field while employed by Dee Explorations Limited, 505 Standard Building, Saskatoon, Sask. Further study and laboratory investigations were carried out by the
writer in partial fulfillment of the requirements for a degree of Master of Science at the University of Saskatchewan, Saskatoon, Saskatchewan. Laboratory work was designed to throw light on the nature, origin, mode of deposition, and factors controlling deposition of the uranium mineralization. It consisted essentially of: a microscopic study of some of the rocks in the area; a study of the heavy minerals present in the Athabasca sandstone, making use of autoradiographs; a comparison of the phosphorus content of some of the rocks in the area; an analysis of the age relationship of faulting and primary mineralization to deposition of the sandstone and the autunite deposits; determination of the permeability of the host rock.

The accompanying map (Plate I) shows the location of the known surface showings, the general geology of the area, and the approximate location of specimens studied.
Acknowledgments

Work for this thesis was carried out under the supervision of Dr. J. B. Mawdsley, head of the Department of Geology, University of Saskatchewan, Saskatoon, Saskatchewan. Many of the samples studied and much information was supplied by Dee Explorations Limited, 505 Standard Building, Saskatoon, Saskatchewan, who own the property on which the Middle Lake deposits are found, and who carried out an exploration program at Middle Lake which included 1250 feet of diamond drilling.

Dr. Brad Gunn, research chemist, Department of Chemistry, University of Saskatchewan, kindly made several photofluorimetric uranium analysis for the writer. Mr. R. T. St. Arnaud, Soils Laboratory, University of Saskatchewan, supervised the phosphorus analysis done by the writer, and autoradiographs were developed by Mr. Gordon McLaughlin, a graduate student in the Department of Biology, University of Saskatchewan.

Financial assistance for this work was provided by the Saskatchewan Research Council.
Previous Work

The deposits were examined by Dr. S. C. Robinson, mineralogist, Canadian Geological Survey, in the summer of 1952. Later, using X-ray techniques, he identified autunite, and also obtained an X-ray pattern resembling that of phosphuranylite, from specimens collected at Middle Lake.

S. J. T. Kirkland made a study of the Tazin-Athabasca unconformity in the Middle Lake area as part of the field work carried out for the Saskatchewan Department of Mineral Resources, under the direction of Dr. J. B. Mawdsley, in the fall of 1952. This data was subsequently used as a graduate research problem at Queen's University (1953). (8)

Mr. P. R. Matthew made a brief study of the solubility of the uranium mineralization at Middle Lake, as part of his undergraduate studies at the University of Saskatchewan (1953). (11)

The Middle Lake area is part of a much larger area mapped by F. J. Alcock in 1935. His report and maps on a scale of 1 inch = 4 miles are available from the Canadian Geological Survey. (1)
GENERAL GEOLOGY

The following is a general account of the geology in the Middle Lake area, comprising about 30 square miles. The Athabasca sandstone will be discussed in most detail since it is host to the radioactive mineralization. For a detailed discussion of the chemical and mineralogical composition of some rocks in the vicinity of the showings the reader is referred to a report by Mr. S. J. T. Kirkland, who studied the pre-Athabasca weathering in that area. (8)

All the rocks in the area are Precambrian in age. Flat-lying or gently dipping beds of Athabasca sandstone, usually considered late Precambrian in age lie with marked unconformity on steeply dipping, early Precambrian, metamorphosed sediments, volcanics and intrusives. The general geology is shown on Plate I, and rock types are listed in probable order of age in Table I, page 9.

The northern and eastern limits of the Athabasca are marked, to the north and south of Middle Lake, by prominent scarps, 15 to 70 feet high. The turbulent course of the Fond-du-Lac River is along the base of these scarps for four miles upstream and one mile downstream from Middle Lake. The Athabasca sandstone outcropping on the east side of the lake is probably an outlier, cut off by erosion or faulting.

The area to the north and east of the aforementioned scarps is underlain by relatively unweathered early Precambrian rocks. Exposed
beneath the Athabasca series along the scarp these same rocks are weathered almost beyond recognition.

In previous work in the area the early Precambrian metasediments have been placed under the heading of Tazin group. Since the type area for that group is some 100 miles to the west and the Middle Lake rocks are not necessarily correlative, the term will not be used in this report.
TABLE I

Table of Formations in the Middle Lake Area - Northern Saskatchewan

LATE

PRECAMBRIAN  Athabasca series - chiefly pure quartz
                                      sandstone and pebble
                                      conglomerate

-------------------- Major Unconformity --------------------

EARLY

Basic dikes and sills
Altered feldspar porphyry

PRECAMBRIAN  Granitic gneiss

          Sedimentary metamorphics
              - "quartzite" (possibly an acid
                 volcanic).
              - calcareous metamorphics
              - amphibole gneiss and some fine
                grained massive rocks of
                similar composition.
Description of Rock Types

Pre-Athabasca rocks.

Rocks classed as amphibole gneiss are the most abundant of the sedimentary metamorphics. They vary from a fine-grained almost massive rock to a coarse-grained mottled gneiss. The major mineral constituents, in decreasing order of abundance are, hornblende, oligoclase, garnet, quartz and pyroxene.

One band of olive-green metamorphic rock, just south of Twin Falls, is composed chiefly of medium to coarse grained diopside and tremolite with some chlorite and garnet. It was probably derived from a calcareous sediment.

Steeply dipping, glassy-looking bands of vari-colored "quartzite" trend north-easterly through the area. Much of it is bright apple-green due to the presence of finely disseminated fuchsite. This rock may be an acid volcanic but there is no direct evidence to support this view. "Quartzite" of a similar nature, but strongly weathered, was observed immediately below the unconformity at the base of the Athabasca series, and angular wind-faceted boulders of it are common in the thin conglomerate at the base of the Athabasca sandstone.

Pink to gray, banded, granitic gneiss occurs in stringers and bands ranging from a few inches to a few hundred feet in width, interbanded with the amphibole gneiss. The chief constituents are
quartz and feldspar with minor biotite, the overall composition varying with varying proportions of these constituents. In general the rock has a crushed or mylonitized appearance, and where this condition is most intense the feldspar is usually stained a deep red color. The odd blob of pegmatitic material was observed but in general the rock is fine to medium grained.

Narrow sill-like masses of a basic rock possessing very striking porphyritic characteristics outcrop just west of the Twin Falls and near the East Showing (see Plate I). Pale green, white, or reddish, 1/8 to 1/2 inch in diameter, sub-angular to rounded phenocrysts of highly altered plagioclase are included in a fine-grained, mafic groundmass. The mineral forming the phenocrysts is almost entirely altered to sericite, but Kirkland (8) was able to identify it in one specimen as basic andesine (An43). The matrix consists of a less-altered mixture of hornblende, feldspar, quartz and garnet. The composition before alteration was probably close to that of a gabbro. The origin is doubtful; it may be intrusive or volcanic.

Fine-grained, dark, basic dikes and sills cut all rocks older than the Athabasca series. The mineral composition of these basalts estimated from thin sections is 65% labradorite and 35% augite. They exhibit a typical diabasic texture.
Athabasca series

The Athabasca series in the Middle Lake area is part of the north margin of a great elliptical shaped area underlain by these rocks, with an extent of approximately 30,000 square miles, having an east-west length of 270 miles, and a maximum north-south width of 120 miles. The northern margin follows along the south shore of Lake Athabasca, the western is the contact with the overlapping Paleozoic sediments, the irregular southern margin crosses the south end of Cree Lake, and it extends eastward to the west shore of Wollaston Lake. Most of the series at Middle Lake at least, is made up of fine to medium grained, buff to gray, pure quartz sandstone. Pebble beds ranging from a few inches to a few feet in thickness with quartz pebbles up to one inch in diameter are abundantly interbedded with the finer sands. Thin shaley beds containing fine mica flakes are present near the base of the sandstone. Lenses of light, olive-green sandstone were encountered in the drilling at the North Showing (see Plate II). It was not determined whether this coloration is confined to certain beds or is a local staining cutting across bedding planes.

The sandstone, in general, is well cemented by secondary chalcedonic quartz which makes up 10% to 20% of a slide. In most cases the only minerals other than quartz are a few grains of hematite, biotite, zircon, apatite, and rarely tourmaline and monazite.

The Athabasca series has been described as being characteristically red. Alcock(1) considered this to be due to oxidation of contained iron during seasonal or other cyclic pauses in deposition. It is true that the sandstone
is red along the scarps north and south of Middle Lake, and also along similar scarps along the south shore of the Fond-du-Lac River west of Stony Rapids, where post-depositional weathering has most effectively oxidized the iron. But on flatter outcrops, back from the scarps the color is nearly always white, buff, or gray. It is, therefore, suggested that the red staining is a more or less local phenomenon, the result of post-depositional weathering rather than intermittent oxidation between periods of deposition. The coloration along the scarp may have been enhanced by a greater concentration of iron deposited there by ground waters percolating toward the scarp. This staining may take the form of irregular patches, haloes, bands, or an entire bed or several beds may be stained deep red or purple.

Another phenomenon, apparently due to iron staining, which was observed both along and away from the scarps, is that of faint parallel color bands, usually red or purple, about 1/16 inch wide and spaced 1/4 to 1/2 inch apart. Usually they are curved and concentric, but in some cases are straight enough to be mistaken for bedding planes to which they bear no obvious relation.

The basal conglomerate of the Athabasca series at Middle Lake is very thin, consisting essentially of a single layer of vein quartz, quartzite, and chert pebbles and small boulders. Many of the smaller boulders have wind-faceted, flat sides and are typical ventifacts. The larger boulders, up to 18 inches in largest dimension are seldom more than 3 or 4 inches thick and consist of slabs of tourmaline-bearing quartz veins or quartzite.
A bed of black conglomerate, one- to two-feet thick, composed of rounded quartz pebbles up to one inch in diameter, coated and cemented with secondary quartz and black iron oxide, is exposed at the top of the scarp at location "C". The iron oxide was identified as hematite varying from an earthy brown variety to adamantine crystals of specularite. It is curious that the high valence iron in this bed is predominantly dark gray or black, while it accounts for the red color in so many other beds along the scarp. A heavy mineral separation yielded, in addition to hematite, pyrite, monazite, apatite, zircon and tourmaline.

Grain gradation, pronounced cross-bedding, ripple marks and mudcracks are characteristic throughout the series. These features attest to an alluvial deposition in broad river flood plains and deltas forming in shallow water. The absence of all but the most insoluble products of weathering suggests extreme chemical weathering of the source rock and that the detritus was transported a long distance. Reworking of the sediments by torrential floods probably affected further sorting and removal of the more soluble constituents. This dissolved and suspended material must have been deposited as a series of calcareous and argillaceous sediments and cherts, possibly in a basin lying in the relatively uninvestigated central part of the area now underlain by Athabasca sediments.
The unconformity separating Athabasca sediments from older rocks is exposed at many points along the scarp which forms the west bank of the Fon-du-Lac River between Black and Middle Lakes and between Middle Lake and the Twin Falls.

All the early Precambrian rocks were evidently exposed to an extreme chemical weathering process for a long period of time. Kaolinitization and other alterations due to weathering are quite evident to a depth of 15 to 30 feet, below the unconformity. Along zones of weakness the weathering processes no doubt penetrated to a much greater depth. A bed of completely disintegrated residual clay material from a few inches to four feet thick lies immediately below the younger sandstone. The nature of the pre-Athabasca weathering, as previously mentioned was studied in detail by Kirkland. The following is part of his conclusions:

"Pre-Athabasca rocks were peneplaned and subjected to intensive chemical weathering, the weathered material consisting of the most insoluble products of rock decomposition, namely quartz, clay minerals, iron oxides, and zircon. Kaolinite appears to be the ultimate end product of this weathering regardless of the original composition of the rock."

The unconformity between Athabasca rocks and underlying older rocks in the Cree Lake area is described briefly by Sproule. Apparently a weathered zone exists there, similar to the one at Middle Lake.
Faulting

Ranking in importance with the unconformity as a structural feature is the Black Lake fault which runs in a north-easterly direction along the northwest shore of Black Lake, and dips about 75° to the northwest. Part of this structure is shown on Plate I. The fault does not bear any direct relation to the secondary uranium mineralization at Middle Lake, but is important in that pitchblende veins are associated with it at the Nisto mine. Its age relationship to the Athabasca sedimentation may be extremely important since if it is pre-Athabasca the pitchblende mineralization in the area is probably also pre-Athabasca and vice versa.

Several other topographic lineaments in the immediate vicinity of Middle Lake may represent faults, but none have been definitely proven. These are shown by a broken wavy line on Plate I.
Folding

The pre-Athabasca rocks in the area are, for the most part, steeply-dipping and no doubt highly folded. Insufficient detailed mapping has been done to delineate such structures.

Steep folding was observed in the otherwise flat-lying Athabasca sandstone on Fir Island, Black Lake, about three miles south of the Nisto mine. This folding was observed by D. A. W. Blake, of the Canadian Geological Survey, and the writer in the summer of 1952, but is not shown on any published map of the area. Fold axes strike approximately east-west and are spaced in the order of a few hundred yards apart. A possible relation between this folding and the Black Lake fault is suggested.
Structural Age Relations

The importance of determining the relative age of the Athabasca series and movement on the Black Bay fault will become evident in the discussion of the origin of Middle Lake mineralization. The evidence is largely conflicting. In the vicinity of the Nisto mine the sandstone appears to have been faulted down on the lake side of the fault, but this apparent relationship could be just as well explained by assuming a steep-sided, local, depositional basin, flanked by the fault scarp. The previously described steep folding in the Athabasca sandstone on Fir Island suggests that these sediments were effected by the same orogenic disturbance which ultimately resulted in faulting, such as the Black Lake fault.

The faulting in the Beaverlodge area 120 miles to the west is definitely known to displace rocks termed Athabasca in that area. However, the faulting there is not necessarily the same age as the faulting on Black Lake. In addition the "Athabasca" of the Beaverlodge area bears little resemblance to the Middle Lake Athabasca. The rocks so termed in the Beaverlodge area consist of an angular talus-like basal conglomerate overlain by interbedded arkosic sediments and basalt flows. These rocks are confined to local basins, the coarse angular conglomerate at least to the proximity of major faults, and appear to have been derived from uplifted and rapidly eroded parts of the immediate area. This is in sharp contrast to the long-transported, pure sandstones, exposed at Middle Lake.
The fact that there is no evidence of intense fracturing, shearing, or hydrothermal alterations in the Athabasca sandstone near Middle Lake might suggest that it was not subjected to the stresses which produced the Black Lake fault zone. However, considering that the younger sediment was relatively plastic, the same stresses which sheared and fractured the highly crystalline early Precambrian rocks may have resulted in only minor warpings in the Athabasca.

In view of the maze of conflicting evidence it appears that this problem will only be solved by direct observation in the field.
THE SECONDARY URANIUM MINERALIZATION

Uranium mineralization in the general area is of three distinct types: (1) primary uranium-bearing pegmatites; (2) primary hydrothermal pitchblende deposits in pre-Athabasca rocks; (3) secondary uranium mineralization occurring in Athabasca sandstone and in an extremely weathered zone immediately below the unconformity at the base of the sandstone. The known occurrences of pitchblende and secondary minerals in the Middle Lake area are shown on Plate I. The primary deposits are of interest in this study because of a possible relationship between them and the secondary material.

Distribution Of The Secondary Uranium Mineralization

Nearly all the known secondary uranium showings are located along the scarps marking the margins of the area underlain by Athabasca sandstone. They occur sporadically over a combined horizontal distance of about four miles, and in a vertical sense, extend from a few feet below the unconformity to the top of the scarp, a distance varying from 10 to 70 or 80 feet.

The vertical distribution of uranium at the North Showing is illustrated on the accompanying vertical sections (Plate II). The graph beside each hole is a plot of diamond drill hole ratemeter readings taken at intervals of 4 inches. The normal background reading for this instrument was about 75 counts per minute. The unconformity is the only horizon consistently showing a concentration of uranium.
Nowhere does the activity continue more than a few feet down into the pre-Athabasca rocks, that is, it does not occur below the extremely weathered zone.

Due to the complex cross-bedding at the North Showing it was difficult to determine whether the mineralization favored certain sandstone beds, although, on a small scale, in hand specimens, concentrations along coarser layers may be observed. Presumably the coarser grained layers were more permeable to mineralizing solutions. Probably some such control applies in a general way, on a much larger scale.

The limited diamond drilling done on these showings suggests that the percentage of contained uranium to be expected is quite low; i.e. in the order of 0.01% to 0.05% U₃O₈ for tonnages of economic significance. Anomalously high assays were returned on grab samples from the scarp face at the North Showing. It is suggested that this material was concentrated there by groundwaters which drained through the rock to the scarp face where they evaporated leaving behind a residue of uranyl phosphates and other salts.

Nature of the Secondary Uranium Mineralization

Autunite (CaO ₂UO₃ ₃P₂O₅ ₈H₂O) and phosphuranylite, another hydrated uranyl phosphate were identified in samples from the North Showing. Most of the uranium is believed to occur as autunite. In all radioactive samples examined the autunite is visible under ultra-violet light as
bright yellow-green fluorescent specks and films. The uranium minerals were not observed in thin section presumably because, due to their solubility, they were removed from the rock during preparation of the slide. However, with the binocular microscope, tiny, lemon yellow crystals of autunite were observed coating sand grains, in crushed samples of Athabasca sandstone. The autunite is entirely interstitial to the sand grains and apparently later than the chalcedonic quartz which cements the sand grains. At any rate, no crystals of autunite were observed trapped in chalcedonic quartz, in the thin sections studied.

 Autoradiographs of heavy mineral concentrates from radioactive Athabasca sandstone indicate that a very small part of the activity was due to radioactive zircon, monazite and slightly radioactive apatite. These minerals possibly contain small amounts of uranium. No pitchblende or uraninite was detected.
Solubility of the Secondary Uranium Mineralization in Athabasca sandstone

Simple water leaching tests were done on crushed samples of radioactive sandstone. When the crushing was fine enough to separate most of the sand grains it was found that one washing removed practically all the radioactive material. More elaborate tests by Mr. P. R. Matthew using both water and weak acid wash solutions proved conclusively that the radioactive material is quite water soluble, under some conditions at least.

Mr. Matthew also ran leaching tests on pieces of radioactive sandstone approximating in size and shape pieces of diamond drill core. The purpose of these tests was to determine whether appreciable amounts of uranium were being lost from the diamond drill core through leaching by the drilling water. He found that tap water at slightly more than atmospheric pressure did remove some of the uranium but probably did not penetrate far into the sample, suggesting a low rock permeability.
Permeability of the Host Rock

Permeability tests were run on three samples of Athabasca sandstone, and for comparison, one sample of carnotite-bearing sandstone from the Colorado Plateau. Details of procedure, calculations and a table of results are included in Appendix III.

The average permeability of the mineralized Athabasca sandstone tested is in the order of 0.1 to 0.2 millidarcys compared to 15 to 20 millidarcys for the Colorado Plateau sample. The solubility of the mineralization suggests a cheap method for economic removal of the uranium by leaching "in situ". The application of such a method to the Colorado Plateau type deposits in the United States is being investigated by at least two concerns. Unfortunately their results to date are not available for publication. Due to the disseminated nature of the autunite, a leach solution would have to permeate the rock to be effective. It is probable, therefore, that a rock with such a low permeability as the Athabasca sandstone would not lend itself readily to a leaching "in situ" process.

With regard to the deposition of uranium, the low rock permeability suggests that the mineralizing solutions would not have wide access to the sandstone, except under high pressures. However, the permeability at the time of deposition may have been quite different than it is at the present time. In fact the autunite itself must have decreased the permeability considerably, since it makes up part of the cementing material.
Phosphorus Content and its Relation to the Uranium Deposits

Most of the uranium at Middle Lake occurs combined with phosphorus. It is therefore important to determine the source of the phosphorus, and the effect, if any, it had upon the deposition of the secondary uranium mineralization. To this end, six samples of Athabasca rocks and eleven samples of pre-Athabasca rocks were analysed for total phosphorus content. The results of these analyses are shown in Table II.

The procedure followed consisted of fusing the pulverized sample with Na₂CO₃, dissolving in hot water or weak HCl, and determination of the phosphorus by a standard colorimetric method which is outlined in Appendix II.

Source of the Phosphorus

Dana (5) lists the formula for autunite as CaO 2UO₃ P₂O₅ 8H₂O =

Lime 61.1, uranium trioxide 62.7, phosphorus pentoxide 15.5, water 15.7 = 100. This indicates that the ratio U to P is approximately 7.7 to 1 by weight. Thus a grade of 0.10% U₃O₈, occurring as autunite, would necessitate a content of approximately 0.01% P, combined in the autunite. Since the grade of most of the material investigated at Middle Lake is less than 0.10% U₃O₈, it would appear that the small amount of phosphorus required could have been derived from any of the rocks listed in Table II. However, since the phosphorus would presumably have to be dissolved by groundwater to become effective, its "availability" is important. (Unfortunately this aspect of "availability" was not considered prior to the laboratory work for this thesis. Analyses of available phosphorus would probably be of more value than those for total phosphorus.) The phosphorus in the fresh
impermeable pre-Athabasca rocks would be relatively unavailable to groundwater. Likewise, detrital minerals containing phosphorus in the Athabasca rocks having withstood intensive chemical weathering and long transportation, must also have been resistant to attack by groundwater. It follows then that the residual weathered rock material immediately below the unconformity is the most probably source of "available" phosphorus, the phosphorus-bearing minerals having been partially broken down by pre-Athabasca weathering. Analyses of both fresh and weathered samples of pre-Athabasca rocks show that the total phosphorus content was not appreciably altered by weathering. This indicates that the phosphorus was not removed at the time of weathering.
TABLE II

Phosphorus Determinations on Rocks From Middle Lake Area

<table>
<thead>
<tr>
<th>SAMPLE NO.</th>
<th>DESCRIPTION</th>
<th>LOCATION</th>
<th>% TOTAL P</th>
<th>%U*</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-6</td>
<td>Radioactive sandstone</td>
<td>A</td>
<td>0.021</td>
<td></td>
</tr>
<tr>
<td>K-17</td>
<td>Radioactive sandstone</td>
<td>A</td>
<td>0.029</td>
<td>0.8</td>
</tr>
<tr>
<td>K-10</td>
<td>Olive-green sandstone</td>
<td>A</td>
<td>0.016</td>
<td>0.002</td>
</tr>
<tr>
<td>K-7</td>
<td>Shaly material from Athabasca</td>
<td>A</td>
<td>0.033</td>
<td>0.004</td>
</tr>
<tr>
<td>K-15</td>
<td>Black pebble conglomerate</td>
<td>D</td>
<td>0.126</td>
<td>0.0002</td>
</tr>
<tr>
<td>K-18</td>
<td>Red pebble conglomerate</td>
<td>D</td>
<td>0.032</td>
<td>0.004</td>
</tr>
</tbody>
</table>

Average for all samples of Athabasca rocks studied - 0.043 0.018

<table>
<thead>
<tr>
<th>SAMPLE NO.</th>
<th>DESCRIPTION</th>
<th>LOCATION</th>
<th>% TOTAL P</th>
<th>%U*</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-14</td>
<td>Altered feldspar porphyry (unweathered)</td>
<td>E</td>
<td>0.013</td>
<td>0.003</td>
</tr>
<tr>
<td>K-12</td>
<td>Altered feldspar porphyry (highly weathered)</td>
<td>A</td>
<td>0.014</td>
<td>0.001</td>
</tr>
<tr>
<td>K-20</td>
<td>? highly altered and weathered</td>
<td>D</td>
<td>0.179</td>
<td>0.009</td>
</tr>
<tr>
<td>K-56</td>
<td>Basic rock (diabase?) (unweathered)</td>
<td>B</td>
<td>0.037</td>
<td>0.006</td>
</tr>
<tr>
<td>ML-60</td>
<td>Basic rock (diabase?) (highly weathered)</td>
<td>B</td>
<td>0.025</td>
<td>0.003</td>
</tr>
<tr>
<td>ML-55</td>
<td>Granitic gneiss (50&quot; below unconformity)</td>
<td>B</td>
<td>0.022</td>
<td>0.002</td>
</tr>
<tr>
<td>ML-59</td>
<td>Granitic gneiss (highly weathered)</td>
<td>B</td>
<td>0.034</td>
<td></td>
</tr>
</tbody>
</table>

(Remaining samples in order of increasing degree of weathering)

<table>
<thead>
<tr>
<th>SAMPLE NO.</th>
<th>DESCRIPTION</th>
<th>LOCATION</th>
<th>% TOTAL P</th>
<th>%U*</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML-2</td>
<td>Granitic gneiss (relatively unweathered)</td>
<td>B</td>
<td>0.032</td>
<td>0.004</td>
</tr>
<tr>
<td>ML-58</td>
<td>Granitic gneiss (weathered)</td>
<td>B</td>
<td>0.072</td>
<td>0.003</td>
</tr>
<tr>
<td>ML-72</td>
<td>Granitic gneiss (strongly weathered)</td>
<td>B</td>
<td>0.027</td>
<td>0.001</td>
</tr>
<tr>
<td>ML-53</td>
<td>Granitic gneiss (extremely weathered)</td>
<td>B</td>
<td>0.021</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Average for all samples of pre-Athabasca rocks studied - 0.042

Average for all samples studied - 0.042

* Uranium determinations by fluorophotometric method.
Ground Water and Deposition of the Secondary Uranium Mineralization

In regard to the part played by groundwaters in the deposition of secondary uranium, the following points are pertinent:

(1) No pitchblende or uraninite was found in heavy mineral fractions from radioactive Athabasca sandstone.

(2) The uranium mineralization is all water soluble.

(3) It occurs interstitial to and cementing the sand grains.

(4) It occurs in the pre-Athabasca rocks only in the highly weathered zone immediately below the unconformity, which was accessible to groundwaters percolating through the Athabasca sandstone.

(5) There is no evidence that hydrothermal solutions have invaded the Athabasca sandstone, in the vicinity of the showings at least.

It is therefore concluded that, since the uranium does not appear to have been transported to its present position by hydrothermal solutions or in detrital mineral grains, it was most probably introduced while in solution in groundwaters.

Source of Uranium for Solution by Groundwaters

Geological information is insufficient to determine the source of the uranium, but the possible sources are listed below with a brief discussion of each:

(1) Hydrothermal pitchblende veins and disseminations in the Athabasca sandstone.
It is conceivable that pitchblende-bearing hydrothermal solutions migrated upward through fractures in pre-Athabasca rocks and, upon striking the unconformity, spread out to form minor disseminations in the relatively unfractured but permeable overlying Athabasca rocks. Alteration to secondary minerals and possibly transportation by groundwaters might follow.

This source is considered improbable chiefly because no pitchblende or uraninite was found in heavy mineral fractions from samples of mineralized Athabasca sandstone, and there is no evidence in the form of calcite veining, hydrothermal hematite staining, and other common hydrothermal alterations, to indicate that the Athabasca rocks have been invaded by hydrothermal solutions.

(2) Hydrothermal pitchblende, or uraninite-bearing pegmatites in pre-Athabasca rocks.

(a) Primary deposits emplaced prior to pre-Athabasca weathering.

Such a source would probably include the uraniferous pegmatites, and possibly the pitchblende deposits, of the area. Pre-Athabasca weathering of such deposits could result in the accumulation of secondary uranium minerals in depressions on the old erosion surface. A modern example of just such a phenomena is a showing on the Bolger property of Eldorado Mining and Refining Limited in the Beaverlodge area, northern Saskatchewan. That deposit is described by Dr. A. H. Lang as follows:

"The unusual feature of the Bolger Showing is that for an area of 6500 square feet the overburden near the showing
contains enough secondary uranium in the form of gummite and probably other minerals to be readily visible because of its yellow color. This deposit is at the foot of a slope, and surface water is believed to have dissolved uranium from the pitchblende (in nearby or underlying hydrothermal veins) and deposited it in gravel, the average content of which is estimated at 1.42c/ (1.42% U₃O₈). "

Upon deposition of the Athabasca sands such secondary, surficial deposits would be buried, perhaps later to be redissolved and redeposited a number of times by circulating groundwaters. Thus, it might be that the uranium concentrated in the clay immediately underlying the unconformity was the source of the concentrations of uranium higher up in the Athabasca sandstone. If this is true irregularities in the old erosion surface might be important. The possibility of successive concentrations of uranium in the Athabasca sediments at successive water table levels is also suggested.

(b) Post-Athabasca hydrothermal pitchblende deposits.

A process by which surface waters could dissolve uranium from post-Athabasca hydrothermal surface showings in pre-Athabasca rocks, and deposit it in the Athabasca sandstone is within the realm of possibility. If all the pitchblende deposits of the area are proven to be post-Athabasca it would stand up better than the theory outlined above.

(3) Detrital Uranium - Bearing Minerals Deposited With The Athabasca Sands.

(a) Detrital Uraninite or Pitchblende.

Davidson and Cosgrove (3) (4) cite persuasive evidence from studies
of modern placers, and from geochemical considerations that uraninite, and/or pitchblende cannot survive rigorous detrital processes, such as was undergone by detritus forming the Athabasca sediments, in the Middle Lake area.

(b) Detrital uranium-bearing apatite, monazite and zircon.

Recent studies of radioactive granites, have revealed that an important part of the activity is due to uranium contained in host minerals such as apatite which have lattice openings large enough to accommodate the large uranium ion. It is probable that some of the Athabasca detritus was derived through weathering of such radioactive granites. A few grains of slightly radioactive, and presumably uranium-bearing, apatite, monazite and zircon were detected, by means of autoradiographs, in heavy mineral fractions of mineralized Athabasca sandstone. While, it is doubtful that uranium in this form was in sufficient concentrations to be the source for the autunite deposits, the possibility should not be overlooked. It is interesting to note that all three detrital minerals mentioned above contain phosphorus, as does autunite.

The writer has speculated on the possibility that the uranium ions carried in solution in groundwaters were attracted to the lattice of a phosphate-bearing mineral, such as apatite. As apatite contains all the elements necessary to form autunite, other than uranium and water, this might be an important step in the formation of autunite.
SUMMARY AND CONCLUSIONS

Nature of the Mineralization

The mineralization consists chiefly of secondary, water soluble autunite, a calcium uranyl phosphate, which is visible under the binocular microscope as fine, greasy, platy, lemon-yellow crystals. Even minute amounts of it can be detected under ultraviolet light, due to its bright yellow-green fluorescence.

Location and Distribution

The autunite occurs as an interstitial cementing material in beds of nearly flat-lying Athabasca sandstone, and disseminated in a clay-like regolith lying immediately below the unconformity at the base of the Athabasca series. The known showings are scattered along the prominent scarps which mark the northern and eastern limits of the Athabasca series, north and south of Middle Lake. Radioactive material may occur anywhere from a few feet below the unconformity, at the base of the Athabasca series, to the top of the scarp, but appears to be concentrated on the unconformity.

Grade

Limited diamond drilling and surface sampling at the North Showing indicates that the percentage of contained uranium is low; ie probably less than 0.05% U₃O₈ equivalent, except in selected samples.
Conclusions

The source of the uranium is a problem open to much conjecture. However, the limited information available suggests that the most probable source was primary pitchblende deposits emplaced in pre-Athabasca rocks prior to pre-Athabasca weathering. Weathering of these deposits may have resulted in the accumulation of secondary surficial deposits in hollows on the pre-Athabasca surface of erosion. After deposition of the Athabasca sands, groundwaters might have dissolved some of the secondary uranium and redeposited it, probably with concentrations at successive water table levels, in the overlying sandstone.

Chief points supporting the above theory are: there is no evidence that hydrothermal solutions have invaded the Athabasca sandstone; deposition of sufficient uranium in detrital minerals with the Athabasca sands is considered improbable; the greatest concentrations of secondary uranium are on the unconformity; there are existing modern, surface deposits similar to those postulated to have occurred on the pre-Athabasca surface of erosion; the most probable source of the phosphorus, which entered into the formation of the autunite, was the weathered pre-Athabasca surface where phosphorus-bearing minerals were broken down by pre-Athabasca weathering.

Regardless of the origin of the uranium, the unconformity at the base of the Athabasca series appears to have been a major localizing
feature. The relatively impermeable layer of clay on the unconformity would prove an equally effective barrier to upward migrating hydrothermal solutions as to downward seeping groundwater solutions, or depressions in the same surface may have acted as collecting basins for secondary uranium deposits prior to the Athabasca sedimentation.

The economic significance of the deposits is difficult to access. The solubility of the autunite suggested a cheap leaching "in situ" process would be feasible, but permeability determinations on the mineralized sandstone indicate that this would not be the case.
REFERENCES


8. Kirkland, S.J.T.: The Tazin-Athabasca Unconformity; Graduate Studies, Queens University, 1953.

APPENDIX I

Heavy Mineral Separations

Heavy mineral separations were done on seven samples (four radioactive, three non-radioactive) of Athabasca sandstone and pebble conglomerate from Middle Lake. Slides of the heavy fractions were then studied under the microscope, making use of autoradiographs. The chief purpose of this study was to determine whether any primary uranium-bear-
ing minerals such as uraninite or pitchblende were present in the radio-
active samples.

The results, as well as a brief description of each sample, are listed in tabular form in Table III. It will be noted that no major primary uranium minerals were detected.

Method

It was desirable to start with as large a sample as possible. The procedure used and the time available made it necessary to limit the original sample to about 40 grams. The sample was first ground to about 100 mesh using a hand mortar and pestle. Care was taken to keep fines to a minimum. The ground sample was then washed in a hot solution of oxalic acid, rinsed in water, and dried in an oven. The washing removed practically all the secondary uranium from the radioactive samples. This was considered desirable since it would limit the number of radioactive particles, and a non-radioactive grain would not appear active due to a coating of secondary uranium.

The heavy mineral separation was affected by floating off the lights in a heavy liquid. This was done in ordinary glass funnels equipped with a
short piece of rubber hose and a pinchcock to facilitate draining off
the heavy liquid. Using this apparatus it was necessary to do each
sample in several small batches.

The heavy fractions were then further separated into three magnetic
fractions: strongly magnetic; weakly magnetic; non-magnetic. The
apparatus used consisted essentially of an ordinary horseshoe electro-
magnet in series with a small rheostat.

Slides were prepared for each of the fractions so obtained and auto-
radiographs were taken of most of these slides.

**Autoradiographic technique**

Autoradiography consists essentially of having a radioactive object
"take its own picture" by exposing a photographic film to the radioactive
emanations.

One of the chief problems in the technique is to obtain a well-defined
"image" of the radioactive particle. Good "resolution" as this desired
effect is termed is attained by:

(1) Having the particle (preferably a smooth face of the particle)
immediately against the activity-sensitive emulsion of the photographic
film.

(2) Using an emulsion thin enough to prevent blurring of the image
by lateral diffusion of rays within the emulsion.

(3) Exposing the emulsion to the radioactivity for the proper length
of time.
The first condition can easily be obtained with rock thin section slides, and polished sections, by pressing the smooth surface firmly against the emulsion. However, with a slide consisting of irregular grains of variable size, perfect contact cannot be obtained. This can be partially offset by scattering the grains far enough apart that correlation is possible in spite of a diffused "image".

The second condition is best satisfied by using an emulsion which is as thin as possible while still being sensitive enough to pick up and record the activity. In this study Kodak Nuclear Plates, Type NTB, with a 10 emulsion were tried on a test slide containing known radioactive particles. Since no noticeable reaction could be detected on the plates they were discarded in favor of ordinary clinical x-ray film. The latter has the advantage of poor resolution due to a very thick emulsion, but is sensitive to extremely weak activity and yielded excellent negative results. Others have reported excellent results using ordinary commercial black and white film.

The time of exposure varies, of course, with the type of film used and the strength of the radioactivity. Using x-ray film, 4 or 5 days' exposure was found adequate to record activity from weakly radioactive minerals (e.g. radioactive apatite). Time of exposure, then, is best determined by experimenting with a slide containing minerals of known activity.

With each "batch" of autoradiographs, a test slide containing pitchblende fragments was included to indicate what sort of reaction was
to be expected from primary uranium minerals in the unknown slides.

Orienting the slide and autoradiograph

One method of orienting slide and film is to place two small fragments of pitchblende on the slide well apart from the material being tested. The developed film is then adjusted until the "images" of the two fragments are directly opposite them. It is an accurate method, but was not used in this study because of the danger of contaminating the slide by a stray piece of pitchblende. Instead, a small V-shaped notch was filed in the end of each glass slide and the film marked with a pin prick opposite each notch, after the slides were fastened to the film. After exposure and developing, the film was cut to proper size and glued to the bottom of the slide.

It was found advantageous to go over the film, before affixing it to the slide, marking all spots due to activity with a tiny India ink spot so it could be picked up easily under the microscope.

Autoradiographic techniques, recommended films, developers, etc. are discussed more fully in the two publications listed under "References" (2) (12).
## Table III (v)
### Study of Heavy Mineral Fractions of Athabasca Sandstone

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Location</th>
<th>Rock Type</th>
<th>Color</th>
<th>Grain Size</th>
<th>Strongly Magnetic</th>
<th>Weakly Magnetic</th>
<th>Non-Magnetic</th>
<th>General</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-6</td>
<td>&quot;A&quot;</td>
<td>Sandstone</td>
<td>Buff</td>
<td>Fine</td>
<td>Chiefly hematite and pyrite, three tiny radioactive spots due to secondary uranium.</td>
<td>Same as strongly magnetic</td>
<td>Nil</td>
<td>Autunite visible in hand specimens under ultra-violet light, autunite removed by washing.</td>
</tr>
<tr>
<td></td>
<td>2 ft. above unconformity</td>
<td></td>
<td>Brown</td>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-7</td>
<td>&quot;A&quot;</td>
<td>Impure Sandstone</td>
<td>Olive</td>
<td>Fine</td>
<td>Nil</td>
<td></td>
<td>Nil</td>
<td>Fine sand grains cemented by unidentified yellowish and greenish material.</td>
</tr>
<tr>
<td></td>
<td>15 ft. above unconformity</td>
<td></td>
<td>Green</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-8</td>
<td>&quot;A&quot;</td>
<td>Unconsolidated sand grains in matrix of yellow uranium mineral</td>
<td>Golden</td>
<td></td>
<td>Chiefly hematite, pyrite, and quartz fragments with attached hematite. No radioactive grains.</td>
<td>Coppery sulphides and quartz grains, a few flakes of biotite. A few faintly radioactive grains.</td>
<td>Nil</td>
<td>From 1/4-inch wide dike in weathered pre-Athabasca rock immediately below the unconformity. Almost all the uranium removed by washing.</td>
</tr>
<tr>
<td></td>
<td>just below unconformity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-10</td>
<td>&quot;A&quot;</td>
<td>Sandstone</td>
<td>Apple</td>
<td>Fine</td>
<td>Chiefly pyrite, some hematite and quartz with attached hematite. Two minor spots on autoradiograph.</td>
<td>Chiefly quartz with small amount of attached pyrite—one grain monazite, one grain zircon. No radioactivity on autoradiograph.</td>
<td>Chiefly quartz with a little attached hematite or pyrite. Two grains of zircon. No radioactivity on autoradiograph.</td>
<td>Very fine, well-rounded quartz grains cemented by light green clay-like material.</td>
</tr>
<tr>
<td></td>
<td>D.D.H. - 28</td>
<td></td>
<td>Green</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 ft. above unconformity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-15</td>
<td>&quot;G&quot;</td>
<td>Pebble conglomerate</td>
<td>Black</td>
<td>Pebbles up to $\frac{1}{2}$&quot;</td>
<td>Almost entirely hematite and hematite with attached quartz.</td>
<td>Almost entirely hematite with attached quartz, 3 grainsapatite, 1 grain radioactive monazite.</td>
<td>Quartz with some hematite - 83% monazite - 15% radioactiveapatite - 4% (some slightly active)</td>
<td>Sand grains and pebbles cemented with chalcedonic quartz and black iron oxide. Bed slightly radioactive throughout.</td>
</tr>
<tr>
<td>------</td>
<td>-----</td>
<td>--------------------</td>
<td>-------</td>
<td>-----------------------------</td>
<td>---------------------------------</td>
<td>-------------------------------</td>
<td>---------------------------------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>K-17</td>
<td>&quot;A&quot;</td>
<td>Sandstone</td>
<td>Buff</td>
<td>Medium</td>
<td>Chiefly hematite and quartz that was not separated. One weakly radioactive grain of emerald greenapatite. Some faint radioactivity</td>
<td>Nearly all earthy hematite and quartz with attached hematite. Some faint radioactivity due to secondary uranium.</td>
<td>Chiefly a pearly white unidentified material, quartz with attached hematite. Some faint activity, presumably due to secondaryuranium.</td>
<td>Well cemented sandstone autunite visible under ultraviolet light as highly fluorescent yellow-green specks interstitial to the sand grains.</td>
</tr>
<tr>
<td>K-18</td>
<td>&quot;D&quot;</td>
<td>Pebble conglomerate</td>
<td>Purple-red</td>
<td>Pebbles up to $\frac{1}{2}$&quot;</td>
<td>Hematite - 90% Pyrite - 9% - some earthy hematite.</td>
<td>Similar to strongly magnetic.</td>
<td>Nil</td>
<td></td>
</tr>
</tbody>
</table>

K-15 (slightly radioactive, no fluorescence) approx. 40 ft. above unconformity

K-17 Pit #4 1 ft. above unconformity

K-18 (Non-radioactive)
APPENDIX II

Total Phosphorus Analysis

The method used is based on the fusion of the sample with sodium carbonate, and the estimation of P by the phosphomolybdate blue reaction.

The solution must be neutralized before color development, and neutralization with H₂SO₄ and di-nitro-phenol indicator is used. The color development is quite sensitive to final pH.

Procedure

Weigh into a platinum crucible 0.5 gr. of rock material ground to minus 60 mesh. Add 2.5 gr. approximately reagent grade Na₂CO₃, mixing well with a rounded stirring rod. Cover with a little more Na₂CO₃.

Heat over burner, slowly until melted, then at full heat of burner, with cover nearly covering crucible opening, until the fusion is clear -- 10-15 minutes at full heat is usually enough. (Luminous flame must not touch platinum).

Put the crucible and cover in a 400 ml. beaker, add 150 ml. of hot water, and keep hot until the melt is dissolved (1-2 hours). Remove platinum and wash, removing adhering particles.

Make up to 250 ml.

Filter through quantitative paper using suction, collecting about 75 ml. of clear filtrate.

To aliquots of 25 ml. add 2 drops di-nitrophenol indicator and discharge the yellow color carefully with 5N H₂SO₄.
Add 5 ml. H₂SO₄ molybdate solution while shaking.
Make up to 100 ml.
Add 6 drops SnCl₂ solution, shake, let stand for 30 minutes, add another drop of SnCl₂ solution, mix well, and read on a colorimeter using red filter.
Express as % P, from a curve prepared in the same way as the aliquots are treated, using standard amounts of P.

The molybdate-sulfuric solution is prepared as follows:
Dissolve 25 gms. of ammonium molybdate in 200 ml. of H₂O, warm to 60° C, filter if necessary. Dilute 280 ml. of arsenic and phosphorus-free conc. H₂SO₄ to about 750 ml. When both solutions are cool, add the molybdate solution to the acid solution and make up to 1000 ml. Store this solution in a dark bottle. This is 10 N H₂SO₄ solution containing 2.5 gms. of ammonium molybdate per 100 ml.

The SnCl₂ solution is prepared as follows:
Dissolve 25 gms. of SnCl₂·2H₂O in 1000 ml. of dilute (10% by volume) HCL. Filter if necessary. Store in a bottle with a siphon or side opening near the bottom of the bottle. Protect the solution from air with a layer of white mineral oil 5 mm. thick. Keep an atmosphere of H₂ gas above the liquid by means of a H₂ generator. (Zn-HCL in a U-tube.) (Dissolve in conc. HCL first and heat if necessary - then dilute to 1 litre).
APPENDIX III

Permeability Determinations

The theory, procedure and calculations used in these determinations are those accepted by the American Petroleum Institute and are dealt with in detail in the following publication:


The permeameter used in these tests is depicted diagrammatically in Figure I. The compressed air source permitted a range of inlet pressures up to about 5 atmospheres. Rate of flow of dry air through the sample was measured by means of capillary tubes which were calibrated against outlet pressure measured in cm. of water.
Samples prepared for tests consisted of a cube of rock approximately 1.5 cm. on a side, cut out with a diamond saw and smoothed on a buffer wheel. The sample was fitted into a rubber stopper containing a square hole slightly smaller than the sample. The stopper containing the sample was then fitted into a special container as shown in the inset in Figure I.

Before any determinations were made, a sample of crystalline rock known to be essentially impermeable was fitted into the apparatus and a test run made. No leakage of air around the sample was detected indicating that a satisfactory seal had been obtained.

The results of subsequent permeability determinations are listed in Table IV.

The following is a sample calculation for Sample K-3:

The equations selected for the calculation are:

\[
K = \frac{U Q_{ave} L}{A (P_1 - P_2)}
\]  
(Equation (35) Page 9,\{\(A.P.I.\) Bulletin\})

Where 

- \(K\) = indicated permeability in darcy's.
- \(U\) = viscosity of fluid in centipoise.
- \(Q_{ave}\) = volume rate of flow at mean pressure (c.c./sec.).
- \(L\) = length of specimen in centimeters.
- \(A\) = cross-section area of sample in cm\(^2\).
- \(P_1\) = inlet pressure (atmospheres).
- \(P_2\) = outlet pressure (atmospheres).

\(K(\text{cm}^2) = P_1/P_2\)
\[ P(\text{ave}) = \frac{P_i + P}{2} \]  
\[ Q(\text{ave}) = \frac{Q(\text{graph}) \times P_2}{P_{\text{ave}}} \]  

Where \( P_{\text{ave}} \) = average mean pressure

\( Q(\text{graph}) \) = volume rate of flow indicated by calibrated outlet capillary tube (c.c./sec.).

Substituting the values from Table IV for Sample K-10, initial run, in equations (2) and (3) gives:

\[ P_{\text{ave}} = \frac{2.99 + 0.948}{2} = 1.97 \text{ atmospheres} \]

\[ Q_{\text{ave}} = \frac{0.13 \times 0.948}{1.97} = 0.063 \text{ c.c./sec.} \]

\[ K = \frac{0.0185 \times 0.063 \times 1.60}{2.10 \times (2.99-0.948)} = 0.00044 \text{ Darcy's} \]

This is the apparent permeability. The true permeability is then obtained by plotting apparent values over a range of inlet pressures and extrapolating to find the value at infinite pressure.
APPENDIX III

(Note: Permeability measured in plane of bedding in all cases.)

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Temp.</th>
<th>Barometric Press.</th>
<th>U Air (Centipoise)</th>
<th>A Cross-section Area</th>
<th>L. Length</th>
<th>( P_1 ) (cm. Hg.)</th>
<th>( P_2 ) (cm. H2O)</th>
<th>( P_1 ) Absolute (atm.)</th>
<th>( P_2 ) Absolute (atm.)</th>
<th>Q Graph (c.c./sec.)</th>
<th>Q Average (c.c./sec.)</th>
<th>Average Mean Pressure (atm.)</th>
<th>K (_1) (Darcy's)</th>
<th>K (_1) Extrapolated To 00 press.</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>K-3</td>
<td>26°C</td>
<td>72.9</td>
<td>0.0184</td>
<td>2.46 cm²</td>
<td>1.56 cm.</td>
<td>207</td>
<td>3.3</td>
<td>3.68</td>
<td>0.962</td>
<td>0.32</td>
<td>0.13</td>
<td>2.32</td>
<td>0.00057</td>
<td>0.2 milli-Darcy's</td>
<td>Radioactive Athabasca Sandstone</td>
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<tr>
<td>K-6</td>
<td>26°C</td>
<td>69.8</td>
<td>0.0185</td>
<td>2.08</td>
<td>1.44</td>
<td>NO DETECTABLE PERMEABILITY</td>
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<td></td>
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<td></td>
<td></td>
<td>Radioactive Athabasca Sandstone</td>
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<tr>
<td>K-10</td>
<td>26°C</td>
<td>71.9</td>
<td>0.0185</td>
<td>2.10</td>
<td>1.60</td>
<td>155</td>
<td>1.3</td>
<td>2.99</td>
<td>0.948</td>
<td>0.13</td>
<td>0.065</td>
<td>1.97</td>
<td>0.00044</td>
<td>0.1</td>
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<td>26°C</td>
<td>71.9</td>
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<td>1.89</td>
<td>1.50</td>
<td>155</td>
<td>0.9</td>
<td>2.99</td>
<td>0.948</td>
<td>0.09</td>
<td>0.048</td>
<td>1.97</td>
<td>0.00035</td>
<td>0.1</td>
<td>Fine grained Athabasca Sandstone. No radioactivity.</td>
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<td>J-1</td>
<td>26°C</td>
<td>69.8</td>
<td>0.0185</td>
<td>2.31</td>
<td>1.46</td>
<td>34.0</td>
<td>10.0</td>
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<td>0.923</td>
<td>1.00</td>
<td>0.81</td>
<td>1.15</td>
<td>0.022</td>
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<td>Mineralized (carnotite), Sandstone from the Colorado Plateau, U.S.A.</td>
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<td>44.9</td>
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<td>52.2</td>
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<td>0.935</td>
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<td>1.17</td>
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<td>66.4</td>
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<td>0.937</td>
<td>1.77</td>
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<td>66.1</td>
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<td>0.939</td>
<td>1.99</td>
<td>1.37</td>
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<td>1.45</td>
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<td>67.4</td>
<td>28.1</td>
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<td>2.69</td>
<td>1.58</td>
<td>1.51</td>
<td>0.018</td>
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</table>
DIAGRAMMATIC SKETCH OF PERMEABILITY APPARATUS
APPENDIX III
NOTE: Graph beside each hole is a plot of diamond drill hole geiger readings. Normal background reading approximately 76 c.p.m.

LEGEND

Sandstone
Kaolin
Granitic gneiss
Altered feldspar porphyry
Amphibolite gneiss

VERTICAL SECTIONS - NORTH SHOWING - MIDDLE LAKE

SCALE: 1 INCH = 20 FEET