FRONTISPIECE

Radiometric Surveying in Redwater Area

A RADIOMETRIC SURVEY OF REDWATER OILFIELD ALBERTA, CANADA.

by

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

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To
My Father

McGILL UNIVERSITY
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SUMMARY

A radiometric survey of Redwater Oilfield was carried out during the summer of 1956. The field work included collections of 450 radon samples, 4000 total count determinations, and collections of 865 soil samples for analysis from 200 holes, 5 feet deep, drilled approximately 1300 feet apart.

During the course of the field season it was observed that radiation measured at the surface of earth or just above it comes from within 0-0.3 feet in loams, 0.6-1.5 feet in sands, and about 2 feet in peat. It was also noticed that the radon content was lower in holes drilled on top of the sand dunes and near the road cuts in comparison with the holes drilled on the sides away from the road cuts. The radon content of sand decreases with the increasing coarseness of sand.

The airborne radium and ground radon data show very good correspondence. A partial "halo" effect appears to exist about a mile to 2 miles from the limits of the pool at the flanks. A correlation between the radium highs and Shatford's (1959) postulated NW--SE & NE--SW fault and fracture systems appears to exist. Zinc and uranium data support the ground radon result.

The conclusions drawn from the Redwater survey were utilized in interpreting data from an unknown prospect (which later turned out to be Ten Section Oilfield, California), and L'Assomption prospect, Quebec. The results suggest an anomalous low associated with the Ten Section pool and a high with the L'Assomption prospect. Several faults have been inferred from the radium data in L'Assomption Area.

A mechanism to explain the existence of radiometric anomalies due to the possible presence of fractures in the rocks through which water and hydrocarbons may migrate is proposed.

Because one can delineate fault and fracture systems through rivers, muskegs and swamps with radium data, it is therefore considered that radium data is superior to total count data. It is concluded that the airborne gamma ray spectrometer may be very useful in locating oil and water bearing areas, fault and fracture systems, and probably many mineral deposits.

CHAPTER I

INTRODUCTION

General:

Since the discovery of radioactivity by Henry Becquerel in 1896 principles of radioactivity have been utilized in developing radiometric methods for geological exploration. Von dem Borne in 1905 made radioactivity measurements in a uranium mine in Europe and observed anamolous radioactivity across a uranium vein in a drift (Ambronn, 1928). According to Reiss (1955) Lind and Whittmore in 1915 made radiation field tests in Colorado, U.S.A. In 1925 Gubkin observed high radioactivity over the producing zone of Maikopsy Oil Field in the U.S.S.R. (Bogoiavlensky, 1928).

Several researchers have observed radiometric highs over faults (Ambronn, in 1918 (Ambronn, 1928); Link et al in 1926 (Hatuda, 1954); Muller, 1927; Patriciu, 1930; Stothart, 1943, 1948, 1950; Lang, 1950; Hatuda, 1954; Browning in Reiss 1955a; Rogers, 1955; Haddad, 1956; Kellog, 1957; Okabe, 1956; Pradel, 1956; Williams et al, 1957; Sikka, 1957a). A few researchers have also observed low radioactivity across faults (Stafford and Beroni, 1957). Howell (1934) did not find any correlation between the radioactivity and faults.

Some writers have suggested the use of radiometric measurements in geological mapping (Koingsberger, 1926; Tiratsoo, 1950; Moxham et al, 1955, 1957; Kellog, 1956; Guillou et al, 1957; Gregory, 1958; Moxham, 1958). Radiometric measurements have been extensively used in the exploration of mineral deposits, especially those of uranium and thorium.

During the past two decades radiometric methods have been applied in oil prospecting. It has been claimed in the literature that either the boundaries of existing oilfields have been extended or new oilfields have been discovered (Stothart, 1943, 1948, 1950; Lang, 1950; Sterret, 1950; Lundberg, 1952; Merrit, 1952, 1954; Lobdell et al, 1954; Reiss, 1955a; Kellog, 1957; Keys, 1957; Laubenbahk et al, 1958). See Table I for a list of oilfields reflecting radiometric anomalies at the surface. Mungerville Oilfield, Texas, was discovered solely on the basis of aeroradiometric data (Figure I). The writer is aware of many more oilfields reflecting radiometric anomalies in North America and other parts of the world, but is unable to disclose the names due to the lack of permission from the sources.

Problem:

It is observed from the published and unpublished radiometric maps that generally a low anomaly is present above an oilfield, and a high anomaly at the flanks (Lundberg, 1952; Merrit, 1952, 1954, 1956, 1957; Lobdell et al, 1954; Alexeyev et al, 1955; Flerov et al, 1955; Spivack, 1955, Keys, 1957; Sikka, 1957a, b; Stafford and Berroni, 1957; Tripp, 1955, 1957; Laubenbakh et al, 1958). Some observers have reported high radioactivity over the production (Gubkin in Bogoiavlensky, 1928; Stothart, 1943, 1948, 1950; Lang, 1950; Sterret, 1950; Nicar in Scherb, 1953; Alexeyev et al, 1955; Browning in Reiss, 1955a; Haddad, 1956; Kellog, 1957; Hoylman, 1958).

A few investigators have found no correlation between the anomalous radioactivity and oil at depth (Clark et al, 1932; Brown, 1956; Gregory, 1956). Gregory (1956) considers that the radioactivity is due to the soils in the area.

TABLE I: List of Oil or Gas Fields Reflecting Radiometric Anomalies

POOL	LOCATION	TRAP	ANOMALY	AUTHOR
Beaver Lodge	North Dakota (a)	Anticlinal	Low	Lobdell et al (1954); Lundberg Explorations Limited
Tioga	"	"	"	"
Capa	"	"	"	Lundberg Explorations Limited
Hofflund	"	"	"	" "
Charlson	"	"	"	" "
Wales Field	Texas (a)	"	"	" "
Cedar Lake	"	"	"	" "
Coalinga	California (a)	"	"	Pringle et al (1953)
Tensection	"	"	High	Kellog (1956)
Tensection	"	"	Low	Sikka (present paper)
Long Beach	"	"	"	Keys (1957)
Signal Hill	"	"	"	"
Cement	Oklahoma (a)	"	"	Stafford and Beroni (1957)
Korobkov	U. S. S. R.	"	"	Laubenbakh et al 1958
Kazin	"	"	"	"
Kizyl-Kum	"	"	"	"
Kum-Dag	"	"	"	"
Cordele	Texas (a)	Fault	High	Stothart (1943)
Darst Creek	"	"	"	"
Luling	"	"	"	"
North Thompson	"	Faulted Salt Dome	" (c)	" (1950); Sterret (1950)
Oklahoma City	Oklahoma (a)	"	"	" (1950); Lang (1950)
Hoover	"	Fault	"	Lang (1950)
Turner Valley	Alberta (b)	Faulted Anticline (d)	Low	Spivack (1955)
Cheleken	U. S. S. R.	"	High	Laubenbakh et al (1958)
Kotourtepe	"	Faulted Anticline	Low	"
Roundtop	Texas (a)	Reef	High	Stothart (1950)
Redwater	Alberta (b)	"	Low	Pringle et al (1953); Sikka (1957; and present paper)
Aspermont Lake	Texas (a)	"	"	Editor (1954)
Mungerville	" (a)	"	"	Lundberg Explorations Limited (See figure 1.)
Van	Texas	Salt Dome	High	Nicar in Scherb (1953)
Maikopsy	U. S. S. R.	Stratigraphic	High	Gubkin in Bogoiavlensky (1928)
East Texas	Texas	"	"	Stothart (1943); Editor (1954)
Ceres	Oklahoma (a)	"	"	Lang (1950)
Virden	Manitoba (b)	"	Low	Lundberg Explorations Limited
Daly	"	"	"	" " "
Lake Tecumseh				
Wilcox Pool	Oklahoma (a)	-	High	Sterret (1950)
Lindsborg	Kansas (a)	-	Low	"
Salt Creek	Texas (a)	-	"	Lobdell et al in Editor (1954)
Smolan	Kansas (a)	-	"	"
Part of Cowly County	"	-	"	Sterret (1950)
Old Fashing	Louisiana (a)	-	"	Stafford and Beroni (1957)

(a) United States of America
(b) Canada
(c) High on the fault, low on the remainder
(d) One Profile

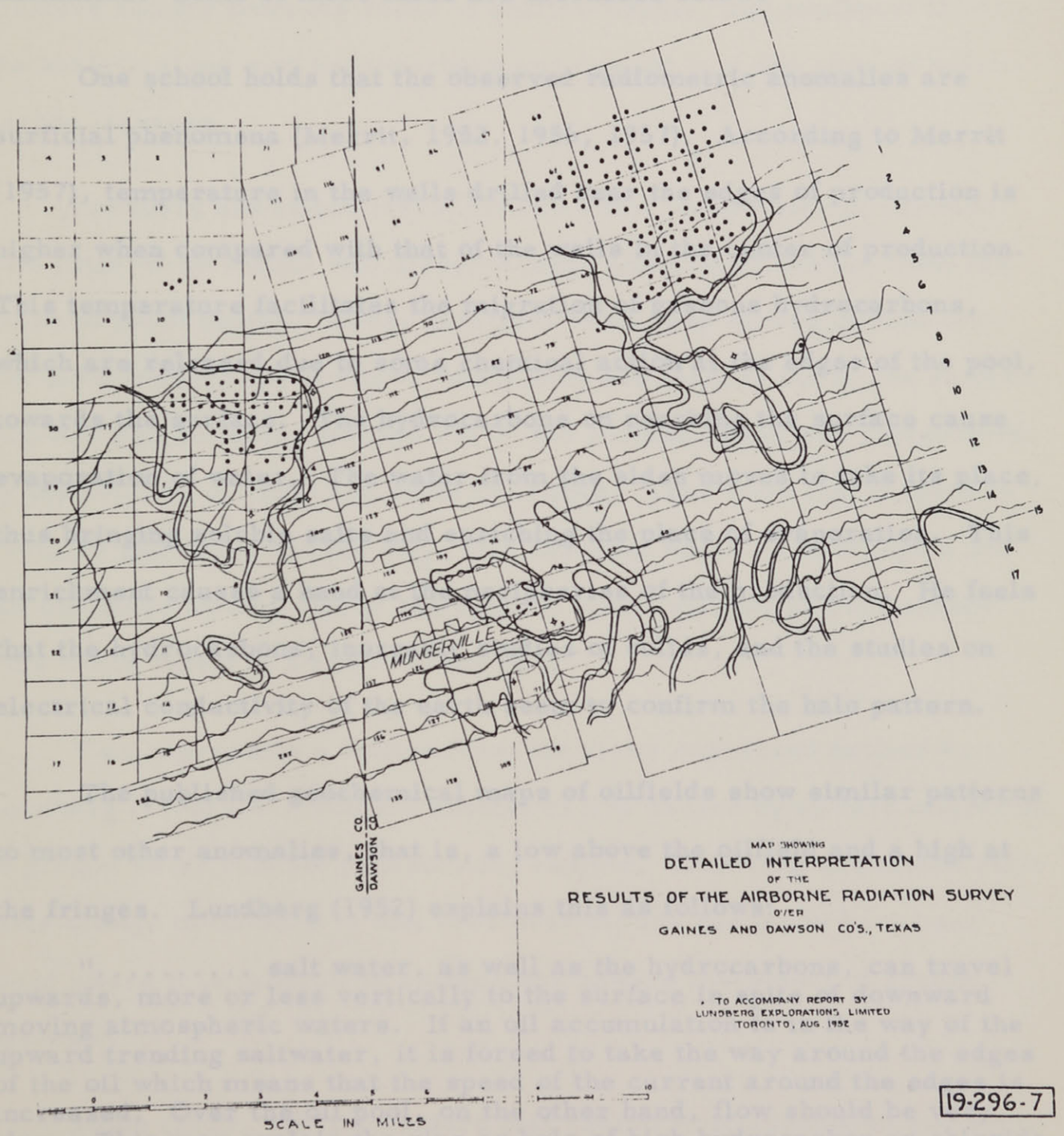

Figure 1: Aero Radiometric Map of Mungerville Oilfield, Texas.

Alexeyev et al (1955) state:

"Some radiometric anomalies in oilfields that have been thoroughly explored by us generally reflect the geological map of the area satisfactorily, though the presence of these anomalies goes beyond their links solely to the nature of the soil or of the underlying rock".

Several hypotheses based on various different ideas have been proposed to explain radiometric anomalies. These hypotheses do not give satisfactory explanations as to the mechanism of the formation of these anomalies. Some of these ideas are discussed below.

One school holds that the observed radiometric anomalies are surficial phenomena (Merrit, 1952, 1956, 1957). According to Merrit (1957), temperature in the wells drilled near the edges of production is higher when compared with that of the wells in the center of production. This temperature facilitates the migration of gaseous hydrocarbons, which are released due to some chemical action at the edges of the pool, towards the surface. The hydrocarbons on reaching the surface cause evaporation of water. The water from the sides moves to take its place, thus bringing soluble salts and enriching the place of evaporation. This enrichment causes a band at the peripheries of the production. He feels that the hydrocarbons, inorganic studies of solids, and the studies on electrical conductivity of the earth seem to confirm the halo pattern.

The published geochemical maps of oilfields show similar patterns to most other anomalies, that is, a low above the oilfield and a high at the fringes. Lundberg (1952) explains this as follows:

"..... salt water, as well as the hydrocarbons, can travel upwards, more or less vertically to the surface in spite of downward moving atmospheric waters. If an oil accumulation is in the way of the upward trending saltwater, it is forced to take the way around the edges of the oil which means that the speed of the current around the edges is increased. Over the oil pool, on the other hand, flow should be very slow. This may explain the ring or halo of high hydrocarbon or chloride concentration observed at the surface, as well as the minimum right above it".

He further states that the radiometric anomalies existing at the surface are not caused by the movement of radioactive substances from the deepseated levels of the oil accumulations. These are probably due to the leakage of hydrocarbons to the surface, which are strong reducing agents. These hydrocarbons will reduce sulfates to sulfide in solution, thereby increasing the dissolving power of water. This water will dissolve radium from the rocks at shallow depths, and transport it to the surface along with hydrocarbons and deposit it at the sites of hydrocarbon leakages.

Lundberg and Isford (1953) consider that waters rich in chloride with little or no sulfate will dissolve large amounts of radium from the rocks at great depths. These chlorides from deep waters diffuse continuously towards the surface, where they are leached out by the surface runoff. The chlorides leached out by the surface runoff are replenished by the solution of more salt from the rocks. They state that if there is an oil or gas deposit in the way, this diffusion would be interrupted and the chlorides leached out by the surface runoff will not be replenished. This would result in a low over the pool.

This represents a change from the views expressed earlier by Lundberg (1952) i.e., that the anomalies are caused by upward migration of ground water capable of dissolving radium. Lundberg and Isford state "this change of thinking is that lows over oil and gas pools have been found where it is difficult to assume any upward movement of ground waters."

Tripp (1955, 1957) considers that radiometric anomalies are superficial, and are a result of diffusion of gaseous hydrocarbons. The gaseous

diffusion increases evaporation, which results in the precipitation of radioelements. These radioelements and hydrocarbons are adsorbed to the surface of certain aluminum silicate structures. The ionic radii of hydrocarbons and radioelements are very similar. But the radioelements are more mobile, and are, therefore, carried laterally in surface groundwaters. This results in a deficiency of radioelement content over the pool coincident with a maximum in the hydrocarbon content.

A great majority of oil deposits are associated with tectonic structures (Alexeyev et al, 1955). Generally the rocks in the tectonic regions are fissured, fractured and faulted. According to Alexeyev et al (1955) these fissures, fractures and faults serve as channelways for the migration of subterranean waters to the surface. The subterranean waters containing radium as radium chloride or sulfide, on coming in contact with the surface waters, will precipitate radium sulphate. According to these writers the scheme proposed by Lundberg (1952), Lundberg and Isford (1953), and Lobdell et al (1954) to explain the "halo" effect has little foundation and is an oversimplication.

It may be pointed out here that the hypothesis proposed by Lobdell et al (1954) is the same as the one proposed by Merrit (1952, 1956, 1957).

According to Kellog (1957) these radiation anomalies originate at the surface of the earth, and are due to the solution of mineral matter in rocks through which ground water has been required to move by the controlling geologic structure. He further states "the surface radioactivity pattern may then reflect subsurface geologic structures to the degree that surface deposition of radioactive salts has been controlled by such structure."

It is believed that uranium in oil may occur as complex organic compounds, or it may be absorbed in the organic matter (Bears, 1945). Erickson et al (1954) have stated that uraniferous asphaltite deposits are formed as a result of volatilization, oxidation, and polymerization of petroleum.

Both oilfield waters and oil generally contain radioelements. The marine shales, which generally have a greater concentration of uranium, are considered to be possible source beds of petroleum. There appears to be a relationship between the organic matter and uranium.

It has been observed from analytical studies that uranium, like other heavy metals, is concentrated in the heavier more asphaltic portions of petroleum (Erickson et al, 1954). Reference has, however, been made to association with the lighter, volatile hydrocarbons (Glococzowski, 1953).

Erickson et al (1954) state:

"..... the consistent occurrence and exceptionally high concentrations of a suite of heavy metals in the ash of crude oil, asphalt, and petroleum extracts suggest these elements were not derived from the strata in which the oil occurs, but were concentrated either by some agency connected with the actual formation of oil or during the possible migration of oil. Organisms like Crustacea ... and as the animals died, they formed the metal-rich organic mud, that were the source beds of petroleum."

Uranium is leached by acid waters from the rocks, and rock forming minerals (Hurley, 1950; Brown et al, 1953 a & b; Phair et al, 1953; Erickson et al, 1954; Breger et al, 1955). Furthermore, according to Hyden (1958) uranium minerals are soluble in oil.

Brine and petroleum contain large quantities of dissolved gases. The most predominant of these gases are carbon dioxide, methane,

nitrogen, hydrogen sulphide, and hydrogen. Carbon dioxide is generally very abundant (sometimes exceeding 90%). The content of the other gases is controlled by the amount of dissolved CO_2 and N_2. The CO_2 content may also indicate the reservoir pressure. Some of these gases in solution such as CO_2 and H_2S are strong leaching agents. It is therefore probable that these gases may facilitate the dissolution of mineral matter from the rocks through which they travel and increase the radioelement content of subterranean waters.

From the foregoing discussion one can infer the following possibilities as to the source and migration of radioelements in the observed anomalies:

a) The source beds of petroleum and the surrounding rocks are a possible source of radioelements in oil and brine.

b) The ascending water and oil probably transport the radioactive substances to the surface.

c) The leakage of gaseous hydrocarbons and other gases at the surface may increase the evaporation resulting in the increased migration of water from the surrounding area. This water would probably dissolve the radioelements and deposit it at the sites of increased evaporation.

d) The volatilization, oxidation, and polymerization of crude petroleum (oil) probably releases uranium and other radioelements at the surface from oil.

e) As the water or oil ascend they may dissolve some of the radioelements from the rocks and carry them in solution to the surface.

These are some of the possible hypotheses to explain the source and movement of radioactive substances; they will be discussed in detail

in the later chapters. In order to assess these hypotheses, it is necessary to consider certain selected oilfields.

The problem of this study is to examine claimed radiometric anomalies from ground and airborne surveys and determine the nature and probable source of radioelements causing these anomalies.

Purpose and Methods:

The purpose of this investigation was to test the hypotheses discussed in the preceding paragraphs by making a detailed ground survey in the Redwater Area, Alberta, Canada.

The methods of study included critical review of the literature, field and laboratory investigations. The results have been presented as follows:

a) Geochemistry of naturally occurring radioelements

b) Principles of gamma ray surveying

c) Field and laboratory techniques

d) Presentation of results from the ground and airborne surveys in Redwater Area, Alberta

e) The application of conclusions drawn from the Redwater results to the data from Ten Section Oilfield, California, and l'Assomption Prospect, Quebec.

f) General discussion.

Location and Area:

The study area is located approximately 50 miles north of Edmonton, Alberta (Figure 2). It is bounded by townships 54-59 and ranges 20-23 west of the 4th meridian (Figure 3). Private, county and provincial

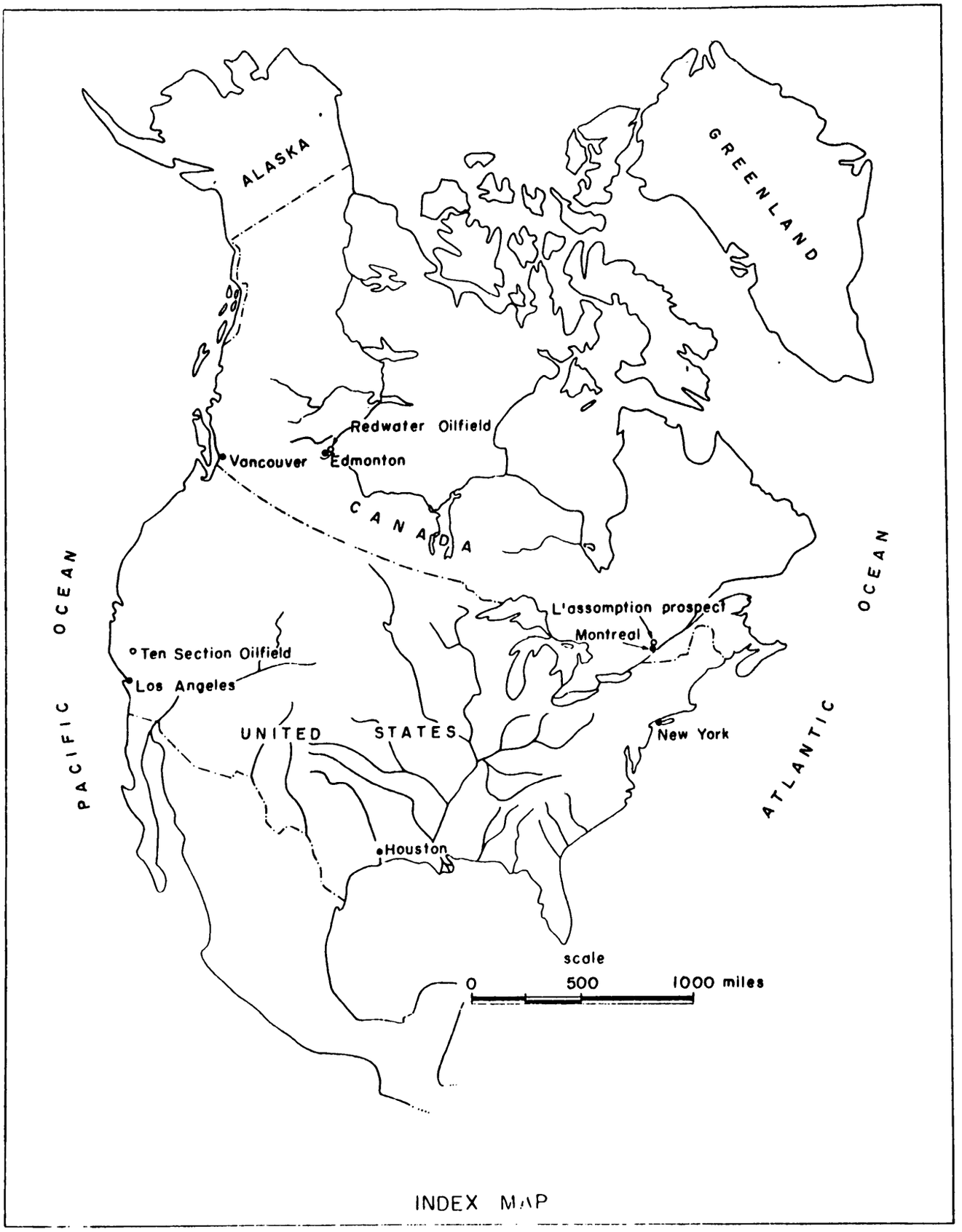
ALASKA
GREENLAND
Redwater Oilfield
Vancouver
Edmonton
CANADA
PACIFIC OCEAN
ATLANTIC OCEAN
L'assomption prospect
Montreal
Ten Section Oilfield
Los Angeles
UNITED STATES
New York
Houston
scale
0
500
1000 miles
INDEX MAP

Figure 2.

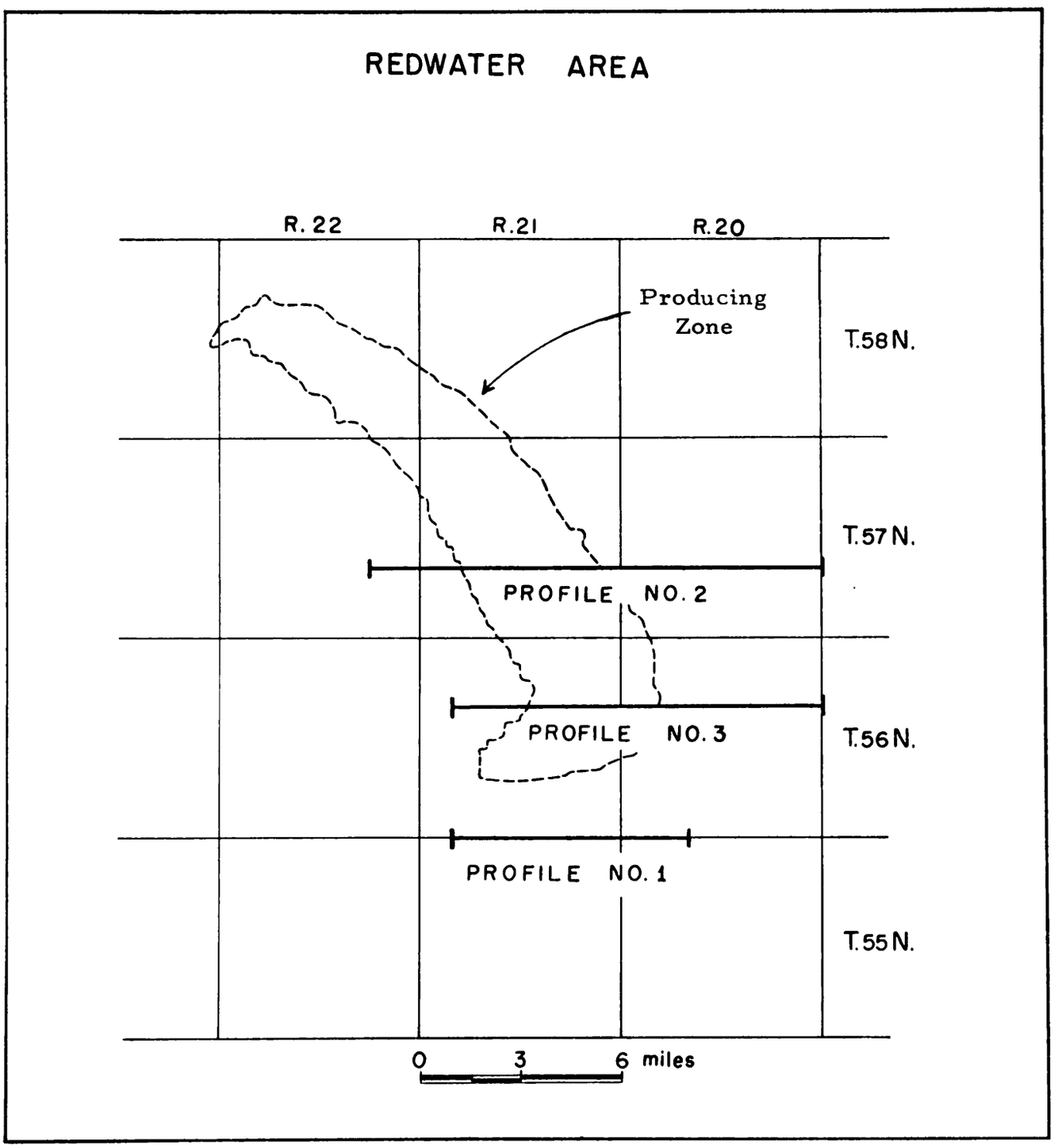
REDWATER AREA
R. 22
R. 21
R. 20
Producing Zone
T. 58 N.
T. 57 N.
PROFILE NO. 2
PROFILE NO. 3
T. 56 N.
PROFILE NO. 1
T. 55 N.
0
3
6 miles

Figure 3.

highways cross the region. The major system of roads is north-south and east-west. Some of the roads become impassable after rain. The area is served by the Canadian National and Canadian Pacific railroads.

The Redwater map area is one of flat to gently undulating land surfaces, and is diagonally cut by North Saskatchewan River, which, along with its tributaries drains to the northeast.

A part of the area is covered with U-shaped sand dunes and muskeg. The depressions are filled with peat.

Previous Work:

Lundberg and Isford (1952), Lundberg and Roulston et al (1952), and Pringle et al (1953) did the early work in aeroradiometric surveying in Redwater Area, and observed anomalous low radioactivity over the producing zone.

Brownell (1953) made a ground survey (Profile III, Figure 3) across Redwater oilfield. He observed that a map produced from the readings taken at five feet below the surface of the earth conforms to the airborne surveys.

Brown (1956) made an airborne survey of the Redwater area during 1955. He found no correlation between the surface radioactivity and the oil at depth. A similar conclusion was drawn by Gregory (1956) who re-evaluated the results of Pringle et al (1953).

Present Work:

The field work for the present study was carried out from May 1956 to October 1956.

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CHAPTER II

GEOCHEMISTRY OF NATURALLY OCCURRING RADIO-ELEMENTS

All naturally occurring elements with atomic number 83 (Bismuth) and larger are radioactive. These elements undergo spontaneous transformations from one atomic species into another, to produce more stable forms by releasing energy. These transformations are nuclear reactions characterized by the different types of radiations emitted. These occur at random and the exact moment when such a reaction will take place cannot be predicted. The process of spontaneous nuclear transformation is termed radioactive decay and the phenomenon is termed radioactivity. The process of radioactive decay can be measured and obeys certain established statistical laws.

The radioactive elements (radio-elements Table II) belong to the uranium (4n + 2), thorium (4n,) and actinium series (4n + 3,). In each of these series there exists a gaseous member with atomic number 86. The gaseous members are sometimes called emanations.

Besides the above mentioned three series, there are other known naturally occurring radioelements (Table III). Potassium^{40} is the most important element of this set. In radiometric surveying the uranium and thorium series, and potassium^{40} are most important and will be considered in detail.

Table II

Uranium Series *

Radioelement	Nuclide	Symbol	Half Life	Radiation (energy in Mev.)		
				Alpha α	Beta β	Gamma τ
Uranium I	Uranium	$_{92}U^{238}$	4.50×10^{9} yr	4.21	—	—
Uranium XI	Thorium	$_{90}Th^{234}$	24.1 days	—	0.2, 0.1	0.09
UraniumX2*	Protoactinium	$_{91}Pa^{234}$	1.18 min	—	2.32, 1.5	2% 0.78, 0.82
Uranium II	Uranium	$_{92}U^{234}$	2.52×10^{5} yr	4.75	—	—
Ionium	Thorium	$_{90}Th^{230}$	8.0×10^{4} yr	4.68, 4.61	—	11% 0.07
Radium	Radium	$_{88}Ra^{226}$	1622 yr	4.79, 4.61	—	0.19
Ra Emanation, (Niton)	Radon	$_{86}Rn\ (Em)^{222}$	3.825 days	5.49	—	—
Radium A	Polonium	$_{84}Po^{218}$	3.05 min	5.99	β^-	—
99.96% α 0.04% β^-						
Radium B	Lead	$_{82}Pb^{214}$	26.8 min	—	0.65	(0.047, 0.035)
Astatine	Astatine	$_{85}At^{218}$	1.5 sec to 2 sec	6.63	—	—
99.99% α ~0.01% β^-						
Radon	Radon	$_{86}Rn\ (Em)^{218}$	0.019 sec	7.12	—	—
Radium C	Bismuth	$_{83}Bi^{214}$	19.7 min	5.44, 5.51	1.65, 3.17	1.76, 2.19
99.96% β^- 0.04% α						
Radium C'	Polonium	$_{84}Po^{214}$	1.637×10^{-4} sec	7.68	—	0.46
Radium C''	Thallium	$_{81}Tl^{210}$	1.32 min	—	1.9	0.047, 0.043,
Radium D	Lead	$_{82}Pb^{210}$	22.2 yr	—	0.025	10% 0.007
Radium E	Bismuth	$_{83}Bi^{210}$	5.02 day	4.93	1.17	—
~100% β^- ~ 5×10^{-6} % α						
Radium F	Polonium	$_{84}Po^{210}$	138.3 day	5.30, 4.5	—	0.80
Thallium	Thallium	$_{81}Tl^{206}$	4.23 min	—	1.51	—
Radium G	Lead	$_{82}Pb^{206}$	Stable	—	—	—

*Uranium X_2 undergoes isomeric transition to form Uranium Z (Pa^{234}) half life 6.7 hr. which in turn emits β radiation and forms Uranium II (U^{234})

Actinium Series *

Radioelement	Nuclide	Symbol	Half Life	Radiation (energy in Mev.)		
				Alpha α	Beta β	Gamma τ
Actinouranium	Uranium	$_{92}U^{235}$	7.13×10^{8} yr	4.52	—	(.09)
Uranium Y	Thorium	$_{90}Th^{231}$	25.6 hr		0.09, 0.30, 0.22	0.022, 0.21
Protoactinium	Protoactinium	$_{91}Pa^{231}$	3.43×10^{4} yr	5.00, 5.04, 4.66	—	0.32
Actinium	Actinium	$_{89}Ac^{227}$	22.0 yr	5.0, 4.94	0.04	0.037
98.8% β^- 1.2% α						
Radioactinium	Thorium	$_{90}Th^{227}$	18.6 days	6.05	—	0.03, 0.64
Actinium K	Francium	$_{89}Fr^{223}$	21 min	α	1.2	0.049, 0.3
Actinium X	Radium	$_{88}Ra^{223}$	11.1 days	6.72	—	0.026, 0.44
Astatine	Astatine	$_{85}At^{219}$	0.9 min	α	β^-	
3% α 97% β^-						
Ac Emanation, (Actinon)	Radon	$_{86}Rn(Em)^{219}$	3.92 sec	6.82	—	0.20, 0.07, 0.39
Bismuth	Bismuth	$_{83}Bi^{215}$	8 min	—	β^-	—
Actinium A	Polonium	$_{84}Po^{215}$	1.83×10^{-3} sec	7.36	β^-	—
~100% α ~ 5×10^{-4}% β^-						
Actinium B	Lead	$_{82}Pb^{211}$	36.1 min	—	0.5, 1.4	0.8
Astatine	Astatine	$_{85}At^{216}$	10^{-4} sec	8.00	—	—
Actinium C	Bismuth	$_{83}Bi^{211}$	2.16 min	6.62	β^-	0.35
0.32% β^- 99.68% α						
Actinium C'	Polonium	$_{84}Po^{211}$	0.52 sec	7.43	—	—
Actinium C''	Thallium	$_{81}Tl^{207}$	4.79 min	—	1.47	0.87
Actinium D	Lead	$_{82}Pb^{207}$	Stable	—	—	—

Thorium Series *

Radioelement	Nuclide	Symbol	Half Life	Radiation (energy in Mev.)		
				Alpha α	Beta β	Gamma τ
Thorium	Thorium	$_{90}Th^{232}$	1.389×10^{10} yr	3.98	—	(0.05)
Mesothorium I	Radium	$_{88}Ra^{228}$	6.7 yr	—	0.053	0.03
Mesothorium II	Actinium	$_{89}Ac^{228}$	6.13 hr	—	2.1, 1.7, 1	0.96, 0.06
Radiothorium	Thorium	$_{90}Th^{228}$	1.90 yr	5.42, 5.34	—	0.084, 0.087
Thorium X	Radium	$_{88}Ra^{224}$	3.64 days	5.68, 5.45, 5.19	—	0.24, 0.05
Th Emanation, (Thoron)	Radon	$_{86}Rn\ (Em)^{220}$	54.5 sec	6.282	—	—
Thorium A	Polonium	$_{84}Po^{216}$	0.158 sec	6.774	—	—
Thorium B	Lead	$_{82}Pb^{212}$	10.6 hr	—	0.33, 0.57	0.24, 0.30, 0.11
Astatine	Astatine	$_{85}At^{216}$	~ 3×10^{-4} sec	7.79	—	—
Thorium C	Bismuth	$_{83}Bi^{212}$	1.01 hr	34% 6.04, 6.08	66% 2.25	0.40, 2.20
Thorium C'	Polonium	$_{84}Po^{212}$	3.04×10^{-7} sec	66% 8.78	—	—
Thorium C''	Thallium	$_{81}Tl^{208}$	3.1 min	—	34% 1.72	2.62, 0.58, 0.51
Thorium D	Lead	$_{82}Pb^{208}$	Stable	—	—	—

*Milmoe and Kanizay, 1956

TABLE III - Additional Naturally Occurring Radioactive Substances[a]

Active Substance	Type of Disintegration	Half-life in Years	Relative Isotopic Abundance in %	Disintegration Products
K^{40}	β, EC*	1.2×10^9	0.012	Ca^{40}, A^{40}
Rb^{87}	"	6.2×10^{10}	27.8	Sr^{87}
In^{115}	"	6×10^{14}	95.8	Sn^{115}
La^{138}	EC,*	2×10^{11}	0.089	Ba^{138}, Ce^{138}
Nd^{144}	α	5×10^{15}	23.9	Ce^{140}
Sm^{147}	α	1.3×10^{11}	15.1	Nd^{143}
Lu^{176}	β	4.6×10^{10}	2.60	Hf^{176}
Re^{187}	β	5×10^{10}	62.9	Os^{187}
Pt^{190}	α	10^{12}	0.012	Os^{186}

* The symbol EC stands for electron capture.

(a) Friedlander et al, 1955

Uranium Series:

The uranium series (Table II) takes its name from uranium which is a very long-lived element (half life = 4.5×10^9 years). Only elements with long half lives, i.e. uranium, ionium, and radium, and also the gaseous element radon are important geochemically, and these will be discussed.

Uranium:

Uranium occurring in nature consists of three isotopes (Table IV).

TABLE IV: Natural Abundance of Uranium Isotopes[a]

Mass No.	Abundance atom %
U^{238}	99.2739 ± 0.0007.
U^{235}	0.7204 ± 0.0007.
U^{234}	0.0057 ± 0.0002.
U^{238}/U^{234}	17.235 ± 550
U^{238}/U^{235}	137.80 ± 0.14

(a) Loundsbury, 1956.

There are other values for the $U^{238}/_{U}235$ ratio but 137.80 ± 0.14 is the one most generally accepted.

U^{238} and U^{235} are the parents of 4n + 2, and 4n + 3 series. U^{234} is a daughter product of U^{238}. U^{235} appears to be of independent origin (Katz and Seaborg, 1957).

Uranium is an oxyphile element. It forms simple oxides, complex carbonates, silicates, phosphates, vanadates, arsenates, sulphates etc. No natural sulphides are known to exist. It is widely distributed in the earth's crust (4 ppm). The relative abundance in various geologic materials is given in Table V.

The atomic radius of uranium is 1.38 Å. Uranium belongs to subgroup VI A of the periodic table. It has four oxidation states: U^{+3}, U^{+4}, U^{+5}, U^{+6}. The existence of various oxidation states of uranium in solution is explained in Figure 4.

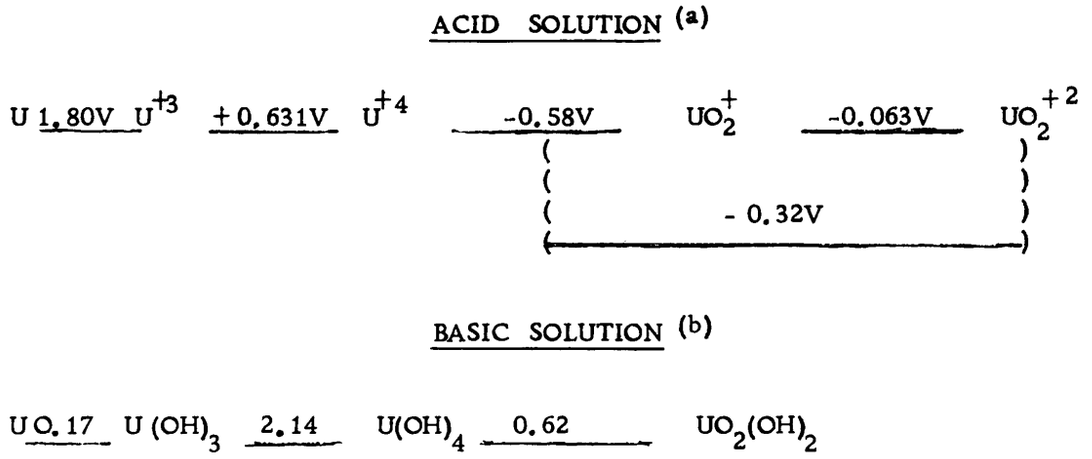


Figure 4. (a) Formal potential in 1M $HClO_4$ at 25°c; (b) in alkaline solution (Katz & Seaborg, 1957).

The trivalent (U^{+3}) ion is unstable with respect to the evolution of hydrogen from water (Latimer, 1952). Therefore its existence in nature is improbable. This is further borne out by the lack of the existence of any mineral species containing U^{+3}. (McKelvey et al, 1955). The pentavalent uranium (U^{+5}) exists in minute quantities and is considered unimportant in the formation of stable ions (Miller, 1955).

TABLE V: Radioelement Content of Geologic Materials

ROCK TYPE	U in ppm	Th in ppm	K in %
IGNEOUS			
Obsidian (j)	8.6		
Rhyolte (j)	2.0-5.6		
Granite (l)	9	20	3.4
Granodiorite (i)	7.7	18	2.5
Granodiorite	2.03-2.4	-	-
Basalts (j)	1.0-1.2		
Continental basalts (l)	3.5	9.1	1.9
Oceanic basalts (l)	3.6	7.1	1.8
Plateau basalts (l)	2.2	5.0	0.8
Gabbro (l)	2.4	5.1	0.7
Gabbro (i)	0.31-0.61	-	-
Eclogite (l)	1.0	1.8	0.4
Peridotite (l)	1.5	3.3	0.8
Dunite (l)	1.4	3.4	0.03
SEDIMENTARY			
Orthoquartzite (m)	0.45 ± 0.05	1.7 ± 0.1	0.64 ± 004
Chattanooga Black Shale (a)	80,79,(n)	5.2,6.5(n)	2.7,2.2,(n)
Chattanooga Black Shale (a)	74,78	8.2-8.1	-
Heebner Black Shale (a)	32,(n)	9.8,(n)	2.2,(n)
Heebner Black Shale (a)	34.5,34.0	8.8, 8.9,	-
Lawrence Red Shale (a)	1.6,(n)	13,(n)	2.9,(n)
Leo sandy shale (a)	3.7,(n)	14,(n)	2.5,(n)
Leo sandy shale (a)	5.2,4.6	14.0,13.4	-
Clays - Russia (c)	2.4	11	-
Underclay (a)	4.2,(n)	13,(n)	2.4,(n)
Pelagic clay (e)	5	-	-
Arkansas bauxite (a)	6.4,(n)	96,(n)	0.3,(n)
Arkansas bauxite (a)	7.0,6.6	79.4,79.8	-
Surinam bauxite (a)	6.1,(n)	132,(n)	0.5,(n)
Surinam bauxite (a)		130	0.3,1.7
Limestone (Austin Chalk) (a)	1.7,2.4,(n)	1.6,5.1,(n)	-
Limestone (d)	1.	-	-
Limestone (b)	0.7-3.8	-	-
Dolomite (b)	0.7-2.4	-	-
Carbonates - Russia (c)	2.1	2.4	-
Evaporites (b)	1	-	-
Phosphates (b)	+100	-	-
Siliceous precipitates (b)	up to 200	-	-
Petroleum (h)	1	-	-
Ocean water	.002(f)	5×10^{-9}(g)	1.10(o)
Ground and River water	.0002(k)	2×10^{-8}(g)	2.12(o)

(a) Adams et al, 1958.
(b) Bell, 1956.
(c) Baranov et al, 1956.
(d) Evans et al, 1941.
(e) Goldberg et al, 1955.
(f) Koczy, 1956.
(g) Koczy, 1954.
(h) Hyden, 1958.
(i) Larsen et al, 1956.
(j) Larsen et al, 1958.
(k) McKelvey et al, 1955.
(l) Monicard et al, 1952.
(m) Murray et al, 1958.
(n) Analysis by Gamma Ray Spectrometry.
(o) Rankama et al, 1950.

The tetravalent (U^{+4}) and the hexavalent (U^{+6}) uranium ions are of common occurrence in nature. The (U^{+4}) with an ionic radius of 0.97Å is stable in a reducing environments, but oxidizes rapidly in water to uranyl ions.

The U^{+4} ion has a large ionic size (0.97Å) and it enters into the crystal structure of minerals to a limited extent. Its presence in apatite, fluorite, and sphene is due to the close proximity of the ionic radii of Ca^{+2}. It is absent in anorthite, which is probably due to the discrepancy in charge (Larsen et al, 1954; McKelvey et al, 1955). The tetravalent uranium (U^{+4}) ion is identical to the tetravalent thorium (Th^{+4}) ion in size and charge etc. This is seen by the extensive solubility of U in the $USiO_4$- $ThSiO_4$ system. Anhydrous silicate of uranium ($USiO_4$) has not been observed in nature (coffinite is a hydrous silicate).

There is a limited substitution of U^{+4} for other tetravalent cations such as Zr^{+4}, W^{+4}, because of the discrepancy in charge (McKelvey et al, 1955). It also forms complex compounds with tantalates-columbates, and rare earths in which the yttrium group of the rare earths predominate. The diversity and large content of various ions in columbates and tantalates offer opportunities for mutual substitution (Frondel, 1956). No phosphate of tetravalent uranium has been observed. Uranium forms dioxide at high temperature (UO_2). Some other anhydrous oxides of the type UO_3 and U_3O_8 are also formed. The type UO_3 does not occur in native oxides.

The primary uranium minerals (uraninite and coffinite) and the others which contain U as a vicarious element do so in the tetravalent form (Frondel, 1956).

The detailed studies of the uranium content of igneous rocks show that it is concentrated in the last differentiates high in SiO_2 and K_2O, and low in CaO and MgO (Larsen et al, 1954, 1955). Hurley (1950), Brown et al (1953), Phair et al (1953), Erickson et al (1954) and Breger et al (1955), observed that uranium can be leached in dilute acid solutions from the rocks and rock-forming minerals. The content of leachable uranium increases with increasing alkali and silica content. This suggests that the uranium (U^{+4}) is in the interstices of the rocks and the rock-forming minerals. It also forms a volatile tetrafluoride with fluorine at 500°C (Seaborg - in 'Inorganic Chemistry' by Sneed et al 1953).

It seems from the above discussion that the paucity of water, probably the presence of fluorine and other halogens, large ion size and high charge delay the crystallization of uranium minerals till a late stage in the history of igneous melts.

Uranium is concentrated in the acid magmas from which granites and syenites crystallize. In pegmatites it is associated with the columbates and tantalates, which are low in uranium (Rankama and Sahama, 1950). It is associated with the high and low temperature veins containing tin and sulfosalts of Co, Ni, Bi, and As. Larsen et al (1954), believe that in the late stage hydrothermal solutions a shift towards more oxidizing conditions alters U^{+4} to U^{+6}. This is observed from Fe^{+2} to Fe^{+3} in solutions which require more energy to oxidize than U^{+4} to U^{+6}. In water, tetravalent uranium oxidizes at a finite rate to form the complex ion $(UO_2)^{+2}$. McKelvey et al (1955) consider that tetravalent uranium is stable under the same conditions as H_2S, HS^-, and S^{-2}. The uranyl ion $(UO_2)^{+2}$ coexists with SO_4^{-2} and HSO_4^- ions.

The hexavalent uranium is very soluble in water. Tetravalent uranium oxidizes rapidly to the complex uranyl ion $(UO_2)^{+2}$. In this ion the two oxygen atoms are on the opposite sides of the uranium atom and U^{+6} is in distorted 6-fold or 8-fold coordination. The uranyl ion is very stable and behaves like a doubly charged ion (Sneed et al, 1953). It forms complex compounds with K^+, Na^+, Ca^{+2}, Mg^{+2}, Cu^{+2}, V^{+5}, As^{+5}, and P^{+5} of the type (Me^+) or $(Me)^{+2}$, $(U^{+6}O_2)^{+2}$ $(R^{+5}O_4)^{-3}$. ($Me \pm K^+$, Na^+; $Me^{+2} = Mg^{+2}$, Cu^{+2}, $R^{+5} = V^{+5}$, As^{+5} and P^{+5}). Murata et al (1951) consider that $(U^{+6}O_2)^{+2}$ $(R^{+5}O_4)^{-3}$ is the most stable part of the structure in the solids.

All natural uranium minerals containing $(UO_2)^{+2}$ are of secondary origin, and are found under oxidizing conditions. There are some 68 of these minerals known at present (Frondel, 1956). Miller (1955) has considered the possibility of uranyl carbonate, phosphate, fluoride, hydroxide and uranous hydroxide, occurring in natural solution at pH7 and 25°C. The carbonate and sulphate complexes are the two chief dissolved constituents of natural waters (McKelvey et al, 1955). An increase in the sulphate content increases the solubility of uranium under oxidizing conditions. Likewise the solubility is increased by an increase in total carbonate ions.

In sedimentary rocks uranium is mostly concentrated in marine black shales, coal, and phosphates. Its association with carbonates, and evaporates is discussed below. Very little is known about the presence of uranium in metamorphic rocks.

The weathering and erosion of rocks releases uranium, which passes into solution in surface and ground waters. The two most mobile

uranium complexes are uranyl sulphate ($UO_2 SO_4$) and urano carbonate ($(UO_2 (CO_3)3)^{-4}$). The former is stable up to pH 4.2 and the latter between pH 7.5 - 10.0 (Scherbina, 1957), pH 6.5 - 11.5 (Miller, 1955).

The transport of uranium in solution is dependent upon lithology, topography, and climatic conditions. The latter play a major role in the exogenic cycle of uranium. In semi-arid to arid regions, the rocks are subjected largely to mechanical weathering yielding a loose aggregate of mineral matter. The groundwater table is either non-existent or very deep. Ground waters carry the uranium to depth, where it may be deposited around the mineral grains or dispersed throughout the ground water system. Some of the uranium may become concentrated in the caliche deposits. In humid regions weathering of the rocks is intense, clay minerals are plentiful, and the ground water table is relatively shallow. Some of the uranium in solution may be adsorbed by the clay minerals (Beers and Goodman, 1944). According to Fredrickson (1948) the adsorption of uranium in the layered structures of the clay minerals is probably due to base exchange phenomena.

Uranium not adsorbed by clay minerals or otherwise precipitated, ultimately finds its way in solution to the sea.

During the course of weathering, accessory minerals like zircon, monazite, xenotime, and apatite, are released in these minerals. Uranium is bound in their crystal lattice and therefore is not released. These minerals locally become concentrated in placers, or go into the resistates (sandstones) etc.

Uranium in solution can easily be extracted or adsorbed by organic matter (Tolmachev, 1943; McKelvey and Nelson, 1950; Szalay, 1952,

1954, 1957, 1958; Breger et al, 1955; Moore, 1954; Manskaia et al, 1956; Masursky, 1956; Hyden, 1958), hydroxide gels (iron, aluminum and manganese), silica gel. Isomorphic substitution for Ca in sedimentary phosphates (Bell, 1956), may also remove a considerable amount of uranium from solution.

Two main types of indigenous organic matter are recognized (Vine et al, 1958), viz. sapropel and humus. Sapropel is a product of spores, pollen, algae, proteins and lipids, whereas the vascular plants are the progenitors of humus and its derivatives (peat, lignite, bituminous coal, and anthracite). Humus of organic matter consists of the humic acids proper, fulvic acids, and the hymato-melonic acids (Manskaia et al, 1956). Tiurin, Forsyth, Ponomareva, have observed humic and fulvic acids in soils, (Manskaia et al, 1956). It is the humic type of organic matter in lignites and black shales which assimilates uranium (Vine et al, 1958).

Manskaia et al, (1956), studied the conditions of the formation of uranyl humates and fulvates. They observed that 82% of uranium is bound by humic acids at pH 4.73. The content of bound uranium in humic acid drops with an increase or decrease in the pH of the solution. In fulvates the bound uranium content is a maximum at pH 7 to 7.5. With an increase in pH above 8 the uranium is redissolved. They also studied the effect of organic matter on uranyl carbonate solutions. The maximum amount of uranium removed from the solution by the organic matter occurred at pH 6 to 6.6. It was also observed that a decrease in absorbed uranium occurred as the pH was increased from 7 to 9 or decreased from 5 to 2.5.

The writer during the course of his field work in Redwater Area observed a considerable drop in the total count (gamma ray) values of soils rich in organic matter and lime. It is probable that the increase in pH and the organic content resulted in the removal of uranium and thus dropped the total counts, which supports the findings of Manskaia et al, (ibid).

Humic acids are responsible in many cases for the enrichment of uranium, and enrichment factors for uranium in humus of about have been observed by Szalay (1955). According to this author the fixation is a reversible cation exchange process which increases with increasing valency and atomic weight. The cations with high valency and atomic weight expel those with low valency and low atomic weight (Szalay, 1958).

Carbonates carry less than 4 ppm uranium (Bell, 1956). This is due to the oxidizing environments, and high concentration of carbonate and bicarbonate ions in solutions. McKelvey et al (1955) consider the absence of uranium in calcite and gypsum is probably related to the discrepancy in charge.

The evaporates contain less than 1 ppm of uranium. The evaporates are deposited in shallow desiccating basins. The turbulent conditions and increase in the carbonate ion concentration in the basin keep the uranyl ion in solution.

The hydroxyl gels of iron, manganese and aluminum, and also silica gel extract uranium in solution by adsorption (Rankama et al, 1950). Barton (1956), and Miholic (1958) also consider that the uranium is

adsorbed or coprecipitated in ferric hydroxide. Uranium may be enriched in the hydrolyzates and oxidates.

Ionium:

Ionium^{230} (atomic number = 90) is a decay product of U^{238} and is an isotope of thorium$^{232}_{90}$. It has relatively long half life (half life = 80,000 years).

The geochemistry of ionium in part is related to its parent U^{238}. In most minerals and soils, ionium is in equilibrium with its parent U^{238}. In solution ionium and uranium take separate courses.

Ionium occurs in only one valency state, i.e. Io^{+4}. The chemical properties of ionium are nearly the same as those of thorium. Ionium as Io^{+4} is a strong reducing agent. It is coprecipitated with the trivalent hydroxides of iron, manganese, and aluminum, because of the close proximity of the ionic potentials of ionium (3.6) to those of iron and aluminum (5) (Goldschmidt, 1954).

Radium:

Radium^{226} is a member of 4n + 2 series of naturally occurring radioelements. There are thirteen known isotopes of radium (Table VI).

Radium^{226} is the longest lived (half life = 1622 years) of the radium isotopes, and will be considered in the following paragraphs.

The average concentration of radium in various geologic materials is given in Table VII. The geochemistry of radium is related to its parent U^{238}. At equilibrium a mineral contains 0.34 parts of radium for each million parts by weight of uranium (Goldschmidt, 1954).

TABLE VI: The Isotopes of Radium[a]

Mass Number	Half-life	Radiation in Mev
213	2.7 min	α , 6.90
219	10-3 sec	" 8.0
220	0.03 sec	" 7.43
221	30 sec	" 6.71
222	38 sec	" 6.51
223 (AcX)*	11.68 day	" 5.704, 5.596; γ 0.026 to 0.44
224 (ThX)	3.64 day	α 5.681; γ
225	14.8 day	β^- 0.31
226*	1622 yr	α 4.791; γ
227	41.2 min	β^- 1.31
228 ($MsTh_1$)	6.7 yr	" 0.012
229	1 min	?
230	1 h	" 1.2 (J2)

(a) Bagnall, 1957

The chemistry of radium is similar to that of barium, but radium is much more mobile than barium (Bagnall, 1957). Most radium salts, with the exception of hydroxide, are sparingly soluble in water. In nature radium is probably carried in solution as a chloride, nitrate or hydroxide. It is easily precipitated as a carbonate or a sulphate from these solutions in a reducing environment. The hydroxide gels of manganese, iron and aluminum may adsorb or coprecipitate radium.

The radium content of precipitates, evaporates and resistates is very low. It is enriched in organic matter and in the hydrolyzates. Because of the short half-life, radium, unsupported by uranium or ionium, is found only in some young minerals (say a few thousand years old). Radium is present in barite ($BaSO_4$) and pyromorphite (PbCl) $Pb_4(PO_4)_3$).. The ionic size of radium (1.42Å) controls its entrance into such minerals, because of its similarity of ionic size with that of Ba (1.34Å) and Pb(1.20Å).

TABLE VII: Radium Content of Geologic Materials

IGNEOUS ROCKS	
Granites (a)	
North America, Greenland, Ireland, Iceland and Japan	$1.50 - 0.12 \times 10^{-6}$
Finland	$4.66 - 0.40 \times 10^{-6}$
Alps	$4.33 - 0.68 \times 10^{-6}$
South Africa	$2.36 - 0.16 \times 10^{-6}$
Basalts (a)	
North America, Greenland, Scotland and Ireland	$0.96 - 0.06 \times 10^{-6}$
England, Germany, France, Hungary	$1.30 - 0.13 \times 10^{-6}$
Plateau Basalts	$0.73 - 0.03 \times 10^{-6}$
Oceanic Island Basalts	$0.90 - 0.03 \times 10^{-6}$
Dunites (a)	
SEDIMENTARY ROCK	
Sandstones (b)	0.71×10^{-6}
Shales (b)	1.08×10^{-6}
Limestones (b)	0.42×10^{-6}
Crude Oil (b)	0.018×10^{-13}
Seawater (d)	$0.8 - 10^{-13}$
Riverwater (c)	0.7×10^{-13}

(a) Larsen and Phair (1954)
(b) Rankama and Sahama (1950)
(c) Koczy (1954)
(d) Koczy (1956)

Radon:

Radon (atomic number = 86; atomic weight = 222) is a gas belonging to the family of inert noble gases. It is the only member of the noble gas family which is radioactive. Radon (half-life = 3.825 days) is a daughter of radium^{226}, and is usually intermixed with thoron^{220} (half-life = 54.5 seconds) and actinon^{219} (half-life = 3.92 seconds). Thoron and actinon are daughter products of the thorium and actinium series respectively. The radon/thoron ratio in nature is 1.5 atoms/sec (Rosen, 1957). This value is in complete disagreement with the figure of 10,000 atoms/sec given by Norinder et al, (1952).

According to Bender (1954); Macek et al. (1935); Cowan (1950); and Healy, (1952) in Gregory (1958), thoron relative to radon is a minor constituent. This implies agreement with the figure of Norinder et al. (1952). However, from the ratio given by Rosen it would appear that the thoron is more than a minor constituent, a feature also apparent from the thorium/uranium ratio of soils (1:1, Marsden et al, 1944). Furthermore Delwiche, (1958) has observed that Pb^{214} (from radon) content of soil air is 50 to 100 times greater than the Pb^{212} (from thoron). Healy, (1952) gives a radon content of air 83 to 8,000 times greater than the thoron content. From this it appears that the soils in different areas may have a different radon/thoron ratio.

There are seventeen known isotopes of radon (Bagnall, 1957). Since $radon^{222}$ is the longest lived isotope it will be considered in the following paragraphs.

Radon, thoron and actinon are sometimes referred to as emanations, and are measured in curie units. The amount of radon in equilibrium with one gram of radium is called the curie. The curie is also defined as the quantity of any material giving 3.70×10^{10} disintegrations per second. Since the curie is a very large unit, millicurie (3.70×10^{7} disintegrations/sec) or microcurie (3.70×10^{4} disintegrations/sec) is commonly used (Glasstone, 1950). The Mache unit (3.60×10^{-10} curies/liter), and the Eman unit (1×10^{-10} curies/liter) have also been used by some authors.

TABLE VIII: Radon content of Various Geologic Materials[a]

Petroleum	.003 to .4	Micro-micro curies/ ton (b)
Oil field water	.000 to 1.4	" " " "
Mineral springs	Up to .1	" " " "
Mid air	1000,000	" " " / cu m
Overland Free air	7 to 1560	" " " / ton
Near the surface	Average 150	" " " "
Mid-oceanic air	Average 1.2	" " " "

(a) Cook; 1952; (b) micro-micro curie = 3.7×10^{-2} disintegrations/ sec.

Radon once released may remain entrapped in the impermeable solids. Under natural conditions very little radon is lost from minerals like zircon (Faul, 1954). The released gas may migrate in aqueous solutions, or in petroleum, or diffuse through the rock media.

Radon is soluble in liquids (Table IX) and is absorbed on coal and potash (Jennings et al, 1948), and silica gel (Bagnall, 1957). The solubility of radon in water decreases with increasing temperature. Rogers (1954) studied the "distribution ratio" ("solubility coefficient" or "partition ratio") of radon in various substances. His results (Figure 3) are in good agreement with those of Boyle (1911), Kofler (1913), and Hevesy et al (1926). The solubility of radon decreases in saline solutions.

A 98% equilibrium between radon and radium is achieved in 30 days (Rosen, 1957). The diffusion coefficients of radon are given in Table X. Radon in soils and rocks diffuses readily into the atmosphere. Radon diffuses slowly through the rocks in comparison with the other gases occurring in the earth. The diffusion of radon is slower at a greater depth than near the surface of the earth, but increasing temperature increases the diffusion (Hatuda, 1954).

The exhalation rate of radon in soils and the atmosphere depends upon the atmospheric conditions - barometric pressure, temperature, moisture content, and the mineral constituent of soils. Table XI gives the exhalation rate of radon in several parts of the world.

TABLE X: Diffusion Coefficient of Radon

Temperature	Diffusion Water	Diffusion Air	Diffusion Toluene	
Ambient	0.066cm^2/ day	-	0.168cm^2/ day	Wallstable (1903) (d)
14°C	0.820(a)	-	-	E. Ramstedt (1919) (e)
14°C	0.853(b)	-	-	"
16°C	0.199	-	-	Jahn (d)
16°C	0.401	-	-	"
18°C	0.918	-	-	E. Ramstedt (e)
18°C	0.99			E. Rona (e)
	0.10^{-5}cm^{2}sec^{-1}	.01cm^2 sec^{-1}		Budde, 1958
	0.07cm^2 sec^{-1} (c)			Hevesy et al, 1938 (e)

a = 10% gelatine in water
b = 2½% gelatine in water
c = at room temperature and 76 cm pressure
d = Bagnall, 1957
e = Hatuda, 1954

TABLE XI: Experimental Values of Exhalation Rate of Radon

Author	Locality	Year	AVERAGE Exhalation rate Curies cm^{-2} sec^{-1}	No. of Measurements
Joly and Smyth (a)	Dublin	1911	23 x 10^{-18}	10
Joly and Smyth (a)	Dublin	1911	113 x 10^{-18}	12
Smyth (a)	Dublin	1912	74 x 10^{-18}	98
Wright and Smith (a)	Manila	1915	30 x 10^{-18}	4
Kosmath (a)	Graz, Austria	1933-34	39 x 10^{-18}	382
Zupancic (a)	Innsbruck, Austria	1932-38	23 x 10^{-18}	66
Zellinger (a)	Hotting, Austria	1933-34	50 x 10^{-18}	150
Cullen (a)	New York	1944-45	9 x 10^{-18}	
Kovach*	New York	1944	87.52 x 10^{-14}	5
Rosen (a)	Kelburn, New Zealand	1957	0.5 x 10^{-18} (maximum) 0.06 x 10^{-18} (minimum)	

* Frozen ground (Kovach, 1944)
(a) Rosen, (1957)

The exhalation rate of radon from soils decreases with increasing barometric pressure (Preisbach et al, 1937; Kovach, 1945; Faul, 1954; Kulhanke et al, 1956; Rosen, 1957). Diurnal and annual variations have

TABLE IX: Coefficient of Solubility of Radon in Various Liquids at Atmospheric Pressure*

Liquid	Temperature °C	Coefficient of solubility
Water	0	0.507
	10	0.340
	20	0.250
	30	0.195 closely
	37 (blood temp.)	0.167 following
	50	0.138 Henry's
	75	0.114 law
	100	0.106

	Coefficient at 18°C	Coefficient at 0°C
Glycerine	0.21	-
Aniline	3.80	4.45
Absolute alcohol	6.17	8.28
Acetone	6.30	7.99
Ethyl acetate	7.35	9.41
Petroleum (liquid paraffin)	9.2	12.6
Xylene	12.75	-
Benzene	12.85	-
Toluene	13.24	18.4
Chloroform	15.08	20.5
Ether	15.08	20.9
Hexane	16.56	23.4
Carbon bisulphide	23.14	33.4
Olive oil	29	-

* Jennings and Russ, 1948.

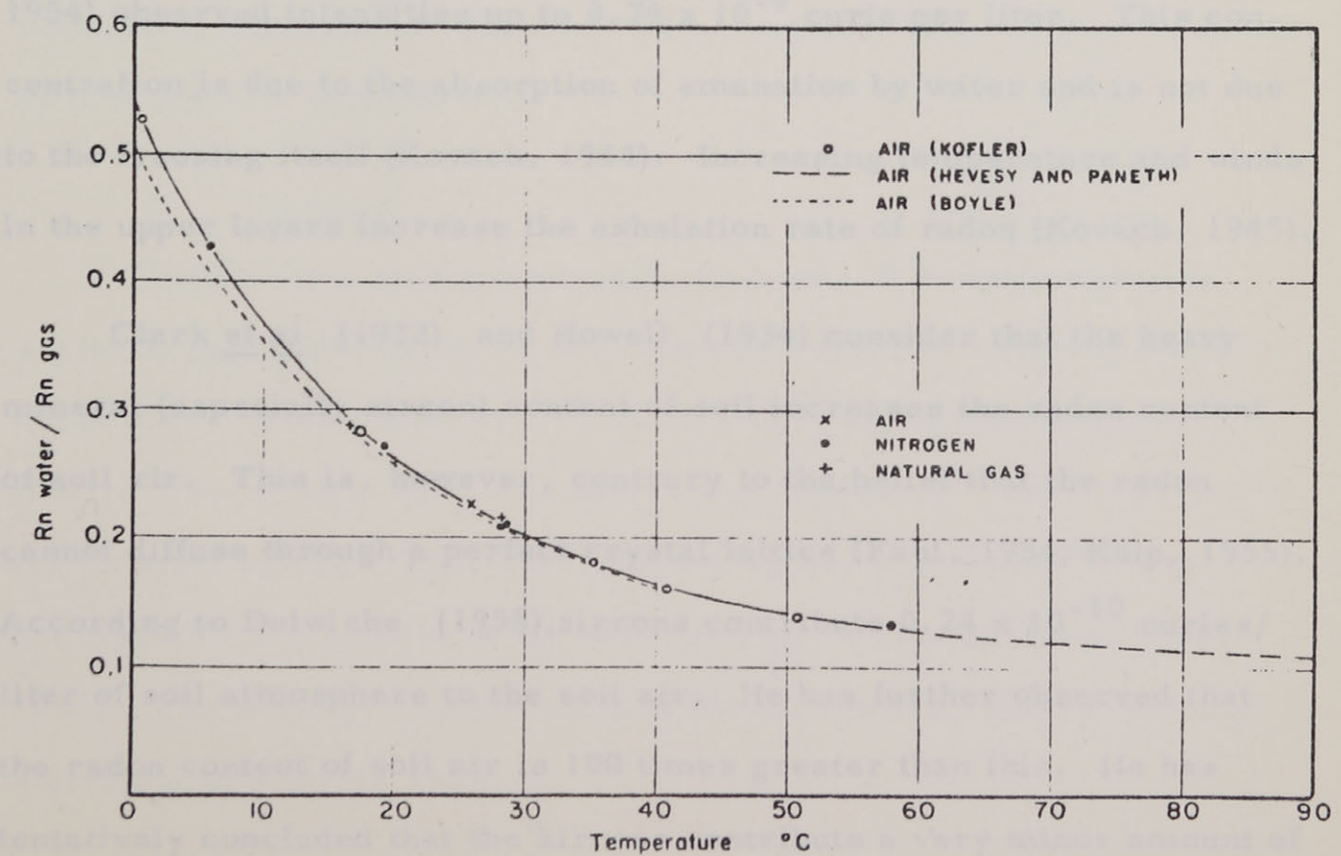


Figure 5 – Radon distribution ratios in an air-water system. (from Rogers, 1954)

been observed by several researchers (Zupancic, 1934; Kosmath, 1935; Zellinger, 1935; Preisbach et al, 1937; Kikawa, 1954; Kulhanke et al, 1956; Lucas et al, 1956; Okabe, 1956; Moses et al, 1957). The maximum in the diurnal variations occurs early in the morning, and the minimum in the afternoon. According to Okabe (1956), the high radon content of soil air in the early morning is due to the release of radon absorbed by dew at night. Lucas et al, (1957) have observed a maximum of radon concentration in December.

The exhalation rate of radon is decreased by rainfall (Kovach, 1944; Kikawa, 1954; Okabe, 1956; Kulhanke et al, 1956; Moses et al, 1957). This is probably due to the absorption of radon by water, and blocking of the pores (Okabe, 1956; Sikka, 1957b).

Snow covered and frozen ground increases the radon content of soil air (Kovach, 1944, 1945; Norinder et al, 1952). Garrigue (Faul, 1954) observed intensities up to 0.74×10^{-9} curie per liter. This concentration is due to the absorption of emanation by water and is not due to the freezing itself (Kovach, 1944). Increasing temperature and winds in the upper layers increase the exhalation rate of radon (Kovach, 1945).

Clark et al (1932) and Howell, (1934) consider that the heavy mineral (especially zircon) content of soil increases the radon content of soil air. This is, however, contrary to the belief that the radon cannot diffuse through a perfect crystal lattice (Faul, 1954; Kulp, 1955). According to Delwiche (1958), zircons contribute 0.24×10^{-10} curies/liter of soil atmosphere to the soil air. He has further observed that the radon content of soil air is 100 times greater than this. He has tentatively concluded that the zircons contribute a very minor amount of

radon to the soil air, and that the greater portion of radon must originate from radium, already released by weathering and adsorbed by the colloidal clays of soil." (page 4).

Murray and Adams (1958) have observed that very little of thorium, uranium, and potassium in common sands is associated with the heavy detrital grains. The Th/U ratio is not affected by the heavy minerals till they occur in large quantities as in placer sands (Murray and Adams, 1958).

From the foregoing discussion the present writer concludes that the heavy minerals contribute an insignificant amount of radon to the soil air.

Thorium Series:

The thorium series (Table II) takes its name from thorium^{222} (atomic number = 90), which is the longest lived (1.39×10^{10} years) element of this series. Because of the long half-life of thorium, it will be discussed in some detail.

Thorium:

Thorium is a strongly oxyphile element. It belongs to the 4n series of naturally occurring radioelements and has thirteen isotopes, (Katz et al, 1957). Thorium^{232} (1.39×10^{10} years) and thorium^{230} (8×10^{4} years) have very long half-lives. Thorium^{232} is the parent of the thorium series. Thorium^{230} is a daughter of uranium^{238}. The average thorium content of the earth's crust is 12 ppm (Goldshmidt, 1954). The average concentration of thorium in the various geologic materials is given in Table V.

Thorium is an essential component of six minerals (Table XII).

TABLE XII: Minerals Containing Thorium as an Essential Constituent[a]

Name	Composition	% Thorium
Cheralite	(Th, Ca, Ce) (PO_4, SiO_4)	30, Variable.
Huttonite	Th (SiO_4)	81.5, usually less.
Pilbarite	ThO_2 UO_3 PbO $2SiO_2$ $2H_2O$	31, Variable.
Thorianite	ThO_2	Series UO_2.
Thorite	Th SiO_4	81.5, Variable.
Thorogummite	Th $SiO_{4\ 1-n}$ $(OH)_{4n}$	24 to 50.

(a) Frondel, 1956, page 569.

Besides these six minerals there are sixty other minerals in which it occurs as a vicarious element. Most thorium occurs in silicates, oxides and the columbates-tantalates. Zircon, xenotime, monazite, and allanite are a few of the minerals in which thorium occurs as a vicarious constituent.

There are two groups of host minerals of thorium (Katz et al, 1957). The first group includes minerals like uraninite, monazite, or zircon in which Th^{+4} ion is accommodated because of the similarity in ionic radius of Th^{+4} with U^{+4}, Ce^{+4}, Zr^{+4}. The second group includes columbates and tantalates which contain diverse, large sized and highly charged cations.

In synthetic mixtures Th^{+4}, U^{+4}, and Ce^{+4} form dioxides which exist in complete solid solutions at high temperatures (Frondel, 1956). In nature there exists a large gap between ThO_2 and UO_2 series. The silicates of uranium, thorium and zirconium form solid solutions in the ternary system U SiO_4 - Th SiO_4 and Zr SiO_4. There is an extensive solubility between U and Th but very limited solubility between Zr and Th silicates.

Thorium occurs in only one valency state, Th^{+4}. Thorium metal is a strong reducing agent.

The geochemistry of thorium is similar to that of uranium, cerium and zirconium in igneous rocks. The large size and high charge limits the entrance of Th into the early formed minerals (orthosilicates containing Mg^{+2} and Fe^{+2}). Like uranium it becomes concentrated in the residual solutions.

Thorium is concentrated in pegmatites and hydrothermal veins. The concentration of Th is greater in alkaline pegmatites as compared to granitic pegmatites. Small amounts of thorium are present in association with columbium in carbonatites (Frondel, 1956).

Larsen et al (1954) consider that at a very late magmatic stage, thorium and uranium part company due to a shift towards more oxidizing conditions.

The weathering of rocks releases thorium minerals like monazite. These minerals are very resistant to weathering and are concentrated in the resistates. Baranov et al (1956) consider that the migration and deposition of thorium takes place through mechanical transfer and gravitational accumulation.

A part of thorium which goes into solution is hydrolyzed, and may be precipitated with manganese, iron, or aluminum. Mathews, (1954) and Goldberg et al (1955) have reported 30 - 40 ppm, and 20 - 30 ppm of thorium respectively in manganese nodules, collected from the ocean bottoms. The pelagic clays from the same area contain 5 ppm thorium.

The clays from the Russian platforms contain 11 ppm thorium (Baranov et al, 1956).

Very little is known about the role of organic matter in precipitating thorium. It is probable that organic matter may also play an important part in the geochemical enrichment of thorium. A co-worker of Szalay (1958) has reported an enrichment factor of 30 for thorium in peats.

Baranov et al (1954) have observed that thorium is assimilated by terrestrial plants and not by plankton.

Potassium:

Potassium is abundantly found in igneous rocks (granites and rhyolites, clays, and shales, but is low or absent in sandstones and limestones. (Table V). Potassium found in nature is made up of three isotopes, (Table XIII).

TABLE XIII: Naturally Occurring Potassium Isotopes

ISOTOPE	ATOMIC ABUNDANCE
K^{39}	93.08 %
K^{40}	0.00119 %
K^{41}	6.91 %

Potassium^{40} is the only radioactive isotope of potassium, and makes up a very small portion of all Potassium, but its mass effect is very great. The gamma energy given off by K^{40} during its decay is 1.45 Mev, and energies below 1.6 Mev are not recorded in airborne gamma ray spectral surveying. The writer has therefore not discussed the geochemistry of potassium. Rankama et al (1950), Goldschmidt (1954), and Gregory (1958) have discussed the geochemistry of potassium in detail.

CHAPTER III

PRINCIPLES OF GAMMA RAY SURVEYING

The elements with atomic weight greater than bismuth$_{83}$ are radioactive. These elements undergo nuclear reactions to form new species by emitting different types of radiations, which are characteristic for each element. Glasstone (1950), Faul, (1954), Friedlander et al (1955), Rankama (1955), and Cork (1957) have discussed their properties in detail. Cook (1952), Peirson et al (1951) and Gregory (1958) have discussed the characteristics of gamma rays in relation to aero-radiometric surveying. Since the purpose of this study is to evaluate the presence of anomalous radioactivity at the surface of the earth around oil pools, the writer will present only the basic properties of gamma rays.

Types of radiations:

There are three types of radiations emanating from naturally occurring radioelements. These are alpha and beta particles, and gamma radiations.

Alpha particles:

Alpha particles are positively charged nuclei of helium atoms, with very weak penetrating power (one inch in air).

Beta particles:

Beta particles are negatively charged electons. The penetrating power of beta particles is approximately 100 times higher than the alpha particle.

Gamma radiations:

Gamma radiations are a form of electromagnetic radiation of ultra short wavelength, travelling at the speed of light (186,000 miles per second). These radiations are products of alpha or beta decay. During alpha or beta decay, a radiogenic product nucleus is formed, which releases its excess energy in approximately 10^{-12} seconds in the form of gamma quanta (photons), in changing to a lower energy state (Figure 6).

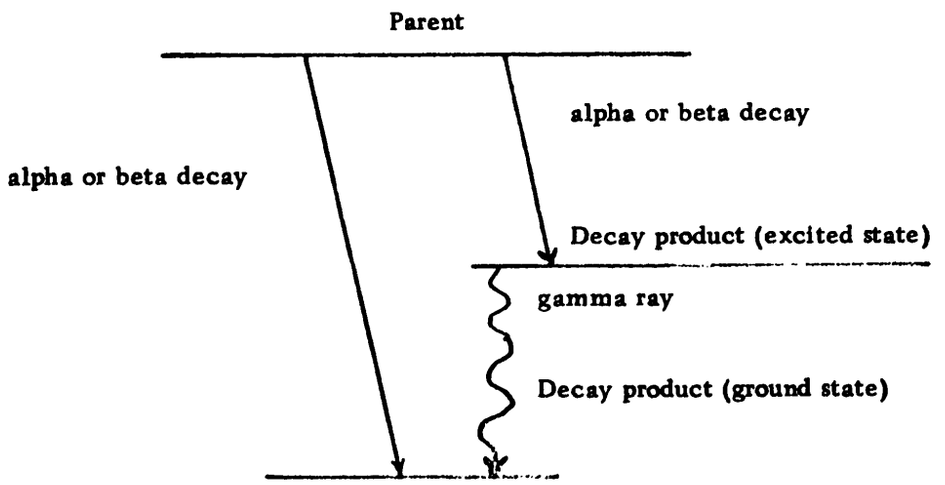


Figure 6. Decay scheme of a nuclide.

Gamma rays are also produced by the deceleration of electrons and beta particles while travelling through matter. This type of production is called Bremsstrahlung (braking radiation). The energy of these radiations varies inversely with the wavelength.

Gamma rays are similar to X-rays and radiowaves. The gamma rays originate in the nucleus whereas the X-rays are formed outside the nucleus. These gamma rays can be broken up into a series of radiations analogous to the spectrum of visible light, and are identified in the form of energies.

Interaction of Gamma Rays with Matter:

Gamma rays interact with matter by several processes, of which the photoelectric effect, Compton effect, pair production, and Rayleigh scattering are most important (Fano, 1953a).

Photoelectric Effect:

The gamma quantum in colliding with an atom knocks out an electron from one of the peripheral shells (Figure 7). Most of the energy of the gamma quantum is transferred to the ejected electron. This effect is predominant in high Z elements and low energy gamma rays (less than 0.500 Mev). The photoelectric effect results in the complete degradation of incident energy.

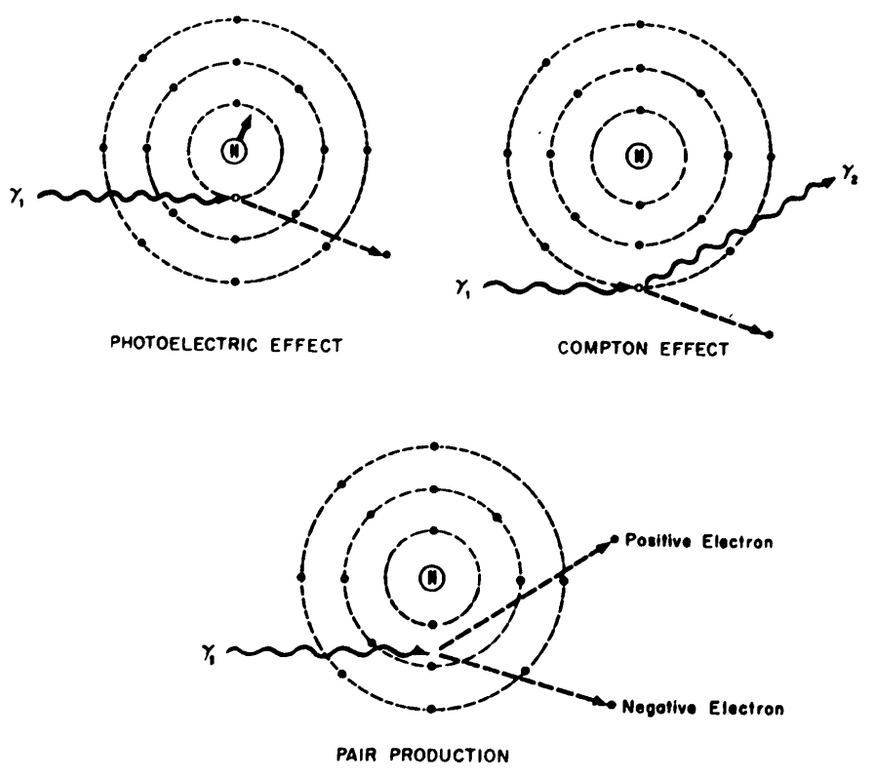


Figure 7: Illustrative examples of the compton, photoelectric and pair production interactions. (From Cook, 1957, p. 248).

Compton Effect:

A gamma quantum (photon) on colliding with a loosely bound or free electron in peripheral shells, loses part of its energy, and is

deflected from its incident path (Figure 7). The relation between the energy loss and the scattering angle is derived from the laws of conservation of momentum and energy. The scattering angle increases with the increasing energy loss. The Compton effect is predominant in intermediate energies. A photon may undergo several Compton processes before final absorption. The energy decreases with each Compton process.

Pair Production:

Pair production is a process by which a photon with an energy greater than 1.02 Mev ($2M_oC^2$) gives rise to a positive electron pair (Figure 7). This process takes place near the nucleus, and in energies greater than 1.02 Mev. The energy of the incident photon is completely lost. The positron interacts with an electron giving rise to two gamma rays, each with an energy $E = M_oC^2 = 0.511$ Mev.

Rayleigh Scattering:

A photon with low energy at small angles imparts only a small recoil. This recoil is imparted to an atom or a molecule, resulting in the degradation of photon energy. This effect is predominant in high atomic weight material and low energies. The contribution due to Rayleigh scattering for energetic gamma rays in lead is about 1% of that due to Compton scattering.

Absorption of Gamma Rays:

The gamma ray intensity decreases with increasing distance from the source. The decrease in the intensity in air obeys the inverse square law for distances less than 75 feet, and the inverse law for distances greater than 75 feet (Gregory, 1958). A body of water five to six feet

deep masks all radiations. Similarly a few feet of clay will also blanket out all the radiations. According to Gregory, (1958), 6 inches of sand, and Wright (in Gregory, 1958) 2.5 feet of sand will reduce the gamma ray intensity of the source to 41.4% and 1% respectively. Increase in the energy of gamma ray quanta decreases the absorption.

Sources of Gamma Radiations:

There are several sources of gamma radiations, as follows:

a) Decay products of naturally occurring radioelements in soil and rocks.

b) Radioactive dust in the atmosphere and on the ground.

c) Cosmic rays.

d) Radioactivity of instruments and equipment.

a) Decay products of naturally occurring radioelements in soil and rocks:

The uranium, thorium and actinium series, and potassium^{40} in soils and rocks are radioactive. The geochemistry and abundance of these elements have been discussed in Chapter II. The important gamma emitters (Sikka, 1957a) are given in Table XIV.

TABLE XIV: Moderate to Hard Naturally Occurring Gamma Emitters

NUCLIDE	ENERGY (Mev)	SERIES
Protactinium ^{234}	0.78, 0.82	Uranium.
Bismuth ^{214}	1.76, 2.19	Uranium.
Polonium ^{210}	0.80	Uranium.
Actinium ^{228}	0.96	Thorium.
Thallium ^{208}	2.62	Thorium.
Thallium ^{207}	0.87	Actinium.
Potassium ^{40}	1.459	Potassium.

The nuclides given in Table I are similar to the ones considered by Gregory, (1958). Protactinium^{234} is a daughter product of uranium, whereas bismuth^{214} and polonium^{210} are daughter products of radon. Bismuth^{214} and thallium^{208} are of great importance in airborne gamma ray spectrometry because of their energies (See Table

Potassium^{40} (K^{40}) decays by K capture and electron emission to argon^{40} and calcium^{40} respectively. See Figure 8 for the decay scheme of K^{40}.

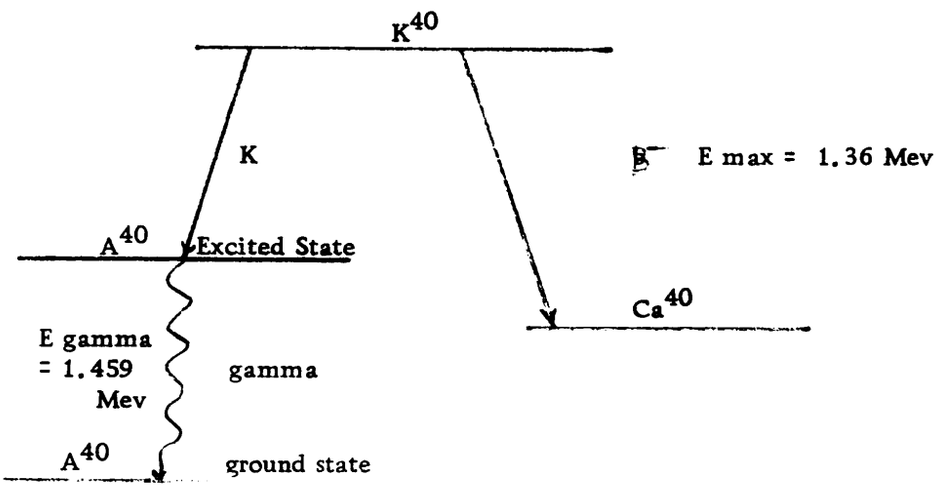


Figure 8: Decay Scheme of Potassium^{40}.

b) Radioactive dust in atmosphere and on the ground:

The radioactive dust in the atmosphere and on the ground is made up of radon and thoron decay products, dust from atomic explosions, and from synthetic radioactivity in the vicinity of manufacturing industries, and air exhaust from oil refineries.

The gamma field due to radon decay products of the air masses near the surface of the ground varies from 4.4 to 42.3%, and 13.76 to 69.5% at altitudes of 450 to 500 feet (Table XVI). This variation depends upon the geologic and topographic terrain the air masses may cross,

refining and manufacturing industries, and the atmospheric conditions in an area. The increased air turbulence decreases the radon content due to thorough mixing.

The gamma field due to thoron decay products depends on the same factors as does that for radon.

The dust from atomic explosions causes a significant increase in the gamma field, but is of very short duration.

c) Cosmic rays:

The earth is constantly bombarded by extraordinary penetrating radiations from beyond its atmosphere. In 1925 these penetrating radiations were called cosmic rays by Milliken. The primary cosmic rays are mostly made up of high energy protons (Cork, 1957). These rays are deflected by the earth's magnetic field according to their energy and direction. Only rays with several Bev energy reach the equator.

Near the earth's surface cosmic rays are made up of soft and hard components. The two components are distinguished arbitrarily by their absorption through 10 cm of lead.

The soft component for all practical purposes is made up of positrons, electrons, and photons with a very small amount of slow mesons, and slow protons. The soft component is formed by the interaction of primary cosmic rays with the matter at the top of and within the atmosphere.

The hard component is mostly made up of mesons, with a small number of fast protons and electrons, and a few energetic electrons and

photons. A meson is a singly charged particle of intermediate mass and short life. It is because of mesons that the hard component possesses strong penetrating power.

The cosmic ray intensity due to the soft component at sea level and geomagnetic latitude 50^{o} is about 20% of the total component (Glasstone, 1950). The proportion of soft component increases rapidly with the increasing altitude, and is about 75% of all the rays at an altitude of 10,000 feet (Friedlander and Kennedy, 1955).

The cosmic ray intensity, after correcting for the atmospheric effect at the geomagnetic equator, is about 7.2% less than that at 40^{o} latitude, it increases slightly between latitude 40^{o} to 45^{o}, and is constant at latitudes greater than 45^{o}. The intensity at a given geomagnetic latitude increases rapidly with the increasing altitude, and starts to drop rapidly at altitudes higher than 50,000 feet.

The atmospheric effect is defined as the variation in intensity due to air temperature, season to season, and place to place.

The cosmic ray intensity increases with the decreasing barometric pressure. This variation is 3.4% per centimeter drop in the pressure (Eliot, 1952).

The cosmic ray intensity shows small variations with time (Table XV). The intensity of cosmic rays decreases from 8 to 10% during intense magnetic storms (Dorman, 1957), and increases at the time of increased solar activity (solar flares).

One can see from the foregoing discussion that the cosmic ray

TABLE XV: **Time Variations of Cosmic-Ray Intensity (Amplitude in %)** •

a)	b)	c)		d)		e)	f)
		$\lambda=50°$	$\lambda=0°$	$\lambda=50°$	$\lambda=0°$		
Seasonal	—*)	2—4	$\leqslant$0,5	—	—	—	Variation of absorption and decay of mesons in the atmosphere with variation of meteorological factors
Diurnal (masking the effect of extraterrestrial origin)	—	$\approx$0,15	$\approx$0,15	—	—	—	
11-year	—	$\approx$2	$\approx$2	—	—	—	Influence of corpuscular streams emitted by the sun, on the cosmic rays (acceleration, retardation and scattering of cosmic rays by the magnetic fields "frozen" in the streams
Annual	—	0,5—1	0,5—1	—	—	—	
27-day	—	$\approx$0,3	0,35	1	—	—	
Diurnal	0,05	$\approx$0,3	0,35	0,6	0,43	1—2	
Semidiurnal	0,02	$\approx$0,03	0,03	—	—	—	
Reduced during time of magnetic storms	$\leqslant$0,5	$\leqslant$10	$\leqslant$10	—	—	20	
Increase during the time of great solar flares	$\leqslant$0,5	~400	$\approx$20	5500	$\approx$50	—	Low-energy cosmic rays arriving from the sun. The mechanism of their generation on the sun may be a statistical mechanism of acceleration
Increase during the time of small solar flares	—	$\approx$0,3**)	—	$\approx$0,6	—	$\leqslant$10	
Stellar-diurnal	$\leqslant$0,02	$\leqslant$0,02	$\leqslant$0,02	—	—	—	Irregular distribution of sources of cosmic rays, diffusion of cosmic rays from the Galaxy ***

* The hyphen denotes the absence of experimental data.

** The increase in the intensity of the hard component of cosmic rays during the time of small solar flares is apparently due, in contrast to the other components, to a variation in the temperature in the upper layers of the atmosphere owing to a variation, accompanying the flare, in the flux of ultraviolet radiation.

*** If it can be shown in the future that these variations actually do exist.

a) Type of variation; b) Hard component underground at a depth of 60 m water equivalent; c) Hard component at sea level; d) Neutrons at sea level or at level of mountains; e) Ionizing component at great heights; f) Nature of variations.

• Dorman, 1957.

intensity varies with the geomagnetic latitude, altitude, time, temperature and barometric pressure. The barometric pressure is the most important factor.

The writer therefore concludes that except for the sudden changes in barometric pressure, sudden magnetic storms and increased solar activity, the variation in cosmic ray intensity at a particular place would be very small. Tiratsoo (1948) has also drawn the same conclusion.

The cosmic ray component of the total radiation recorded by a scintillation counter varies from place to place and with altitude (Table XVI). It is therefore necessary to measure the cosmic ray component to obtain the true gamma ray field from the soils and rocks.

TABLE XVI: Various Components of Radiations (in percent)

	Cosmic Ray	Terrestial Radioactivity	Atmospheric Radon	Instrumental	Thoron & Others	Mesons & Hard Electrons
GROUND						
Oak Ridge, Tennessee, U.S.A.(a)	17.4	78.2	4.4	-	-	-
U.S.S.R. (b)	3.9	30.08	42.3	-	23.0	-
New Zealand (c)	19.07	-	-	4.37	-	76.3
AIR ( )						
Oak Ridge (a)(c)	34.5	51.6	13.76	-	-	-
U.S.S.R.(e)	6.5	24.0	69.5	-	-	-
New Zealand	19.07	-	-	-	-	-
U.S.A.(d)(e)	35	50	15	-	-	-

Instruments used: U.S.A. Scintillation counter; U.S.S.R.; New Zealand, Geiger counter.

a. Davis et al, 1957
b. Baranov, 1956
c. McAllum, 1955
d. Moxham, 1958
e. Measurements made at 450 feet and 500 feet respectively in U.S.S.R. and U.S.A.

This is done by making measurements with a scintillation counter, either in an aircraft or in a canoe over a body of open water six to eight feet deep. The cosmic ray intensity can be minimized by using cancellation circuits (Cowper, 1954).

In addition to cosmic rays other penetrating radiations have been observed with thunderstorms. The effect of these radiations on the total gamma ray field is very small (Gregory, 1958).

d) Radioactivity of the Equipment:

The radioactivity of the material in a detector, luminous panels and dials, and fabric of the aircraft contributes a small amount of background radiation.

Besides the above mentioned sources, tube noises will also add a very small amount to the total background radiation.

Instruments:

There are four types of instruments commonly used in radiometric surveying. These are ionization chambers, geiger counters, scintillation counters, and scintillation spectrometers. The ionization chambers are not commonly used in the field. The ordinary geiger counter is very sensitive to cosmic rays, and very little to gamma rays. This makes the geiger counter less efficient.

The scintillation counter makes use of the same principle as that of fluorescent light. It consists of a photomultiplier tube and a phosphor. The phosphor absorbs gamma rays, and on absorbing a gamma ray produces a light flash, which is converted into pulses of electric current

and is measured. The phosphors are made up of thallium activated sodium iodide, or plastic. Thallium activated sodium iodide crystals have a high density and are preferred.

The scintillation counter has the following advantages:-

a) A very high efficiency for the gamma rays. The efficiency can be increased to 100% by using larger phosphors.

b) the energy of the ionizing particles is roughly proportional to the pulse height.

c) the cosmic ray background is low.

Scintillation Spectrometer:

Lundberg and Roulston et al (1952), Brownell (1953), and Pringle et al (1953), studied the presence of radium and potassium, with a scintillation spectrometer, in soils from Redwater Oilfield, Alberta. These authors have suggested and pioneered the use of the scintillation spectrometer in geological exploration.

Alexeyev et al (1955) have suggested the development of instruments to study gamma ray spectra in the field. The gamma ray spectrometer has been developed to determine the uranium, thorium and potassium content of rocks (Hurley, 1956, a,b; Adams and Richardson et al, 1958; Murray and Adams, 1958). Demille (1958) has built a scintillation spectrometer for the analysis of radioactive ores. Gustafson et al (1957) have studied fission products in soils with a gamma ray spectrometer.

Airborne scintillation spectral data have been utilized in delineating faults and outlining oil and gas deposits (Sikka, 1957a, and present paper).

Several research organizations and commercial companies are in the process of developing gamma ray spectral bore hole logging. The Kennedy Oil Company of Tulsa, Oklahoma is using a car-borne gamma ray spectrometer for oil exploration.

The basic principle of the scintillation spectrometer is the same as that discussed above under scintillation counters.

A scintillation spectrometer consists of scintillator photomultiplier system, linear amplifier, discriminator, high voltage supply unit, and a scaler or a recorder.

The scintillation photomultiplier system consists of a sodium iodide crystal (scintillator) and a photomultiplier tube. The crystal converts the radiation energy into photons of visible light by three main processes, viz, photoelectric, Compton, and pair production. These processes have been discussed in the preceding pages. The effect of Compton and pair production can be minimized by using larger crystals.

The photomultiplier tube converts the light pulses into current pulses and amplifies them. The end result is a voltage pulse appearing across a high resistance which is proportional in size to the radiant energy spent in the crystal.

The pulses coming out of the photomultiplier tube are of very small amplitude (a few tenths of a volt). In order to be analyzed by a discriminator these are amplified in the range of 1-100 volts. Linear amplifiers are used for increasing the amplitude. The pulses out of the amplifier are fed into a discriminator which provides the pulse height analysis by sorting out the unnecessary pulses. There are two main

types of discriminator in common use, viz. integral and differential. The integral type is most commonly used. It consists of a threshhold device, which accepts all pulses exceeding a chosen pulse height level and rejects those which are smaller in amplitude.

In airborne spectrometry all the pulses below 1.60 Mev are rejected, i.e. only pulses from Bi^{214} and Tl^{208} are measured. This allows the sorting out of mass effects due to K^{40} and also the effects of Compton and pair production peaks.

Russel (1955), Stead (1955), Herzog (1956), Davis et al (1957), Bowie et al (1958), and Gregory (1958), have discussed the instrumentation and techniques in great detail. There are many articles in the literature describing the instruments and techniques. Since the progress in radiometric instrumentation and technique is very rapid, the writer has mentioned only the most recent publications.

CHAPTER IV

FIELD AND LABORATORY TECHNIQUES

Sampling Techniques:

The sampling stations of the present study were spaced by the author at a distance of 650 to 900 feet apart along two east-west profiles (Figure 3). The distances were measured with the aid of an odometer, and later were surveyed. The roadways and road allowances were used in determining the direction of traverses. The stations were located 40 to 100 feet from the roadways and road allowances to prevent contamination from the drift (wind blown material), and the effect of transported material used in the construction of roads. In selecting the sampling stations, consideration was given to the topography and soil types. There were two types of stations, i.e. surface stations and drilling stations.

The surface stations were those stations where measurements were made at and above the surface of the ground.

The drilling stations were those stations where three holes A, B and C five feet deep were drilled in an equilateral triangle with sides 10 feet long. The distances were measured with tape.

The holes were drilled with hand and power augers. After taking all the measurements, the holes were plugged with wooden corks. The wooden corks were painted with waterproof cement, a hole drilled in the center, and sealed with masking tape.

The material drilled out was laid on plastic sheets and split into various soil horizons i.e. A, B, C and D. The soil horizons are described below.

Each soil sample was mixed, split, weighed by a spring balance, and stored in a polyethylene bag. The bags in turn were stored in ice cream containers or in cloth bags depending on the quantity of sample taken.

Soil Mapping:

The soils were mapped according to the procedures used by the Dominion Soil Survey of Canada, and the United States' Department of Agriculture, viz., sands, silts and loams. Figure 9 gives a detailed grouping of soils. The size limits of various soil separates in use by the United States' Department of Agriculture are given in Table XVII.

TABLE XVII: Size limits of Soil Separates[a]

SEPARATE	DIAMETER RANGE (mm)
Very coarse sand	2.0 -1.0
Coarse sand	1.0 -0.5
Medium sand	0.5 -0.25
Fine sand	0.25-0.10
Very fine sand	0.10- .05
Silt	.05- .002
Clay	less than .002

(a) United States Dept. of Agriculture Handbook No. 18, 1951, page 207.

These size limits are different from the ones used by geologists.

Sands:

All soils in which the sand fraction is more than 70% of the material by weight constitute a sand group. The sand group is divided into sand and loamy sand.

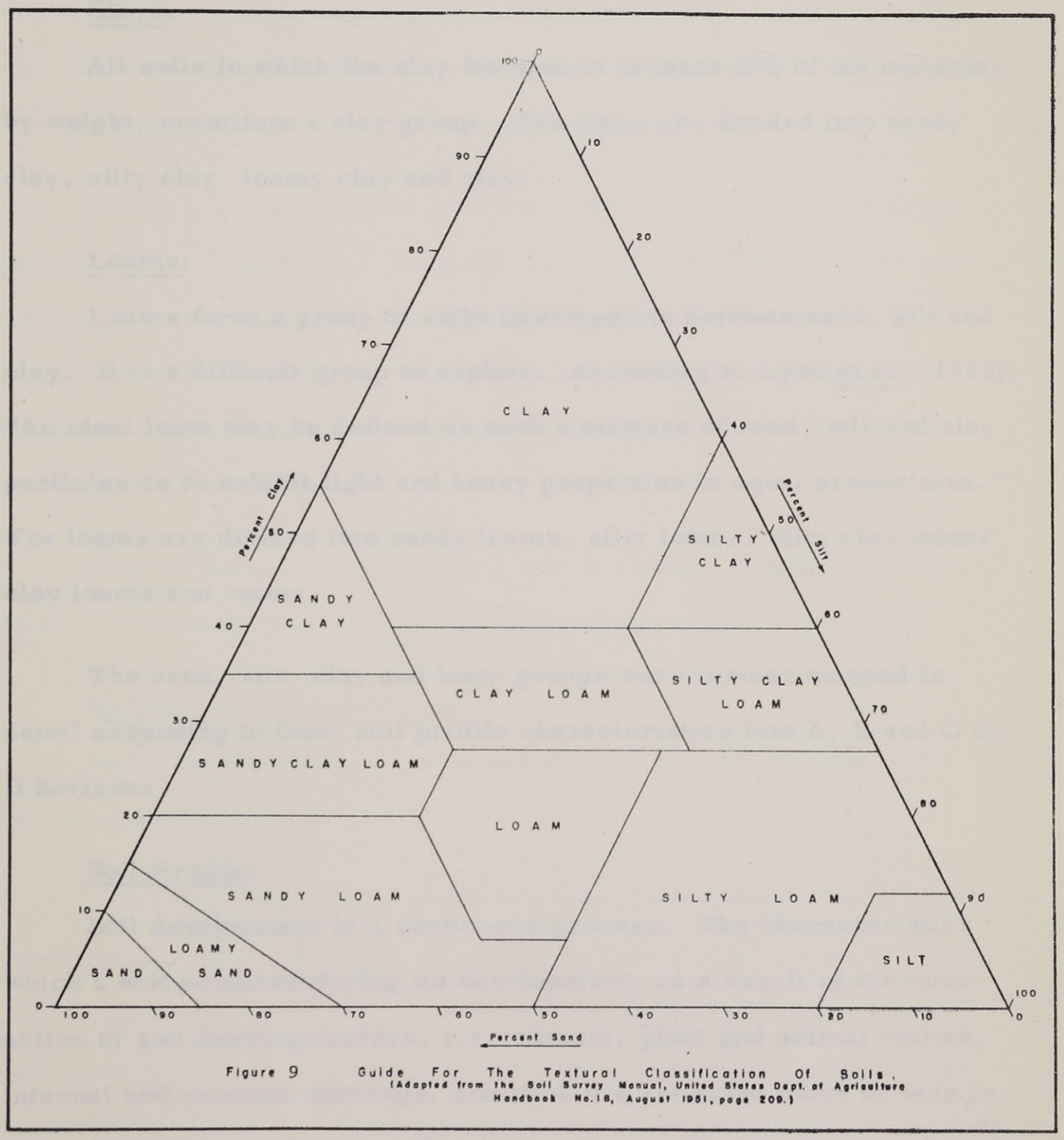


Figure 9 Guide For The Textural Classification Of Soils.
(Adapted from the Soil Survey Manual, United States Dept. of Agriculture Handbook No. 18, August 1951, page 209.)

Silts:

All soils in which the silt fraction is more than 80% of the material by weight constitute a silt group.

Clays:

All soils in which the clay fraction is at least 35% of the material by weight, constitute a clay group. The clays are divided into sandy clay, silty clay, loamy clay and clay. .

Loams:

Loams form a group of soils intermediate between sand, silt and clay. It is a difficult group to explain. According to Lyon et al, (1952), "An ideal loam may be defined as such a mixture of sand, silt and clay particles as to exhibit light and heavy properties in equal proportions." The loams are divided into sandy loams, silty loams, silty clay loams, clay loams and loams.

The sand, silt, clay and loam groups were further mapped in detail according to their soil profile characteristics into A, B and C or D horizons.

Soil Profile:

Soil development is a continuous process. The characteristics which a soil acquires during its development, as a result of the interaction of soil forming factors, i.e. climate, plant and animal matter, internal and external drainage, and time are reflected more or less in the form of distinct layers. These layers are called horizons and designated A, B and C or D. The horizons A, B and C or D have characteristic properties, which help in differentiating various soil types.

A vertical section through these horizons down to the unweathered parent material is called a soil profile (Figure 10).

The horizon "A" lies at the surface, and shows maximum leaching due to the percolating rain waters. All the material dissolved from the "A" zone is deposited in horizon "B", which is a zone of accumulation. The horizons "A" and "B" together are called solum.

The unweathered parent material underlying the A and B horizons is called the "C" horizon. When the material underlying the "A" and "B" horizons is different from the materials in these horizons, the lower horizon is called the "D" horizon. A soil profile developed under excess moisture conditions shows a more or less sticky "G" horizon in the lower part of the solum.

The horizons A, B and C or D can be further subdivided. Lyons et al, (1952) have described these subgroups in detail.

Radioactivity Measurements:

The radiometric work consisted of total gamma ray and radon (alpha) measurements.

It has been observed that the weather plays an important part in ground and aero-radiometric surveys (Figure 11; MacFadyen and Guedes, 1956). It is seen from Figure 11 that there is a drastic drop in the radiation intensity immediately after rain, followed by a gradual rise towards the normal. This is probably due to the absorption of radiations by excess moisture and carrying away of radon in solution. With these considerations in mind, no work was done for 3 days after every rainfall.

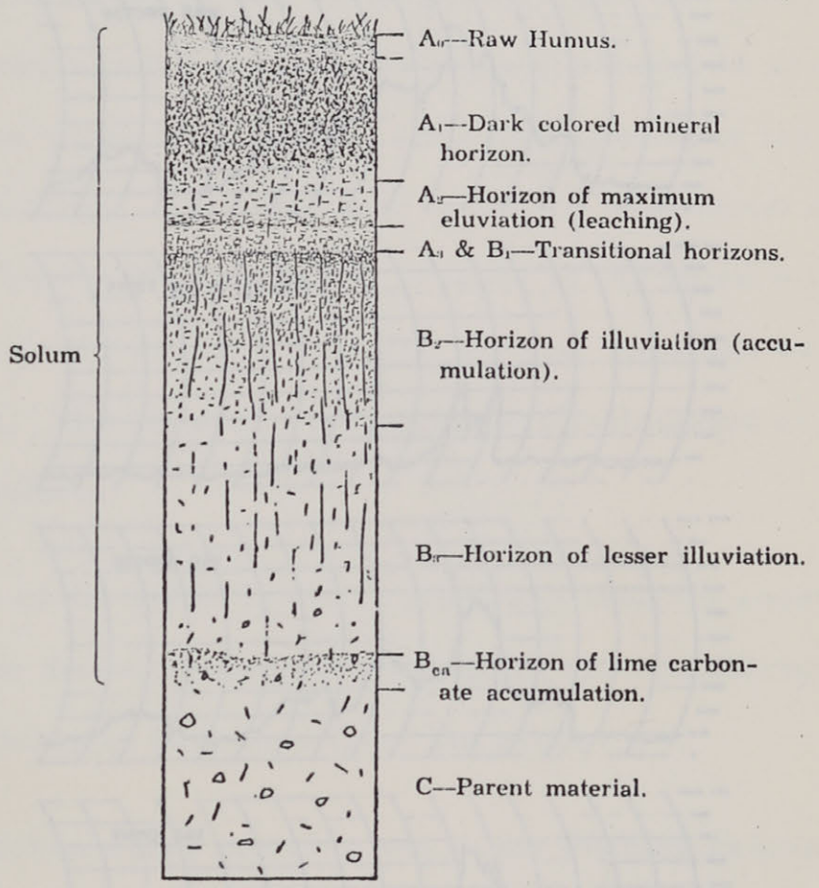
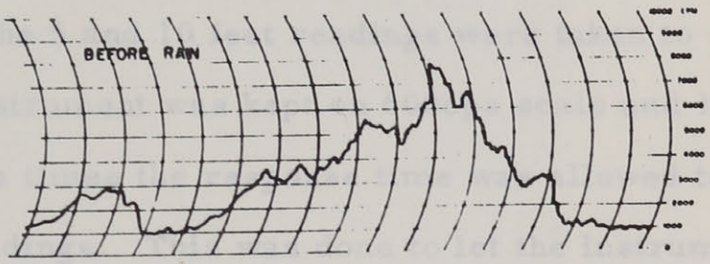
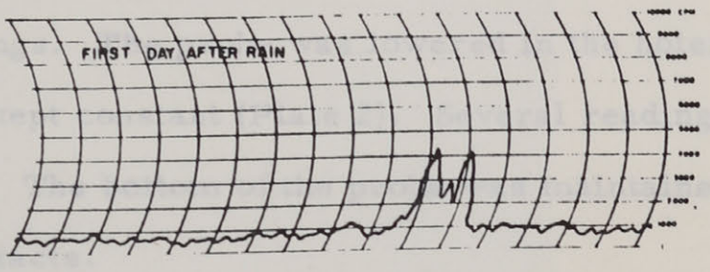


Figure 10. Schematic diagram of a soil profile. (from Odynsky et al, 1952).

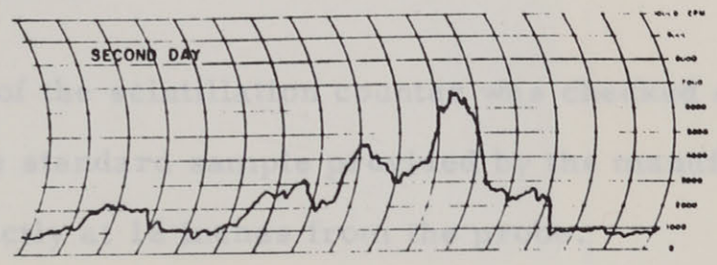
Radiometric profile of a specific track after a prolonged dry period showing maximum detectability



Profile of the same track flown one day after moderate rainfall gives poor registration even in the strongest radiation zone and fails to register peripheral areas



Reflight two days after rainfall, showing improved resolution but relatively low intensity



Reflight three days after rainfall, shows good repetition of original conditions, but still reflects masking in areas of low intensity

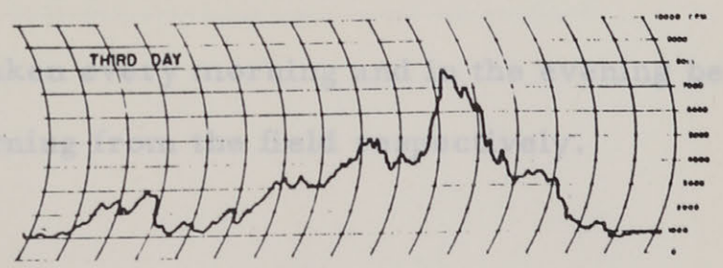


Figure 11. Effect of humidity in airborne radiometry. (Adapted from MacFadyen and Guedes, 1956.)

Total Counts:

The total counts were taken in the holes, at the surface, and 5 and 10 feet above the surface of the ground, with a 1009 Airscint CAE (Canadian Aviation Electronics) scintillation counter. The bottom of the probe was kept exactly at 5 and 10 feet above the surface of the ground by using a steel rod (Plate I). The 5 and 10 feet readings were taken to study the mass effects. The instrument was kept on 600cps scale and 16 seconds response time. Three times the response time was allowed to lapse before making any readings. This was done to let the instrument adjust itself to the surroundings. The probe was lowered in the holes with a cord and the distance kept constant (Plate 2). Several readings were taken in each horizon. The bottom of the probe was maintained at 2 to 3 inches below the contacts.

The calibration of the scintillation counter was checked every morning by placing the standard sample provided by the manufacturers of the instrument, exactly at 12 inches from the probe.

A reading was taken every morning and in the evening before leaving and after returning from the field respectively.

Radon Counts:

Potassium^{40} does not emit a radioactive gas. Bismuth^{214} and Polonium^{210}, daughter products of radon, are two major gamma emitters. These two elements are shortlived solids, and cannot be measured easily. It was therefore considered convenient to measure radon. The radon measuring equipment consisted of radon flasks, a photomultiplier tube and a Tracerlab SC18A scaler unit.

Plate 1. Scintillometer probe 10 feet above the surface.

The radon sample flasks were made as follows: Erlenmeyer flasks (125ml capacity) were coated from inside with a thin layer of silicone grease. The excess grease was wiped off and a liberal amount of silver activated zinc sulphide was sprinkled on. The flasks were then rotated to get a uniform coat. The excess of zinc sulphide was tapped off. The flasks were sealed by cementing brass discs ($1\frac{1}{2}$" x 1/10") with Armstrong's A.I. cement. The brass discs were fitted with two 1/4" d 4.4 and 1.5 inches long copper tubes (Figure 12).

The sample flasks were evacuated, filled with radon from the radon generator (Figure 12) and sealed. The sealed flasks were allowed to stand for three hours to obtain equilibrium of radon with radon daughters. The sample flasks were placed on top of a photomultiplier tube connected to a Tracerlab Superscaler SC18A, and counted several times for one minute count each. See Plate 3 for the radon counting equipment. Figure 13 shows the electronics of photomultiplier system.

The radon generator was made up of a 1 cubic foot plywood box containing 2 lbs. of 2 to 3% U_3O_8. The box had been standing for more than a month.

The radon gas was collected from the holes which had been plugged for two weeks. A six foot long 1/4" copper tube was inserted to the bottom of the hole through a bore in the wooden plug. The copper tube was fitted with a glass filter at the top, and connected to sample flasks, which in turn were connected to a bicycle pump. The valve in the bicycle pump was reversed to create a vacuum, when the piston was pulled up. The pump worked in one direction only. One gentle stroke

Plate 2. Logging of holes

Plate 3. Radon Counting equipment

SCHEMATIC DRAWING FOR THE CALIBRATION OF RADON FLASKS

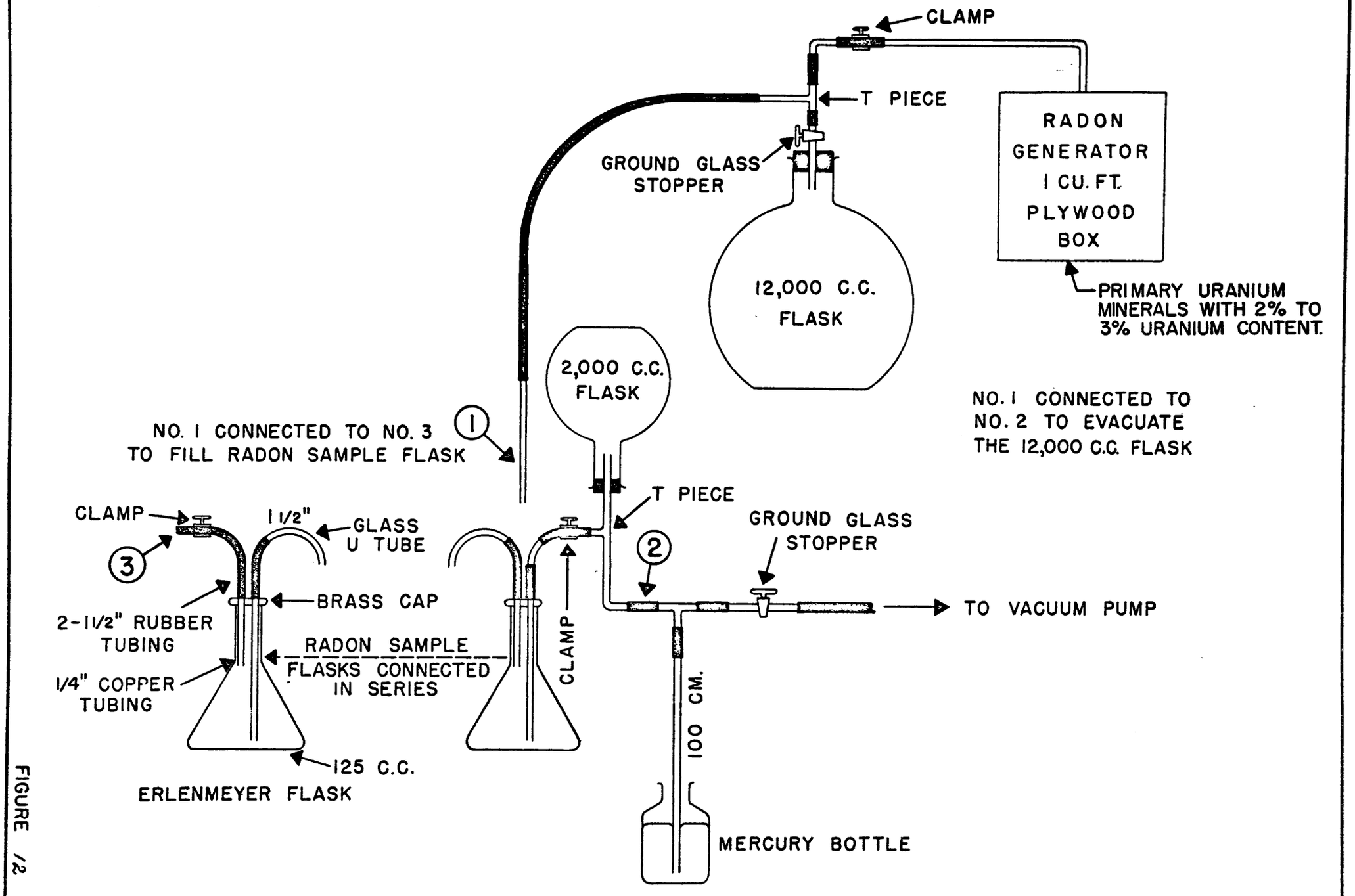


FIGURE 12

was given to evacuate the sample flasks and to collect the gas from the holes. The flask was sealed with Hoffman screws.

From a set of three holes two consecutive samples were taken from one hole and one each from the other two holes. The sample flasks were left for three hours before counting. The flasks were counted for 3 to 30 minutes depending upon the level of concentration. Some of the flasks were recounted several times to study the statistical variations. A sample flask filled with air was always counted to study the background counts due to the flasks. The results are given in Chapter V.

Geochemical Techniques:

The pH and heavy metal content of the soil samples collected were measured in the field.

pH Measurement:

The pH was measured by pouring a few drops of pH indicator over 0.5 grams of soil placed on a piece of wax paper. The indicator was allowed to flow back and forth, till steady color was obtained. The obtained color was compared with a color chart. When the color was obscured by the soil color, a few specks of barium sulphate were used to bring out the color.

The pH indicator was provided by the Dominion Soil Survey of Canada, Alberta Branch.

Total Heavy Metal Content:

A field method described in detail by Bloom (1955) was used in determining the heavy metal content.

0.1 gram of soil was placed in 25 ml graduate cylinder, with a plastic scoop. A 5 ml portion of buffer solution was added and shaken vigorously with a 0.5 ml portion of dithizone solution for 30 seconds. It was allowed to stand and a 0.5 ml portion of dithizone added and shaken. This process repeated till a blue purple color was obtained.

Heavy Mineral Content:

Sand samples No. 140-ABC, ,129, and 58AB were examined for zircon, monazite, and allanite content (radioactive minerals). The following procedure was adopted:

Five grams of the 100-150 mesh sample, previously soaked overnight in water was digested for 10 minutes with 3N HCl. The digested mixture was suspended in 1000cc of water in 1000 ml capacity glass beaker, allowed to stand for one minute, and decanted. The suspension and decantation process was repeated until the water was clear. This process of repeated suspension and decantation removes clay and silt less than 0.01 mm fraction. The washed material was dried and weighed.

The dried material was slowly introduced into the Davis tube (filled with water) of a Dings Magnetic separator (Laboratory model). The tube was allowed to move gently in a forward and backward motion. This helped to separate the material into individual grains. The tube was surrounded by a strong electromagnet, which attracted the magnetite grains to the walls. The material was refed several times to ensure the complete removal of magnetite. The magnetite fraction was washed, dried and weighed.

The dried residue minus magnetite was introduced in a separatory

funnel containing methylene iodide, thoroughly shaken and allowed to stand. The two fractions (heavy and light) obtained were washed with carbon-tetrachloride and dried. The heavy fractions were further separated into various fractions ranging from 0.1 amperes to 1.0 amperes with a Frantz isodynamic separator. Each fraction was examined under immersion oil (1.696) with a petrographic microscope. The results are given in Chapter V.

CHAPTER V

RESULTS - REDWATER OILFIELD, ALBERTA

Geology:

The production in the Redwater oilfield is from the coralline and algal bioherm of Upper Devonian age. The plan view of reef is in the form of an equilateral triangle with raised outer edges. It has an average thickness of 900 feet (Haskett, 1951) and an approximate area of 200 square miles. The Ireton member of the Woodbend formation overlying the reef is predominantly green shale and acts as a caprock. A generalized description of the local formations is given in Table XVIII. Figures 14, 15 and 16 give the geology, stratigraphy and structure respectively of the Redwater oilfield. Since the purpose of the present study is to evaluate the radiometric anomaly associated with this oilfield, the geology of the area is therefore treated briefly.

Pedology:

General:

The variable mixture of weathered rocks and minerals, organic matter, and air is called soil (Odynsky et al, 1952). The soils are resultant products of environmental conditions, and owe their characteristics to climate, topography (relief and drainage), nature of organic matter, time and parent material.

Climate is dependent on topographic features and geographic setting. Low rainfall results in the development of a thin black zone and low concentration of humus. Humid conditions result in the rapid

LEGEND

MESOZOIC

3 EDMONTON FORMATION ····

argillaceous sandstone, dark, bentonitic shale; coal seams.

2 BEARPAW FORMATION ····

light coloured clay, thin beds of sandstone; ironstone nodules; in places conglomerate with black quartzite and chert pebbles.

1 PALE & VARIEGATED BEDS···

light and dark coloured shale, bentonitic arenaceous shale and sandstone; coal seams.

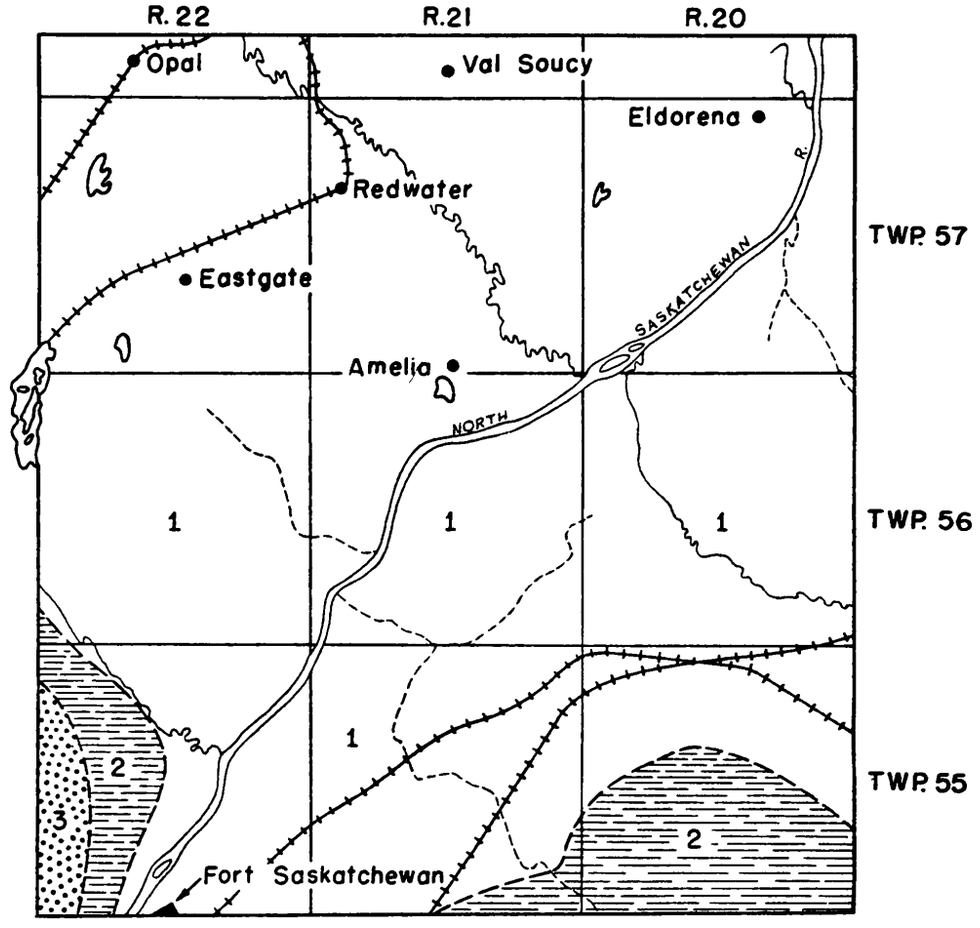
railroad

geologic contact (inferred)

streams

scale

0 4 8 miles



GEOLOGIC MAP OF REDWATER AREA

Alberta, Canada

FIGURE···· 14

Table: XVIII Generalized description of rock formations in Redwater Area (A).

	Age	Formation	Member	Lithology	Enviroment
	Pleisto-cene	Drift		Clay, boulder clay, sand and gravel in various proportions; unconsolidated	Glacial
MESOZOIC	UPPER CRETACEOUS	Edmonton		Sandstone; soft, fine grained, cross bedded, inter bedded with light and dark sandy shales, bentonitic clays, ironstone bands, and their coal seams.	Non-Marine
		Bearpaw		Shale: dark grey to grey black, fissile, micromicaceous, in part glauconitic and carbonaceous.	Marine
		Belly River		Shale and sandstone: limestone, coal, siderite and bentonitic bands are common .	Non-Marine
		Lea Park		Shale: dull grey, fissile, silty with some thin sandstone beds, glauconitic.	Marine
		Colorado Group	Upper Shale	Shale: dark grey to black, calcareous speckled, interbedded with thin beds of bentonitic shale, silty shale and siderite, scattered ironstone fragments.	Marine
			Middle Shale	Shale: dark grey to black, calcareous, interbedded with scattered bands of siderite, and bentonite. Speckled in part, lower part non-calcareous.	
			Viking	Shale: dark grey to black, interbedded with fine to medium grained sand.	
	LOWER CRETACEOUS	Blairmore		Shale: grey to dark grey and black interbedded with argillaceous limestone, medium grained sandstone, siltstone and coal. Sandstone and siltstone carbonaceous. Traces of ironstone. Sandstone: fine to medium grained, carbonaceous, argillaceous and pyritic in part. Glauconitic and quartzose. Siltstone: limy with numerous shale partings. It becomes shaly with depth. Shale interbedded with limy siltstone, and sandstone bands, fossiliferous. Sandstone: fine grained, quartzose carbonaceous, slightly argillaceous.	Non-Marine to Marine Brackish Water
PALEOZOIC	DEVONIAN	Wabamun		Dolomite: light grey to brown and green. Green color due to shale partings. Medium to coarse crystaline and granular, fine grained pyrite scattered throughout the section.	Marine
		Winterburn	Gramina	Dolomite: white to buff, vuggy, traces of grey sandstone grading into very fine sandstone.	Marine
			Calamar	Shale: pale green dolomite and green dolomitic siltstone, vuggy.	Marine
			Nisku	Dolomite: light brown to brown with traces of dolomitic siltstone, vuggy.	Marine
		Woodbend	Ireton	Dolomite: light grey to green, dense argillaceous to shaly and grading into dolomitic shale. Brachiopods present.	Marine
			Leduc	Limestone: cream to buff, and light brown. Dense to very finely crystalline and finely fragmental.	Marine
			Cooking Lake	Limestone: light brown finely fragmental, dolomitic in places.	Marine
		Beaverhill		Limestone: grey to light brown argillaceous, dense, irregular grey shale streaks	Marine

A. The data summarized from the following well logs.

a. Imperial Eastgate 1-34-57-22-W4
b. Imperial Fedorah No. 1 LSD 13. 22-57-23-W4
c. Haskett, 1951.

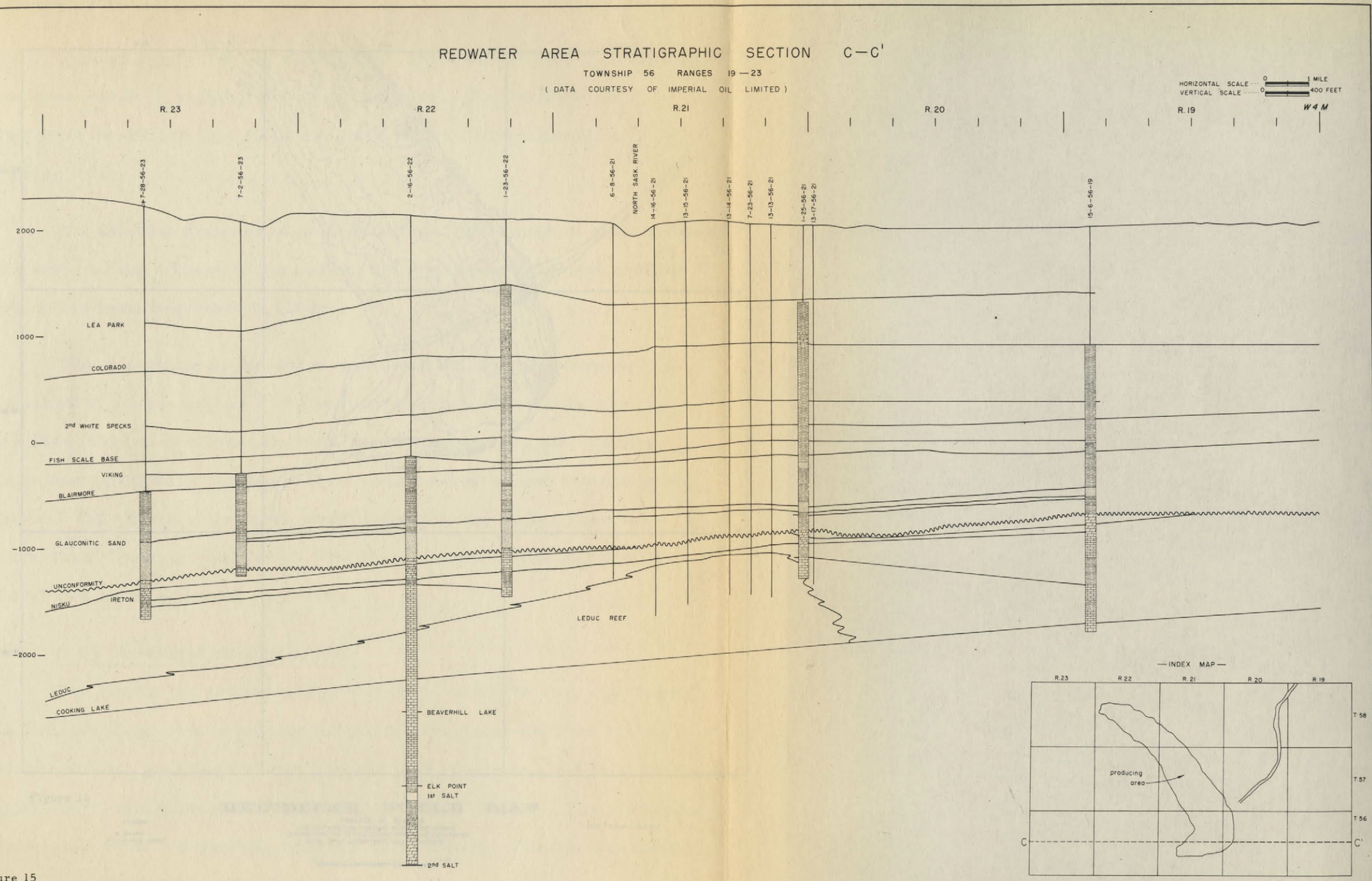

REDWATER AREA STRATIGRAPHIC SECTION C—C'
TOWNSHIP 56 RANGES 19—23
(DATA COURTESY OF IMPERIAL OIL LIMITED)
HORIZONTAL SCALE 0 1 MILE
VERTICAL SCALE 0 400 FEET
R. 23
R. 22
R. 21
R. 20
R. 19
W4M
7-28-56-23
7-2-56-23
2-16-56-22
1-23-56-22
6-8-56-21
NORTH SASK. RIVER
14-16-56-21
13-15-56-21
13-14-56-21
7-23-56-21
13-13-56-21
1-25-56-21
13-17-56-21
15-6-56-19
2000
1000
0
-1000
-2000
LEA PARK
COLORADO
2nd WHITE SPECKS
FISH SCALE BASE
VIKING
BLAIRMORE
GLAUCONITIC SAND
UNCONFORMITY
NISKU
IRETON
LEDUC REEF
LEDUC
COOKING LAKE
BEAVERHILL LAKE
ELK POINT
1st SALT
2nd SALT
— INDEX MAP —
R.23
R.22
R.21
R.20
R.19
T.58
T.57
T.56
producing area
C
C'

Figure 15

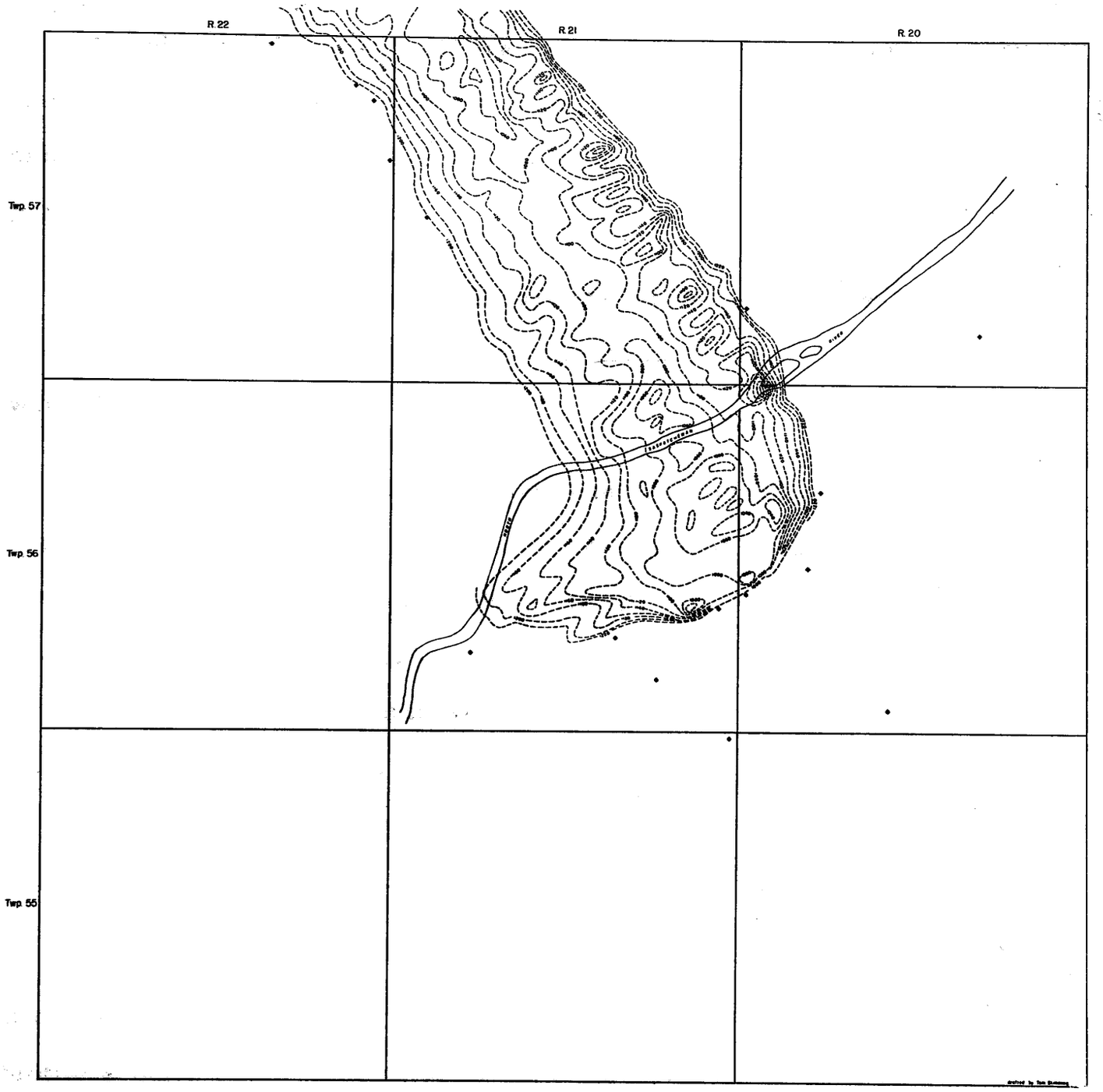


Figure 16

REDWATER FIELD MAP

PROVINCE OF ALBERTA

..... SHOWING STRUCTURE CONTOURS ON THE LEDUC MEMBER .....

ADAPTED FROM THE PETROLEUM AND NATURAL GAS CONSERVATION BOARD, 644-11TH AVENUE WEST, CALGARY, ALBERTA

-LEGEND-

◆ abandoned

structure contour

0 1 2 3 miles

NOTE Revised to Dec 1957

decomposition of organic matter and excessive leaching of the mineral content of soils, thus producing a light colored surface horizon below the leaf litter.

Besides zonal climatic differences, the local changes in topographic features result in varying climatic conditions. For example, the moisture conditions on a slope are much different from those in the adjoining valley.

The internal drainage of soils affects the movement of salts through the soil profile. These factors affect the formation of the soil profile, which has been described in Chapter IV.

The interaction of the above mentioned soil forming factors has resulted in the development of a variety of soil profiles along the two profiles (Figure 3) mapped in the Redwater Area. The soil profiles have been grouped according to their parent material and are described below. Only those soils which were mapped by the writer have been described. Bowser et al (1947; 1951) have described the soil profiles developed on other parent materials.

Soils Developed on Glacial Till:

The glacial till is brown to grey-brown, sandy to silty clay loam. It contains fragments to pebbles of biotite hornblende chlorite schist, biotite schist, granite, white to buff and pink quartzite, buff sandstone, grey chert, ironstones, and fragments to lenses of coal. The pH varies between 7.5 and 9 depending upon the lime content. The till was mainly derived from the Edmonton formation.

The Angus Ridge Loam (solodized-solonetzic profile), and Camrose Loam (solodic profile) are two soils developed on glacial till, and are described below.

Angus Ridge Loam (A.R.L.):

Angus Ridge loam is developed on well drained, gently rolling topography. See Plate 4 for a complete description of the soil profile. In Plate 4, the B_2, B_3 and B_{Ca} horizons are missing. The A horizon lies unconformably over the D horizon.

The B_2 horizon is composed of brown to dark clay loam, with a pH of 5.6. It shows medium columnar structure, and readily breaks into blocks.

The B_3 horizon consists of clay loam to clay and is weakly nutty in appearance. It shows very weak columnar structure and has a pH of 6.5.

The B_{Ca} horizon is similar to B_3 but has a pH of 7.8.

Distinguishing Characters: "A deep black surface, a thin grey sub-surface horizon, and a brown clay loam subsoil that contains stones, coal flecks, and small ironstones" (Bowser et al, 1947).

Camrose Loam (Cam.L.):

Camrose loam is developed on level to gently undulating topography and is found on gentle slopes. It is a soil of poor to fairly good drainage. See Plates 5 and 6 for a complete description of the soil profile.

Distinguishing Characters: A fairly loose and black A horizon; an ash grey A_2 horizon; a very hard columnar B horizon, and a concentration of salts in the B_3 horizon.

A — Black loam. Minor amount of sand, roots, pH 7.25.

Dark brown loam, pockets of sandy and limy clay loam (Prairie Dog Holes)

D_1 — Brown silty caly loam, with pebbles and boulders of biotite hornblende chlorite schist, ironstone, biotite granite buff sandstone; biotite schist, granite and ironstone pebbles disintegrating; pebbles and boulders $\frac{1}{2}$" to 5" in diameter pH 7.5; unconformity.

D_2 — Grey brown silty clay, lenses of coal, few ironstone fragments, limy, pH. 9.0.

Plate 4. A profile of Angus Ridge loam exposed 2 miles north of Skaro, Alberta.

A_1	Black loam, rich in roots, pH 6.5.
A_2	Brown loam, platy, leached zone.
B_{21}	Dark brown loam, blocky, nutty, blocks and nuts stained with organic matter and minor amount of limonite, minor columnar structure, pH 8.0.
B_{22}	Brown clay loam, veinlets of sodium salts and lime, scattered pebbles of chert and quartzite, pH 8.0.
B_{Ca}	Grey clay loam, with scattered pebbles of chert, ironstone, granite and quartzite, varying in size 3mm to 20mm, from a few lenses of coal, pH 8.5.
C.	Grey silty clay loam with pebbles of ironstone, grey chert, granite, quartzite, and fragments to lenses of coal 1" x 2", glacial till. pH 9.

Plate 5. A profile showing Camrose loam exposed west of grade school, Bruderheim, Alberta.

A_1 Black loam, rich in roots, pH 6.5.

A_2 Brown loam, platy, leached zone.

B_{21} Dark brown loam, blocky, nutty, blocks and nuts stained with organic matter and minor amount of limonite, minor columnar structure, pH 8.0.

Plate 6. A close up of A and B horizons of Camrose Loam illustrated in plate 5.

Soils Developed on Alluvial Lacustrian Material:

The alluvial lacustrian material is of clay loam to sandy loam composition overlying glacial till. Ponoka loam and Penhold loam are two main profiles developed on this material, and are described below:

Ponoka Loam (Pk. L.):

Ponoka Loam is a well-drained soil formed on level to gently rolling topography. The following is the description of a Ponoka loam soil profile exposed 3/4 mile west of grade school, Bruderheim, Alberta.

Feet		
0 - 0.1		Leaves, humus.
0.1 - 0.2	A_O	Humus rich black loam.
0.2 - 0.3		Brown decayed roots.
0.3 - 0.6		Black loam, scattered roots.
0.6 - 2.0	A_1	Black loam, mildly prismatic, pH 6.5.
2.0 - 2.1	A_2	Ash brown loam, platy, leached, pH 6.2.
2.1 - 2.8	B_2	Brown sandy clay loam to clay pH 6.0.
2.8 - 3.2	B_3	Brown loam to sandy clay loam, pH 6.5.
3.2 - 4.5	B_{Ca}	Brown clay loam to clay $\frac{1}{2}$" wide alternating with clay 1" wide. Rich in lime, pH 7.35.
4.5 - 5.0	C	Grey brown sandy loam, rich in lime, scattered pebbles of grey quartzite and ironstone, pH 8.0.

Distinguishing Characters: A deep black A_1 horizon, a thin, light-colored A_2 horizon, and a uniform sandy loam to sandy clay loam B horizon, usually stone free.

Penhold Loam (Pe. L.):

Penhold Loam is a black soil developed on alluvial lacustrian material in low spots with poor to fair drainage. It has very high lime content. The A horizon is grey-black, weakly prismatic and tongues into yellowish brown B horizon. See Plate 7 for a complete description of this soil profile.

A_1 Black loam; minor columnar structure; Prairie Dog holes; pH 8.0.

B Rich yellow loam; contact irregular; pH 8.5.

B_{Ca} Brown loam; rich in lime, lime in the form of veinlets and stringers mixed with fine sand; pH 9.0.

D_1 Brown with streaks of bluish grey silty clay, breaks into blocks of varying sizes; pH 9.0.

Plate 7. A profile of Penhold loam exposed west of Grade School, Bruderheim, Alberta.

Soils Developed on Alluvial-Aeolian Deposited Materials:

Peace Hills Loamy Sands (Ph.L.S.):

Peace Hills loamy sands occur on dune-like gently rolling topography, and have developed from alluvial-aeolian parent material. These are stone free soils. See Plate 8 for a detailed description of Peace Hills loamy sands soil profile.

Peace Hills Sandy Loams (Ph.S.L.):

Peace Hills sandy loams have developed from alluvial materials. These are somewhat excessively drained soils found on level to gently rolling topography. These are fine to coarse textured soils. Their profile is slightly solodic, and stone free. The following is a generalized description of a Peace Hills sandy loam profile (Bowser et al, 1951).

Inches		
14	A_1	Black sandy loam, weakly prismatic, usually firm enough to slightly overhang in the roadcut. pH 6.3.
½ - 2	A_2	From a light brown to dark brown sandy loam, slightly porous. pH 6.1.
20 plus	B	Loam (sandy), brown to yellow brown. Some organic staining along the vertical cleavage lines in the upper portion of the profile. pH 5.8.
	B_{Ca}	A low concentration may occur at 40" or deeper from the surface.
	C	Yellow brown to brown. Loam to sandy loam. pH 5.9.

Miscellaneous Soils:

a) Sands: The sands are alluvial and aeolian-deposited. The aeolian sands have developed from alluvial materials. See Plate 9 for a complete description of a dune sand profile.

Sands exposed along the profile I and II (Figure 3) are fine to medium grained, subangular to rounded, and frosted. The sands south of North Saskatchewan river are predominantly fine to medium grained,

A_o	Leaves; roots; loamy sand
A_1	Grey, black to black fine grained loamy sand; roots and leaves; pH 6.6.
A_2	Grey, fine grained loamy sand; scattered roots; pH 6.6; contact gradational
B	Yellow brown, fine grained loamy sand; pH 6.7.
	Dark brown, fine grained loamy sand; hard layer; contact gradational
C_{Ca}	Grey, fine grained sand; rich in lime; lime along roots and rootlets; pH 7.5.

Plate 8. A profile of Peace Hills loamy sands exposed north side of road 1500' east of west boundary 35-55-21-4, Redwater Area, Alberta.

Drift	Dark grey loose loamy sand.
A_o	Black loamy fine grained sand, roots, humus rich.
A_1	Tan brown fine to medium grained sand. Fine grained fraction predominant. Loose, scattered roots.
B	Yellowish brown fine to medium grained sand. Fine grained fraction predominant. Scattered grains of quartz 2 mm in diameter present; compact; scattered roots.
	Dark brown fine to medium grained sand, hard layer.
C_{Ca}	Grey, fine to medium grained sand, lime in the form of blocks and veinlets present. pH 8.5

Plate 9. A profile of sand exposed north side of road, 1200 feet east of west boundary 32-55-21-4, Redwater Area, Alberta.

gravel is found lying at the surface of sands, suggesting that these sands have been reworked by water.

A cursory examination under a binocular microscope shows 80 - 85% quartz with few grains of chert. The remainder is magnetite, pink feldspar, ilmenite, coal, green amphibole, pyroxene, epidote, pink to dark red garnet, and micas.

b) Peat soils (slough and low areas): Peat soils consist of sedge, and mixed sedge and sphagnum peats. These are found in low, poorly drained areas. The peats are underlain by glei material, of varying composition. A soil horizon in which the material has been modified by fluctuating water table is called glei (Bowser et al, 1947). It is mottled to rusty brown and grey, compact, and sticky.

c) Alluvium: Alluvium is found in ox-bows and old stream channels. There is very little horizonation. The texture varies from sand to loam.

Radiometric Results:

Radon Data:

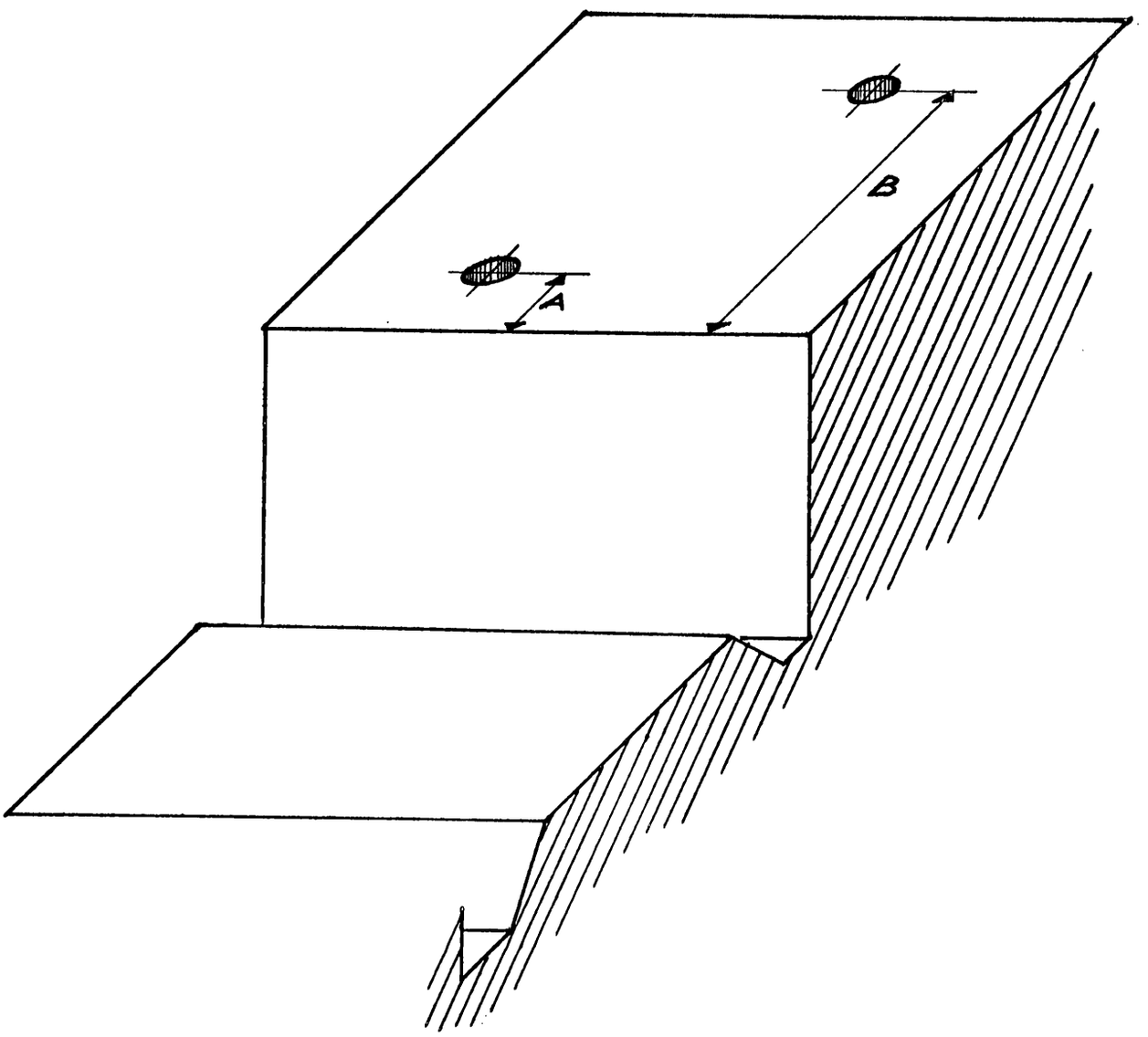
During the course of the field season it was observed that the radon content of holes drilled near road cuts was lower than in holes drilled farther away. Holes on the crests of dunes also showed a drop in radon concentration, in comparison with holes drilled on the flat part of the dune. The observations of the writer, made independently, confirm Okabe's (1956) findings. According to Okabe this drop is due to the escape of radon on the lateral sides of the road. The present writer feels that the distance between road cut and the different holes plays an important part (Figure 17). The radon from A has to travel a smaller

distance in than that from B. Therefore, there is a little less radon in A. A sample flask filled with air was counted every day to determine the background of the flasks. It gave 0 counts per min., during the period of survey.

A plot of the medium-grained fraction (-28 + 60 mesh) of sands obtained from the mechanical analysis showed a drop in the radon content of holes with the increasing coarseness of sands (Figure 18). It is probable that radon escapes readily through medium-grained sand because of the increased pore space and looseness. Holes filled with water gave 4 - 14 cpm (counts per minute) of radon. The presence of prairie dog holes also decreased the radon content. It was observed that if a hole gave 75 cpm, 15 days after plugging, it gave a similar count one day after cleaning and replugging.

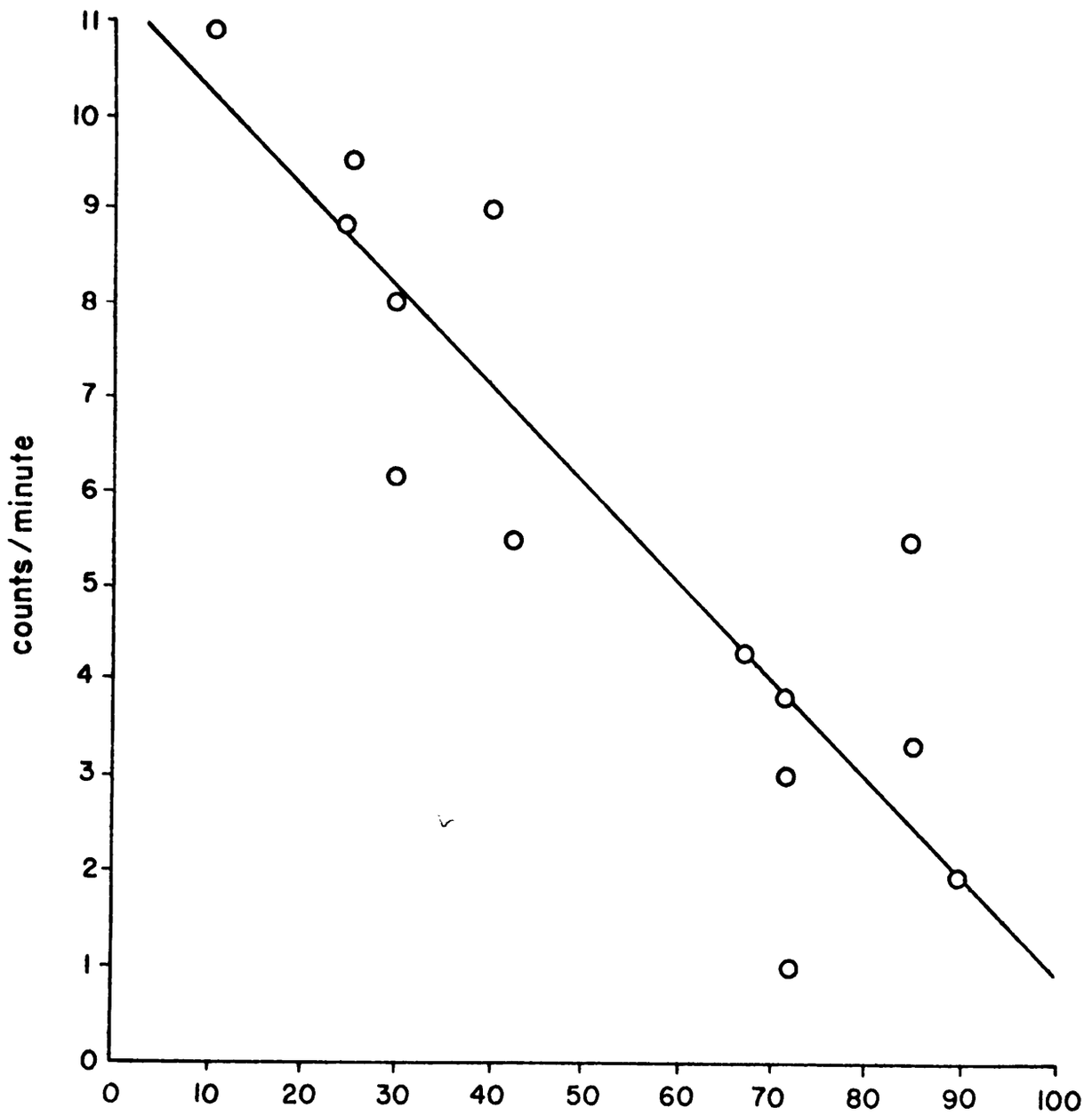
Some of the holes were sampled a number of times to study the variations at a sampling site, and also study the reproducibility of the measurements. The variations were $\pm$ 20% (Tables XIX, & XX). The accuracy and the reproducibility of radon measurements was further confirmed by the excellent correspondence between the airborne radium and ground data for radon (Figures 19, 20, 21).

Radon data were plotted along with the airborne radium data (Figures 19, 20 and 21). A plot of the radon data corrected for various soils was also made by subtracting the mean radon content (Table XXI), and dividing the residual by the standard deviation of each type (Figures 19, 20, 21, and 22).



RADON IN HOLES NEAR A ROAD CUT

FIGURE 17



EFFECT OF GRAIN SIZE ON THE CONCENTRATION OF RADON IN SANDS

FIGURE····· 18

TABLE XIX: Accuracy of Radon Measurement

STATION NO.	SAMPLES	MEAN RADON COUNT
5	3	52.77 ± 1.57
6	5	32.66 ± 2.44
9	6	64.05 ± 8.3
11	4	39.25 ± 2.5
15	7	47.58 ± 2.14
19	5	49.18 ± 1.78
23	6	68.04 ± 3.74
33	4	15.30 ± 2.10
38	4	10.57 ± 0.42
44	5	3.59 ± 1.86
49	5	8.74 ± 1.42
131	3	3.73 ± 1.86
138	6	0.88 ± 1.42
140	5	3.07 ± 0.43

TABLE XX: Reproducibility of Radon Measurements with Time

STATION NO.	DATE SAMPLED	HOLE	COUNTS/MIN.
108	Oct. 16, 1956	A	14.33
		B	13.33
	Oct. 18, 1956	A-1	14.35
		A-2	12.70
		B	13.65
		C	10.40
121	Oct. 18, 1956	A	59.0
		B	57.9
		C	66.58
123	Oct. 14, 1956	A	22.0
		B	26.6
		C	25.3
	Oct. 18, 1956	A	30.0
		B	29.5
		C	25.9
125	Oct. 14, 1956	A	7.0
		B	7.5
	Oct. 18, 1956	A	9.5
		B	9.9
		C	8.3
138	Oct. 13, 1956	A	0.76
		B	0.93
	Oct. 18, 1956	A	0.9
		B	1.2
		C	0.8

TABLE XXI: Mean Radon Content of Soils

SOIL	RADON CONTENT IN COUNTS/ MIN.
Loams	
On alluvial lacustrian parent material	51 ±9
On till parent material	38 ±15
Sandy Loams	19.29 ±6
Sands	7.63 ±3

No differentiation was made between the fine and coarse grained sands, due to the small number of samples.

Figures 19, 20, and 21 also show airborne radium data corrected for various soils. The airborne radium data were corrected with mean and standard deviation values used in plotting Figure 31, but using the soils shown in Figures 19, 20, 21 under soil data.

The term "radium data" is incorrect, because the gamma ray spectrometer measures only energies above 1.50 Mev which are from Bi^{214} and Tl^{208}. Since this term is used by Lundberg Explorations Limited, who provided the data, the writer has therefore used the same term.

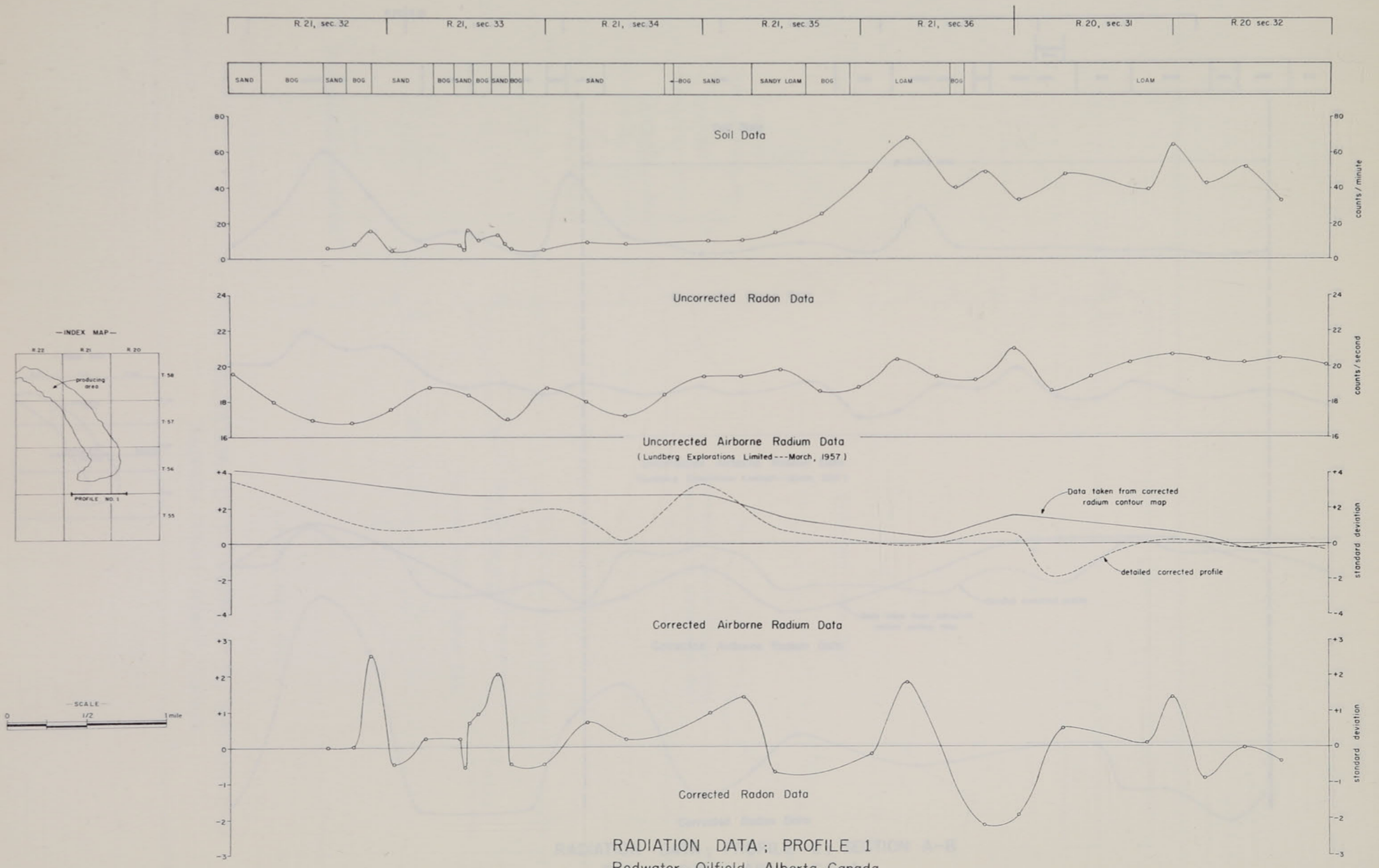
The corrected radon data are plotted in the form of standard deviation from the mean.

Discussion of Results:

Profile I:

The uncorrected radon in Figure 19 shows a drop towards the west, the highest being in the loams and lowest in the sands.

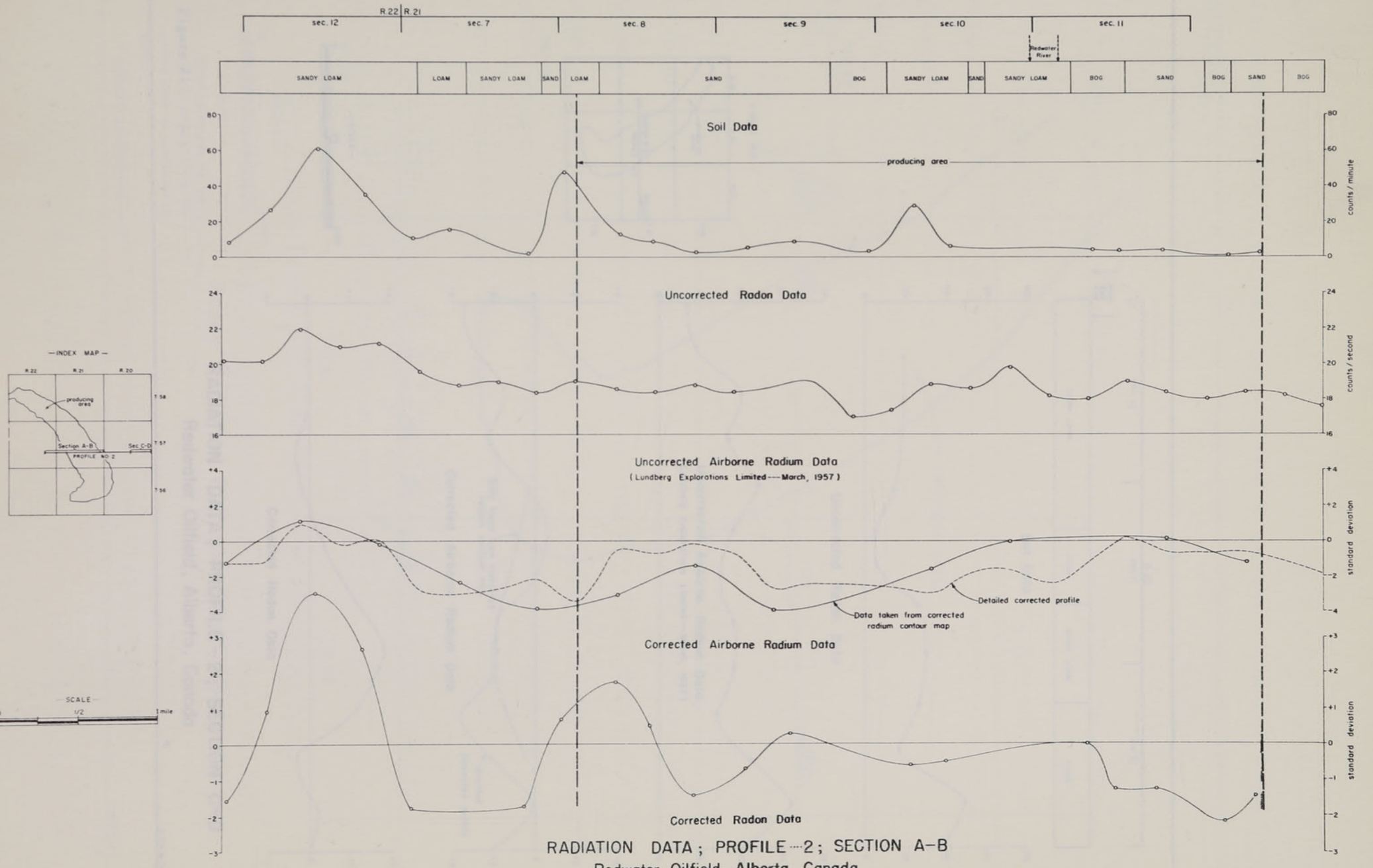
The corrected radon shows low in R.21 section 32 and 33. These are due to the sampling sites in muskeg area. There are four significant



RADIATION DATA ; PROFILE 1
Redwater Oilfield , Alberta, Canada

Figure 19

drafted by Tom Skimming



RADIATION DATA ; PROFILE — 2 ; SECTION A–B
Redwater Oilfield, Alberta, Canada

Figure 20

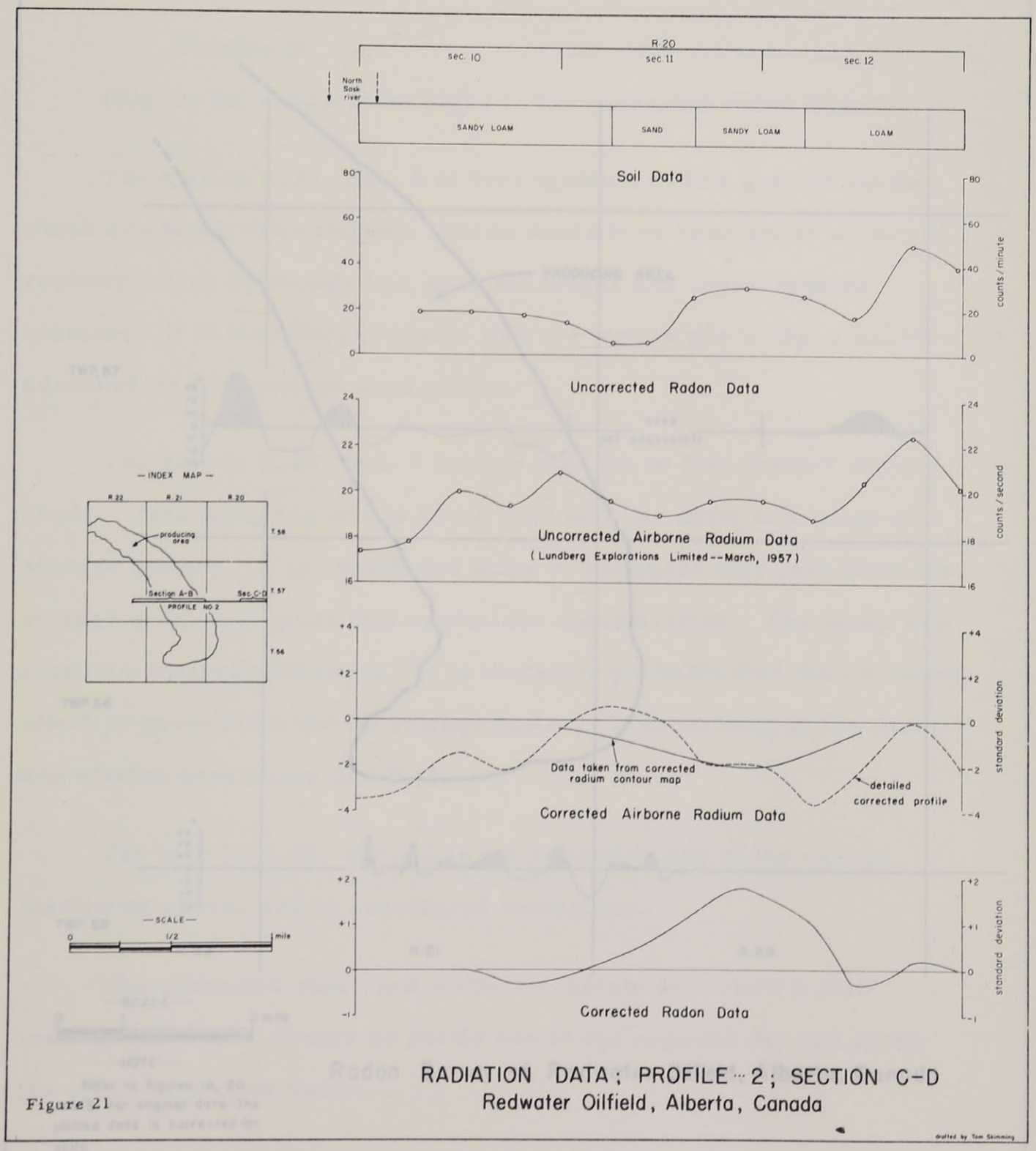
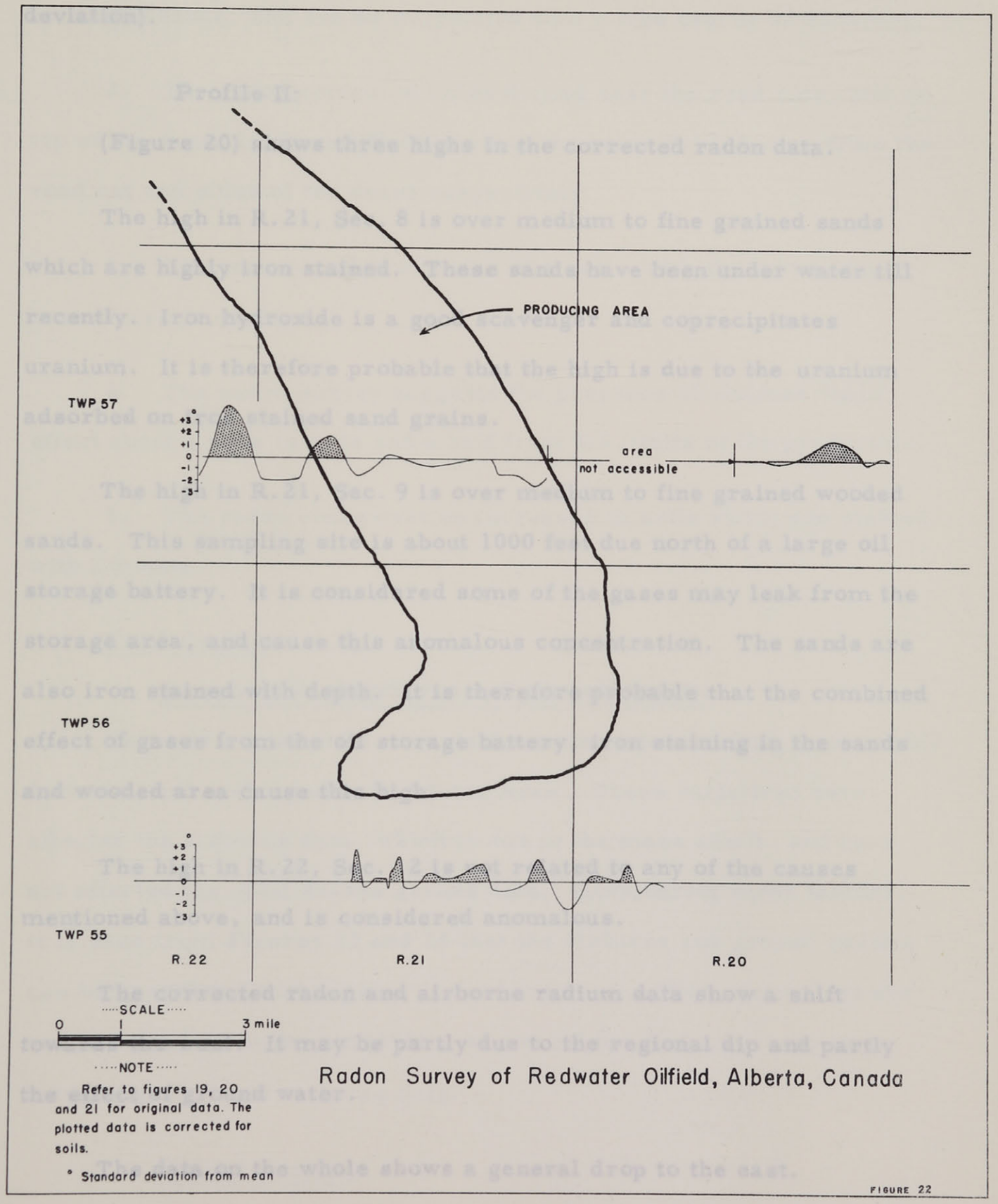


Figure 21

RADIATION DATA; PROFILE -- 2; SECTION C-D
Redwater Oilfield, Alberta, Canada

drafted by Tom Skimming



Radon Survey of Redwater Oilfield, Alberta, Canada

FIGURE 22

highs in Range 21, Sec. 32, 33, 35 and R.20 border of Sec. 31 and 32. The remaining area shows in general the background pattern (± 1 standard deviation).

Profile II:

(Figure 20) shows three highs in the corrected radon data.

The high in R.21, Sec. 8 is over medium to fine grained sands which are highly iron stained. These sands have been under water till recently. Iron hydroxide is a good scavenger and coprecipitates uranium. It is therefore probable that the high is due to the uranium adsorbed on iron stained sand grains.

The high in R.21, Sec. 9 is over medium to fine grained wooded sands. This sampling site is about 1000 feet due north of a large oil storage battery. It is considered some of the gases may leak from the storage area, and cause this anomalous concentration. The sands are also iron stained with depth. It is therefore probable that the combined effect of gases from the oil storage battery, iron staining in the sands and wooded area cause this high.

The high in R.22, Sec. 12 is not related to any of the causes mentioned above, and is considered anomalous.

The corrected radon and airborne radium data show a shift towards the west. It may be partly due to the regional dip and partly the effect of ground water.

The data on the whole shows a general drop to the east.

Figure 21 shows a high which may be either related to Redwater Oilfield or to an oilfield about 4 miles east of the area.

Conclusions:

1. The ground radon and airborne radium data show very good correspondence, and can be correlated with a high degree of accuracy.

2. The radon content of holes drilled near the road cuts, and on top of the dunes is about 10% lower than the holes drilled away from the road cut and sides of the dunes respectively.

3. The concentration of radon decreases with the increasing coarseness of sands.

4. The radon survey suggests the presence of claimed "halo" effect about a mile to mile and a half from the limits of the production.

5. The radon concentration increases in soils which are stained with limonite.

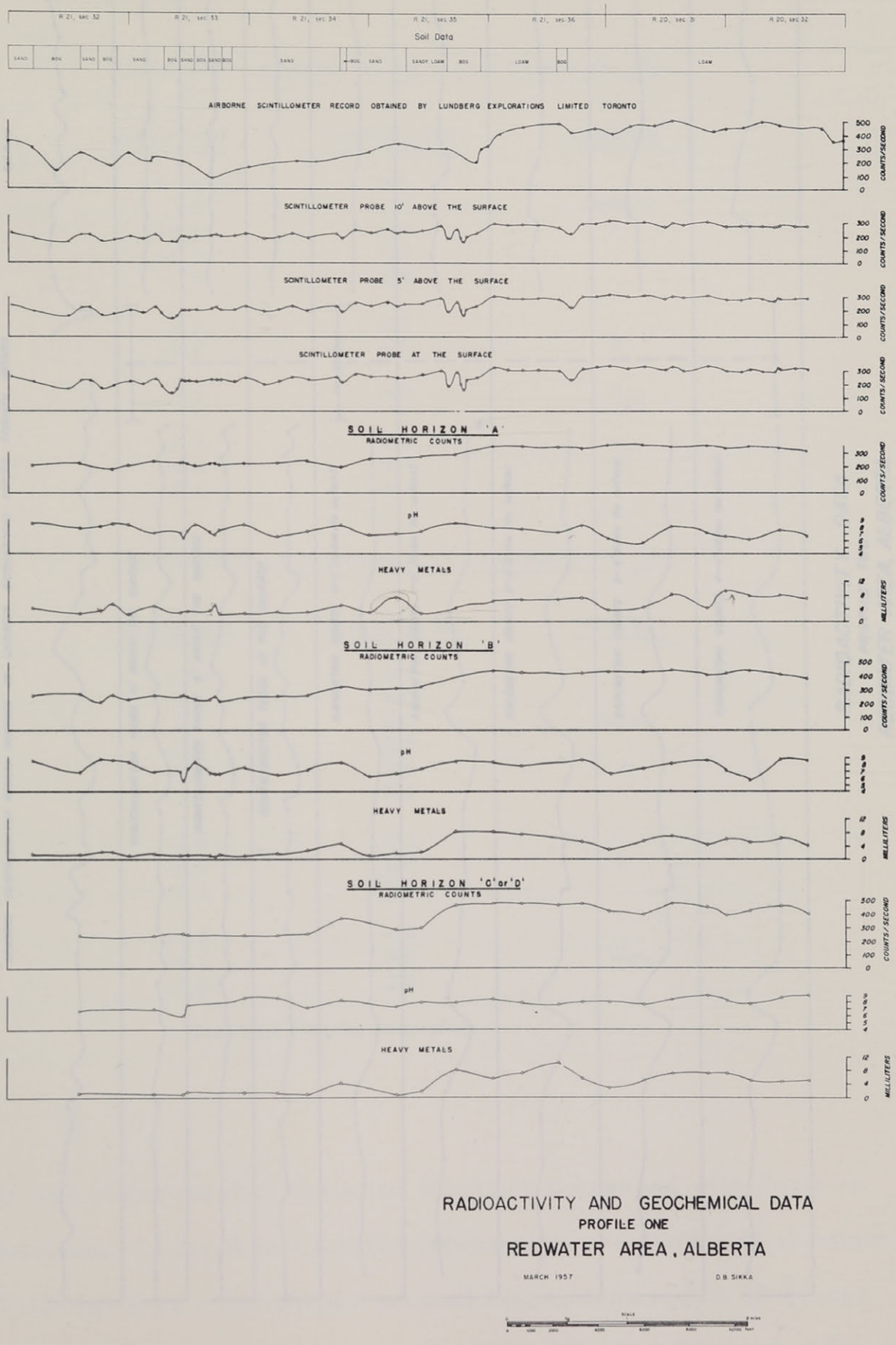
Total Counts:

Comparison of airborne and ground results:

There is a great deal of variation in the micro-relief, geomorphic features, and soil types in Redwater Area. These variations have affected the airborne data, which is due to the mass effect, and have not affected the point source ground data. Considering these factors, it is seen from Figures 23 and 24 that the airborne and ground results can be correlated with a great deal of accuracy. This contradicts the results obtained by Brown (1956), who could not find any correlation between ground and airborne data.

Ground Results:

Readings taken in an empty room during morning and evening over a three-month period gave an average of 175-180 cps.



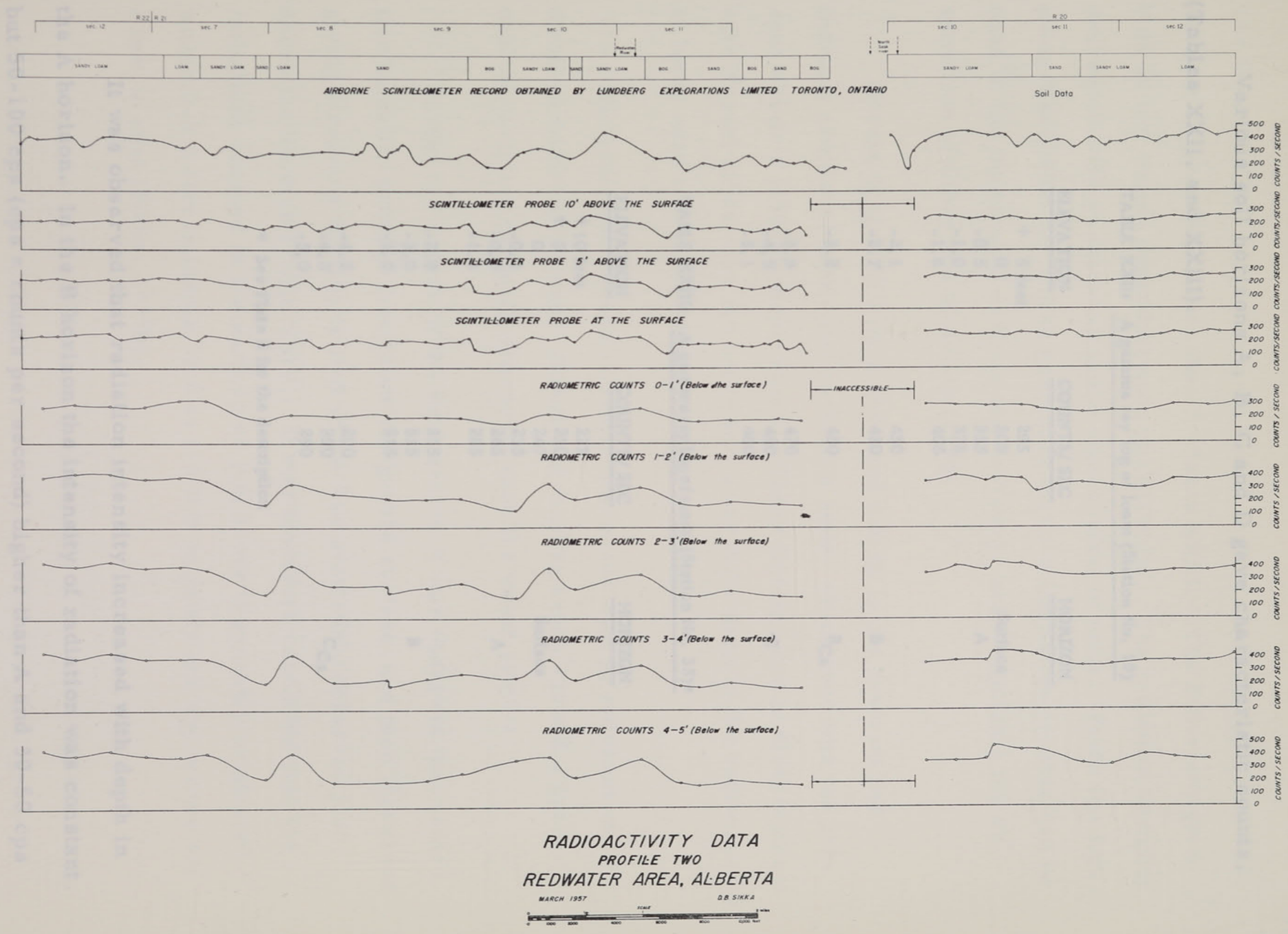
RADIOACTIVITY AND GEOCHEMICAL DATA

PROFILE ONE

REDWATER AREA, ALBERTA

MARCH 1957 D.B. SIKKA

Figure 23



RADIOACTIVITY DATA
PROFILE TWO
REDWATER AREA, ALBERTA

MARCH 1957 D.B. SIKKA

SCALE 1 mile

Figure 24

Various soil horizons A, B, C and D gave characteristic counts, (Tables XXII, and XXIII).

TABLE XXII: A gamma ray log of loam (Station No. 19)

ELEVATION	COUNTS/ SEC	HORIZON
+ 5 feet	295	
0	305	Surface
-0.5	355	A
-1.0	375	
-1.6	405	
-2.1	430	
-2.7	430	B
-3.2	450	B_{Ca}
-3.9	470	
-4.5	480	C
-5.1	480	

TABLE XXIII: A gamma ray log of sands (Station No. 35)*

ELEVATION	COUNTS/ SEC	HORIZON
+10 feet	223	
+ 5	230	
0	247	Surface
-0.3	235	
-0.9	265	A
-1.4	285	
-2.0	315	
-3.0	315	B
-3.6	315	
-4.2	290	
-4.5	290	C_{Ca}
-5.0	290	

* See Plate 8 for the description

It was observed that radiation intensity increased with depth in the A horizon. In the B horizon the intensity of radiation was constant, but 50-100 cps (cps = counts per second) higher than A and 30-50 cps lower than C depending upon the parent material. In many cases B_{Ca} could also be identified (Table XXII). It was 20-25 cps higher than B.

The C horizon gave higher counts than A and B, but the C_{Ca} (lime rich) horizon in sands was lower than B (Table XXIII). The D horizon gave high or low counts depending upon the material. The radiation intensity decreased with an increase in the sand content of soils. From the foregoing discussion the writer concludes that a scintillation counter can be used in the mapping of various soil horizons, which confirms the observation of Gibbs and McAllum (1955).

Gorski et al (1957) have observed a drop in the uranium and thorium content of sandy and carbonate soils, which confirms the present writer's (1957b) observations. These findings are in disagreement with Russel (1944) who did not observe any difference in the radioactivity of loose sand and sandstones cemented with lime.

The radiation intensity usually decreased with an increase in distance from the source. Slough and muskeg areas showed a great deal of variation probably dependent upon the water content.

During the course of the field season it was observed that radiation intensity dropped just below the ground surface, and then increased giving a reading similar to that which was previously observed just above the surface (Table XXIV). It was therefore concluded that the radiations mapped at the surface or just above it probably originated within 0-0.3 feet in loams, 0.6 to 1.5 feet in sands and approximately 2 feet in peat (Sikka, 1957b).

Alexeyev et al (1955) have theoretically shown that 70% of all the gamma radiations coming from the surface of the ground originate at depths of 0-6 cm. They further state that in practice the instrument records gamma radiations originating in a 10 cm layer of the earth's surface, i.e. from the topmost layer of soil.

TABLE XXIV: Relation of gamma radiations measured at or above the surface with depth in counts/ second

ELEVATION IN FEET	STATIONS							
	6	17	38	42	44	46	73	129
+10	-	-	223	185	190	215	206	-
+ 5	285	310	230	195	200	225	200	170
(Surface) .0	310	340	253	231	218	240	225	185
-0.3	300	333	237	215	206	210	216	170
-0.6	300	400	253	232	222	210	271	165
-1.0		430	-	-	-	215	-	175
-1.5	-	430	-	-	-	230	-	
-2.0	-	-	-	-	-	-	-	190
-2.5	-	430	-	-	-	-	-	190
-3.3		430	-	-	-	-	-	190
-3.7	-	-	-	-	-	-	-	190
	Loam	Loam	Sand	Sand	Sand	Sand	Sandy Loam	Sand

The conclusion drawn by the present writer (1957b) is independent of Alexeyev et al's (1955) considerations. The present writer considers that compactness of soils plays an important part, i.e., with increasing compactness of soil, gamma rays will originate at shallower depths.

The area traversed by Profile I (Figure 23) showed well developed soil horizons, and each horizon gave characteristic counts. The data were therefore plotted according to the soil horizons. A greater part of Profile II (Figure 24) is covered with sands which show little or no horizonation. It was therefore found convenient to plot these results with depth.

Discussion:

Profile I:

It is observed from Figure 23 that there is a gradual decrease in radiation intensity from east to west. Three levels of radiation are observed. Comparing the three radiation levels with the soil map it is seen that these levels correspond with the various soil groups -- loam,

sandy loam, loamy sand, and sand. The results in the A, B, C horizons also indicate the same general correlation. The average intensity of the various soil types is given in Table XXV.

TABLE XXV: Average radiation intensity of various soils

SOIL HORIZON	CLAY LOAM	LOAM	SANDY LOAM	WOODED SANDS	SANDS
Surface	327 ± 6.7	304 ± 12.5	260	254	227 ± 4
A	353 ± 1.3	335 ± 14.2	269	251	225 ± 5
B	431 ± 8.1	411 ± 12	318	299	253 ± 4
C	N	N	298	285	244 ± 3

N = dependent upon the type of material
Silty clay = 478 ± 2
Till (loam to clay loam) = 400

The writer also observed increased radioactivity in wooded areas. The wooded loams and sands were approximately 8.55% and 12% higher, respectively, than loams and sands. The present writer confirms the observation of Brown (1956) who observed increased radioactivity in wooded loam areas.

The total count data for the surface readings of clay loams and loams were statistically examined. The F test gave $F = 39.02\ (1,21)$, which meant there were significant variations in the radioactivity of clay loams and loams. This was based on 5 stations in clay loam and 18 in the loam area. There were 4 stations in loams which were similar or equal in absolute value to the ones observed in clay loams. Similar analysis of the aero-radiometric total count data of clay loams and loams on different materials gave $F = 1.008\ (3,419)$ which meant there was no difference in the measured radioactivity of clay loams and loams regardless of the parent material. The present writer considers, however, that a larger number of samples is needed to draw any significant conclusion.

This seems to support the claims of Dokuchieve, a famous Russian pedologist, who claimed as early as 1870 that given similar climatic conditions, regardless of parent material, the soil produced in equal intervals of time would be the same.

There appears to be a general correspondence between the radiometric results and the total heavy metal results in the C horizon.

Profile II:

The sands in Section 11 (Figure 24) are similar to the sands exposed in R.21 - Sec. 32-34 (Figure 23), but are coarser. These sands gave 180 cps (Profile II) and 210-215 cps (Profile I). The sands in Profile II show a decrease in the radiation intensity with depth.

The underlying material below the surface soil in sections R.21, Sec. 12, R-20, Section 7, western corner of Section 8, and Section 10, is till composed of sandy to silty clay with fragments to pebbles of ironstone, quartzite, granite and coal. It gave an average of 430-435 cps in R.22, Sect. 12, and R.21, Sec. 7, 400 cps in the western corner of R.21, Sec. 8, and 380 in R.21, Sect. 10. Similar till in profile I gave 410-415 cps. The readings taken in the morning and evening varied by about 4%. The difference between the soil over the pool and the flanks is about 20%. The writer considers this difference to be significant. It is further supported by uranium and radon data which also show an increase at the flanks.

The sands in R.21, Sect. 8 and 9 are medium to fine grained, and gave 200-205 cps at the surface, and increasing with depth to 230-250 depending upon the amount of limonitic staining. The increase in iron staining increased the total counts. It is also supported by the radon

data as mentioned earlier, which also increased with an increase in iron staining. Iron hydroxide is a good scavenger. It is probable that it has adsorbed some of the uranium in solution, and radioactive decay of uranium and its daughters have caused an increase in the radon and total counts.

Conclusions:

Considering the complexities of soil types, varying geomorphic features, and the drainage pattern, the following general conclusions are drawn:

1. The airborne and ground data show general correspondence, and can be correlated with a good degree of accuracy.

2. Radiations measured at the surface of the earth or just above it are probably coming from within 0-0.3 feet in loam; 0.6-1.5 feet in sands; and up to 2 feet in peat.

3. Various soil horizons give characteristic counts, which suggest that the scintillometer may be useful in mapping various soil horizons.

4. The radiation intensity decreases in sands rich in lime, and increases in sands stained with limonite.

5. The intensity of radiation increases in wooded soils (sands = 12.0% and loams = 8.55%).

6. The radiation intensity of soils over the pool is 20% less than similar soils at the flanks.

Geochemical Results:

pH and Total Heavy Metal Content:

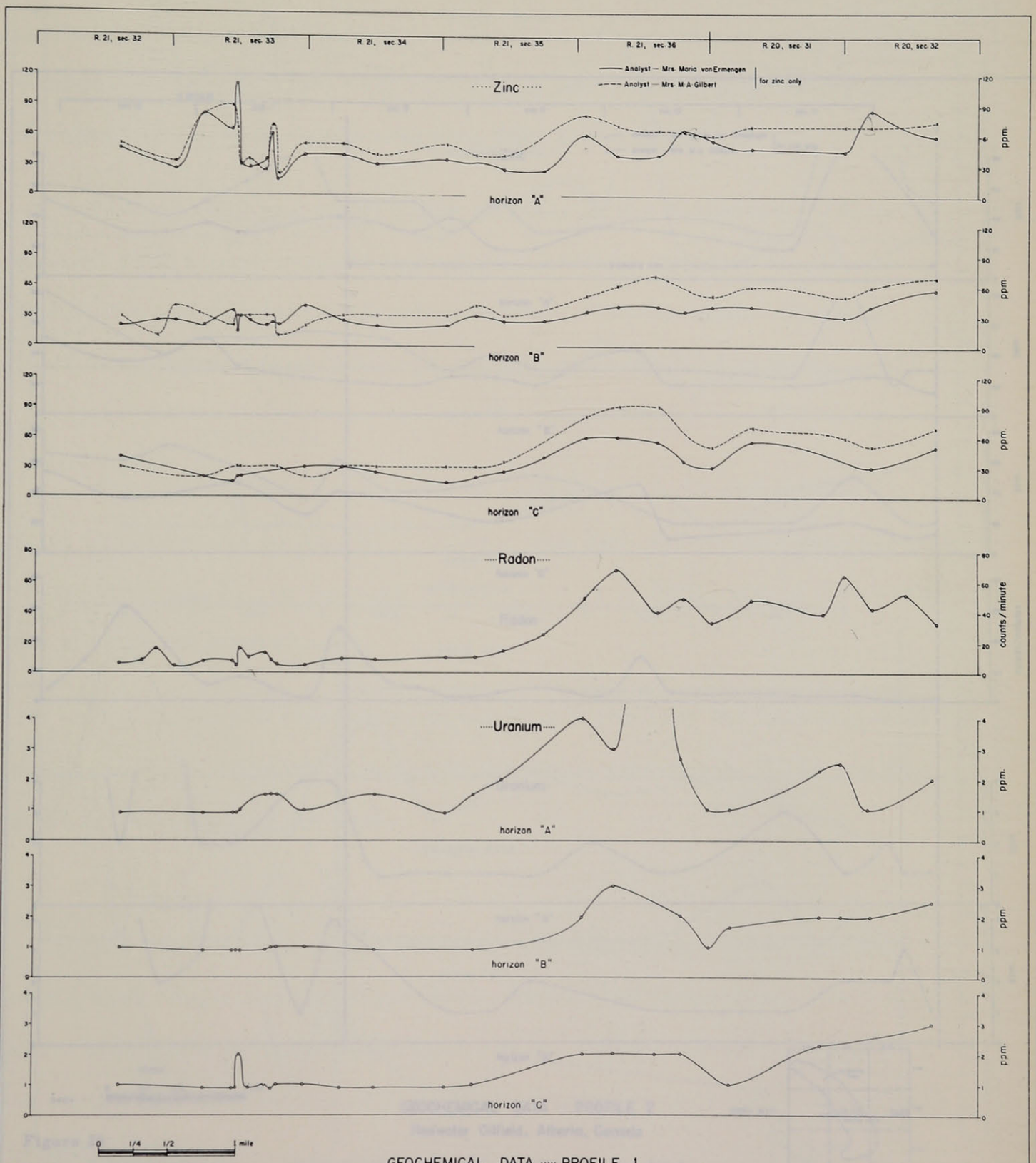
The pH and heavy metal content of soils helped in identifying various soil horizons. The change in pH greatly affects the solution, concentration and deposition of heavy metals. The low pH increases the solubility, and the increasing pH increases the chances of precipitation and deposition.

The pH and exchangeable heavy metals curves (Figure 23) show a great deal of correspondence. There are few erratics, which are probably due to the extraction technique used.

The total heavy metal in A horizon (Figure 23), and radon data (Figure 19) show a great deal of similarity. The correspondence between the heavy metals in the A horizon and radon data suggest the possibility of the concentration of Bi^{214}, Po^{214}, and Pb^{210} (these are daughter products of radon) in the A horizon. This is further strengthened by the observation from total counts, i.e., radiations are emitted from within 0 to 0.3 feet in loam, up to 1.5 feet in sands and approximately 2 feet in peat. The correspondence between the heavy metals content and radon becomes less with the depth.

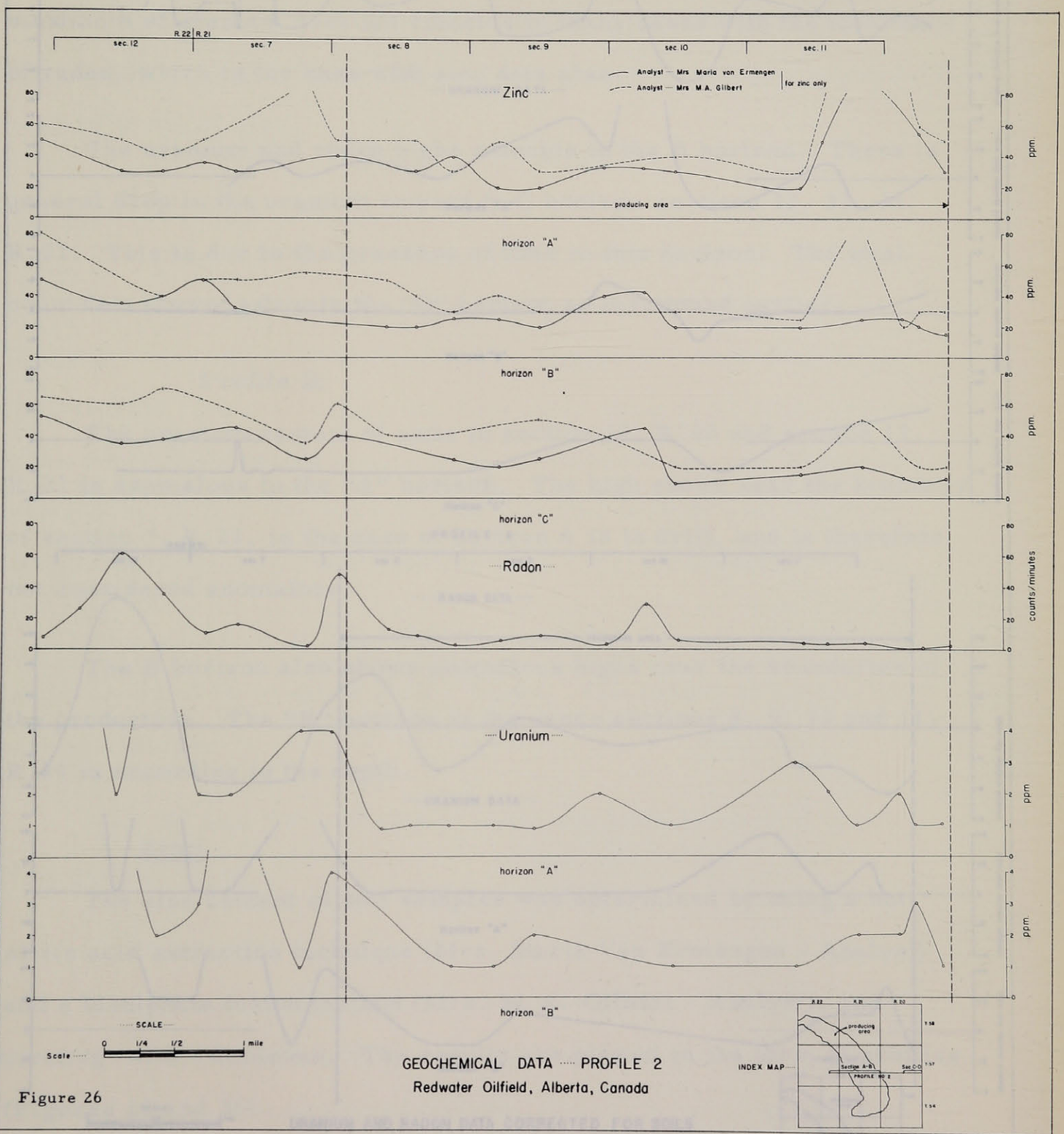
Uranium:

The uranium content of soils was determined fluorimetrically by the chemical laboratories of the United State Geological Survey, Federal Centre, Denver, Colorado. The analytical error is $\pm$ 10%. The observed and corrected results (corrected for soil types) are plotted in the form of profiles (Figures 25, 26 and 27). The corrected results were plotted by subtracting the mean value of uranium content on each soil, and dividing the residual with the standard deviation.



GEOCHEMICAL DATA ····· PROFILE 1
Redwater Oilfield, Alberta, Canada

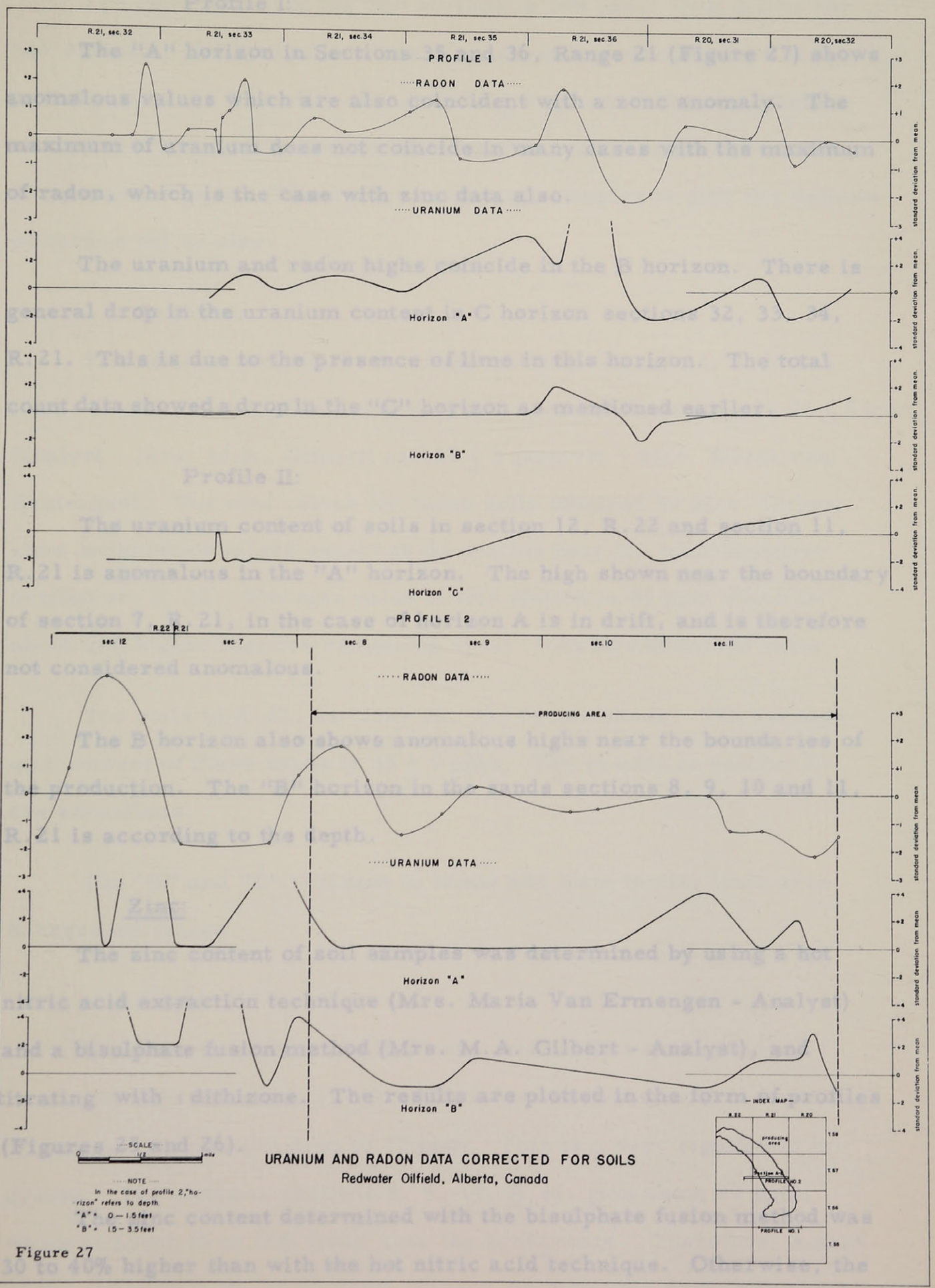
Figure 25



GEOCHEMICAL DATA ····· PROFILE 2

Redwater Oilfield, Alberta, Canada

Figure 26



URANIUM AND RADON DATA CORRECTED FOR SOILS

Redwater Oilfield, Alberta, Canada

Figure 27

Profile I:

The "A" horizon in Sections 35 and 36, Range 21 (Figure 27) shows anomalous values which are also coincident with a zonc anomaly. The maximum of uranium does not coincide in many cases with the maximum of radon, which is the case with zinc data also.

The uranium and radon highs coincide in the B horizon. There is general drop in the uranium content in C horizon sections 32, 33, 34, R.21. This is due to the presence of lime in this horizon. The total count data showed a drop in the "C" horizon as mentioned earlier.

Profile II:

The uranium content of soils in section 12, R.22 and section 11, R.21 is anomalous in the "A" horizon. The high shown near the boundary of section 7, R.21, in the case of horizon A is in drift, and is therefore not considered anomalous.

The B horizon also shows anomalous highs near the boundaries of the production. The "B" horizon in the sands sections 8, 9, 10 and 11, R.21 is according to the depth.

Zinc:

The zinc content of soil samples was determined by using a hot nitric acid extraction technique (Mrs. Maria Van Ermengen - Analyst) and a bisulphate fusion method (Mrs. M.A. Gilbert - Analyst), and titrating with dithizone. The results are plotted in the form of profiles (Figures 25 and 26).

The zinc content determined with the bisulphate fusion method was 30 to 40% higher than with the hot nitric acid technique. Otherwise, the results obtained with the two methods show fairly good correspondence.

The zinc content of the "B" horizon is 14% lower than that of the "A" horizon. Values in C horizon were dependent upon the type of parent material. The silty clay gave 80 ± 8 ppm with the bisulphate method and 50 ± 5 with nitric acid extraction. Similarly till was about 55 ppm and 40 ppm. There were not enough samples to give any definite pattern in till or clay.

Profile I:

The soils in section 36, R.21 and sections 31 and 32, R.20 are loams to clay loams. The average zinc content of these soils is 70 ± 5 ppm (analyst - Mrs. M.A. Gilbert) and 50 ± 5 (analyst - Mrs. Maria Van Ermengen). The zinc values for these soils obtained by Mrs. Gilbert show background values except at the station near the west boundary section 36, R.21. The zinc value at this station is 80 ppm which is about 14% higher than the remaining area. It is an anomalous value.

The soils in R.21, sections 32, 33, 34 are sands. The average zinc content of these sands is 35 ± 5 ppm. The results in section 33 are anomalous.

The "B" and "C" horizons in sands and loam to clay loam give background values.

Profile II:

The soils in section 11, R.21 are sands. The average zinc content of sands is about 35 ± 5. The values in this area rise from 30 ppm to 102 ppm and drop to 20 ppm. This is a very significant increase. The sands in sections 8, 9, 10, R.21, give about 20 ppm, which is about 35 to 40% lower than the background. Therefore, a part of the sands over the production shows a considerable drop. The high

near the east boundary of section 7 is over the drift, and is therefore not considered anomalous.

The B and C horizons (which are according to the depth - B+ 1.5 - 3.5 feet and C 3.5 to 5 feet) show similar trends.

Copper:

Copper was determined at the Geochemical Laboratories, Geological Survey of Canada, Ottawa. The results are plotted in the form of a profile (Figure 28). The determined values are near the lowest detection limit, and therefore no conclusion can be drawn.

Nickel:

Nickel was determined spectrographically at the Geochemical Laboratories, Quebec Department of Mines. The results are plotted in the form of a profile (Figure 29). Replicate analyses showed that the nickel results may be in error from 20 to 30%. In view of this fact no samples were run for profile II, and therefore no conclusion has been made.

Vanadium:

Vanadium was analysed by the Geochemical Laboratories, Quebec Department of Mines. The results are plotted in the form of a profile (Figure 29). Replicate analyses indicate errors of 4 to 100%. Therefore, no conclusion is drawn.

Conclusions:

The writer wishes to point out that the number of samples analysed in various soils is small, and therefore the conclusions drawn are tentative.

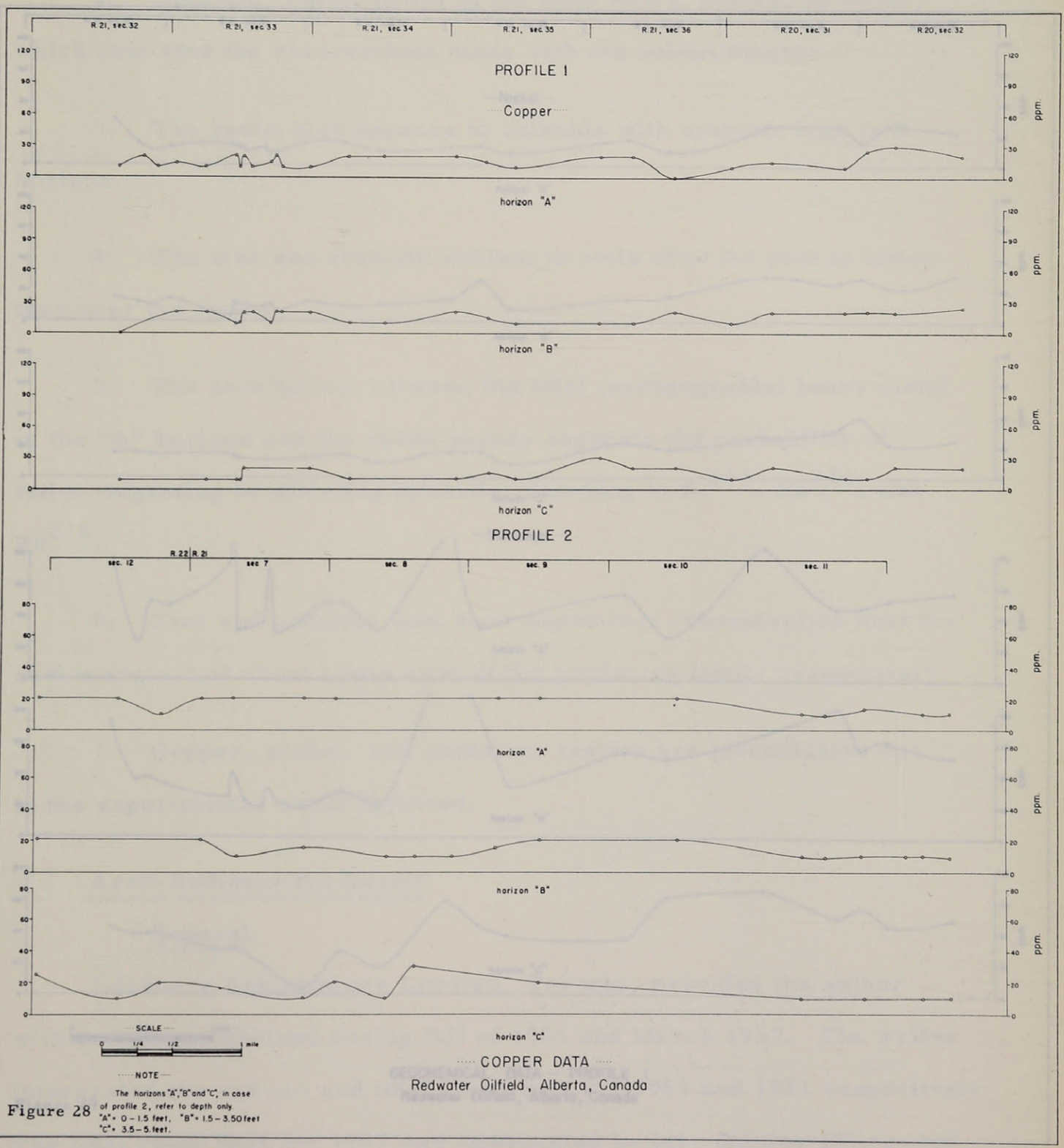
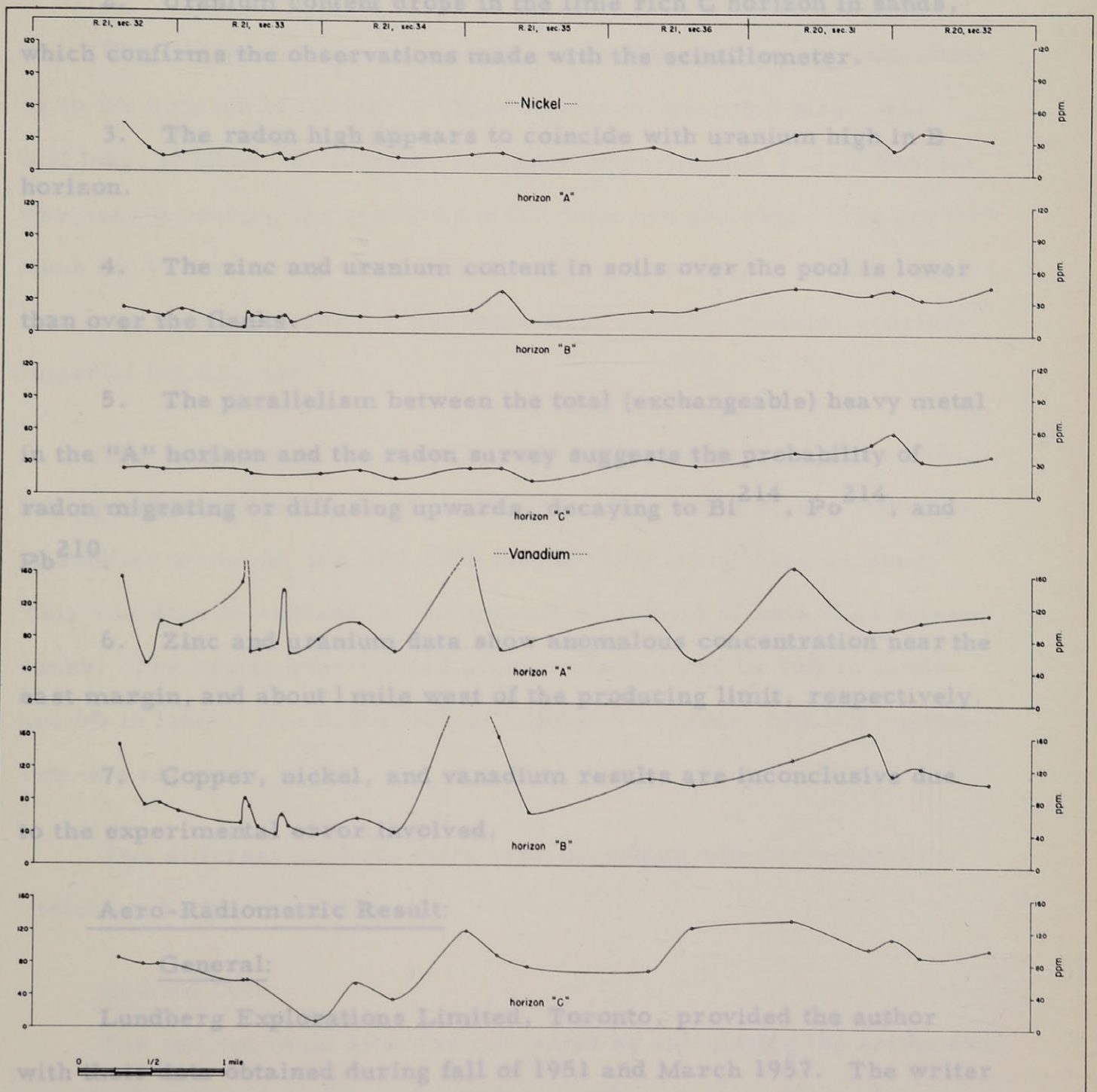

R.21, sec.32
R.21, sec.33
R.21, sec.34
R.21, sec.35
R.21, sec.36
R.20, sec.31
R.20, sec.32
PROFILE 1
Copper
horizon "A"
horizon "B"
horizon "C"
ppm.
PROFILE 2
R.22 R.21
sec. 12
sec. 7
sec. 8
sec. 9
sec. 10
sec. 11
SCALE
0 1/4 1/2 1 mile
NOTE
The horizons "A","B" and "C", in case of profile 2, refer to depth only.
"A"= 0 – 1.5 feet, "B"= 1.5 – 3.50 feet
"C"= 3.5 – 5. feet.
COPPER DATA
Redwater Oilfield, Alberta, Canada

Figure 28



GEOCHEMICAL DATA ····· PROFILE 1
Redwater Oilfield, Alberta, Canada

Figure 29

1. Uranium and zinc highs in the A horizon do not coincide with the radon highs.

2. Uranium content drops in the lime rich C horizon in sands, which confirms the observations made with the scintillometer.

3. The radon high appears to coincide with uranium high in B horizon.

4. The zinc and uranium content in soils over the pool is lower than over the flanks.

5. The parallelism between the total (exchangeable) heavy metal in the "A" horizon and the radon survey suggests the probability of radon migrating or diffusing upwards, decaying to Bi^{214}, Po^{214}, and Pb^{210}.

6. Zinc and uranium data show anomalous concentration near the east margin, and about 1 mile west of the producing limit, respectively.

7. Copper, nickel, and vanadium results are inconclusive due to the experimental error involved.

Aero-Radiometric Result:

General:

Lundberg Explorations Limited, Toronto, provided the author with their data obtained during fall of 1951 and March 1957. The writer interpreted the radium and total count data for 1957 and 1951 respectively. The total count data for 1957 was interpreted by Mr. Stanley Ellingwood, Dept. of Geological Sciences, McGill University, Montreal, who had no knowledge as to the location of Redwater Oilfield. This was done to have

an independent interpretation of the data to complement the writer's findings, and also to test the validity of factors developed by the present writer and described below.

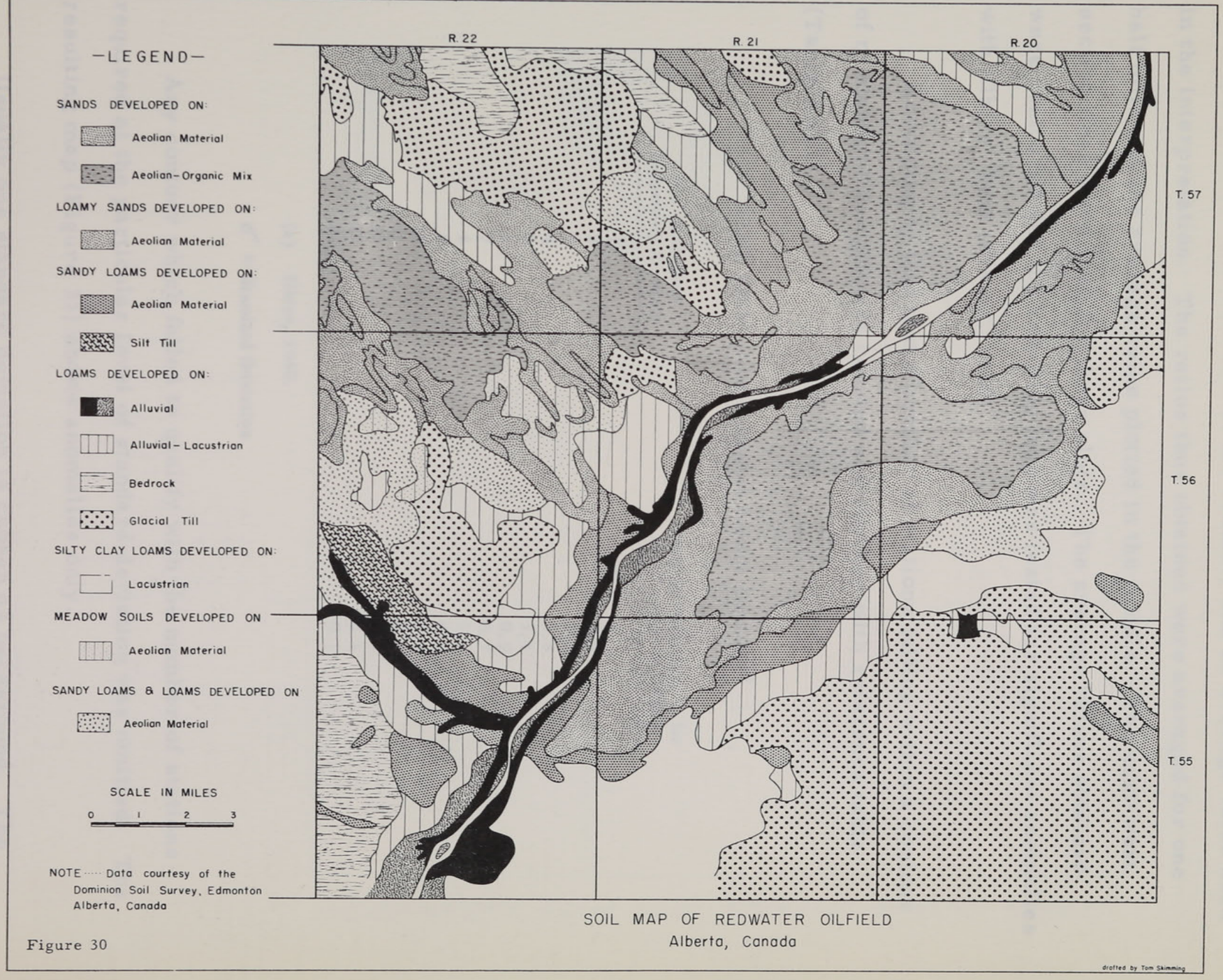
The interpretations were made on overlays without any indication as to the location of oilfield in order to prevent personal bias. The soil map, (Figure 30) courtesy Dominion Experimental Farms Service, was used in making the corrections for soils and drainage. The corrections for wooded areas were made by superimposing soil and drainage-corrected overlays over the Redwater Area airphoto mosaic, courtesy Imperial Oil Limited.

The radiation values were brought to the datum line. All values falling within one half mile of the North Saskatchewan River, 1000 feet of smaller streams, and 500-1000 feet of the muskeg were dropped. This was done to correct for the anomalous effects of water and stream banks. The values over wooded areas were reduced by 10% in sands, and 6% in loam. Due to the lack of altimeter records, altitude correction was not made.

Two different methods were used in making soil corrections for radium and total count data.

Radium Data:

The radium count data was corrected by calculating the arithmetic mean and standard deviation for various soils, viz clay loam, loam, sandy loam and sand on different parent materials. The arithmetic mean and standard deviation were calculated according to Tripp's method (Tripp, 1948). The mean was subtracted from the original values and the ratio between the residual and the standard deviation



SOIL MAP OF REDWATER OILFIELD
Alberta, Canada

Figure 30

plotted. The values falling within 1000 feet of the soil contacts were averaged for the different soils at the contact, and an average value used in the interpretation. The ratios thus obtained were averaged for one half mile and the average value plotted in the middle. The east-west section lines were used for these plots. The average values obtained were contoured and the resulting map was tested for significant anomalies with Elkins' Test (Elkins, 1940).

According to this test a number of stations falling within a contour of m standard deviation is counted and checked with reference table (Table XXVI).

TABLE XXVI: Value of Smallest Reliable Anomaly[a]

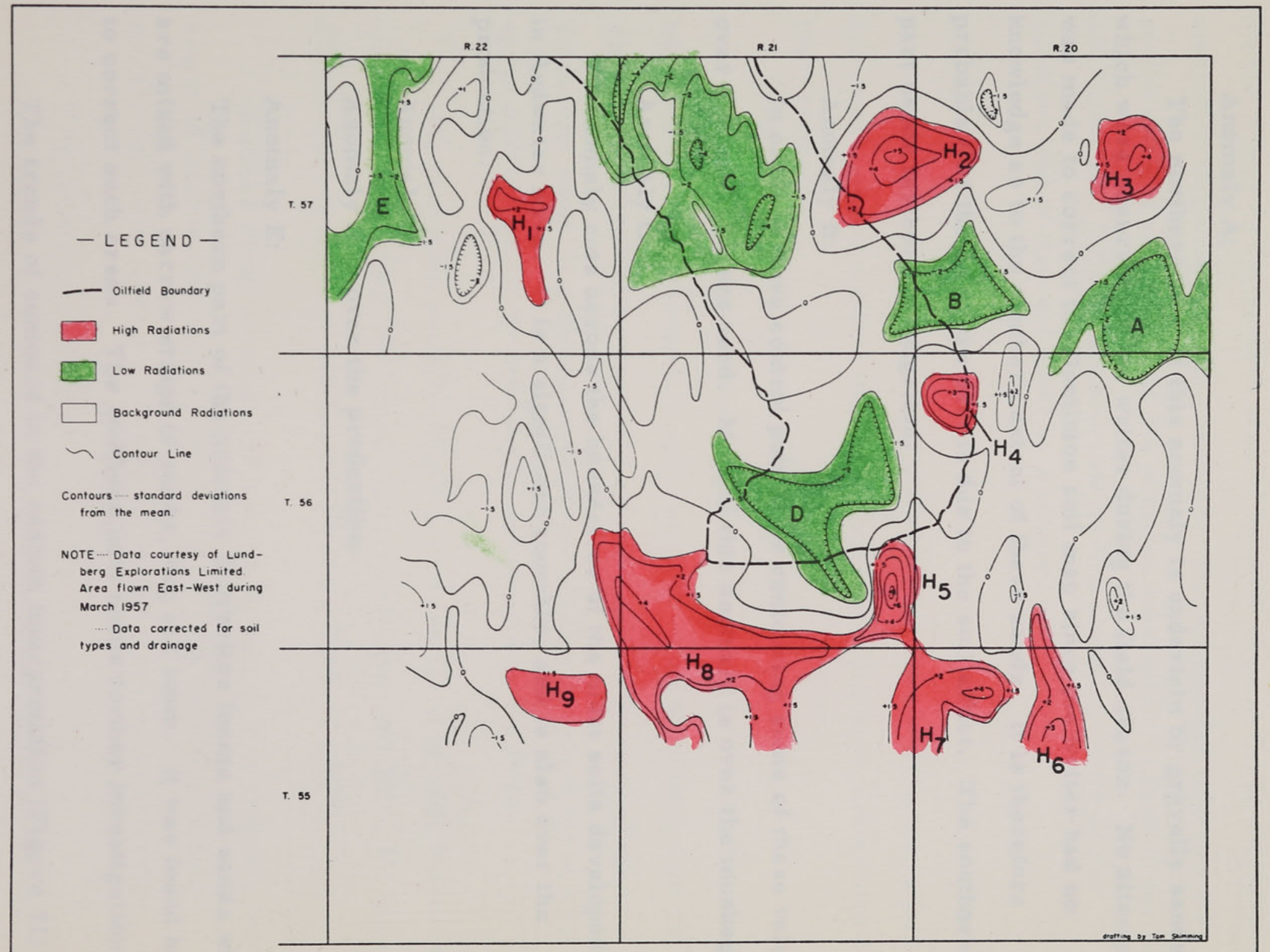
No. of Stations Supporting Anomaly	Limiting Probability is for 4 σ (about 0.00006)
1	σ 4
2	2.5
3	1.9
4	1.4
5	1.1
6	0.9
7	0.7
8	0.6
9	0.5
10	0.4
11	0.3
12	0.2
13	0.1
14	0.1

(a) Elkins, 1940.

σ = Standard Deviation

Any contour which failed to qualify with the number of stations required at the particular level of standard deviation was omitted. The resulting map (Figure 31) shows anomalies only.

Usually one standard deviation is chosen as background. The writer has used $\pm$ 1.5 standard deviation as background to correct for any inaccuracies in soil contacts, and in the plotting of the original data.



AERORADIOMETRIC RADIUM COUNT SURVEY OF REDWATER OILFIELD
Alberta, Canada

Figure 31

Results:

There are five anomalies in the area viz A, B, C, D and E.

Anomaly A:

The northern part of this anomaly is underlain by gravelly sands which were observed by the writer during the field season. No attempt was made to correct the Dominion soil map since the writer had no knowledge as to the southern extent of these sands. It is therefore probable that the northern part is due to the soil effect. The southern part needs further investigation.

Anomaly B:

In order to have control points for contouring some of these values over the muskeg were used. Most of this anomaly is over the muskeg.

Anomaly C:

Anomaly cuts across the boundaries of the most soils developed in Redwater Area. It is a significant anomaly, and is also over the production.

Anomaly D:

Anomaly D is over the production.

Anomaly E:

The northern part of the anomaly E overlies loams and sands which are mixed with narrow strips of sands, bog and loam. It was found hard to correct such areas. The southern part needs further investigation.

The trends of contours in the radium interpretation (Figure 31) are northwest -- southeast and northeast -- southwest, the predominant direction being northwest -- southeast. The total count data for 1957

(Figure 33) show a similar trend to a lesser extent. The radiation intensity is higher on the eastern edge of the pool. The presence of high intensity on the eastern edge of the pool suggest the probable concentration of fractures in the bedrock. The strong high (H_5) and its southwestward trend suggest the possible existence of a fault in the NE -- SW direction. This appears to confirm the postulated fault at the southern end of the reef mass by Shatford (1959).

According to Shatford (1959) there are two sets of fault and fracture systems, viz, the earlier ones (direction NE -- SW) associated with pre-cretaceous tectonics; the later ones associated with Cretaceous and later tectonics.

He further states, "with respect to the Redwater field, the evidence indicates that the strongest faulting in a NW -- SE direction, took place approximately at the borders of the field, and the borders of the biohermal zone; in a direction northeast southwest it took place mainly at the saddles and at the NW and SE boundaries of the field."

It is therefore probable that the areas bounded by zero contours on the border of TWP 56-57 and Range 21 are over the NE -- SW fault system across the reef saddle postulated by Shatford (1959).

Shatford (ibid) considers that highs H_2 and H_5 are probably the result of intersecting fault systems. H_4 occurs over such a zone. According to him lows L_1 (C) and L_2 (D) are over the reef highs.

Total Counts - 1951 Data:

The radiation values left after the drainage correction were averaged for every one half mile for different soils, viz, clay loam, loam, sandy loam and sand. The averaged value for each soil type was multiplied by the soil factors (Table XXVII).

TABLE XXVII: Soil Factors

SOILS	MEAN RADIATION VALUE[a] in cps	FACTOR
Clay loam	327	327/ 327 = 1
Loam	304	304/ 327 = 1.07
Sandy loam	260	260/ 327 = 1.22
Wooded sands	254	254/ 327 = 1.28
Sands	227	227/ 327 = 1.43

(a) From Table XXV.

All the values falling within 1000 feet of the soil contacts were multiplied by the factors for different soils adjacent to the contact and averaged. This was done to avoid to some extent anomalous results due to one or the other soil.

The procedure described in the preceding paragraphs brought the different soils to a clay loam fraction, thus resulting in a map of the area as if it had been covered with clay loams. The mean and the standard deviation were calculated according to Tripp's method (Tripp, 1948). The mean value was subtracted from the original and a plot of the ratio between the residual and standard deviation was made and contoured. The resulting map (Figure 32) was tested for 4 standard deviations as in the case of Radium count, and it therefore shows only anomalies.

Results:

There are three main anomalies in the map area (Figure 32), viz A, B and C.

Anomaly A:

Anomaly A overlies the production. The southward extension in Twp. 55, R.21 and westward extension in Twp. 57, R.22, is due to the method of interpretation used. This becomes quite obvious when

AERORADIOMETRIC SURVEY OF REDWATER OILFIELD
Alberta, Canada

Figure 32

Figure 32 is compared with Figure 33. In the case of Figure 32 sands were not differentiated according to the parent material, which was done in the case of Figure 33. This discrepancy could have been corrected, but the writer omitted it to show the differences caused by making soil correction according to the parent material.

Anomaly B:

The area covered by this low is underlain by soils rich in organic matter and lime (15%). Uranium forms complexes with carbonates which are stable between pH 7.5 - 10.9 (Scherbina, 1957) and pH 6.5 - 11.5 (Miller, 1955). Manskaia et al (1956) have observed that increase in pH 7-9 increases the solubility of uranium in solution. It is therefore probable that either no uranium was deposited or has been carried in solution.

From the foregoing discussion, the writer concludes the low under consideration is due to the soils in the area.

Anomaly C:

The writer enquired from Imperial Oil Limited regarding the presence of any wells in the anomaly in Twp. 55 - Range 22, and the reply to the enquiry is presented below.

"There are seven holes in this township of which five had gas shows (four in Viking and one in the Cooking Lake). Two of the Viking tests were of commercial size, one of five million, and one of thirty-five million cubic feet per day. In addition, one well had a show of oil (gassy oil - cut mud) from the Cooking Lake. None of these wells encountered reef, although three were drilled deep enough to have found reef had it been present" (personal correspondence, Skeels, 1959).

This anomaly is also present in Figure 33, but is represented by zero contour surrounded by strong highs.

Total Count - 1957 Data:

The total count data for 1957 was interpreted by Ellingwood, as mentioned earlier. His method of interpretation and results are described below (Ellingwood, 1959).

Method:

"The total count values from the radiation profiles were scaled off at two-tenths of a mile intervals along east-west flight lines, and plotted on the soil map (Figure 30) of the area. All values within 500 feet of bogs and small streams and within 2640 feet of the North Saskatchewan River were discarded. The remainder were tabulated according to soil types, viz, clay loam, loam, sandy loam and sand, depending upon the parent material. Only readings more than 1000 feet from the contacts between soil types were used. The arithmetic mean was found for each soil, and the soil factors were computed (Table XXVIII).

TABLE XXVIII: Soil Factors for 1957 Total Count Data

SOIL TYPE	PARENT MATERIAL	MEAN	FACTOR
Clay loam	Lacustrian	220	1.00
Loam	Bedrock	215	1.02
Loam	Alluvial Lacustrian & Till	211	1.04
Sandy Loam	Silt till	217	1.01
Sandy Loam	Aeolian	201	1.09
Meadow	Aeolian		1.09
Sand	Aeolian	195	1.13
Sand	Aeolian-Organic	191	1.15

"The clay loam was taken as one and the remaining soils were brought to its level. Meadow soils cover only a small area, and the factor was estimated by visual examination.

"The values remaining on the map after drainage corrections were multiplied with appropriate sine factors (Table XXVIII). Where two soil types were in contact and the reading was within 200 feet of the contact, the average of the two factors was used; where the readings were between 200-1000 feet from the contact an average factor was derived by doubling the factor for the soil type directly underneath, adding the factor for the adjoining soil type, and dividing the total by three. This was done to minimize possible errors caused by variations in aircraft speed and wandering from the flight line. The values in the wooded sandy areas were reduced by 10%.

"An arithmetic mean and standard deviation of the corrected values were calculated according to Tripp's method (Tripp, 1948). The mean was subtracted from the corrected values and plot of ratio between the standard deviation and the residual was made. The standard deviations were averaged to one half mile centers and contoured. The background was taken as + 1.5 standard deviation. Elkins Test (Elkins, 1940) was applied to define anomalous areas, and the final map (Figure 33) shows only these anomalies.

Interpretation:

"The low anomaly in the northwest corner of the map conforms almost exactly with an area of bog, narrow strips of sand, and a soil which is a mixture of sandy loam and loam. This anomaly is probably due to the effects of these soils.

"A large low anomaly lies at the boundary between TWP. 57, R.21, and TWP. 57, R.20. The southern section of this anomaly lies in an area which is mostly bog and where little control was available. The northern end lies largely in an area where two soils are in contact. The combination of these factors makes the validity of the anomaly questionable.

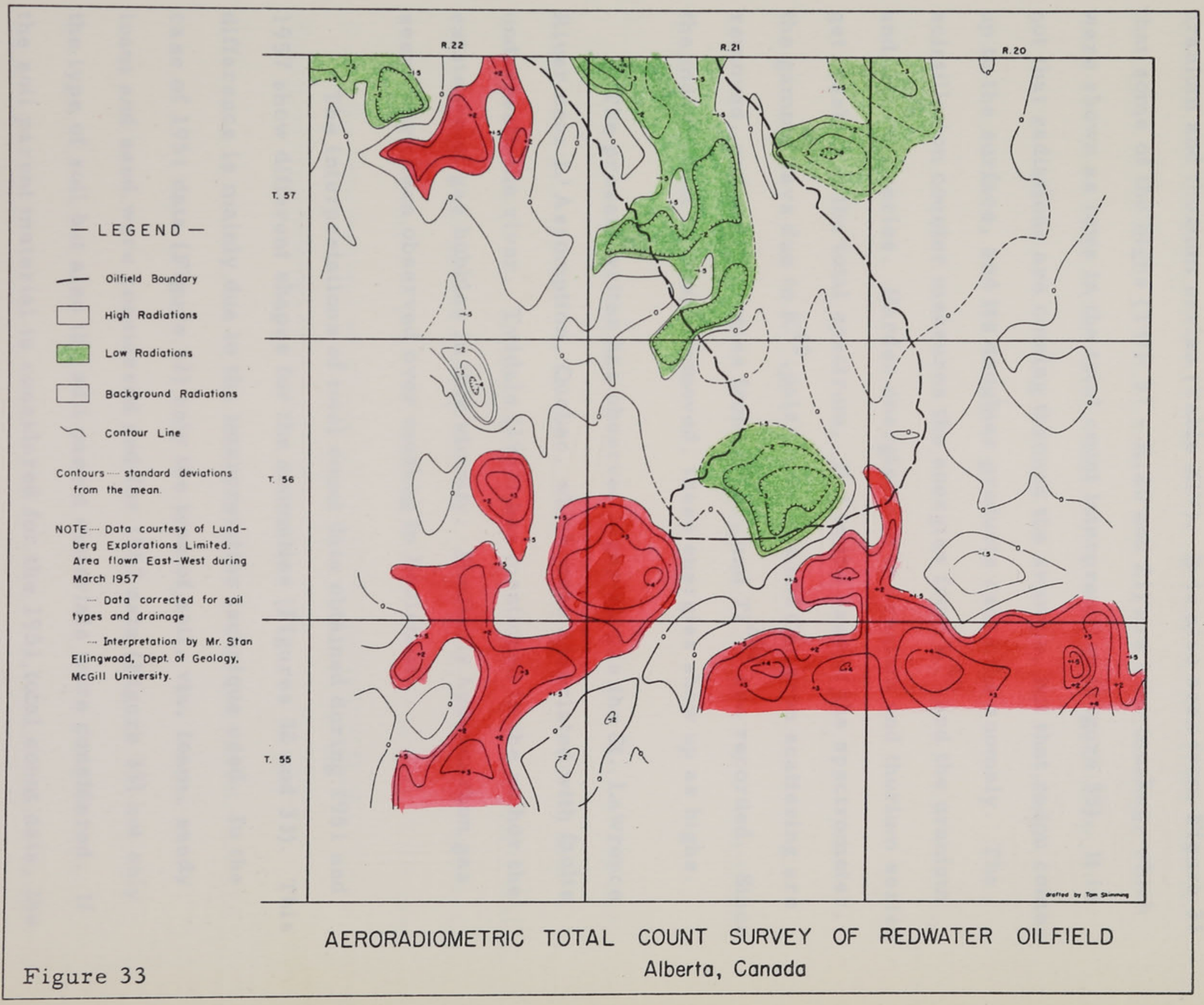
"The remaining two lows are not explained by any of these factors. The one in TWP. 56, R.21 occurs in an area which is partially boggy, but the bogs are not as extensive in this area as they are in the areas mentioned above.

"The largest low covering much of the western half of TWP. 57, R.21 offers the best possibility. Bogs are not abundant here and the anomaly crosscuts five of the eight soil types found in the area, so neither of these can be considered as possible causes of the anomaly. The direction of elongation of this anomaly points towards the other interesting anomaly and may indicate that these may be both on the same oilpool. The North Saskatchewan River crosses the area between them, and its influence could cause them to be separated. It is interesting to note that the zero contour, particularly on the east side and less so on the west side, also follows this elongation direction.

"Two other areas, though not anomalous, are of potential interest because they are relatively much lower than the surrounding area. One of these extends southwestward from the anomaly in TWP. 56, R.21. Should this anomaly prove to be continuous with largest one, this relative low might be a continuation of the same structure and may also be a source of oil. The other relative low is on the west side of TWP. 55, R.21. It is quite small as compared to the other and probably unimportant."

Discussion:

It is observed from the comparison of Figures 31 and 33 that a greater part of the anomalous high area in Figure 31 has been reduced



AERORADIOMETRIC TOTAL COUNT SURVEY OF REDWATER OILFIELD
Alberta, Canada

Figure 33

in its areal extent. This reduction is caused by the removal of energies less than 1.60 Mev, which includes K^{40} and some of the members of the uranium and thorium series (Table XIV). It is also seen from Figure 31 that some of the highs (TWP 57 - R. 20 and 21) are over muskeg, which were shown as lows in the total count interpretation (Figure 33). It is not that radiations are coming through the swamps, but that radon comes up to the surface, and its daughter products cause the anomaly. The scintillation counter measures the energies from K^{40} and the uranium and thorium series. Harder energies due to uranium and thorium series get masked in the total spectrum. But in the case of the spectrometer, the gamma rays due to K^{40}, pair production and Compton scattering are removed, and only energies from Bi^{214}, and Tl^{208} are recorded. Since the mass effect has been removed, these energies show up as highs.

The present writer has observed highs across the St. Lawrence River near L'Assomption, Quebec, which were associated with faults underneath the river. Twidale (1957) has mentioned to the author the existence of gas bubbles in this vicinity. Similarly hydrocarbon gas seeps have been observed over muskeg in Louisiana.

The interpretations of total count data obtained during 1951 and 1957 show different shapes for the anomalies (Figures 32 and 33). This difference is mainly due to the interpretation technique used. In the case of 1951 data (Figure 32) only the type of soil, viz, loam, sandy loam and sand were considered and for 1957 data (Figure 33) not only the type of soil but also the soil parent materials were considered. If the soil parent material is considered for the 1951 total count data, the resulting map (Figure 32) would be similar to Figure 33. In order to show the importance of making soil correction according to the soil parent material, the results have been presented in this form.

A study of the heavy mineral content of sands from the Redwater Area did not reveal any concentration of radioactive minerals such as zircons. Adams et al (1958) have shown that the radioactivity in sands is mainly associated with the quartz. Furthermore, Kulp (1955) and Faul (1954) consider that radon is not released from perfect lattice minerals. Delwiche (1958) has shown that radon from zircons only contributes about 1/100th of the total radon content of soil air. In the aero-radiometric surveying with gamma ray spectrometer only energies above 1.60 Mev are recorded. The energies above 1.60 Mev are due to Bi^{214} and Tl^{208}, which are daughter products of radon and thoron respectively. It is therefore concluded that the heavy minerals have contributed a very little amount of radioactivity to cause any significant radiation patterns.

The writer considers that observed radiation data reflect the soil map, which is similar to the conclusion drawn by Brown (1955) and Gregory (1957). It is further observed that the residual anomalies left after making the necessary corrections for soils and drainage features described earlier are probably associated with the oil pools. This confirms the observations of Merrit (1955; 1957), Alexeyev et al (1955), Tripp (1957), Laubenbakh et al (1958).

The anomalies (lows) shown in figures are discontinuous and the "halo" or "ring" or "edge" effect is not completely developed at the flanks of the pool. Similar observations have been made in other geochemical investigations (McDermott, 1940). Ransone's (1957) geochemical map of Sonjourer field, Texas shows scattered highs around the edges of the pool.

Several authors from their studies of different kinds of geochemical indices have concluded that generally higher than normal values are present in the form of a ring or halo at the flanks of a pool (Rosaire, 1938, 1940, 1952; Horovitz, 1939, 1945, 1954, 1957b; Mogilevskii, 1940; Pirson, 1940; Ransone, 1948; Lundberg and Isford, 1953; Merrit, 1955, 1957; Sokolov, 1956; Tripp, 1957).

According to Yasenev et al (1954), "The ring shape of the anomaly (halo effect), in particular, does not have any scientific foundation."

The same authors further state, "It would be possible to speak about definite forms of anomalies if the actions were taking place in homogenous medium. Geochemical methods investigate the migration of gas, which takes place under the most diverse conditions. The forms of anomalies must, therefore, be diverse, and this is what actually we meet in practice."

The present writer considers that the processes of formation of various geochemical anomalies are numerous and complex, and depend upon variety of physico-chemical conditions occurring in nature. Many of these processes and the resulting anomalies probably have a cause and effect relationship to one another. The presence or absence and shape of an anomaly depend upon the geological and geochemical environment.

For example Yasenev et al (1954) have observed that methods based on direct indications (different variety of gas surveying) give quite satisfactory results in geosynclinal areas, but in many instances fail to give positive results in a platform area.

Gleeson (1959) from the studies on the formation of heavy metal anomalies around sulphide deposits has concluded that the existence or absence of an anomaly depends upon the oxidizing or reducing environment.

Kovda et al (1951) according to Kartseve et al (1954) have observed different backgrounds and anomalous values for different climatic zones.

Kartsev et al (1954) state, "in the interpretation of the results of hydrochemical surveys of ground and surface waters in order to establish the presence and position of tectonic upheavals, and the tracing of surface tectonic lines, it is essential to consider climatic, topographic, hydrogeological, and lithological factors."

The foregoing discussion confirms the views of the present writer that the geological and geochemical environments are important in the formation, and the presence or absence of anomalies.

It therefore seems probable that geomorphic features such as muskeg and slough, rivers, some of the soils (especially those rich in lime and organic matter) and the structural features (faults, fissures, and fracture systems, etc.) have played their part in causing the edge effect to be discontinuous. In order to explain the relationship of scattered highs at the flanks and lows over the Redwater pool, a mechanism is suggested, and is discussed in chapter VI.

Conclusions:

1. Not only the soil parent material, but also the type of soil, viz, sands, sandy loam, and loam etc. should be considered in making the soil corrections.

2. The lows left after the drainage and soil corrections (Figures 31 and 33) are probably related to the oilpool.

3. The radium data suggest the possibility of faults, and the high appears to lie over Shatford's (1959) postulated fault and fracture systems.

4. Anomalous highs can be observed through swamps and muskeg areas from the airborne radium data.

5. Conclusions nos. 3 and 4 above suggest that airborne data may be very useful in delineating not only oil bearing structures, but also various structural features (faults and fracture zones).

6. The geochemical and geological environments are very important in the formation or absence of geochemical anomalies.

7. The similarity of low anomalies (Figures 31 and 33) obtained with and without using soil factors, shows that factors can be utilized in making soil corrections.

CHAPTER VI

MECHANISM TO EXPLAIN THE FORMATION OF RADIOMETRIC ANOMALIES

General:

This chapter contains general considerations about the formation of various types of anomalies, followed by the writer's presentation of mechanisms allowing upward migration of materials through fissure systems. Much of the information described in the following pages is based on other people's data.

Several hypotheses based on various different ideas have been proposed to explain radiometric anomalies. There are two schools of thought regarding the origin of radioelements causing radiometric anomalies, as follows:

a) The radioelements are surficial in origin (Merrit 1952, 1956, 1957; Tripp, 1955, 1957, Kellog, 1957, Sokolov, 1956).

b) The radioelements are deep seated in origin (Lundberg 1952, Lundberg 1956; Lundberg and Isford, 1953; Alexeyev et al, 1955).

a) Radioelements Surficial in Origin:

Merrit (1957) considers that gaseous hydrocarbons migrate from the edges of oil pools towards the surface. The hydrocarbons on reaching the surface cause evaporation of water. The water from the side moves to take its place, thus bringing in soluble salts and enriching the place of evaporation. This enrichment causes a band at the periphery of production.

According to Tripp (1955, 1957) the radiometric anomalies are surficial, and are a result of diffusion of gaseous hydrocarbons. The diffusion of gaseous hydrocarbon increases evaporation, which results in the precipitation of radioelements. The radioelements and hydrocarbons are adsorbed to the surface of certain aluminum silicate structures. The ionic radii of hydrocarbons and radioelements are very similar, but the radioelements are more mobile, and are, therefore, carried laterally in surface ground waters. This results in a deficiency of radioelement content over the pool coincident with a maximum in the hydrocarbon content.

Kellog (1957) considers that radiometric anomalies are surficial. They are due to the solution of mineral matter in rocks through which ground water has been required to move by the controlling geologic structure.

According to Sokolov (1956) filtration or microfiltration may draw the radon emanation, which is generally present in soils, from relatively shallow depth. The filtration or microfiltration is due to gaseous diffusion. He admits it is an oversimplified explanation.

b) Radioelements are deep seated in origin:

Lundberg (1952) considers that radiometric anomalies existing at the surface are caused by the movement of radioactive substances from the deep seated levels of the oil accumulation.

Lundberg and Isford (1953) consider that water rich in chlorides with little or no sulfate will dissolve large amounts of radium from the rocks at great depth. The chlorides from deep waters diffuse continuously towards the surface, where they are washed out by the surface runoff.

The chlorides washed by the surface runoff are replenished by the solution of more salt from the rocks. They state that if there is an oil or gas deposit in the way, this diffusion would be interrupted and the chlorides washed out by the surface runoff will not be replenished, and this would cause a low over the pool.

Sokolov (1956) does not agree with the views of Lundberg (1952), and Lundberg and Isford (1953) on the grounds that water under the oil-pool may not be richer in radium than the water above the pool, and there is plenty of sulphate above the oilpools.

Alexeyev et al (1955) state many of the oil deposits are associated with tectonic structures. Generally, the rocks in the tectonic regions are fissured, fractured, and faulted. These authors consider that these fissures, fractures and faults serve as channelways for the migration of subterranean water to the surface. The subterranean water containing radium as radium chloride or sulfide, on coming in contact with the surface waters, will precipitate radium sulphate.

Various writers have thus invoked several processes; (a) diffusion of gaseous hydrocarbons causing increased evaporation at the surface resulting in the deposition of salts in solution in the ground or surface water; (b) diffusion of salts in solution or otherwise to the surface, (c) migration of subterranean waters rich in salts to the surface.

The role of diffusion as a process for the migration of gases and salts is controversial. Most probably it does play some part in the migration of gases and salt, but the extent to which it does has not been fully investigated.

The presence of hydrocarbon and hydrochemical anomalies as discussed below suggest that hydrocarbons and water do migrate more or less vertically towards the surface.

Most of the authors (Lundberg, 1952; Lundberg and Isford, 1953; Merrit, 1955, 1957; Tripp, 1955, 1957; Sokolov, 1956; Kellog, 1957) have not considered the probable presence of microfractures in the strata. Microfractures play an important part in the formation of mineral deposits. According to Umpleby (1936) similar fractures may exist in oil strata, and serve as avenues for the vertical movement of solutions. The present writer agrees with this observation. The view is further strengthened by the paucity of fractureless building stones. Moreover, photogeologists have observed that the intensity of fractures increases outward from the centre of the structures (Blanchet, 1957; Mollard, 1957, 1958).

Link (1951) has suggested that surface fractures or fissures may serve as effective avenues for the escape of oil and gas. He has observed oil and gas seeps at the surface around the Norman Wells pool in North West Canada, which is an example of coral reef reservoir. According to him (1959):

"The oil and gas seepages which occur on the delta of so-called Bosworth Creek at the Norman Wells field appear to come from the outcrops of upper Devonian sandstones of the Imperial series. However, they actually are caused by oil and gas migrating via fractures which extend from the surface down through the underlying Ford Creek shales and into the Devonian Reef (Kee Scarp) reservoir. The Kee Scarp Reef lies within the Fort Creek shales which are overlain by the Imperial series of upper Devonian age.

"Proof of the above interpretation was the fact that oil and gas was found from the grass-roots down in ever increasing quantities as the cable-tool hole discovery well was drilled under my supervision".

Russel (1958) states:

"Several uranium ore deposits are located above or near producing

oilfields where natural gas could move along faults from the gas reservoir beds to the ore zone. This situation is present at both Lance Creek, Wyoming and Cement, Oklahoma".

Regarding Cement, Oklahoma, he has this to say:

"Twenty-nine tons of uranium ore, containing 1.28% U_3O_8, has been mined from the crest of an oil producing anticline at Cement, Oklahoma. The mined ore body was controlled by nearly vertical fractures; however, gamma-ray logs from widespread drill holes indicate anomalous radioactivity at a depth of about 100 feet in sandstone bed.

"Oil and gas have been produced from a depth of 1,800 feet but pockets of gas have been encountered within 500 feet of the surface[12]. Extensive faulting and fracturing have provided adequate channels for the migration of both natural gas and ore solutions".

Furthermore, the rocks in the vicinity of the field have been leached to some extent. Stafford and Beroni (1957) had mentioned to the present writer the existence of radiometric "highs", at the flanks of the pool which appear to have no relation to the uranium deposit.

In view of the foregoing discussion, the possibility of fractures playing a role in the migration of subterranean waters or gases towards the surface cannot be eliminated.

In order to suggest a plausible working mechanism, which to some extent is a synthesis of various hypotheses previously proposed, the following subjects will be considered:

a) Migration of hydrocarbons

b) Migration of water

c) Avenues or passages through which hydrocarbons or water may migrate.

Migration of Hydrocarbons:

Surface manifestations (macro-indications) such as oil and gas seeps, sulphur water, paraffin dirt beds, sour dirt etc. have resulted

in the discovery of many oil and gas fields (Table XXIX). The presence of macro-indications suggested the existence of microindexes, which led to the development of many kinds of new techniques to measure the content of soil air, hydrocarbons, mineralization, paraffin dirt, waxes etc. in the soils.

Several investigators have observed a variety of geochemical indexes which are due to the migration of gaseous or liquid hydrocarbons from the oil or gas pools towards the surface (Laubmeyer, 1933; Sokolov, 1933, 1956; Rosaire, 1938, 1940, 1952; Horovitz, 1939, 1945, 1954, 1957; McDermott, 1940; Pirson, 1940; Merrit, 1942; Tripp, 1944, 1957; Ransone, 1948, 1957; Yasenev et al, 1954; Louis et al, 1955).

Rosaire, Horovitz, McDermott, Merrit, and Ransone have been associated with each other at some stage during the development of geochemical methods of prospecting for oil and gas, based on the idea that gaseous and liquid hydrocarbons migrate to the surface. All of these authors consider that migration of hydrocarbons towards the surface from the oil or gas pool takes place near the edges of the pool.

Geochemical Survey, Dallas, Texas, state:

"From January, 1942 until January, 1957 the Company, Geochemical Surveys, developed, leased, and drilled or caused to be leased and drilled, 98 prospects which were first class geochemical anomalies. Of these 98 prospects, 25 resulted in profitable oil or gas fields in which Geochemical Surveys has a participating interest ..... of the 98 geochemical prospects to date, the first 25 were tested without benefit of additional seismograph or core drill work; 5 field discoveries resulted. The remaining 75 geochemical prospects were thoroughly detailed with one of the structural tools and 20 field discoveries resulted".

Louis et al (1955), from the studies of Vellinger on heavy hydrocarbons in the soil of Guaro anticline, have concluded that in some cases the application of geochemical prospecting can bring in some useful information to indicate the presence of petroleum.

TABLE XXIX: A Partial List of the Oilfields Drilled on the Basis of Surface Indications

FIELD	LOCATION	AUTHOR	SURFACE INDICATIONS
Orange	Texas	Deussen et al (1936)	gas seepages, paraffin dirt, and strong sulphur springs
High Island Dome	Texas	Halbouty (1936)	mound, inflammable sulphurus gases
Conroe	Texas	Michaux et al (1936)	gas seepages
South Liberty	Texas	Halbouty et al (1951)	sulphur springs, oil and gas seeps
Cumarebo	Venezuela	Payne (1951)	gas and oil seep, and anticlinal structure
Jennings	Louisiana	Barton et al (1926)	mound and gas seeps
Spindletop	Texas	Halbouty et al (1951)	mound, gas seeps, paraffin dirt, and sulphur water
Maidan-I-Naftun	Persia	Powers (1926)	oil seeps
Gemash	Egypt	Powers (1926)	oil seeps
Iowa	Louisiana	Eby (1948)	surface gas seeps
Lockport	Louisiana	Rosaire (1952)	gas seeps
Sweet Lake	Louisiana	Howe et al (1935)	gas seeps
St. Martinville	Louisiana	Howe et al (1933)	paraffin dirt and gas seep
Cameron Meadow	Louisiana	McGurkin (1948)	gas seeps
Patterson	Louisiana	Rosaire (1952)	gas seeps
Racoon Bend	Texas	Teas et al (1936)	gas in shallow water wells

A list of oil or gas fields discovered on the basis of geochemical anomalies is given in Table XXX.

TABLE XXX: List of Oil or Gas Field Discovered on the Basis of Geochemical : Prospecting (Soil Analysis) by Geochemical Surveys, Dallas, Texas.

	OIL OR GASFIELD	TRAP
1.	Reddin	Pennsylvanian Reef
2.	Adamson	Structural closure
3.	Hardy	Sand pinch outs on structural nose
4.	Willman	Sand pinch outs on structural nose
5.	Spiekerman	Sand pinch outs on structural nose
6.	Ingram	Structural closure
7.	Green Lake	Structural closure
8.	Farrell	Structural closure
9.	Long Mott	Structural closure
10.	Akens	Structural closure
11.	Bird	Structural closure
12.	Gibson	Pennsylvanian Reef
13.	Caldwell Ranch	Sand lens
14.	Sojourner	Sand pinch outs on structural nose
15.	South Crews Fry	Sand lens
16.	Trailer	Sand lens
17.	Gillespie	Sand pinch out
18.	Ballinger Palo Pinto	Porosity trap
19.	N. Weinert	Sand pinch out
20.	Shafter	Structural closure
21.	Section Seven	Structural closure
22.	Plains	Structural closure
23.	Bittern Lake	Sand lens
24.	Seydler	Sand lens
25.	South Crews Gardner	Sand lens

According to Horovitz (1954) out of 109 anomalies revealed by hydrocarbon surveys over a period of 11 years ending in 1953, 39 were drilled, which resulted in 23 productive areas, or in other words 59% confirmation.

Similar studies in U.S.S.R. have resulted in 60% success (Sokolov, 1956).

Evidence indicates that hydrocarbon anomalies are due to oil pools; for instance, Yasenev et al (1954) state:

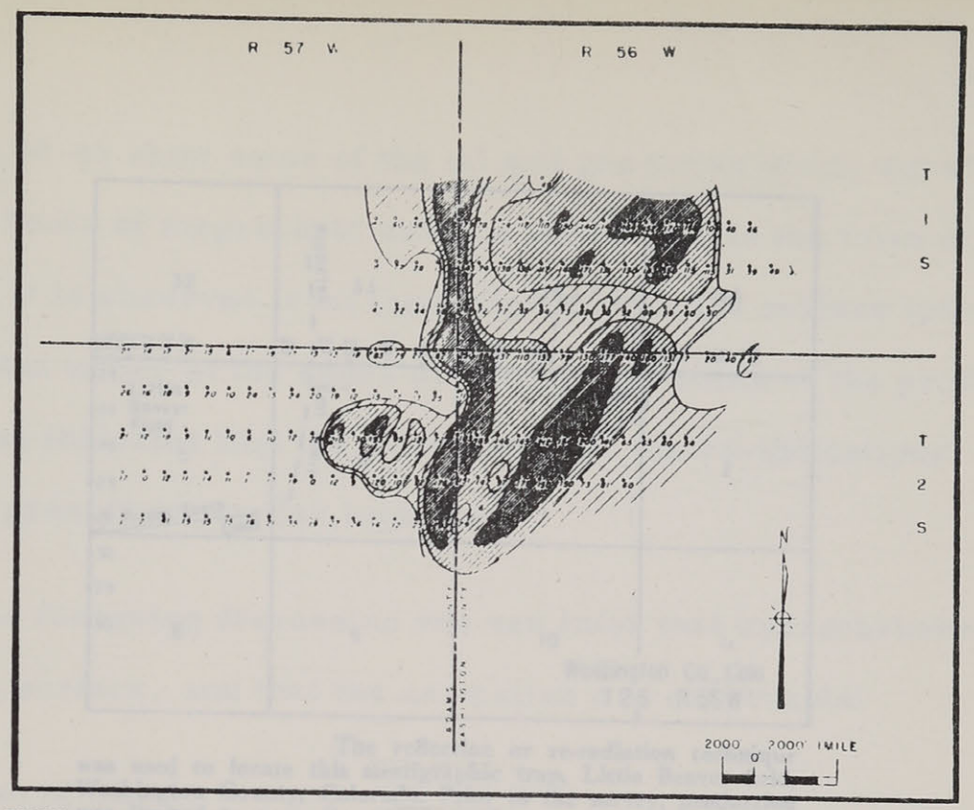
"Numerous investigations concerned with ascertaining the possibility of contemporary formation of heavy hydrocarbons have shown that the possibility of their formation in the subsoil is very small; even if they are formed there, their quantities would lie beyond the limit of sensitivity of present instruments".

Figures 34, 35, 36 and 37 show hydrocarbon and electrical induction anomalies in the vicinity of Little Beaver field, Washington County, Colorado. The two anomalies are coincident.

According to Slattery (1958) electrical induction anomalies are due to the presence of secondary mineralization halos of geochemical origin.

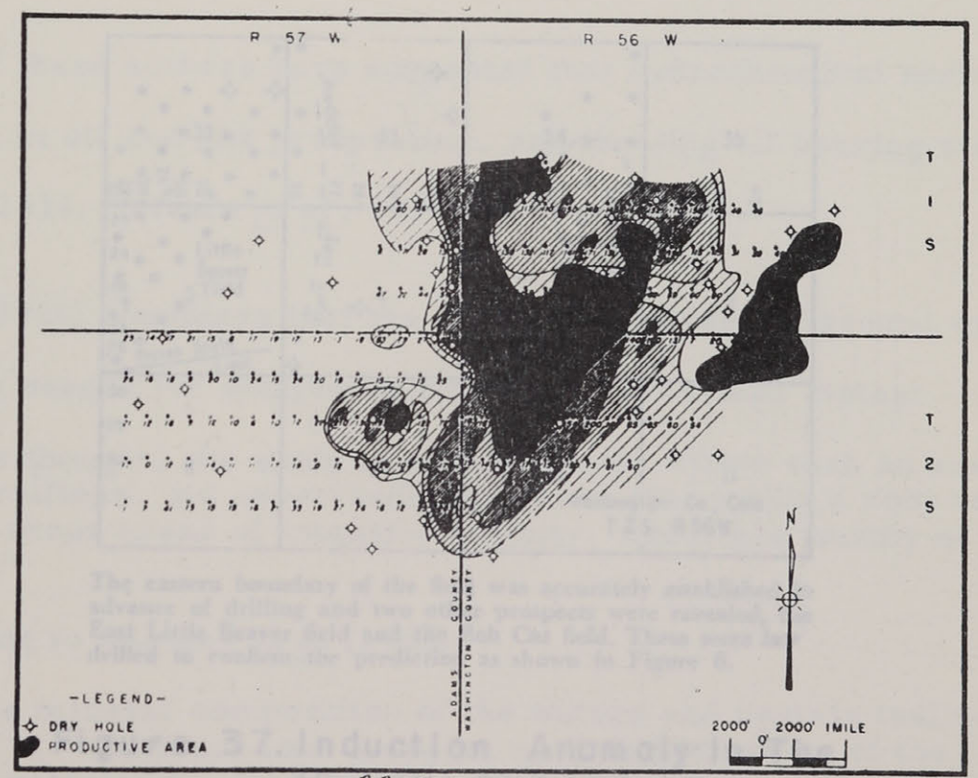
Rosaire (1938) from studies on electrical transient (Eltran) and seismic refraction methods for oil and gas prospecting, and lower drilling rates at the edges of the pools, observed shallow stratigraphic variations. These variations he considered were due to the presence of secondary mineralization at shallow depth. According to him the mineralization may be caused by the vertical migration of hydrocarbons and ground water along bedding planes.

Merrit (1956, 1957) had made similar observations. Slattery's (1958) data seems to confirm the findings of Rosaire (1938), and Merrit (1956, 1957).



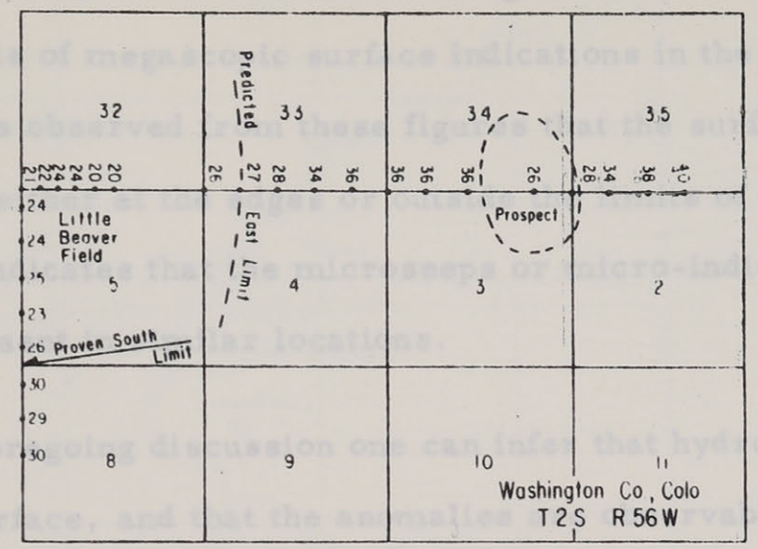
ETHANE and heavier hydrocarbon data in the vicinity of Little Beaver oil field, Denver basin, Colorado. Strong anomalous area which resembles those of other petroleum provinces is recognized easily.

Figure 34. Hydrocarbon Anomaly In The Vicinity Of Little Beaver Field, Colorado (From Horovitz, 1957)



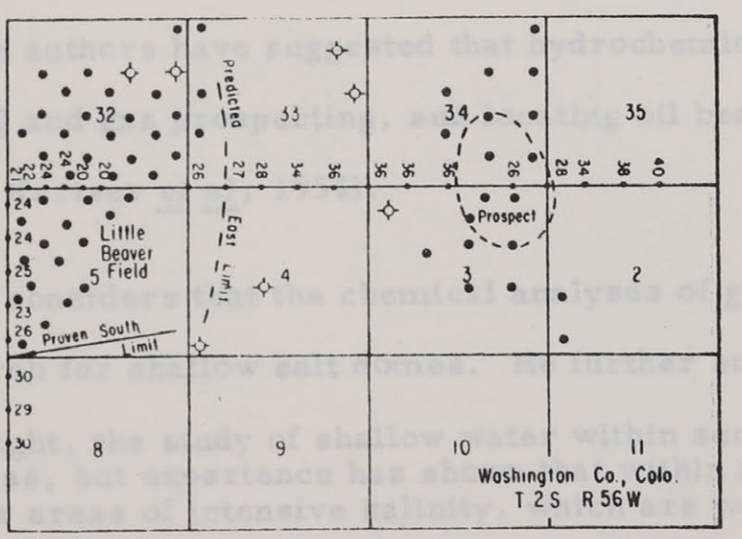
SAME AREA AS SHOWN *ABOVE* plus the development to August 1956. Configuration of the hydrocarbon anomaly is similar to that of Little Beaver field. Small anomaly to the southwest of main feature is associated with a minor producing area. Hydrocarbon data were acquired after discovery of Little Beaver but before discovery of field to east.

Figure 35. Hydrocarbon Anomaly Plus Development To August 1956 In The Vicinity Of Little Beaver Field, Colorado (From Horovitz, 1957).



The reflection or re-radiation technique was used to locate this stratigraphic trap, Little Beaver field, Washington County, Colorado. Prior to the survey, production was limited to a small area along the east line of section six.

Figure 36, Induction Anomaly In The Vicinity Of Little Beaver Colorado, Before Drilling (From Slattery, 1958).



The eastern boundary of the field was accurately established in advance of drilling and two other prospects were revealed, the East Little Beaver field and the Bob Cat field. These were late drilled to confirm the prediction as shown in Figure 6.

Figure 37. Induction Anomaly In The Vicinity Of Little Beaver Colorado, After Drilling (Slattery, 1958)

Figures 38-45 show some of the oil and gas fields which were drilled on the basis of megascopic surface indications in the form of gas or oil seeps. It is observed from these figures that the surface indications are located either at the edges or outside the limits of the production. This also indicates that the microseeps or micro-indications would also be present in similar locations.

From the foregoing discussion one can infer that hydrocarbons do migrate to the surface, and that the anomalies are observable.

Migration of water:

Several authors have observed correlation between the geologic structure and the concentration of salts in subterranean waters (Dott et al, 1930; Case, 1934; Minor, 1934; DeSitter, 1947; Kartsev et al, 1954).

Some of these authors have suggested that hydrochemical surveys may be useful in oil and gas prospecting, and locating oil bearing structure (Minor, 1934; Kartsev et al, 1954).

Minor (1934) considers that the chemical analyses of ground water may aid in the search for shallow salt domes. He further states:

"At first thought, the study of shallow water within such an area seems to be fruitless, but experience has shown that within a zone of salinity there occur areas of intensive salinity, which are worthy of consideration".

According to Kartsev et al (1954):

"Both the mineral composition of the waters and certain individual components of it - salts and ions - can be used as indicators of the occurrence of petroleum. Pecularities of the salt composition of waters in a number of cases may also help to elucidate geological structure".

The same authors claim:

"Soviet science is far ahead of the foreign science in the theory and method of predicting the presence of petroleum by means of hydro-

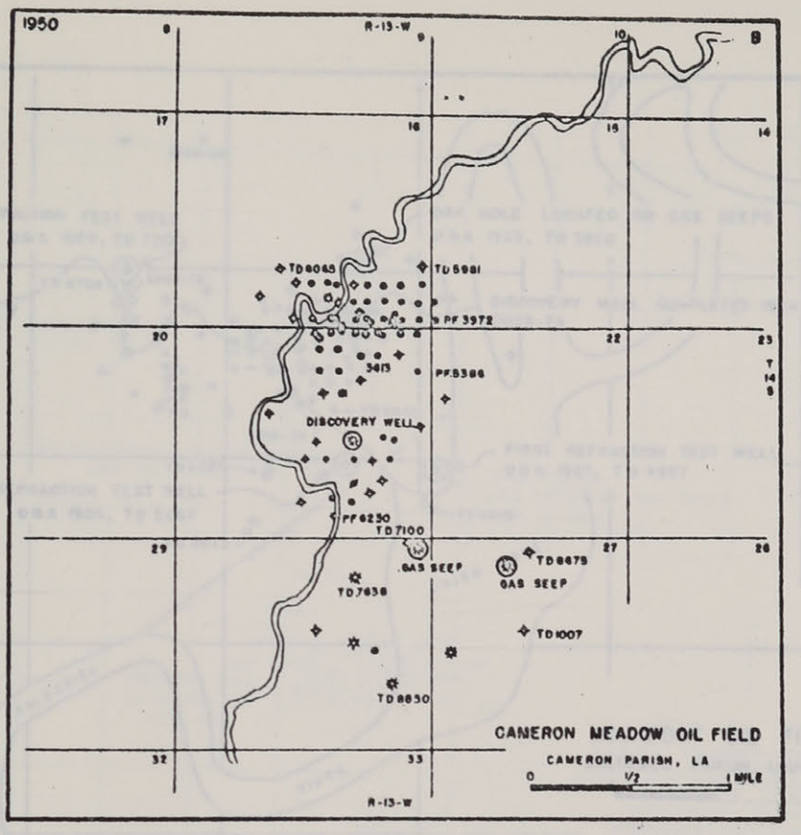


Figure 38 (From Rosaire, 1952)

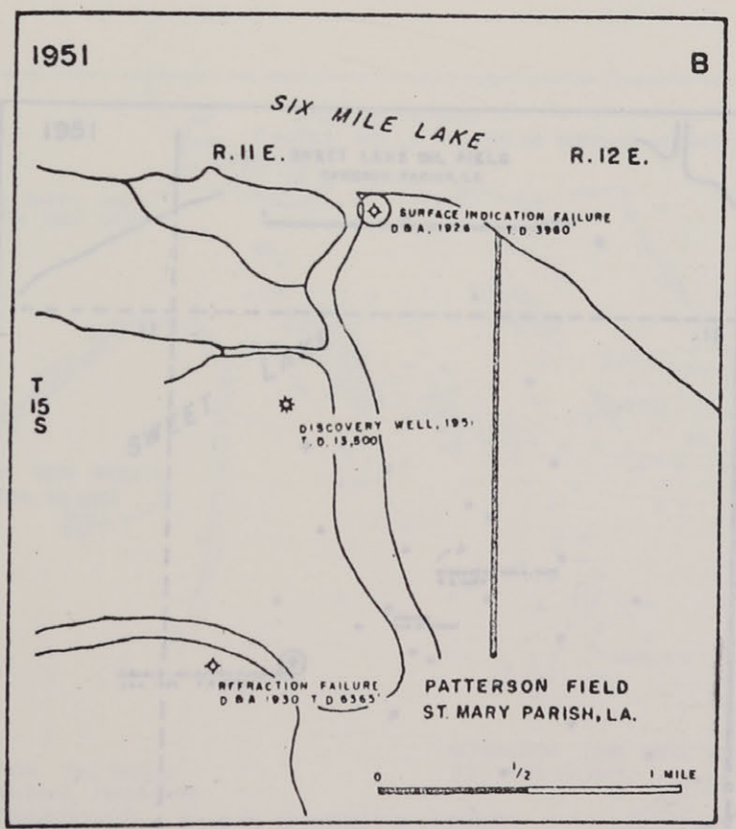


Figure 39 (From Rosaire, 1952)

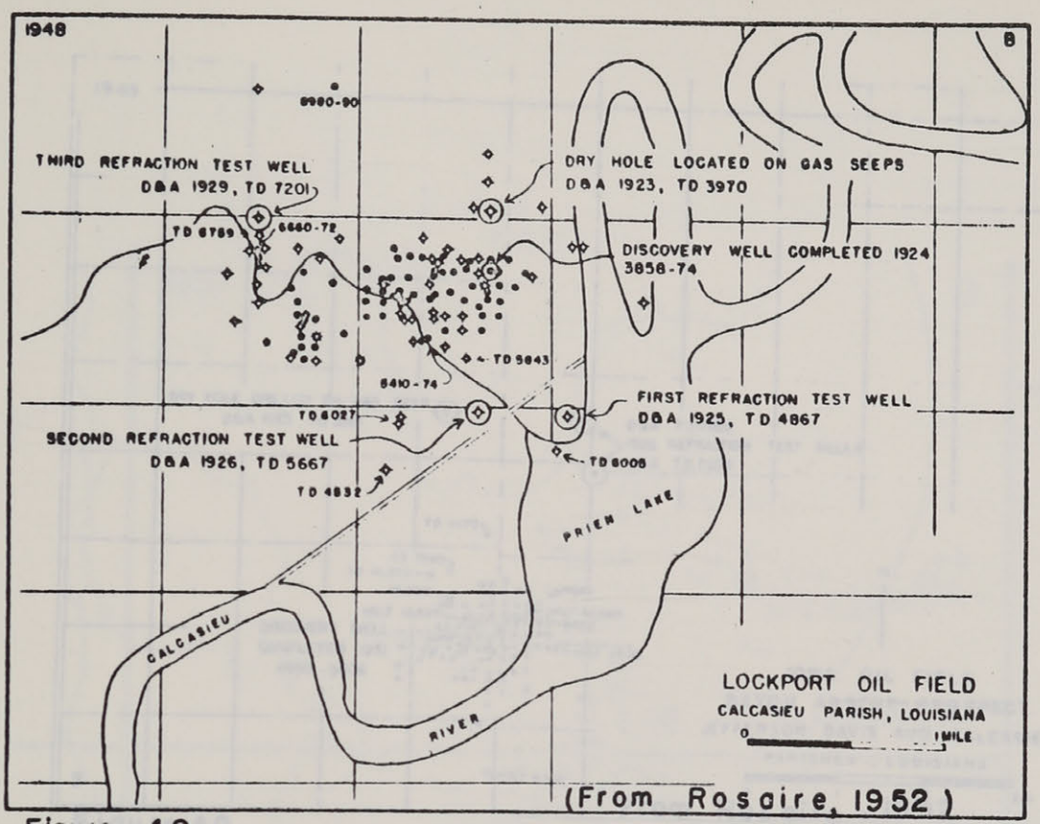


Figure 40

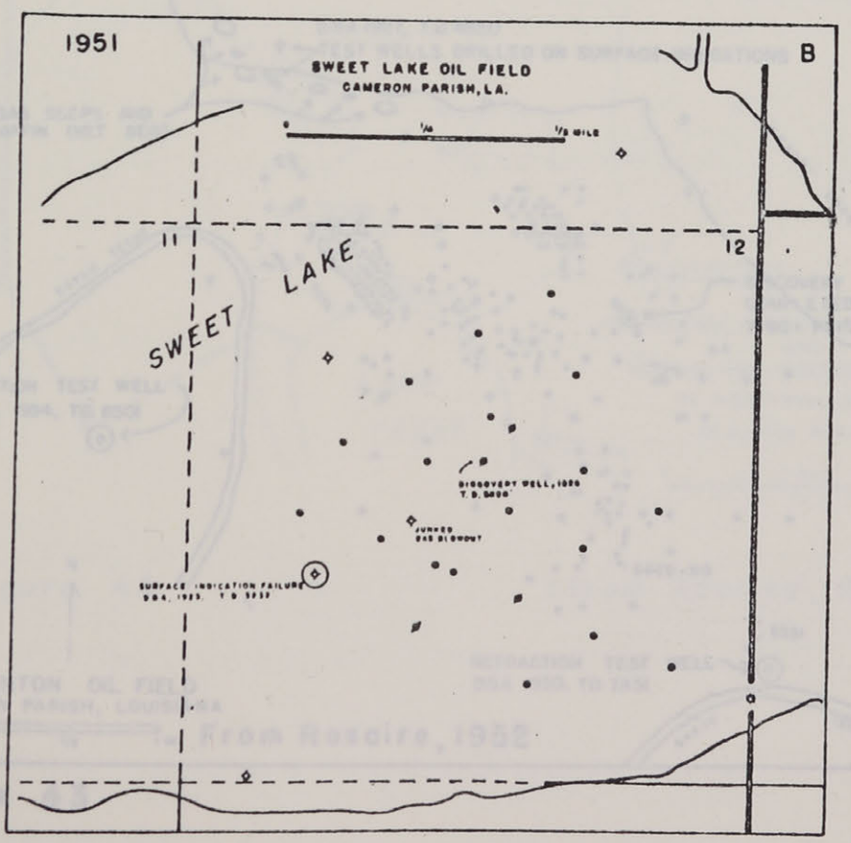


Figure 41 (From Rosaire, 1952)

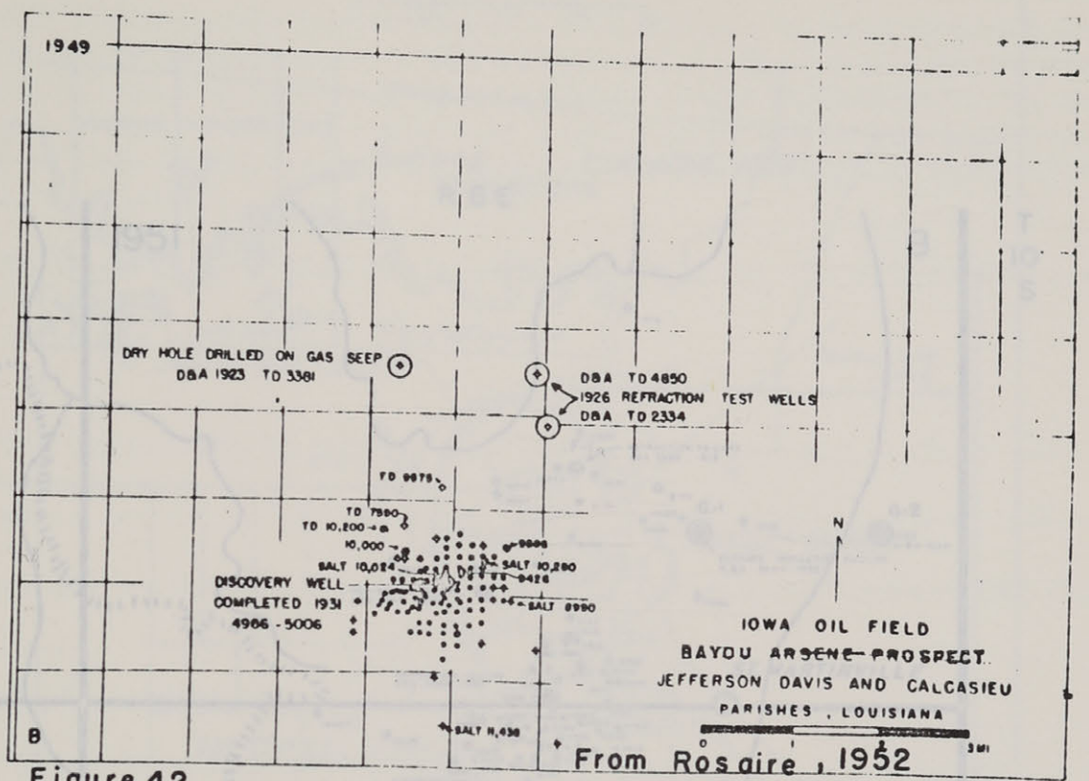


Figure 42

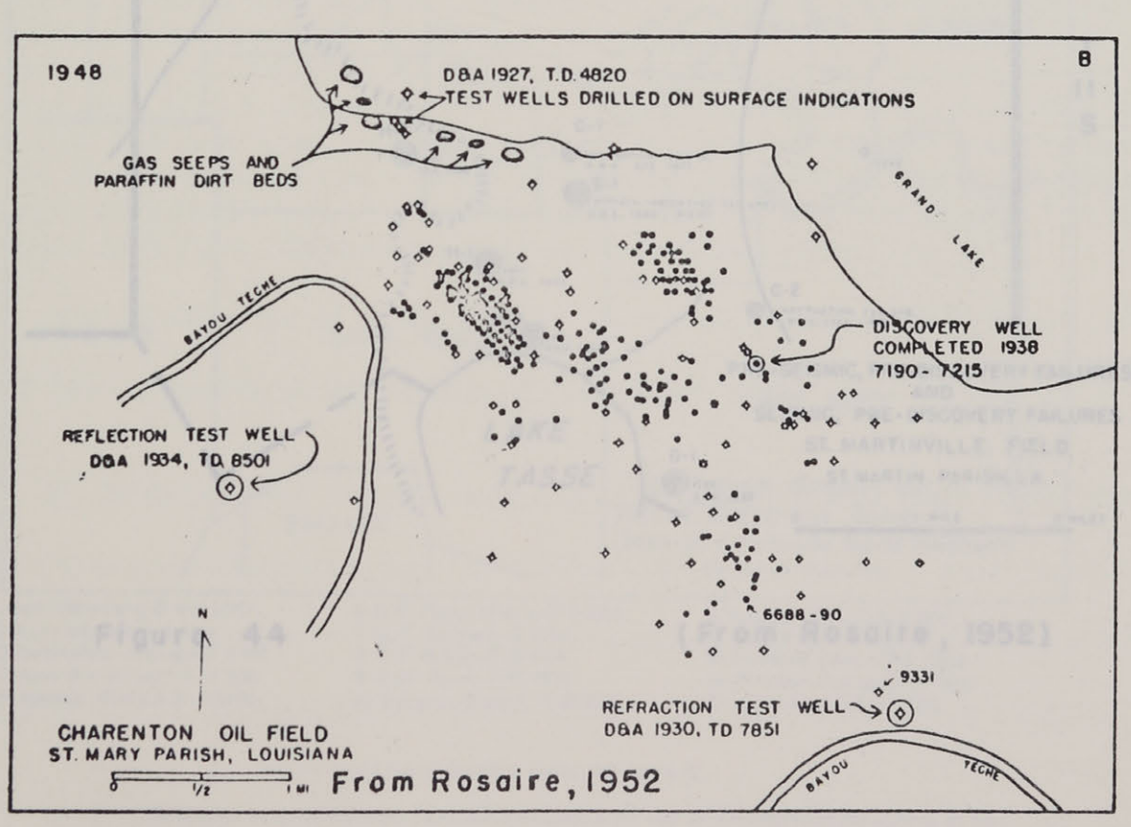


Figure 43

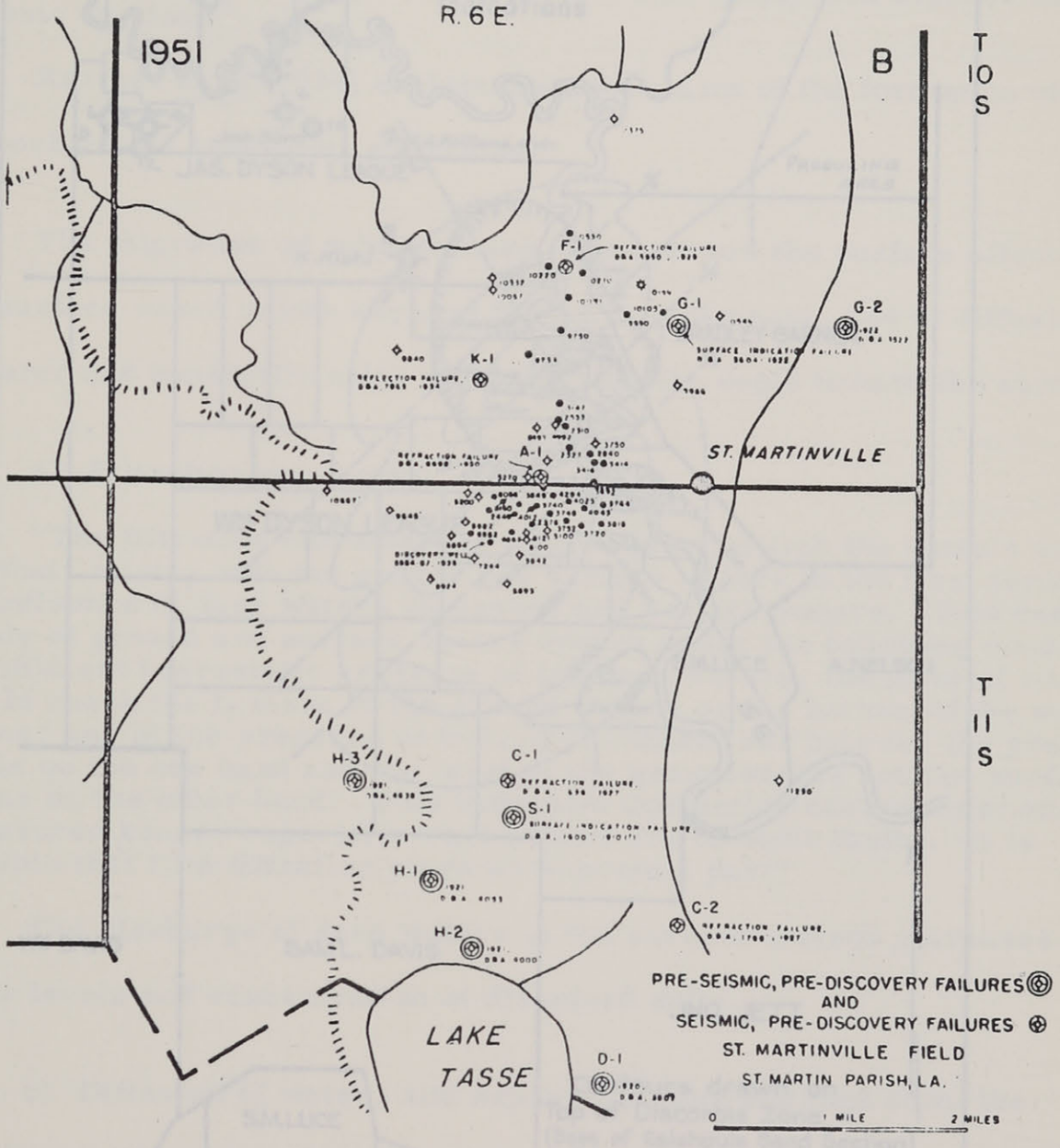
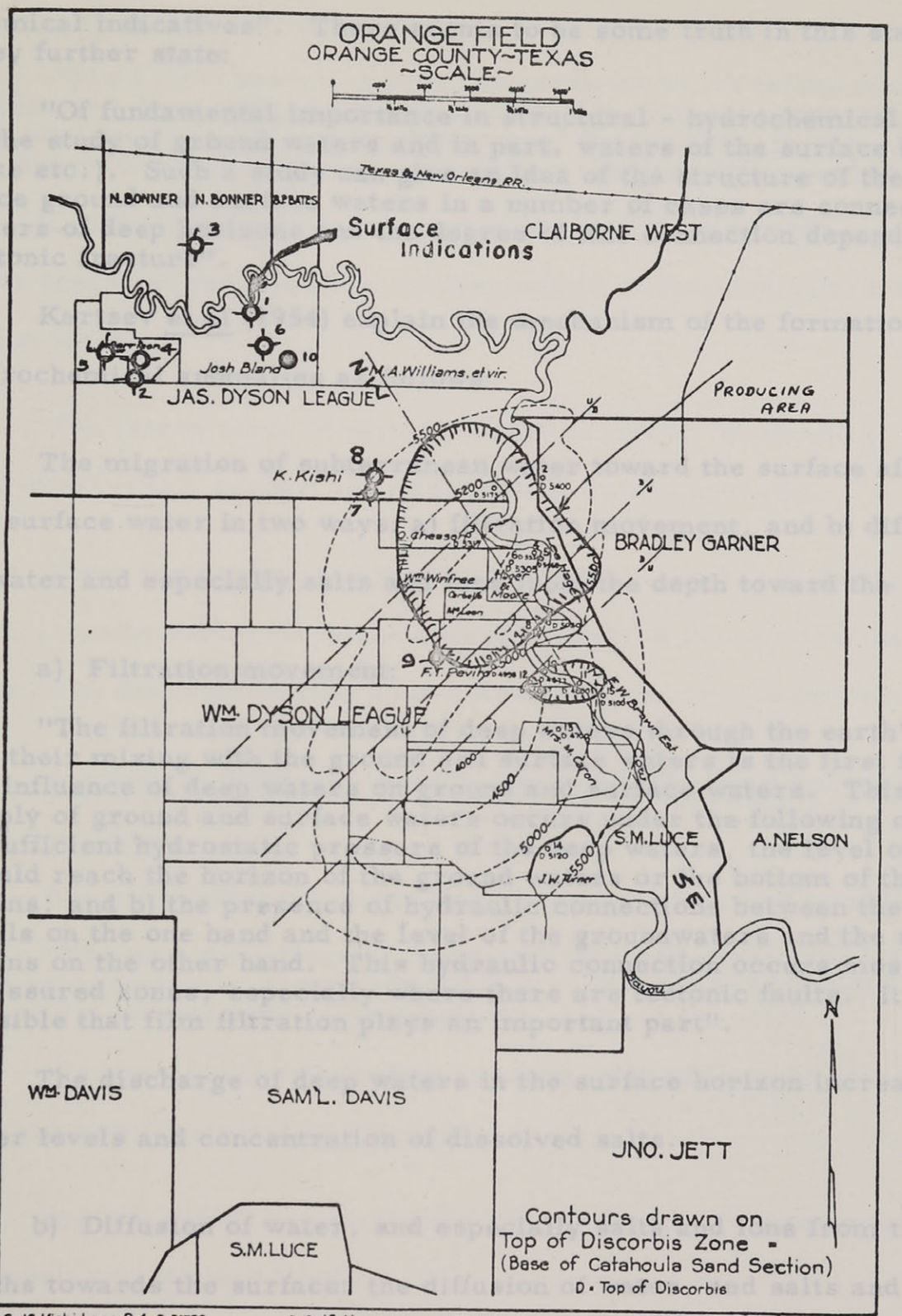


Figure 44 (From Rosaire, 1952)



1-Gulf-Kishi Lang-B-4-D-5175?
2-Sun-Johnson-1-D 5400
3-Continental-Chesson 13-D 5317
4-Sun-Gunstream 5-D 5358
5-Rycade-State A-5-D 5468
6-Gulf-Hager Moore 12-D 5305
7-Gulf-Boyles 3-D 5050
8-Gulf-Boyles 2-D 4774
9-Gulf-Pevito 11-D 4998
10-Rycade-State E-13-D 4677
11-Rycade-State E 2-D 4800
12-Gulf-Pevito 10-D 4677
13-Humble-Caron 1-D 4700
14-Sinclair-Turnex 1-D 5120
15-Sun-Brown 6-D 5100

— · — · — Line of Section shown on Figure 6.

—Structure map of Orange field with contours on top of *Discorbis* zone shown in feet. Location of the several faults together with central graben is shown.

Figure 45 (From Deussen et al, 1936)

chemical indicatives". There seems to be some truth in this statement. They further state:

"Of fundamental importance in structural - hydrochemical surveys is the study of ground waters and in part, waters of the surface basins (lake etc.). Such a study can give an idea of the structure of the depths since ground and surface waters in a number of cases are connected with waters of deep horizons and the degree of this connection depends on the tectonic fracture".

Kartsev et al (1954) explain the mechanism of the formation of hydrochemical anomalies as follows:

The migration of subterranean water toward the surface affects the surface water in two ways: a) filtration movement, and b) diffusion of water and especially salts and ions from the depth toward the surface.

a) Filtration movement:

"The filtration movement of deep waters through the earth's surface and their mixing with the ground and surface waters is the first form of the influence of deep waters on ground and surface waters. This deep supply of ground and surface waters occurs under the following conditions: a) sufficient hydrostatic pressure of the deep waters, the level of which should reach the horizon of the ground waters or the bottom of the surface basins, and b) the presence of hydraulic connections between the pressure levels on the one hand and the level of the groundwaters and the surface basins on the other hand. This hydraulic connection occurs most often in fissured zones, especially where there are tectonic faults. It is possible that film filtration plays an important part".

The discharge of deep waters in the surface horizon increases the water levels and concentration of dissolved salts.

b) Diffusion of water, and especially salts and ions from the depths towards the surface: the diffusion of water, and salts and ions proceeds separately. The diffusion of salts is considered more important because of the higher concentration of salts in solution with depth.

According to Alexeyev et al (1955), Kovda et al (1951) consider that the hydrochemical anomalies and soil salt anomalies, produced by the diffusion of salts, are actually the result of the inflow of deeplying mineralized waters into tectonic dislocation and smaller fissures.

Alexeyev et al (1955) state:

"The hydrochemical anomalies produced by the inflow of deeplying waters are determined by the situations of the lines or zones of tectonic dislocations and by the geomorphology of the terrain. In some instances the hydrochemical anomalies may reflect the deep oil deposits".

Lundberg (1952), Lundberg & Isford (1953) and Lundberg (1956) have suggested the migration of deep seated waters and salts towards the surface.

The isocon maps of salts by DeSitter (1947), Workman et al (1948) and Wuest (1951) suggest the migration of waters upwards.

From the foregoing discussion it is inferred that probably the subterranean waters do migrate upward towards the surface; the migration may be by diffusion or film filtration movement, or a combination of both.

Avenues or passages through which hydrocarbons and water may migrate:

Blanchet (1957) concluded from a study of many oil structures that:

"The total deviations in the statistical mean direction of the fracture sets, when measured and analysed, are found to be related to structural or stratigraphic anomalies".

His observations regarding fracture intensity versus structural position are illustrated in Figure 46.

Mollard (1957) has confirmed Blanchet's (1957) observations. According to Mollard (ibid):

"From the fact that surficial lineaments directly overlie bedrock fractures, which is indicated by the nature of leaching processes described earlier, there appears to be an attractive possibility that a controlled programme of geochemical field sampling could develop a worthwhile tool in the search for petroleum fields. The prospect of finding air-photo tonal anomalies associated with ascending heavy hydrocarbons along fractures and fissures in the bedrock is at once suggested".

Norden (1957) has found some coincidence between geochemical "highs" and the linear fracture patterns observed from airphotos.

Crombie (1958) mentioned to the writer that Texaco's photogeologists had observed concentration of linear fracture patterns at the flanks of structures. This appears to confirm the observations of Blanchet (1957) and Mollard (1957-1958). Blanchet (1957) and Mollard (1957; 1958) discuss the mechanism of the formation of these fracture patterns.

According to Edwards (1956):

"Schneiderhöhn reports that the faults, fissures and joint systems in these Trias-Jura-Cretaceous rocks commonly follow a tectonic pattern of the underlying older rocks that is consistent right back to the PreCambrian; and he considers that these persistent trends have been repeatedly rejuvenated by successive tectonic movements".

Smekhov et al (1958) have made an extensive study of macro fractures (mainly in outcrops), and micro fractures (in cores). According to these investigators:

"Fracturing in granitoid rocks (Paleozoic-Jurassic), developed in that same region, and also in limestone and dolomites of the Bukkhar stage of the Paleogene, occurring low in the section possess the same trends as fracturing of the Jurassic limestones. This regularity permits discerning of an "inheritance" of the orientation of the fracturing for a considerable part of the sedimentary cover even under the conditions of the presence of breaks between units of its stratigraphic subdivisions (Cretaceous-Jurassic, Jurassic-Paleogene)".

In other words, the fractures in the granitoid rocks are reflected in the overlying strata, even under the presence of distinct breaks between various stratigraphic units (Cretaceous - Jurassic, Jurassic - Paleogene). The same authors state that the most intense zones of fractures are at the flanks of the structures, although the number of systems having different trends increases on the crest. The intensity of fractures increases with depth; the wells with maximum yield of oil are located at the flanks and periclines of the uplifts.

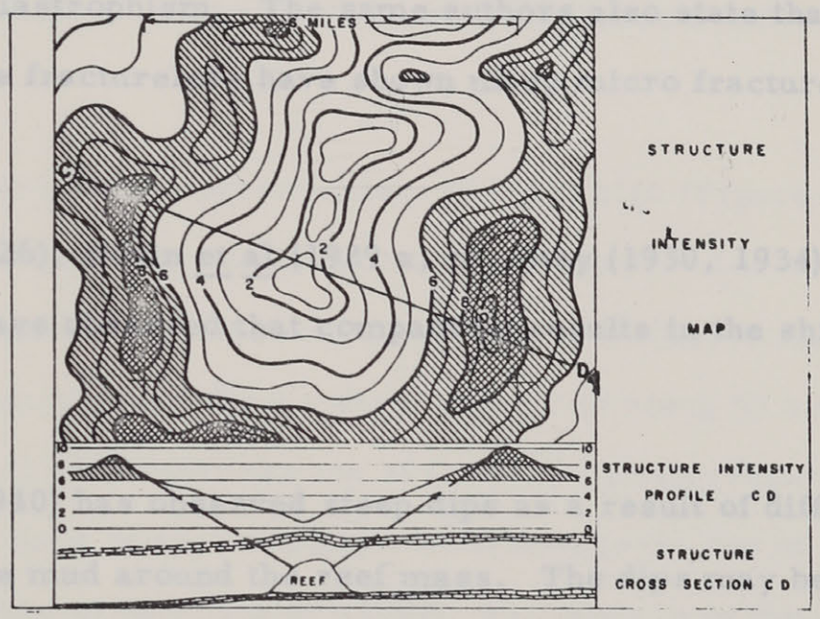


Figure 46. Structure Intensity Map Of The Wizard Lake Reef, Alberta, Made From Air Photos (From Blanchet, 1957).

The results of Smekhov et al (1958) appear to confirm the findings of Blanchet (1957) and Mollard (1957-1958).

There are two types of micro fractures, tectonic and diagenetic-tectonic (Smekhov et al, 1958). Smekhov et al, consider that the presence of diagenetic fractures is almost eliminated in the fractured rocks. These diagenetic fractures merge into the tectonic fractures due to lithogenesis and diastrophism. The same authors also state that rocks which appear to be fractureless have shown many micro fractures under thin sections.

Hedberg (1926), Nevin et al (1929 a, b), Athy (1930, 1934) and Terzaghi (1950) have observed that compaction results in the shrinkage of sediments.

Terzaghi (1940) has observed steep dips as a result of differential compaction of lime mud around the reef mass. The dips may be as steep as 80^{o}.

Nevin et al (1929 b) from the study of folds associated with the buried hills in north central Oklahoma, have observed steep dips which they consider are probably due to the presence of subsurface faults.

According to Athy (1934) the amount of compaction which takes place with the burial of sediments is much more than previously considered. He further states that the depth of burial and compaction are probably related exponentially. During the study of folded structures in the mid continent region he observed normal faults associated with the folds resulting from the differential compaction of the sediments.

Athy (ibid) has further shown that a hill 600 feet high buried under 6000 feet of sediments would produce a vertical closure of 245 feet on the first bed; 121 and 36 feet respectively on beds 1000 feet and 4000 feet above the hill.

Hughes (1959) suggested to the author that differential compaction would probably produce deflection of bedding of overlying sediments, and a potential system of shear and tension fractures overlying the reef mass.

The Redwater reef is approximately 900 feet high (Figure 47). It is assumed that the reef mass behaved as a rigid mass. According to Athy's (1930) calculation the strata at AA (Figure 48) after burial under 2000 feet of sediments would show a drop of 283 feet along SS and 87 feet at 2000 feet, which is near the top of Colorado group (Figure 47). Figure 47 shows a drop of approximately 80 feet near the top of Colorado group at the boundary of Sect. 20-21, TWP. 57. This is in the vicinity of "high" H_2 (Figure 31).

Differential compaction produces a relative movement between the rigid reef mass and the yielding sediments of the basin. This relative movement causes adjustments of sediments in the basin, which are in the form of steepening of the dips; stretching of any given stratum extending over the boundary of the reef and basin; and development of a system of shear and tension fractures. A hypothetical consideration for the development of the shear and tension fracture is given in Figure 48.

The sediments along AA (Figure 48) are modified to BB after compaction under 2000 feet of sediments. According to Athy's (1930) calculation, this should be approximately 280 feet. The net result would

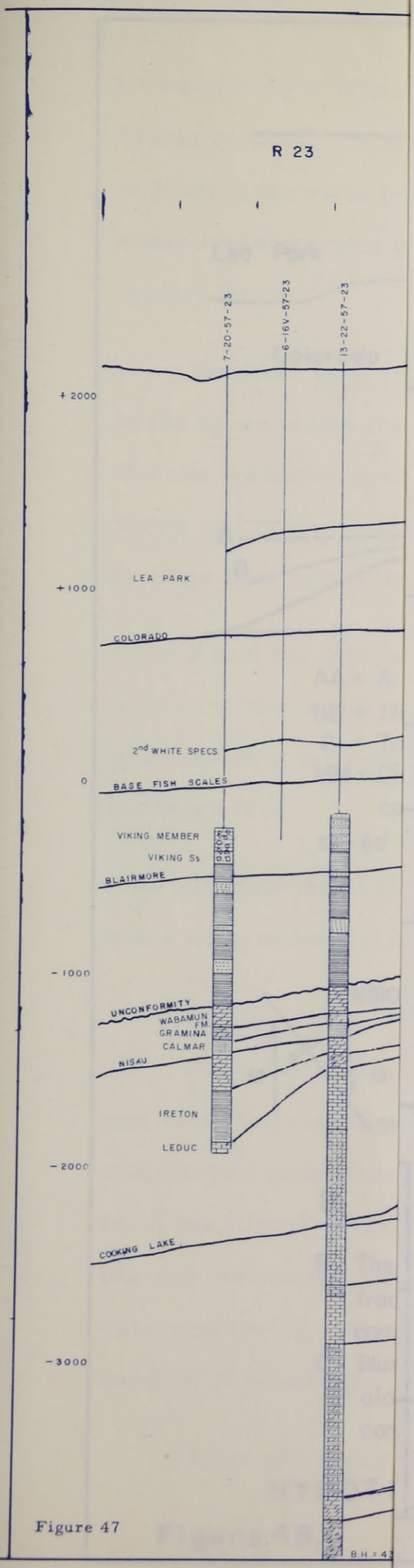
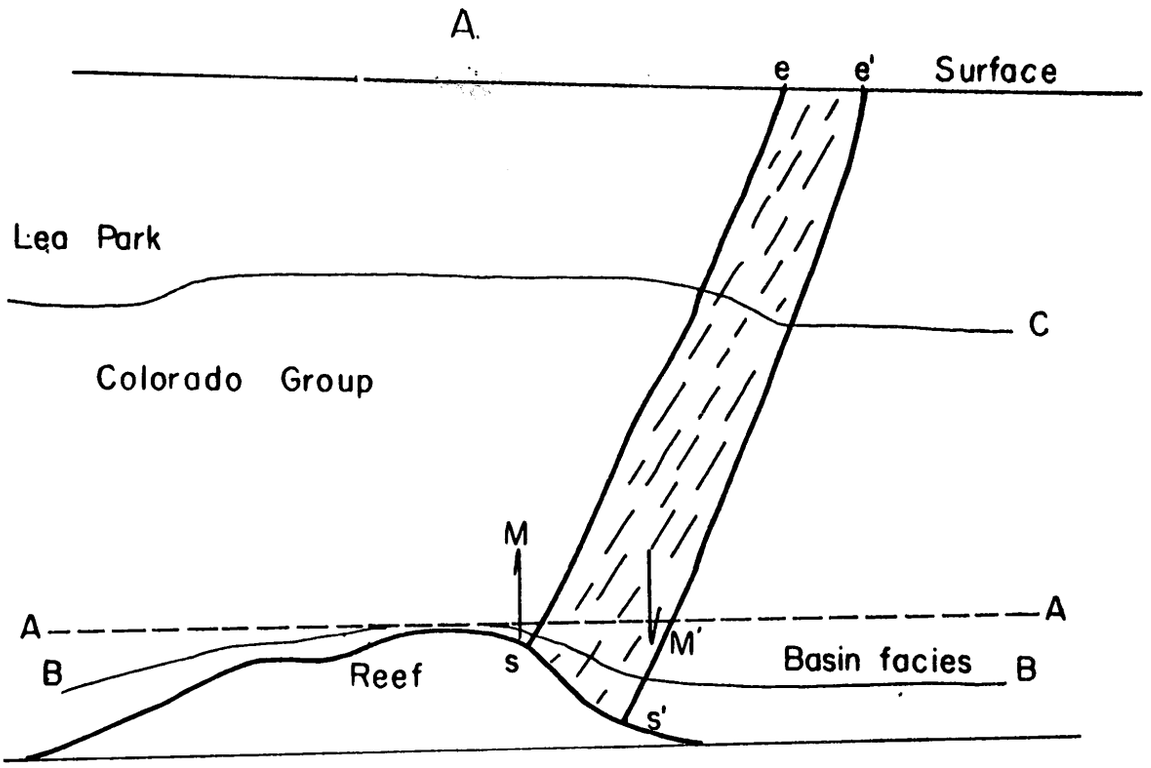
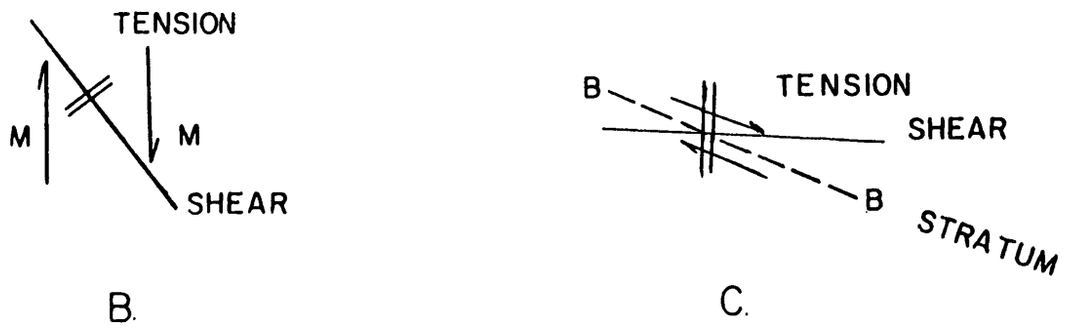

R 23
7-20-57-23
6-16V-57-23
13-22-57-23
+2000
+1000
0
-1000
-2000
-3000
LEA PARK
COLORADO
2nd WHITE SPECS
BASE FISH SCALES
VIKING MEMBER
VIKING Ss
BLAIRMORE
UNCONFORMITY
WABAMUN FM.
GRAMINA
CALMAR
NISKU
IRETON
LEDUC
COOKING LAKE
B.H. = 43

Figure 47



AA = A datum, or a stratum at the time of deposition
BB = The same stratum after compaction
C = Top of Colorado group
MM = Differential movement over reef slope ss' after compaction
ss'-ee' Zone of possible fractures



B. C.

B. The development of possible shear and tension fractures arising under conditions of differential compaction Relative movement given by MM'

C. Illustrates the additional possibility of movement along the deflected stratum BB during continuous compaction.

HYPOTHETICAL DEVELOPMENT OF FRACTURES

Figure 48.

be steepening of dips along SS and production of shear fracture. However, in this respect, the structural model of Nevin et al (1929 a) reproduced in Plate X shows at least one fracture with noticeable movement. These shear fractures with increased burial may produce tension fractures and normal faults.

Smekhov et al (1958) have observed that the fractures are reflected in the upper strata through the unconformities. It is therefore concluded that the fractures produced along SS are probably reflected in the upper strata and at the surface. Blanchet's (1957), and Mollard's (1957; 1958) findings lend to support to the conclusion drawn by the present writer.

From the foregoing discussion, it is inferred that macro and micro fractures are probably present in the overlying strata of Redwater Reef and may serve as channelways for the migration of various materials to the surface.

Some of the radiometric highs appear to be associated with probable sites of fractures.

Summary:

From the foregoing discussion it is observed that hydrocarbons and water migrate towards the surface. Various writers suggest that radiometric anomalies are caused by a) diffusion of gaseous hydrocarbons from the oilpools resulting in the evaporation of water at the surface and causing the concentration of radioelements; b) migration subterranean waters carrying radioelements in solution; c) diffusion of salts in solution or otherwise.

The present writer has shown the importance of fracture in the

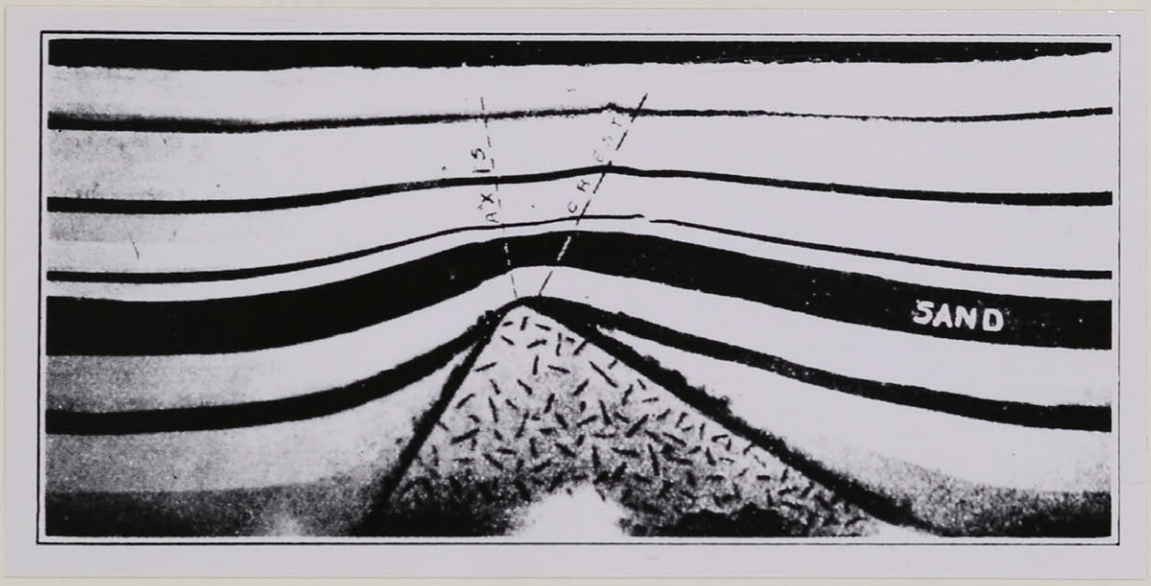


Plate X: A Shear Fracture With Noticeable Movement
(From Nevin and Sherril, 1929b)

rocks, which may serve as avenues or passages for the migration of the liquids and solids to the surface of the earth.

Proposed working mechanism:

Assumptions:

The writer has made the following assumptions which are based on the discussion in the preceding pages:

1. Gases like CO_2, N_2, H_2S, and H_2 migrate towards the surface both in gaseous form and in solution.
2. Hydrocarbons and water migrate towards the surface.
3. Micro and macrofractures are present in rocks.
4. The process of migration is mainly effusion and in part diffusion.

The radiometric anomalies probably are due to complex interchange of the various components mentioned above, and therefore the part each one may play is described individually.

Role of gases:

Brines and petroleum contain large quantities of dissolved gases. Predominant among these gases are carbon dioxide, methane, nitrogen, hydrogen sulphide, and hydrogen. Carbon dioxide is generally very abundant (sometimes exceeds 90%). The amount of dissolved CO_2 and N_2 controls the content of other gases. Some of these gases in solution are strong leaching agents. It is therefore probable that these gases may facilitate the dissolution of mineral matter from the rocks through which they travel, and increase the radioelement content of upward migrating waters.

Carbon dioxide under pressure can also leach materials. It seems likely that some of the mineral matter may be carried with CO_2 migrating towards the surface. At the surface these gases may carry some of the water from the soil into the air, thus causing evaporation, which in turn would increase diffusion and filtration. The water from the sides would

migrate to take the place of water evaporated, thereby enriching the radioelement content at the site of evaporation.

Role of hydrocarbons:

Water can carry 200 ppm of oil in solution. Hyden (1958) has observed that crude oil dissolves uranium minerals. It is therefore probable that dissolved oil may aid in increasing the uranium content of the upward migrating waters. The oil alone may also migrate and carry some of the uranium to the surface.

The gaseous hydrocarbons at the surface would increase evaporation which in turn would result in increased diffusion or effusion. The water from the sides may migrate to the sites of evaporation and cause enrichment.

Liquid petroleum due to loss of more volatile fractions may result in the development of a plastic or solid phase, similar to lignite which could extract uranium from solution (Hyden, 1958).

According to Hyden (1958):

"Dodd et al (1952), discovered the film forming at the oil water interface was metalliferous, and that the film material yielded black tarry solids on drying. Dunning et al (1953) identified vanadium and nickel porphyrins in oil water interface. In this manner vanadium and nickel bearing asphalts or asphaltite may accumulate at the water contact and this material in turn may extract uranium from ground water. This manner of accumulation may explain some occurrences of uraniferous asphaltite and also some of the radioactive anomalies often reported at the oilfields (Lang, 1950; Lundberg, 1952; and Merrit, 1952)".

The mechanism of extraction of uranium from solution suggested by Hyden (1958) is most probably one of the means by which uranium is deposited.

The other possibility is the reduction of hexavalent uranium in solution to the tetravalent state by H_2S dissolved in oil or mixed with gaseous hydrocarbons. According to Hyden (1958), Gruner reported the precipitation of uranium dioxide by bubbling H_2S through sulfate solutions.

Russel (1958) and Hyden (1958) have suggested that some of the uranium deposits in Wyoming may have been formed by the reduction of hexavalent uranium in ground waters with H_2S.

The foregoing are some of the methods by which uranium may be deposited at the site of hydrocarbon and water leakages.

The coincidence of radiometric highs with hydrocarbon highs over Ten Section Oilfield (Figures 49 and 50) suggest this possibility.

Role of Diffusion:

Diffusion plays some part, the extent of which has not been fully evaluated. The following are some of the possible ways diffusion may aid in the migration of salts, ions and gas.

Sokolov (1956) considers if the underground water comes in contact with moist rocks, the salts would diffuse. In water the diffusion coefficient of salts (NaCl, Na_2SO_4, Na_2CO_3) is .4 to 1.2 x 10^{-5} Cm^2/sec (Sokolov, 1956).

Antonov (Sokolov, 1956, p. 156) observed the diffusion coefficient of chlorine in clays (10^{-5} to 10^{-6} Cm^2/sec) and in sands (14 x 10^{-6} Cm^2/sec in low concentration, and 4 x 10^{-6} Cm^2/sec for high concentration). He states that chlorine would diffuse faster than gaseous hydrocarbons by weight. Sodium chloride would diffuse 2 to 3 times faster then methane by weight. The diffusion is dependent upon concentration.

It seem likely that in moist rocks underlain with formations rich in fluids, the diffusion of salt does take place. In the absence of fractures such a process would facilitate the migration of material from below.

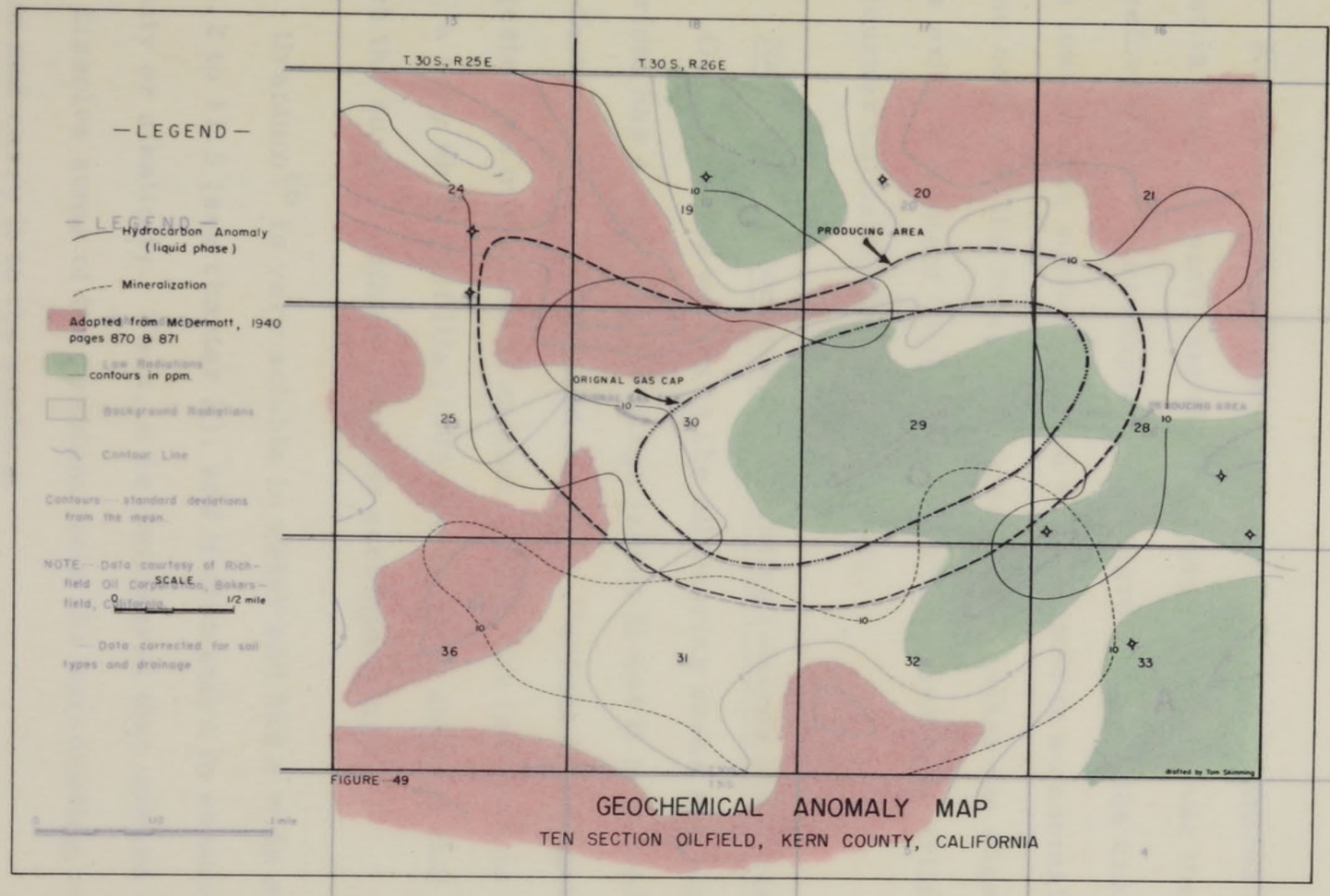


FIGURE 49

GEOCHEMICAL ANOMALY MAP

TEN SECTION OILFIELD, KERN COUNTY, CALIFORNIA

RADIOMETRIC SURVEY OF TEN SECTION OILFIELD
Kern County, California

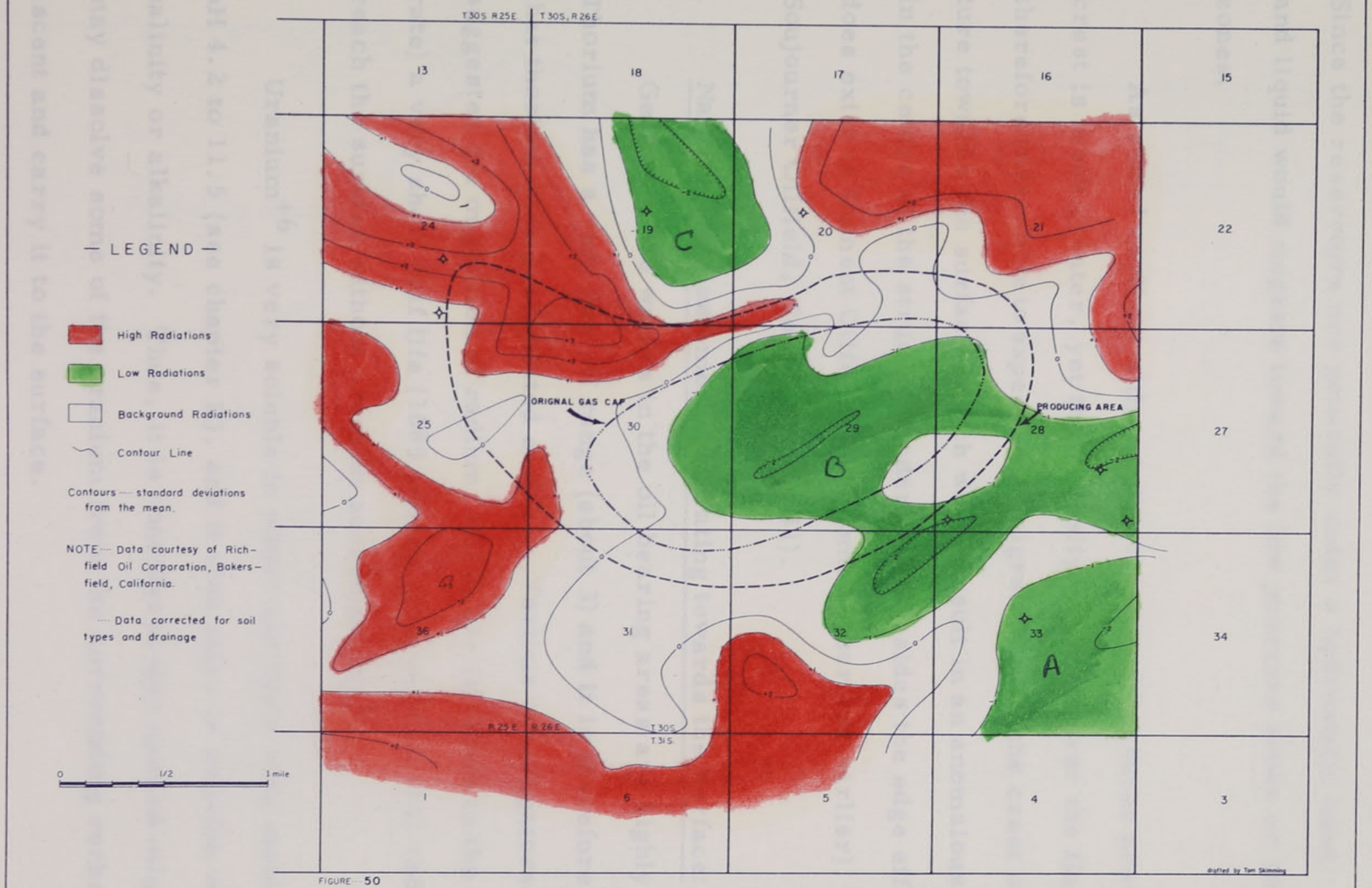


FIGURE---50

RADIOMETRIC SURVEY OF TEN SECTION OILFIELD
Kern County, California

Role of fractures:

Fracture zones provide avenues for the escape of gases and liquids. Since the reservoirs are generally under a hydrostatic head, the gases and liquid would migrate toward the low pressure areas or the fracture zones.

As stated earlier, although the variety of fractures present at the crest is much greater, yet the intensity is higher over the flanks. It is therefore reasonable to expect some migration from the crest of the structure towards the surface, which would result in an anomalous condition in the centre of the structure under study besides the edge effect. This does exist at Cement Oilfield, Oklahoma (described earlier), and Soujourner Oilfield, Texas (Figure 51).

Nature of radioelements migrating towards the surface:

Generally the waters in the oil bearing areas are highly saline. Thorium has a very low pH range (about 3) and it is therefore probable that thorium gets precipitated earlier. Various investigators have suggested the migration of radium, which has (relative to the migration rate) a very short half life (1685 years); it is unlikely that radium would reach the surface without uranium accompanying it.

Uranium^{+6} is very soluble in water and has a wide stability range: pH 4.2 to 11.5 (see chapter II), and it also stays in solution with increasing salinity or alkalinity. Thus, it is considered that upward migrating water may dissolve some of the uranium from the surrounding rocks in upward ascent and carry it to the surface.

The anomalies observed at the surface are probably due to the following:

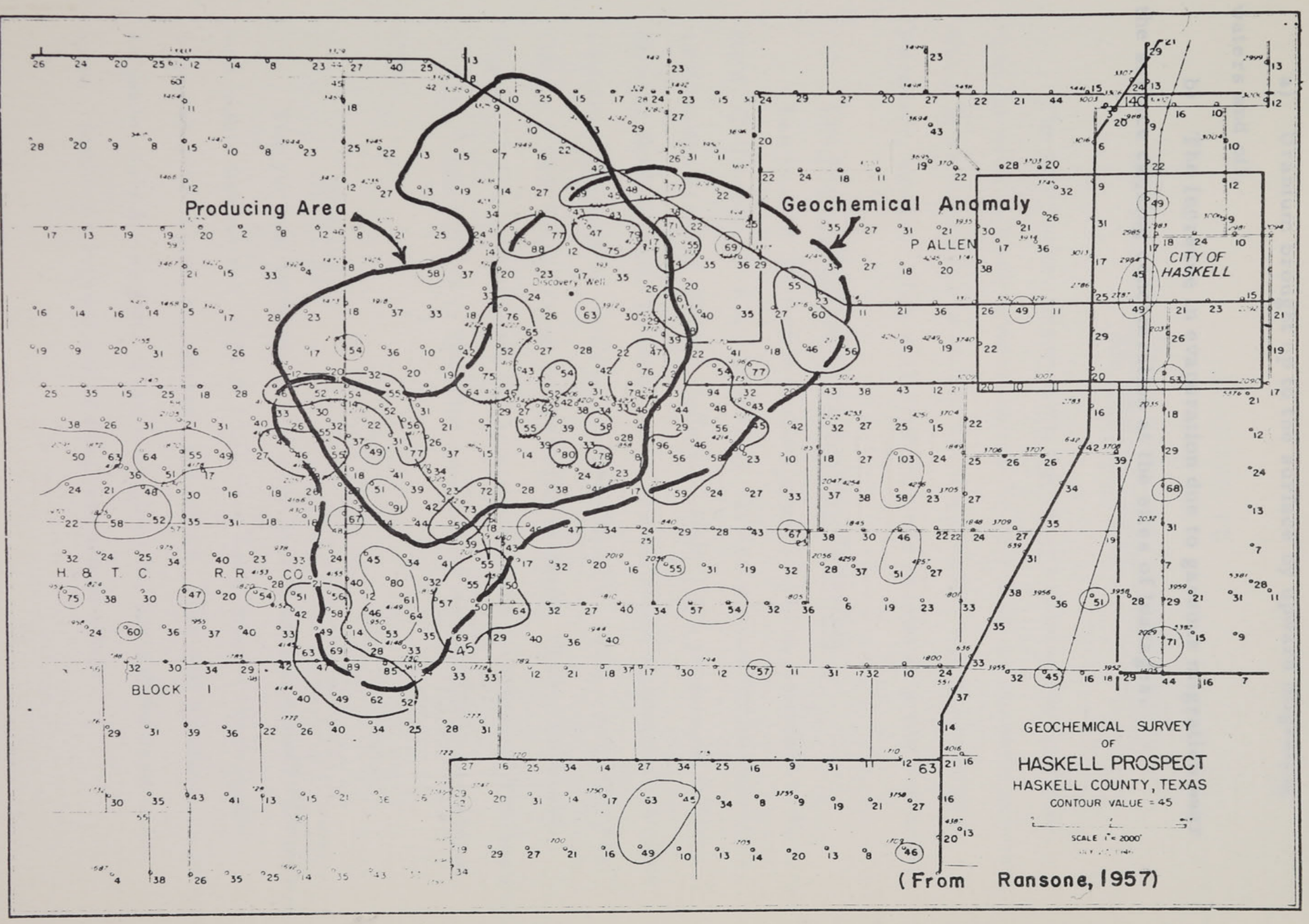


Figure 51. Geochemical Survey Of Sojourner Field, Texas.

a) Uranium brought up to the surface by upward migrating waters and oil.

b) The increase in evaporation due to gaseous migration near the surface causing concentration at the sites of leakages.

CHAPTER VII

APPLICATION OF REDWATER OBSERVATIONS TO OTHER AREAS

The conclusions drawn from the results obtained at Redwater Oilfield were utilized in interpreting the data from an unknown prospect, which later turned out to be Ten Section Oilfield, and L'Assomption Prospect, Quebec. The evaluation of these results is presented below.

Ten Section Oilfield, Kern County, California:

Ten Section Oilfield is located about 10 miles southwest of Bakersfield, California, U.S.A. (Figure 2). It was discovered on January 2, 1936 on the basis of seismic reflection high. The production is from Stevens Sand of upper Miocene age. The oil accumulation occurs in an anticline, the axis of which is arcuate (Gentry, 1943). According to Gentry (1943) there are no known faults at depth. Table XXXI and Figure 52 give respectively the stratigraphy and structure of Ten Section oilfield. The oilfield is $3\frac{1}{2}$ miles long and $1\frac{1}{2}$ miles wide at the widest point.

Pedology:

The surface soils are grey brown to dull brown, mildly calcareous, and highly micaceous. These soils have been derived from recent accumulation of granitic alluvial sediments. The soil profiles are poorly to moderately developed. Figure 53 gives the soils developed in the area. Some of these soils have a high content of alkali.

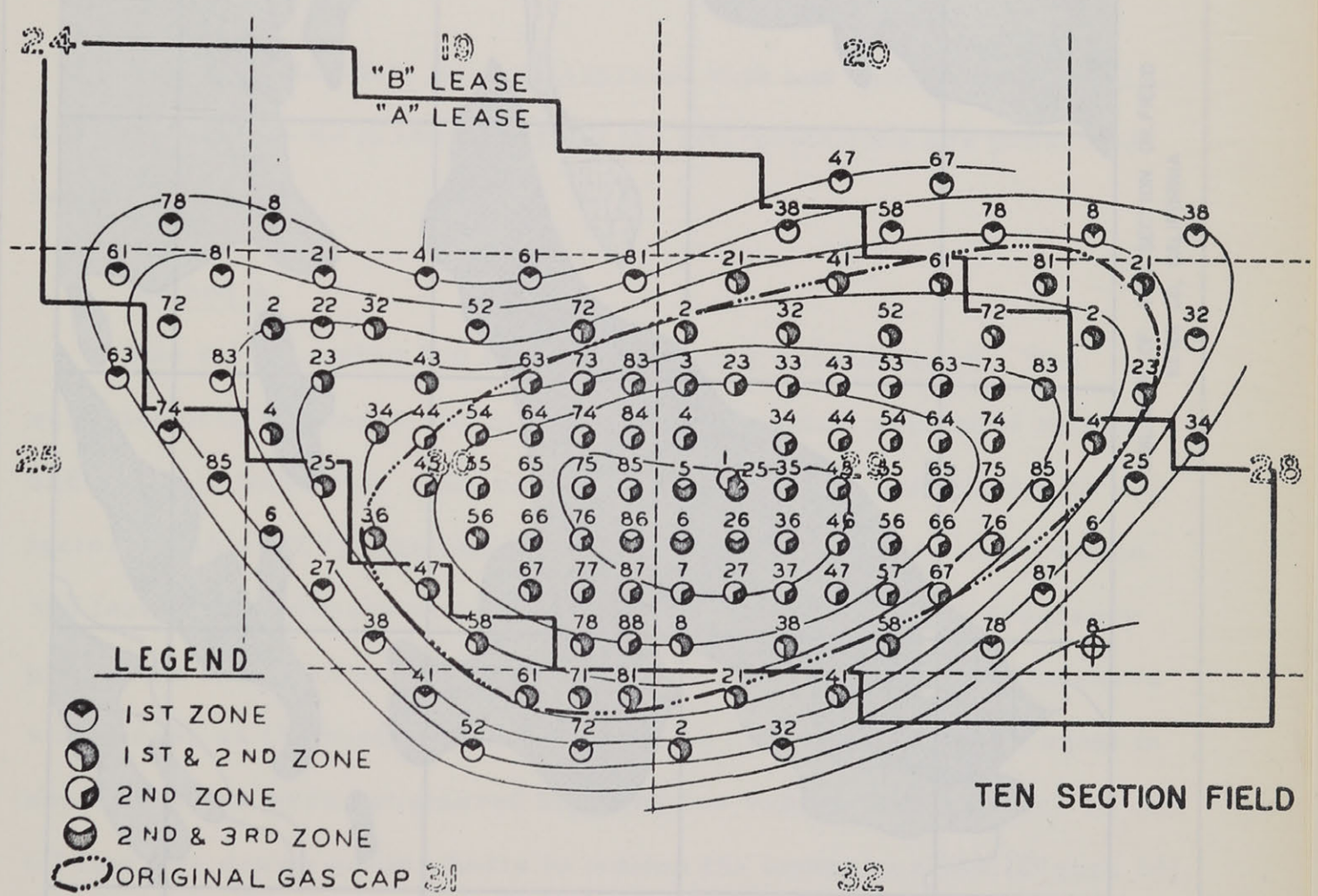
TABLE XXXI

STRATIGRAPHY

TEN SECTION OIL FIELD (a)

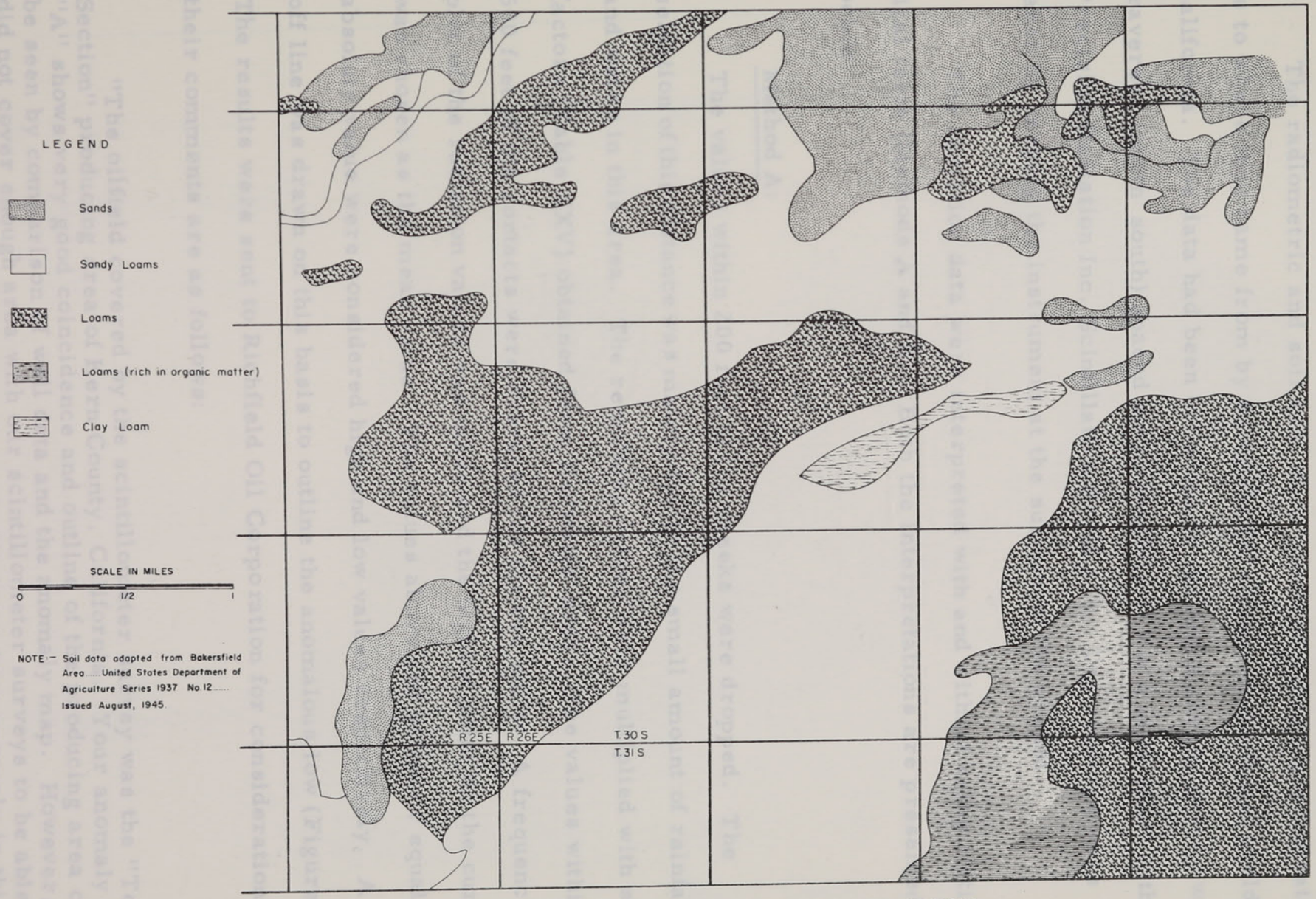
	Age	Formation or equivalent	Approximate thickness in feet	Lithology
CENOZOIC	Recent	Alluvium	700	Lenticular beds of clay, silt, sand and gravel.
	Plio-Pleistocene	Tulare	1800	Buff to gray brown sand, silt, and clay. Continental.
	Pliocene	San Joaquin	2300	Buff to gray silty clay, sand, and silt. Brackish water to shallow marine in origin.
		Etchegoin	2100	Light gray clays, fine sand, and silty. Marine.
	Upper Miocene	Reef Ridge Shale	700	Brownish-gray fissile clay shale. Marine.
		Stevens Sand	2600	Gray quartzose, usually ill-sorted, silty and coarse-grained sand. Marine.
	Upper & Middle Miocene	Lower Fruitvale Shale	900	Brown clay shale usually well-bedded and laminated with fine sand partings.
	Middle Miocene	Round Mountain Silt	900	Gray-brown, relatively poorly-bedded, silty shale. Marine.
	Lower Miocene	Freeman-Jewett Silt	1000	Brown sandy shale, finely-bedded, often ashy and carbonaceous. Marine
		Vedder Sand	1000	Light gray coarse-grained sand. Marine.
		Salt Creek Shale	400	Hard dark gray-brown massive shale.
	Eocene	Kreyenhagen Shale	400	Dark brown massive to platy hard shale. Marine
		Famoso Sand	700	Gray to green-gray ill-sorted fine to coarse-grained, silty sand.

a. MINCH, 1952



MAP OF TEN SECTION FIELD SHOWING CONTOURS ON ELECTRIC LOG MARKER XA

Figure 52 (From Leitz, 1949)



SOIL MAP OF TEN SECTION OILFIELD
KERN CO, CALIFORNIA

Figure 53

Radiometric Results:

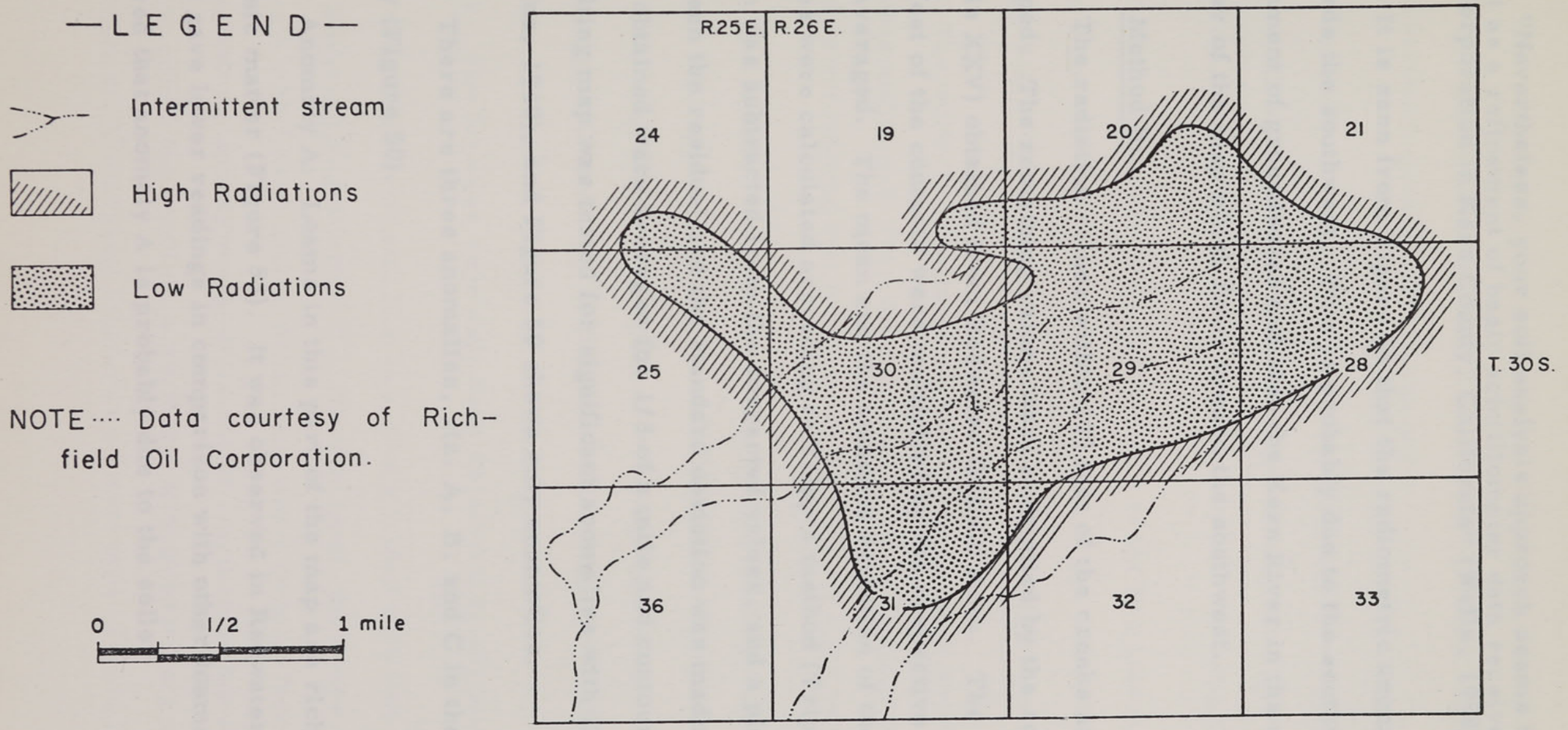
The radiometric and soil data were provided without any indication as to where they came from by Richfield Oil Corporation, Bakersfield, California. The data had been collected by making a ground survey with traverses (north south) spaced approximately 1/3 of a mile apart with a Precision Radiation Inc. Scintillation Royal 118. The readings were taken by keeping the instrument at the surface of the ground.

The radiation data were interpreted with and without using statistical tests (Methods A and B). Both the interpretations are presented below.

Method A:

The values within 200 feet of the creeks were dropped. The selection of this distance was mainly due to the small amount of rainfall and water in this area. The remaining values were multiplied with soil factors (Table XXV) obtained from Redwater area. The values within 500 feet of the contacts were averaged for the two soils. A frequency plot of the radiation values was made and the highest point on the curve was chosen as the mean value. The values above and below or equal in absolute value were considered high and low values respectively. A cut-off line was drawn on this basis to outline the anomalous low (Figure 54). The results were sent to Richfield Oil Corporation for consideration and their comments are as follows:

"The oilfield covered by the scintillometer survey was the "Ten Section" producing area of Kern County, California. Your anomaly map "A" shows very good coincidence and outline of the producing area can be seen by comparison of well data and the anomaly map. However, we did not cover enough area with our scintillometer surveys to be able to draw definite conclusion as to what constitutes a true anomaly in this general area.



RADIOMETRIC SURVEY OF TEN SECTION OILFIELD

Kern County, California

Figure···· 54

drafted by Tom Skimming

"Nevertheless, your soil analysis approach seems to have a definite merit as a refinement of basic scintillometer data received by Richfield Oil Corporation in Kern County, California" (Wells, 1958).

It is seen from Figure 54 that the radiometric anomaly is displaced towards the southwest. This is probably due to the southwestward movement of groundwater and also the Kern River in the northwest corner of the map which flows toward the southwest.

Method B:

The radiation values within 200 feet of the creeks and canals were dropped. The remaining values were multiplied by the soil factors (Table XXV) obtained from Redwater Oilfield Area. The values within 500 feet of the contacts were multiplied by the respective soil factors, and averaged. The mean and the standard deviation of the corrected values were calculated according to Tripp's method (Tripp, 1948). The mean was subtracted from the corrected values, and a plot of ratio between the residual and the standard deviation was made. The values thus obtained were averaged for 1/3 of a mile and contoured. The resulting map was tested for significant anomalies with Elkins Test (Elkins, 1940), and Figure 50 shows only anomalies.

There are three anomalies, viz. A, B, and C in the area under study (Figure 50).

Anomaly A: Loams in this part of the map are rich in lime and organic matter (Figure 53). It was observed in Redwater Area that such soils gave lower readings in comparison with other loams. It is considered that anomaly A is probably due to the soils.

Anomaly B: Anomaly B (Figure 50) cuts across clay loam, loams, and sandy loams (Figure 53). This is an interesting anomaly, and it also overlies a greater part of the pool.

Anomaly C: Anomaly C cuts across loams and sandy loams. Similar soils in other parts of the map, have given higher readings. It is an interesting feature, and should be further investigated.

There is a difference in the detail of the two anomalies observed in the area. The writer considers that in areas where there are not enough data, the statistical tests may wash out a part of the anomaly.

The writer's results contradict the findings of Kellog (1957) who has observed a high over the production. This appears to be due to Kellog's not making any corrections for various soils in the area.

The hydrocarbon anomaly (Figure 49), and radiometric low (Figure 50), appear to coincide with the limits of original gas cap in Ten Section oilfield. This coincidence may be due to the presence of an annular fracture zone at the flanks of Ten Section anticline, which may have served as a passage for the migration of hydrocarbons and water. The fracture zone may have developed as follows:

Ten Section oilpool lies in a gently folded anticline (Figure 52) with limbs dipping at about 7^{o}. Stevens Sand, the reservoir rock, is overlain with brown shales which have chert beds. Chert and shales are relatively strong rocks which would fracture on bending. According to Balk (1937) the bending of weak and strong materials results in the development of marginal fractures or joint fans (Figure 55).

It is therefore assumed that either the conditions illustrated in B (Figure 55) or combination of B and C (Figure 55) probably have resulted in the bending of shale and chert. Smekhov et al (1958) as mentioned in chapter VI state that fractures in the underlying rocks are reflected at the surface even through the unconformities. Thus it is considered that these fracture zones may have served as passages for the migration of hydrocarbons and water towards the surface which have caused these geochemical anomalies.

The relationship between the hydrocarbon anomaly radiometric low, and structure is illustrated in Figure 56. This relationship supports the probability of combination of conditions depicted in B and C (Figure 55) existing together.

L'Assomption Prospect, Quebec:

L'Assomption Prospect, Quebec (Figure 2) is situated about 25 miles north of Montreal, near the town of L'Assomption. The oil and gas rights of the area under study are possessed by Oil Selections Limited, who have been active in the area. Several wells have been drilled to develop a gas field (Figure 57). The area has also been covered by geophysical means.

Geology:

Very little is published on the geology of this area, which is covered with 60-100 feet of over burden. L'Assomption Prospect lies on the western flank of the St. Lawrence Lowland Basin. The basin is canoe shaped with beds of the western limb dipping 1^{o} to 6^{o} south-eastward. Dips average 2^{o} (Clark, 1956).

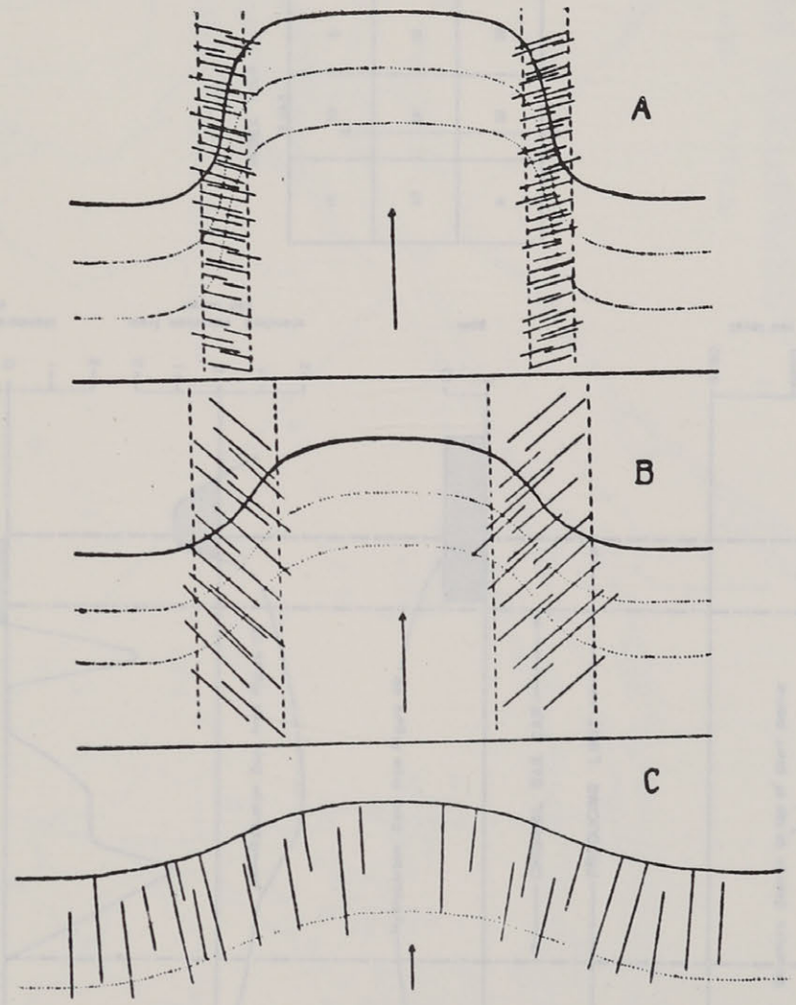
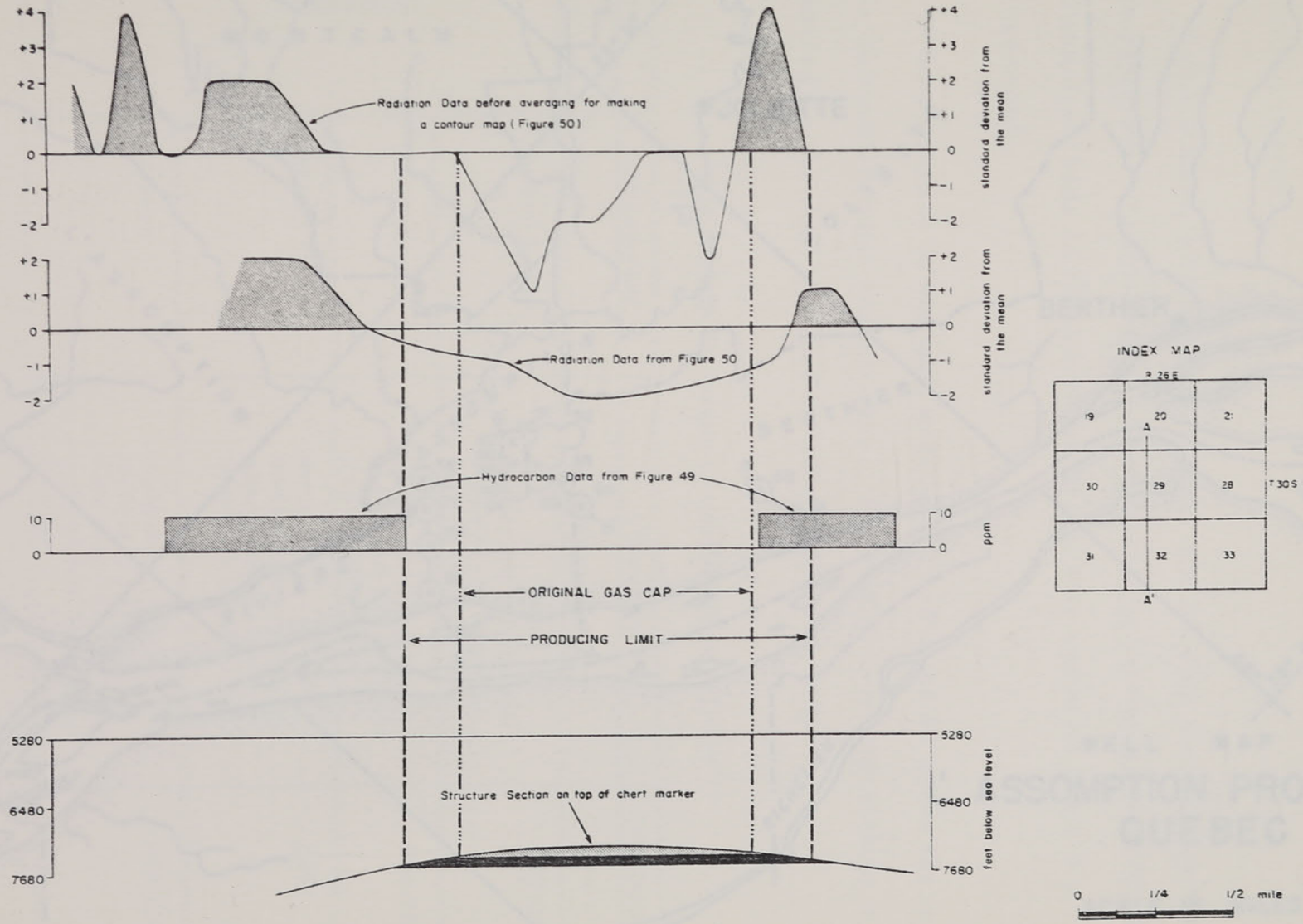


FIGURE 85.—*Bending of weak and strong material and the attendant development of marginal fractures or joint fans*

At (A) a weak substance protrudes in the direction of the arrow, between stationary walls to the left and right. The zones of intense lengthening (between the dashed lines) are relatively narrow, as shown by the curvature of the three lines. Under suitable conditions, tension joints open within these zones, approximately normal to the lines of local elongation. In nature, the marginal fissures near intrusive contacts are due to a similar lengthening of the magma. At (B) the material is stronger than in (A). The zone of bending is wider, the elongation per unit area less intense. Fractures within the border zones are more widely spaced, and dip steeper. At (C) a strong substance is bent. Distinct zones of bending disappear, and a continuous symmetric arch results. The fractures are arranged in a broad fan. The fans of tension joints in massifs are believed to form under similar conditions; hence, they are steeper than marginal fissures, and reach from one end of the massif to the other. Compare Figure 86.

FIGURE 55. Development of marginal fractures due to bending of weak and strong materials (from Balk, 1937).



SECTION A–A' TO SHOW THE RELATIONSHIP OF HYDROCARBON AND RADIOMETRIC DATA TO THE TEN SECTION OIL POOL

FIGURE ---- 56

drafted by Tom Skimming

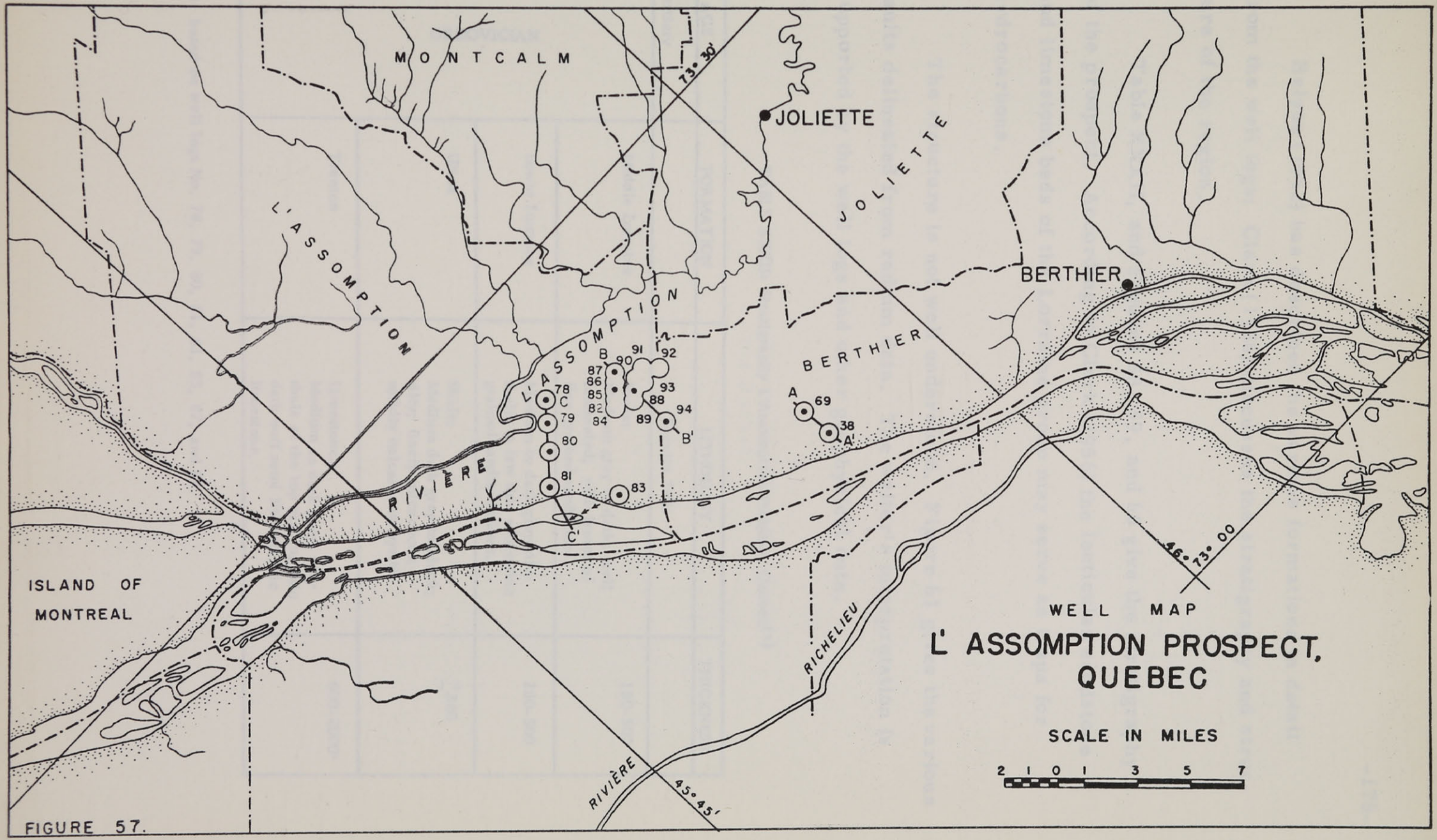

MONTCALM
73° 30'
JOLIETTE
JOLIETTE
L'ASSOMPTION
L'ASSOMPTION
BERTHIER
BERTHIER
A
69
38
A'
B
90
91
92
87
86
85
82
84
93
88
89
94
B'
78
C
79
80
81
83
C'
RIVIÈRE
RIVIÈRE
ISLAND OF
MONTREAL
RICHELIEU
46° 73° 00
45° 45'
WELL MAP
L' ASSOMPTION PROSPECT,
QUEBEC
SCALE IN MILES
2 1 0 1 3 5 7

FIGURE 57.

Belyea (1952) has described the various formations in detail from the well logs: Clark (1956) discusses the stratigraphy and structure of the region.

Table XXXII, and Figures 58, 59, and 60 give the stratigraphy of the prospect. According to Clark (1956) the lenticular sandstone and limestone beds of the Lorraine group may serve as traps for hydrocarbons.

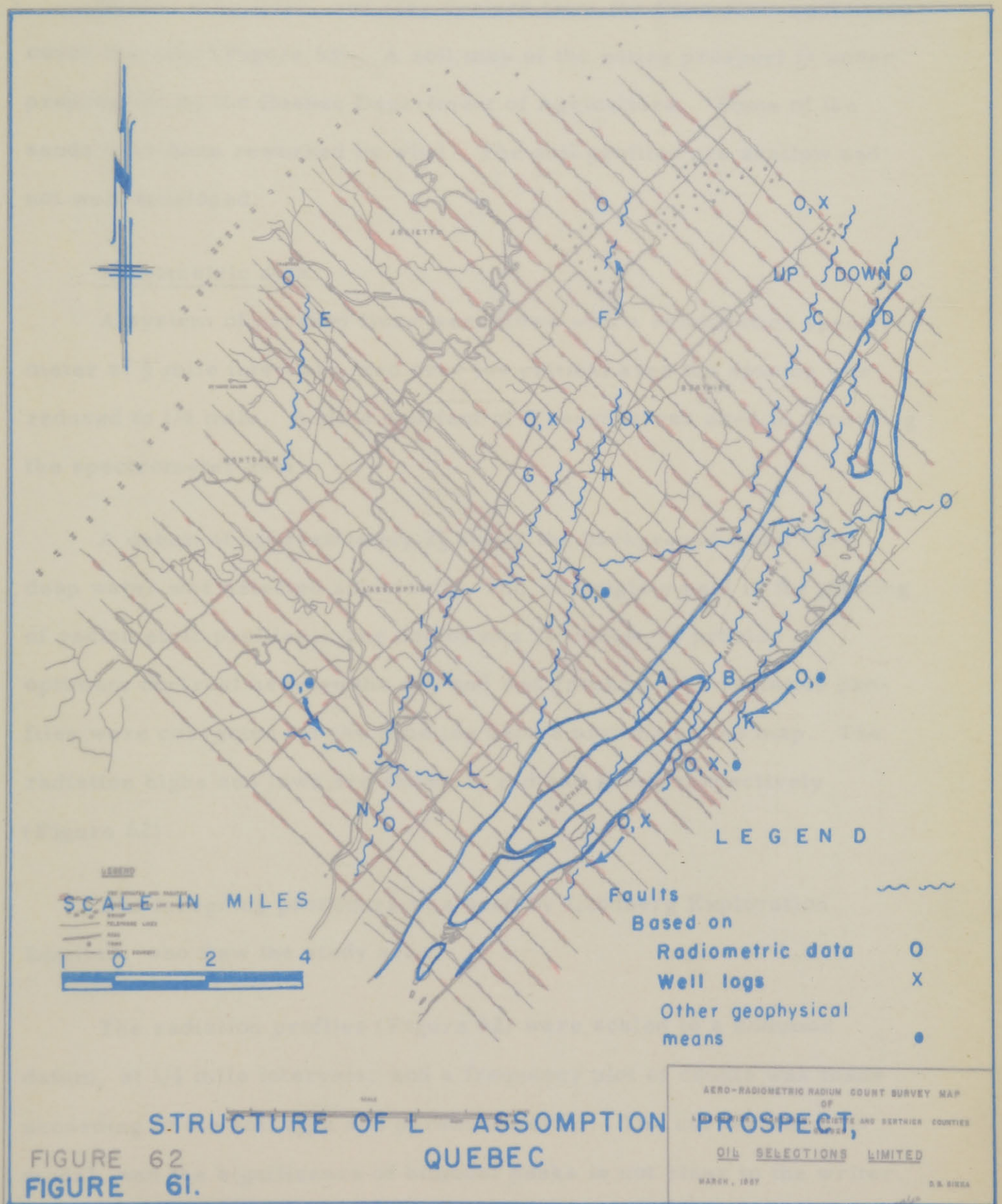
The structure is not well understood. Figure 61 gives the various faults delineated from radium data. The writer's interpretation is supported by the well logs and other geophysical data.

TABLE XXXII: Stratigraphy L'Assomption Prospect, Quebec[a]

AGE	FORMATION	LITHOLOGY	THICKNESS
Tertiary		Syenite Sills	
ORDOVICIAN	Middle Lorraine	Shale; Medium grey to dark; well laminated; with lenses of fine grained sandstones.	180-300
	Lower Lorraine	Medium to dark grey silty shale; a few thin white fine grained sandstone beds.	250-500
	Utica	Shale; Medium dark grey to black; silty; finely micaceous; mildly calcareous: pyritic	±380
	Trenton	Limestones; Medium to dark grey; silty shale at the top grading into dark buff semi lithographic limestone.	600-2000'

(a) based on well logs No. 78, 79, 80, 81, 83, 85, 87, and 88.

Figure 58, 59, and 60, in
the Pocket.



STRUCTURE OF L'ASSOMPTION PROSPECT, QUEBEC

FIGURE 62
FIGURE 61.

FIGURE 62

AERO-RADIOMETRIC RADIUM COUNT SURVEY MAP
OF
L'ASSOMPTION, MONTCALM, JOLIETTE AND BERTHIER COUNTIES
QUEBEC

OIL SELECTIONS LIMITED

MARCH, 1957

D. B. SIKKA

Pedology:

Sands, clay loam, and clay derived from the Champlain sediments cover the area (Figure 63). A soil map of the entire prospect is under preparation by the Quebec Department of Agriculture. Some of the sands have been reworked by wind. The soil profiles are shallow and not well developed.

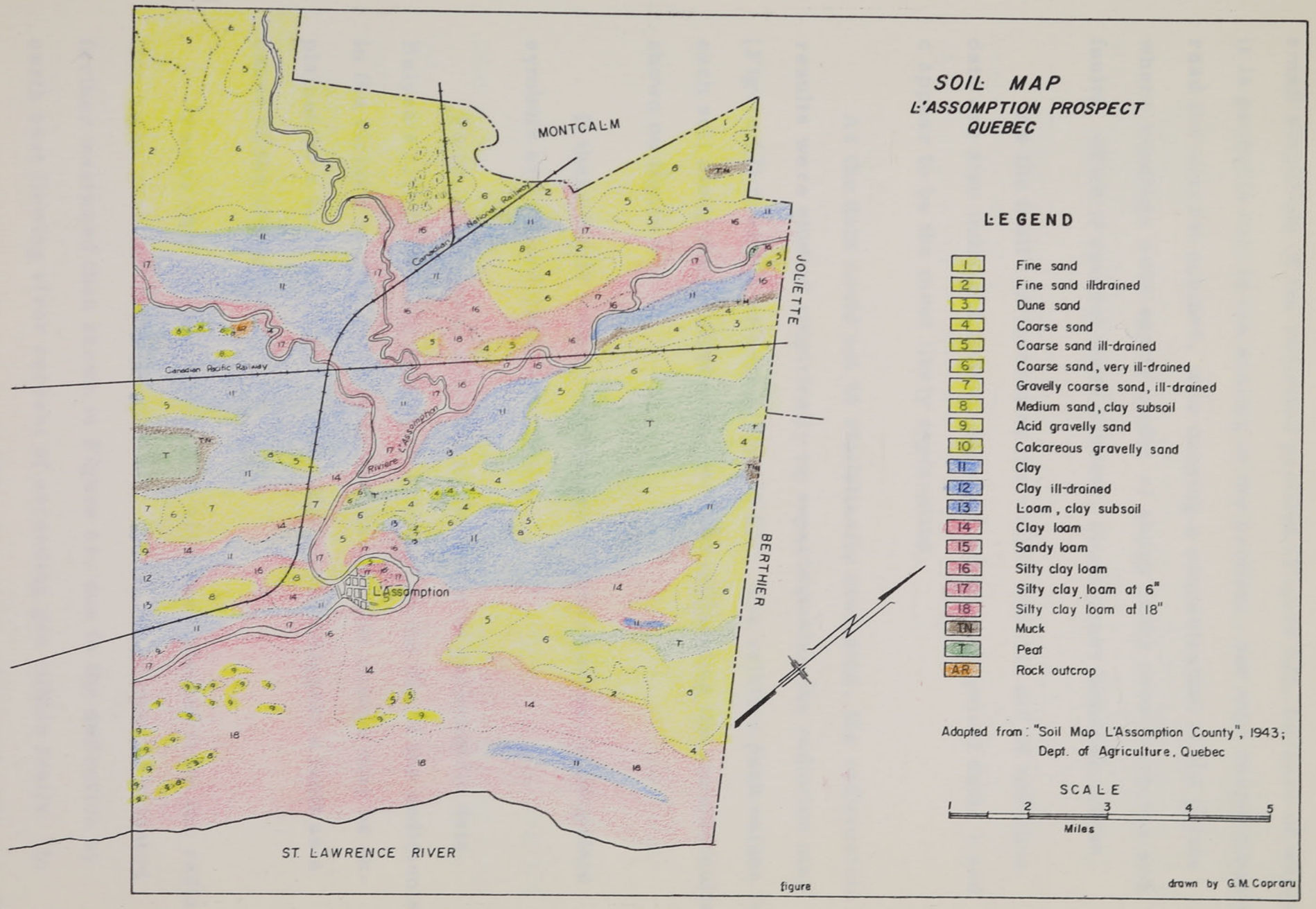
Radiometric data:

A system of parallel lines were flown with a scintillation spectrometer at $\frac{1}{2}$ mile intervals, and over the critical area the spacing was reduced to 1/4 mile. A time constant of 5 seconds was used in recording the spectrometer data.

A datum of approximately $2\frac{1}{2}$ times the background count over deep water was selected arbitrarily, and was rigidly held in the plotting of radiometric profiles. The datum was so chosen to provide an optimum contrast between the dry and wet ground. The radiation profiles were corrected for the time lag before plotting on the map. The radiation highs and lows are shown in red and green respectively (Figure 62).

The foregoing procedure was used by Lundberg Exploration Limited, who flew the study area.

The radiation profiles (Figure 62) were scaled to a common datum, at 1/4 mile intervals, and a frequency plot of counts was made according to the soil type and parent material. The curves were bimodal, and the significance of bimodal peaks is not clear to the writer. They may be due to: a) limited coverage of various soils; b) the very



SOIL MAP
L'ASSOMPTION PROSPECT
QUEBEC

LEGEND

1	Fine sand
2	Fine sand ill-drained
3	Dune sand
4	Coarse sand
5	Coarse sand ill-drained
6	Coarse sand, very ill-drained
7	Gravelly coarse sand, ill-drained
8	Medium sand, clay subsoil
9	Acid gravelly sand
10	Calcareous gravelly sand
11	Clay
12	Clay ill-drained
13	Loam, clay subsoil
14	Clay loam
15	Sandy loam
16	Silty clay loam
17	Silty clay loam at 6"
18	Silty clay loam at 18"
TN	Muck
T	Peat
AR	Rock outcrop

Adapted from: "Soil Map L'Assomption County", 1943; Dept. of Agriculture, Quebec

SCALE

1 2 3 4 5

Miles

figure

drawn by G.M. Copraru

small amplitude of the radiation profiles (Figure 62), because of which it is probable that in the scaling of the profiles, one may unconsciously read the nearest number, thus causing a concentration at the points where readings were easily made; c) sharp peaks over fractures and faults, which if several were present, could cause bimodal curves.

As the faults delineated by the writer with the aid of radiation data are also indicated by well logs and other geophysical data, b and c appear to be the most likely explanation.

As the data could not be statistically evaluated, the radiometric results were studied empirically by superimposing the radiation map (Figure 62) over the soil map (Figure 63). The relative peak values in each soil along the profiles were used for delineating the various faults shown on figure 61.

If these faults have been detected by other means, appropriate symbols are affixed next to the fault.

Fault 'A' has been detected on the basis of radiometric data. Belyea's (1952) well log data show a change in the dip of the sediments in the vicinity of fault A. She considers that this change may be explained by a fault or a fold. The radiation data suggest a fault as a cause of the change in dip.

Faults 'B', 'K' and 'D' (Figure 61) were detected from the radiation highs over the river (Figure 62). These faults may be situated farther westward than shown in Figure 61, due to the deflection by north east flowing river current of ascending gas bubble trails. In the vicinity of these faults gas bubbles have been observed at the surface

of the river (Twidale, 1957). Radon and hydrocarbons come to the surface, where radon decaying to Bi^{214} causes the radiometric highs.

Other geophysical measurements also suggest the probable presence of faults B and K.

The various faults shown in Figure 61 were detected solely on the basis of radium data. The supporting geological and other geophysical data were provided to the author at a later date.

Potential Oil and Gas Prospects:

There are three prospects A, B, and C (Figure 64).

Prospect A is still being explored. The intersections of faults G, H, J, and O may form a trap. Due to the presence of several faults, the "halo theory" cannot be invoked in the case under consideration.

Prospect B:

The prospect B is covered with clay which show a considerable drop in the radiation intensity. Three faults I, L & N intersect each other. The intersection may result in fault trap. Gas has been observed at shallow depth in various wells drilled for water near L'Assomption. This prospect should be investigated further.

Prospect C:

Faults G and H may form a trap in the vicinity of the area covered by Prospect C. Soil data for this prospect are lacking and therefore the radiometric data cannot be fully evaluated. Prospect C appears interesting and should be investigated further.

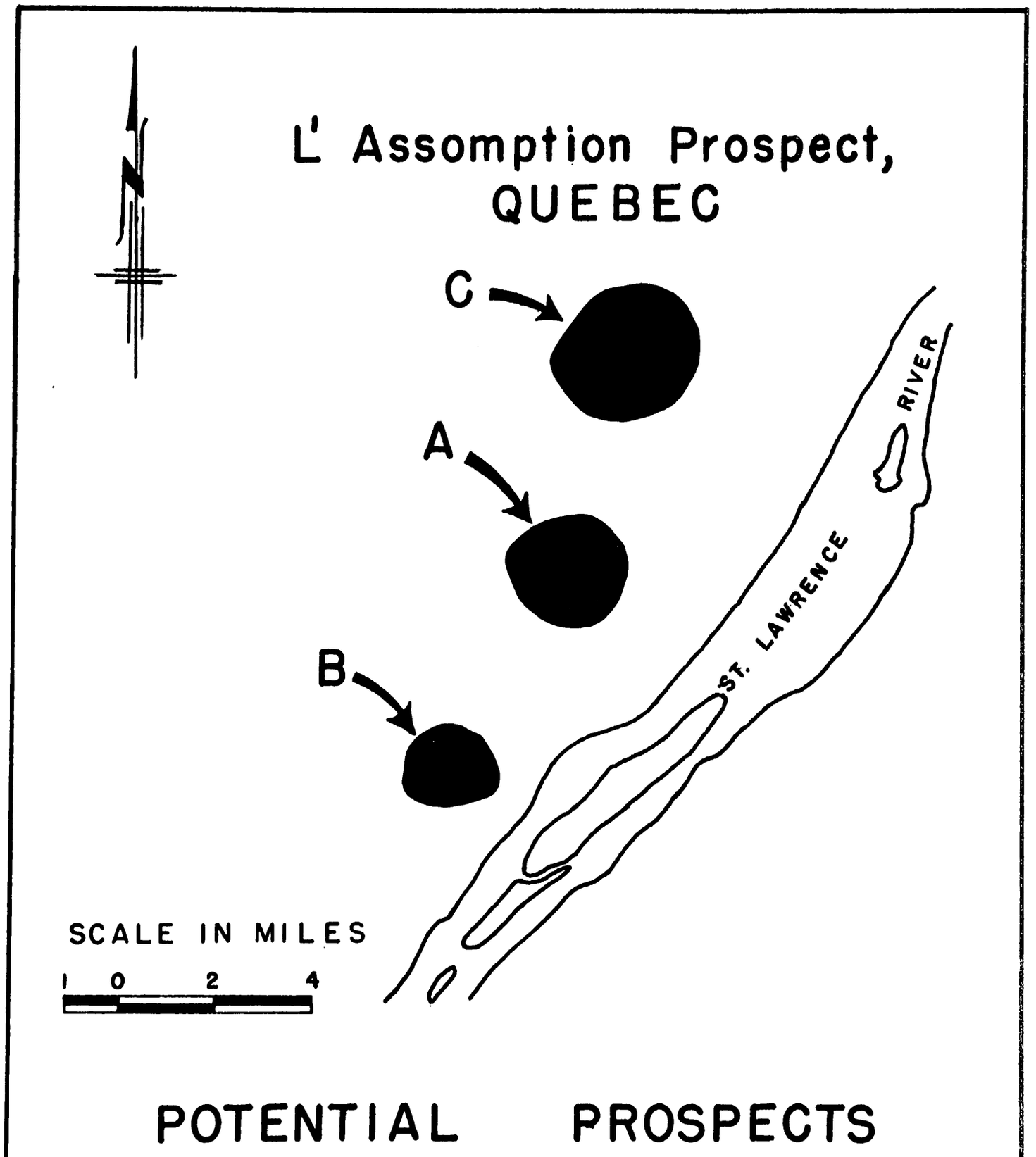

L' Assomption Prospect,
QUEBEC
C
A
B
ST. LAWRENCE
RIVER
SCALE IN MILES
1 0 2 4
POTENTIAL PROSPECTS

FIGURE 64.

Conclusion:

1. The L'Assomption Prospect area includes several interesting faults which probably form oil and gas traps.

2. Well log and other geophysical data support the results obtained from the evaluation of radiometric data.

3. There are three potential prospects.

CHAPTER VIII

RECOMMENDATIONS

During the course of the present study the writer was partially handicapped in calculating the mean and the standard deviations, because of the lack of a sufficiently large number of samples in each soil type necessary in making corrections. In view of the foregoing the following phases should be investigated to improve the interpretation techniques and test the validity of conclusions already drawn.

1. The radon and heavy metal (zinc, vanadium, and uranium) content of various soils over and at the flanks of the pool should be determined to establish a mean of these amounts, which in turn may facilitate the calculation of various correction factors necessary in the interpretation of data.

2. The areas with anomalous radioactivity should be sampled to bedrock to study the variations in the uranium content with depth. This may aid in establishing the source of radioactivity.

3. The investigation suggested in 1 and 2 above may be carried out in other areas, with a view to establishing uniform correction factors as is done in other geochemical and geophysical methods.

CHAPTER IX

ORIGINAL CONTRIBUTIONS BY THE AUTHOR

The writer has made the following contributions:

1. Radiations measured at the surface or just above it came from within 0-0.3 feet in loams, 0.6-1.5 feet in sands, and 2 feet in peat.

2. The radon content of sandy soils decreases with increasing coarseness of sands.

3. The radon content of holes drilled on top of dunes and near road cuts, is lower than that of holes drilled on the sides of dunes and away from road cuts.

4. Radiation intensity decreases in lime-rich sandy soils, and increases in sands with increasing limonite stain.

5. Ground radon data and airborne radium data show a good general correspondence.

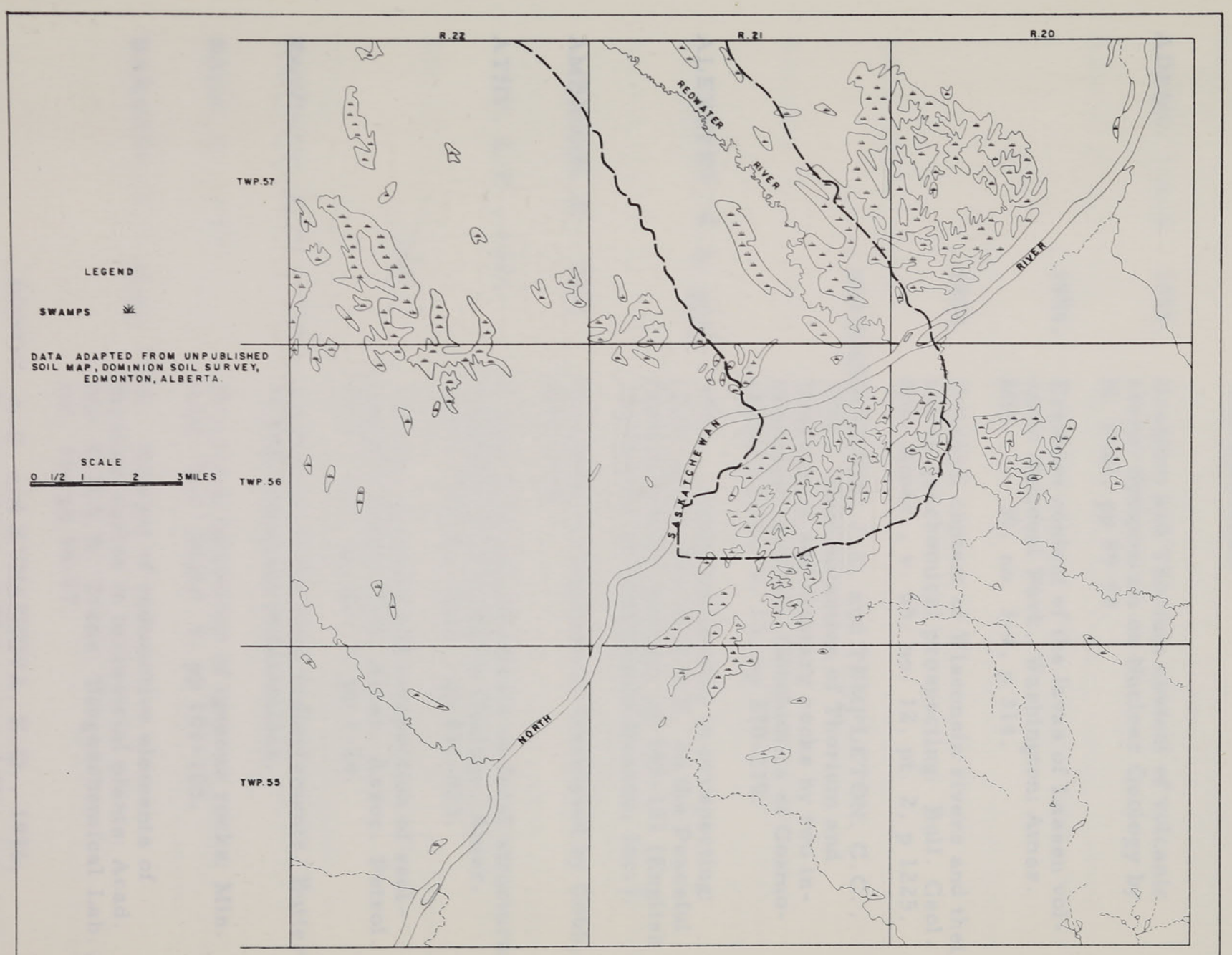
6. Factors have been developed to make necessary soil corrections, and their validity is suggested.

7. Mapping of probable faults has been feasible by airborne radium data in the Redwater Area and L'Assomption Prospect, Quebec.

8. The existence of an anomalous low, bordered by scattered areas of highs, at Redwater Oil Field is suggested.

9. A radiometric anomaly associated with the Ten Section Oilfield, California, has been described and evaluated.

10. Interpretation techniques have been developed and improved which may help to put radiometric methods of oil prospecting on a sound footing.



DRAINAGE MAP OF REDWATER OILFIELD, ALBERTA.

APPENDIX — I

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L'ASSOMPTION PROSPECT SECTION A—A'

Figure 58

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Figure 59

SECTION B—B'

L'ASSOMPTION PROSPECT

QUEBEC

SCALE IN FEET

VERTICAL 400 0 400 800 1200

HORIZONTAL 40 0 40 80

-LEGEND-

- shale
- calcareous shale
- sandy shale
- limestone
- argillaceous limestone
- mineralization (pyrite)
- syenite
- metabentonite

Fault—location based on radiation data

NO. 94

LOWER LORRAINE

UTICA

missing core

NO. 88

TRENTON

NO. 85

SLICKENSIDES

SEA LEVEL

NO. 87

LOWER LORRAINE

UTICA

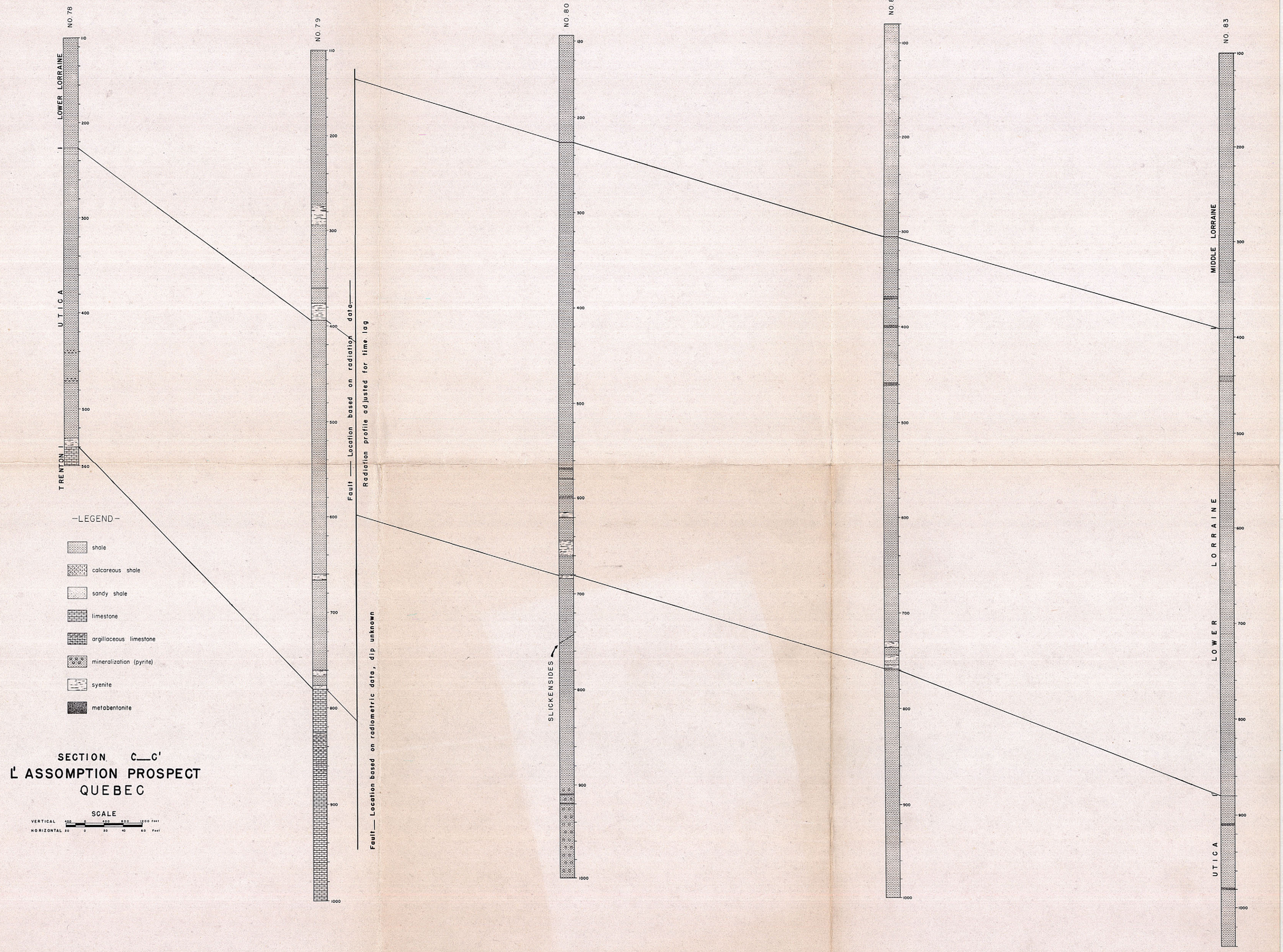

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Figure 60