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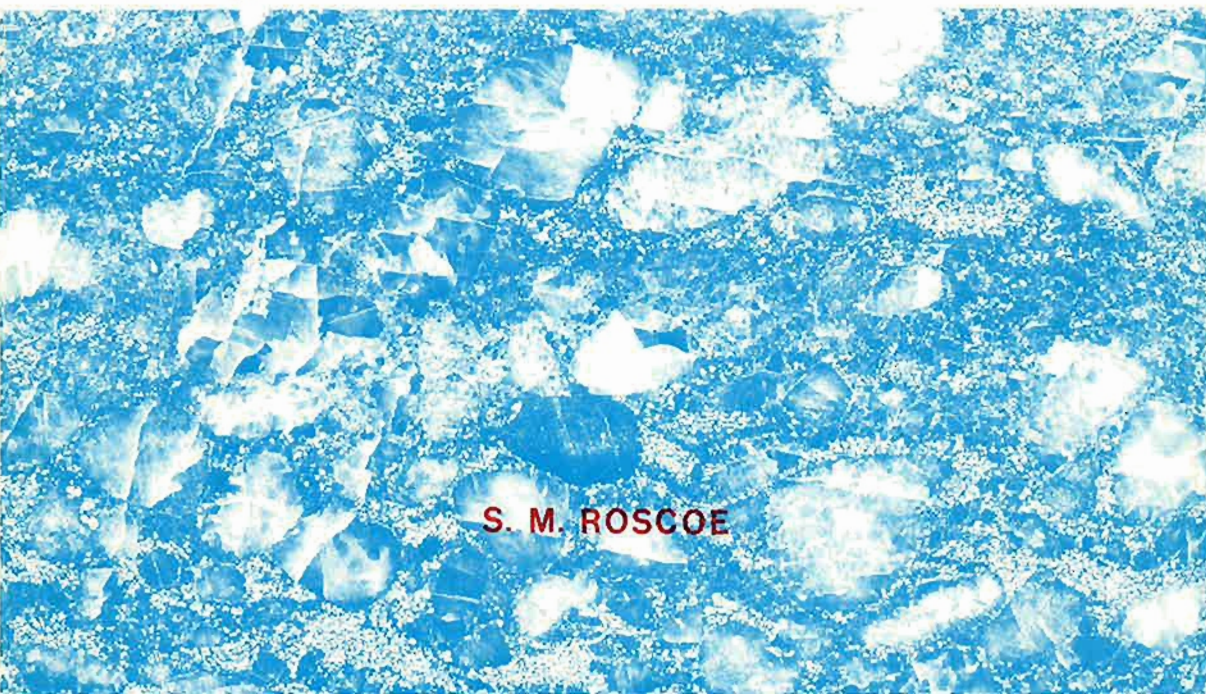
GEOLOGICAL SURVEY OF CANADA · 1842 ·

PAPER 68-40

Huronian Rocks and Uraniferous Conglomerates in the Canadian Shield



S. M. ROSCOE

COVER ILLUSTRATION

Photograph and autoradiograph of an ore specimen from Quirke Mine, actual size. Individual grains of radioactive minerals (light in autoradiograph) and to a lesser extent pyrite (light in photograph) are concentrated at the bases of two conglomerate layers. These minerals occur in interstices between quartz pebbles and allogenic quartz and feldspar grains, not along fractures that cut pebbles, conglomerate matrix and underlying quartzite. Dark pebble at centre is chert. Many quartz pebbles have been darkened, particularly at their rims, through radiation damage. Apparent sizes of many radioactive grains are exaggerated due to dispersion of gamma rays, and clusters of small grains appear as single areas of radioactivity. The smallest, most radioactive grains are uraninite. The relative proportion of these to larger, less radioactive minerals, brannerite-rutile, monazite and zircon, decreases upward in the lower conglomerate layer. Pyrite is more closely associated with the latter minerals than with uraninite.

Owing to a photographic reversal of the upper part of the cover design, line 3 of the description should read ... (dark in autoradiograph) ...

GEOLOGICAL SURVEY

OF CANADA

PAPER 68-40

HURONIAN ROCKS AND URANIFEROUS CONGLOMERATES

S.M. Roscoe

DEPARTMENT OF

ENERGY, MINES AND RESOURCES

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Illustrations

HURONIAN ROCKS AND URANIFEROUS CONGLOMERATES OF THE CANADIAN SHIELD

INTRODUCTION

The Geological Survey of Canada began a study of uraniferous conglomerates in 1954 under the supervision of the writer. Field work, centred at Elliot Lake but extending throughout much of the Huronian belt, was carried out mainly during the 1954 to 1958 seasons. Results of this work and related laboratory studies were reported in Geological Survey and other publications between 1957 and 1963 but further laboratory work has been completed since then. Information from recent geological mapping by the Ontario Department of Mines, the Geological Survey, and others, together with mining developments and uranium exploration drilling has greatly extended knowledge of the lateral and stratigraphic extent of Huronian rocks in the Sault Ste. Marie-Sudbury region and has opened the door to broader interpretations concerning the geological environment of conglomeratic uranium deposits. The writer has made numerous field trips since 1958 to the Elliot Lake area, all other parts of the Huronian belt and to other belts of Proterozoic rocks thought to be somewhat similar to Huronian rocks.

Publications relating to Huronian stratigraphy, isotopic analyses of lead and sulphur associated with uranium ores, and ore chemistry were in preparation in 1966 when resurgence of uranium exploration produced new interest in geological information concerning Huronian rocks and ores. It has been decided that these specialized papers should be incorporated in a more comprehensive report treating all aspects of the geology of conglomeratic uranium deposits.

Exploration for uraniferous quartz-pebble conglomerate beds should be predicated to a large extent on interpretations of the history of deposition of Huronian rocks. In order to advance such interpretations intelligibly it is essential to establish some means of referring to relevant lithostratigraphic units. New data have established regional correlations that were previously questioned or that were unsuspected prior to 1953 and there is no longer any doubt that some revisions in Huronian terminology, along the lines suggested by the writer in 1957 and 1960 and followed in this report, are required and will simplify, rather than complicate, communication.

The problem of whether the uraniferous conglomerates in Huronian rocks formed as placer concentrations of detrital minerals or through introduction of uranium into permeable or otherwise favourable strata has been of

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widespread general interest. This is a matter of economic as well as academic importance. If the deposits were placers, possibilities of finding others are relatively limited but guides to exploration should be very definitive. However if they were epigenetic it would be much more difficult to evaluate or delimit possibilities of finding related (but perhaps dissimilar) deposits in the Huronian belt and in other regions. This question of origin strongly influenced the conduct of this study. Data suitable for testing epigenetic and placer hypotheses were sought. Epigenetic hypotheses do not pass such 'tests'. The placer hypothesis does. It leads, however, to a consideration of the possibility that the deposits were formed at a time when the earth's atmosphere contained no free oxygen and that similar important deposits may not be found in younger rocks.

ACKNOWLEDGMENTS

This study was unusually dependent on compilation of data obtained during exploration work and mine development work by many companies. Collection of these data was made possible by the kind interest that company officials and employees, consulting geologists and others showed in our work. It would be impossible to enumerate all of those who have contributed in this way and who extended special courtesies to the writer and members of his parties but F. Barnes, R. Benner, M. DeBastianni, D. Derry, E. Evans, A. Ferguson, R. Hart, J. Hogan, S. Holmes, M. Johnson, F. Joubin, D. Keyes, E. Lalond, E. Lees, W. Nethery, R. Pountney, A. Raney, R. Rice, D. Robertson, J. Silman, D. Sprague and G. Westner, at least, should be mentioned.

The synthesis in this report of the geology of the region containing Huronian rocks has drawn upon a tremendous body of geological literature and offers some refinements of the classic regional study made by W.H. Collins. Work by J.E. Thomson and R.M. Ginn in the Espanola area, together with data from exploration drilling in the Elliot Lake area offered the first clues for such refinements but they are based in large part upon recent mapping by James Robertson and K.D. Card of the Ontario Department of mines and M.J. Frarey of the Geological Survey of Canada. Discussions and field trips with these workers have had a strong influence on interpretations given in this report.

The writer was fortunate in having P.J. Pienaar associated with him in field work during 1955, 1956, and 1957. Pienaar, who had previous experience with radioactive conglomerates in South African goldfields, logged much of the drillcore studied in this project and made specialized studies of sedimentary features in underground workings and on surface. In addition to directly assisting the writer, he collected material for a dissertation on the Huronian sedimentary rocks that contain the known conglomeratic uranium ores. The major part of this dissertation has been published as Geological Survey Bulletin 83. For those particularly interested in Huronian stratigraphy

and sedimentation the bulletin is an essential complement to this publication. Some interpretations regarding sedimentation favoured in this report differ slightly from those favoured by Pienaar. Some analyses of ores and minerals in ores given by Pienaar in his dissertation but not in Bulletin 83 have been used in this report.

Mineral separations, mineral identifications and various types of analyses were made by staff members of Geological Survey laboratories. The writer thanks A.H. Lang, H.R. Steacy, S.C. Robinson and R.J. Traill for advice and assistance in connection with such laboratory work and with this study in general. He is also grateful for services performed by officers of the Mines Branch, Department of Energy, Mines and Resources.

Critical reading of this manuscript by R.T. Bell was most helpful. M.J. Frarey, J.C. McGlynn and C.H. Stockwell read lengthy sections and many other colleagues have given valuable advice on specialized aspects of the work and the text.

USAGE OF THE TERM 'HURONIAN'

The first geological map of what has become known as the 'Original Huronian area' between Sault Ste. Marie and Blind River was made by Alexander Murray in 1858. He mapped a sequence of sedimentary rocks that nonconformably overlie granitic rocks in the area. Sir William Logan (1863) considered that these rocks, which he called 'Huronian series', were continuous with rocks that he had noted on the shore of Lake Temiskaming in 1845. He believed that all Azoic (Precambrian) rocks would be found to belong either to an older Laurentian series or a younger Huronian series. The terms Archean and Proterozoic were later used to express this concept of a two-fold division of rocks formed in Precambrian time but it is worth noting that such a division was originally attempted in the Lake Huron area.

In the context of modern stratigraphic nomenclature (see Dunbar and Rodgers, 1957, p. 293), the term Huronian was originally used as a time-stratigraphic term denoting not only one specific sequence of strata deposited subsequent to deep erosion of older Precambrian rocks but any other coeval sequence. Fossils are the principal means of making such correlations in Phanerozoic rocks. In their absence, time-stratigraphic classifications of rocks must be based on isotopic age determinations or on lithological correlations with rocks so dated. Unconformities by themselves are unreliable for long range time-stratigraphic correlations and must be used with caution in short range correlations of dissimilar rocks. In different places, for example, different formations through a great stratigraphic thickness of Huronian rocks rest nonconformably upon Archean basement rocks. Obviously these are not precise time-stratigraphic equivalents. Moreover, within a few miles of such nonconformities, Keweenawan rocks and Paleozoic rocks are found similarly resting nonconformably upon Archean rocks. It is the rocks themselves that we correlate, not their age relationships.

Stockwell (1964) has classified Canadian Precambrian rocks on the basis of their time of formation with relationship to the major periods of orogeny that have been recognized in the Canadian Shield rather than according to specific sequences of dated rocks. Huronian rocks, according to this scheme, were deposited during the Aphebian Era which is defined as the time interval between the Kenoran orogeny that ended about 2,500 m.y. ago and the Hudsonian orogeny about 1,600 m.y. ago. The term Aphebian, or a derivative term such as Early Aphebian, Lower Aphebian, or Paleoaphebian, satisfies practical requirements for expressing age relationships of Huronian rocks. It is not possible to establish actual dates for the beginning and cessation of Huronian sedimentation (time-rock classification). Thus there is no need to use the term Huronian as other than a rock-stratigraphic term. As the Huronian sequence contains units of group rank, the appropriate term for the sequence as a whole is Huronian Supergroup – a term used in this context by J.E. Thomson (1962). Rocks found within the sequence can of course be referred to simply as Huronian rocks.

In this paper, the Huronian Supergroup is considered to include all of the formations that have long been considered Huronian, newly recognized units concordantly underlying these formations as they were described by Collins (1925), and correlative strata and strata that are concordant, or nearly so, with these through appreciable areas. This definition will result in the inclusion in the Huronian Supergroup of strata that have been referred to as Sudbury Group and volcanic rocks that underlie these concordantly but not any strata that are demonstratably Archean (older than 2.4×10^9 years according to K-Ar determinations) or other than Aphebian in age. The Whitewater Group of Aphebian age will be excluded by the above terms of reference.

Huronian Formations that are essentially concordant through most of the region may be angularly discordant in places. Even if nonconformities are found, lithological details within the underlying and overlying successions must be given preference as criteria for correlation. All of the rocks herein included in the Huronian Supergroup were probably deposited very early in the Aphebian Era according to isotopic evidence that will be reviewed later, so there is little room in this chapter of the geological history of the region for two separate, major orogenic cycles. Deposition of the rocks was probably syntectonic as indicated by the presence of volcanic rocks and greywacke within the sequence, rapid facies changes and rapid thickening of units away from the source area, soft sediment deformation structures, and thickening, thinning and erosion of sediments evidently related to warping and faulting in basement rocks during sedimentation. A nonconformity, if found within such a mobile belt would not necessarily indicate that two distinct orogenic cycles had taken place.

GENERAL FEATURES OF THE HURONIAN SUCCESSION

LITHOLOGY

The lithology of strata included in the Huronian Supergroup as defined above is outlined in Table I, together with names herein applied to individual lithostratigraphic units. Detailed descriptions of units, as given by Collins (1925), and by Pienaar (1963), Robertson (1961-1967) and others in local areas, are not presented but some general remarks may serve to emphasize that the succession is most distinctive and is completely amenable to stratigraphic work. It is dominated by thick sequences of coarse quartzose arenites separated by unsorted conglomeratic rocks and finer grained argillaceous rocks. There are no repetitions of thick identical units of any of these three types of rocks within the succession.

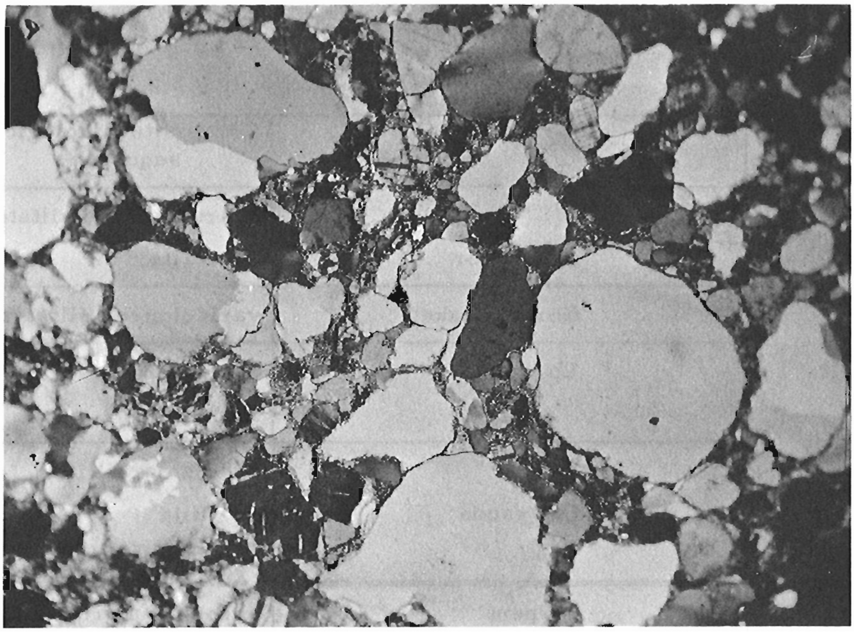
Arenites

With the exception of the uppermost quartzites, the arenites are texturally, mineralogically and chemically submature. Different units differ in their proportions of quartz, potash feldspar, plagioclase feldspar and originally allogenic sericitic and chloritic matrix material as well as in other features such as general grain size, sorting, thickness of beds, character of crossbedding, ripple-marking, mudcracks, and colour of fresh and weathered surfaces. The formations thicken to the south with accompanying decrease in grain size in this direction. Crossbedding indicates deposition by southerly flowing streams. Radioactive quartz-pebble conglomerates occur most abundantly within gritty, relatively poorly sorted clastics that are commonly green due to abundant sericite in the matrix (Pl. I B). Such rocks are most abundant within the Matinenda Formation but are also present in stratigraphically higher arenaceous units in their northernmost, sourceward, occurrences where lower units are missing.

PLATE I. Photomicrographs, matinenda subarkose, partially crossed nicols, times 25.

A. Comparatively 'well-washed' with little interstitial argillaceous material, Pronto Mine area. 200888-A.

B. Comparatively 'poorly-washed' with abundant interstitial argillaceous material, Pecors Lake area. 200888-B.



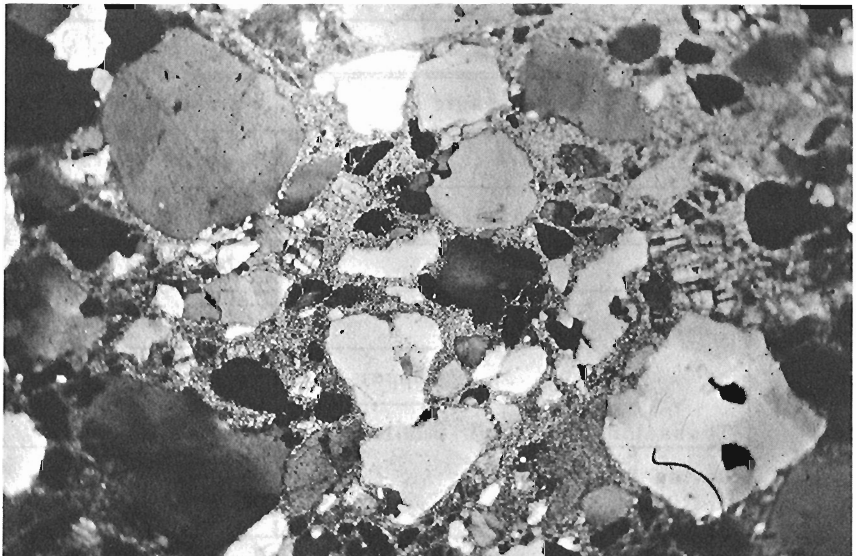


TABLE I

HURONIAN FORMATIONS

Group	Formation	Composite lithological sequence
	Bar River	quartzite, red siltstone quartzite
	Gordon Lake	varicoloured siltstone
Cobalt	Lorrain	quartzite arkose
	Gowganda	reddish argillite argillite conglomeratic greywacke, grey and pink arkose.
	Serpent	arkose-subgreywacke
Quirke Lake	Espanola	dolomite, siltstone siltstone, greywacke limestone
	Bruce	conglomeratic greywacke
	Mississagi	coarse subarkose
Hough Lake	Pecors	argillite, siltstone
	Ramsay Lake	conglomeratic greywacke
Elliot Lake	McKim	subgreywacke, argillite
	Matinenda	gritty subarkose
	Copper Cliff	acid volcanics
	Thessalon Pater Stobie	basic volcanics
	Livingstone Creek	subarkose

Conglomeratic Greywacke

Conglomeratic greywacke units comprise the Ramsay Lake Formation, and the Bruce Formation, and are thick and abundant in the Gowganda Formation. These rocks are the products of mass transport and deposition by agencies such as mudflows, turbidity currents or glaciers. They also thicken to the south but this thickening, particularly in the case of the Gowganda Formation, is less marked than that of the arenites. All are overlain by fine-grained sediments that thicken to the south. Whatever the agencies of transport and deposition may have been, these were periodically triggered by tectonic movements that were part of the pattern of those that controlled all Huronian sedimentation. The formations contain scattered to well packed angular to rounded granules, pebbles, cobbles and boulders in a matrix of greywacke, siltstone, argillite, or arkose. The clasts are predominantly granitic rocks but include metavolcanics and all other rocks present in the Archean terrain north of the Huronian belt and, locally, rocks that may have been derived from underlying Huronian Formations. The main conglomeratic units - Ramsay Lake, Bruce and Gowganda Formations - show characteristic differences in their matrix material and in the character of their clasts. These differences will be described later but it can be pointed out that with varying degrees of confidence it is possible to distinguish between these formations on lithological grounds alone depending on the extent and degree of isolation of individual outcrops.

Fine-Grained Argillaceous Rocks

Fine-grained argillaceous rocks include argillaceous feldspathic quartzite (or subgreywacke), siltstone, argillite, slate, and limestone. The main occurrences of these pelitic rocks are in the McKim Formation, the Pecors Formation, the Espanola Formation and in the upper part of the Gowganda Formation. The McKim Formation, the thickest and stratigraphically lowest argillaceous unit, has been referred to as greywacke but relatively unmetamorphosed specimens lack the unsorted fabric that many authorities consider diagnostic of greywacke. Similarly the central part of the Espanola Formation, which Collins (1952) named the Espanola Greywacke Member, is composed mainly of subgreywacke and limey siltstone. The Pecors Formation, referred to by Robertson (1961-1967) as Middle Mississagi Argillite, contains beds of massive and finely laminated grey and green argillite but most beds are clastic rocks that can be described as subgreywacke, siltstone, and fine grained quartzite.

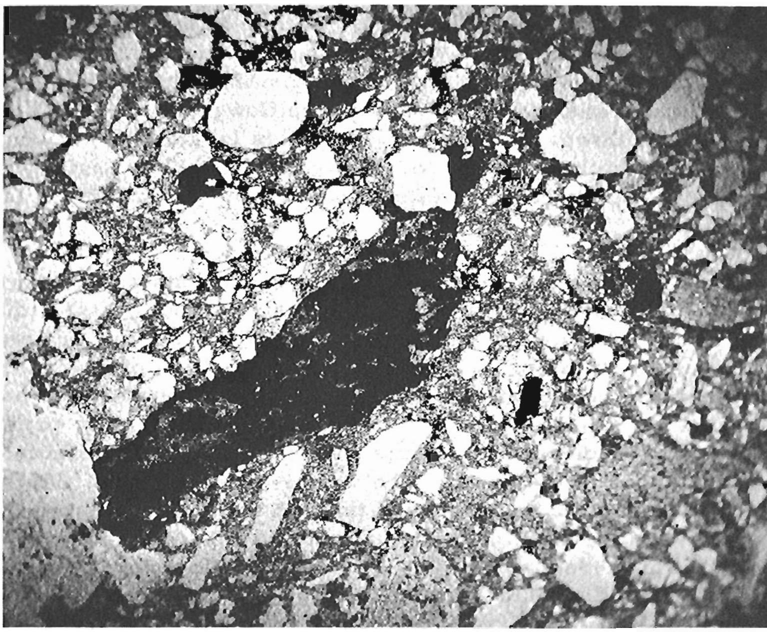
DIVISION OF THE HURONIAN SUCCESSION INTO GROUPS

The Huronian succession contains three cyclical sequences, each comprised of conglomeratic greywacke overlain by fine-grained sediments in turn overlain by quartzite. The lowest cycle, represented by the Ramsay

PLATE II. Photomicrographs of conglomeratic greywacke, plane polarized light, times 25.

A. Bruce Formation; opaque material (black) in greenstone clast and in matrix is pyrrhotite. 200888-C.

B. Ramsay Lake Formation overlain by black argillite of the Pecors Formation. 200888-D.



Lake Conglomerate, the Pecors Formation and the Mississagi Formation, is succeeded by the sequence, Bruce Conglomerate, Espanola Formation and Serpent Formation. The highest sequence, known as the Cobalt Group, includes the conglomeratic lower portion of the Gowganda Formation, the upper portion of the Gowganda Formation which is largely free of conglomerates but contains thick sections of laminated siltstone and argillite[1], and the thick sequences of quartzites named the Lorrain Formation and the Bar River Formation.

Each of these repeated assemblages represents a major cycle that began (probably following some erosion of underlying sediments) with mass deposition of unsorted material, followed by deposition of fine grained sediments in quiet, shallow water, and ended after deposition of coarse arenites under strong current conditions. These repetitions of events must have genetic and time significance in terms of regional downwarping, prevalence of relatively static conditions, or uplifts within the depositional area and in adjacent source areas to the north. The writer (Roscoe, 1957a, 1957b, 1960b; and in Pienaar, 1963, p. 7) has proposed that the two lower of these cyclinal sequences be given formal names of equal rank to that of the Cobalt Group, the uppermost of the three. The name Quirke Lake Group was proposed for the sequence, Bruce-Espanola-Serpent Formations beneath the Cobalt Group; the name Hough Lake Group[2], for the sequence Whiskey-Pecors-Mississagi Formation below the Quirke Lake Group.

---

[1]Robert Thomson (1957) pointed out that two mappable Huronian units, each up to 1,000 feet thick, were found beneath the Lorrain Formation in the Cobalt area and he proposed that, rather than continuing to refer to these as divisions of the Gowganda Formation, they be given two new formational names: Coleman, for the lower conglomeratic unit; Firstbrook, for the upper thin bedded greywacke unit. These units can be recognized throughout a large area extending 60 miles southwest of Cobalt and Elk to Wanapetei Lake near Sudbury. Analogous divisions of rocks known as Gowganda Formation could be made in many if not most parts of the separate belts southwest of Sudbury and between Elliot Lake and Sault Ste. Marie. It seems advisable to retain the name Gowganda Formation for the conglomeratic sequences in all areas but to apply new formational names such as Firstbrook Formation to overlying distinctive, nonconglomeratic units where these are applicable.

[2]The initial proposal (Roscoe, 1957a, b) was that the name Mississagi be elevated from formational to group rank and be considered to include a lower formation, Whiskey, that had a conglomeratic basal member and an argillaceous upper member. The modified proposals (Roscoe, 1960b) used in this report were presented to the Committee on Stratigraphic Nomenclature in 1959. Pienaar (1963) used the terms, Hough for the group and Mississagi and Whiskey for formations, including both the polymictic conglomerate and the argillite in the Whiskey Formation. Other differences between usages in this report and those in Pienaar, 1963 are: Elliot Lake Group rather than Elliot Group which was preempted, Quirke Lake Group rather than Quirke Group and Hough Lake Group rather than Hough Group.

The above proposal is contentious as the two new group names would collectively displace the name Bruce[1] Group – a name that evolved, through Bruce series (Collins,1914) and Lower Huronian series, from the classic time-stratigraphic division of the Huronian 'system' into two separate 'series' based on an unconformity below the Gowganda Formation. In a rock-stratigraphic system of nomenclature, however, the division between sequences herein referred to as Quirke Lake and Hough Lake Groups would seem to have the same qualitative significance in terms of tectonic history as the distinction between Cobalt Group and underlying strata. The individual groups have similar lithological characteristics and similar patterns of regional distribution but are significantly different in detail in both respects. The proposed system of nomenclature provides a more convenient way of describing these differences and discussing regional correlations.

In addition to the three groups discussed above, there is a fourth group of mappable Huronian lithostratigraphic units which concordantly underlie the Hough Lake Group. The writer (Roscoe, 1957a, b) has proposed that the name Elliot Lake Group be applied to such formations in the Elliot Lake area. The conglomeratic uranium ore deposits occur in this group.

In the Sudbury-Espanola area, sedimentary formations that concordantly underlie the Hough Lake Group have been included in the Sudbury series (Coleman, 1914; Burrows and Rickaby, 1934; Collins, 1925, 1936), Bruce series (Cooke, 1946), Elliot Lake Group (Ginn, 1960); Young and Church, 1966) and Huronian and/or pre-Huronian (Thomson, 1962). There is now widespread agreement that these strata are correlative with strata named Elliot Lake Group by Roscoe (1957a, b) but there may be some question as to whether the name Elliot Lake Group should be retained and its use extended into the Sudbury area or whether the term Sudbury Group should be used regionally. The latter name has been applied in recent years (as in Thomson, 1962, Table I) to sedimentary rocks that were formerly referred to the Sudbury series but it has not been well defined in terms of component strata. The name 'Sudbury' has been also applied to several other rock units and structures, such as: Sudbury Irruptive, Sudbury gabbro, sudburite, Sudbury breccia, and Sudbury Basin. The word Sudbury is synonomous with great nickel deposits, the word Elliot Lake with great uranium deposits. The group in question is the major known host for conglomeratic uranium deposits in the Sudbury-Espanola area as well as in other parts of the region. Perhaps it would be appropriate to extend use of the term Elliot Lake Group into the Sudbury area. For simplicity in this report the rocks will be referred to as 'Elliot Lake Group' rather than 'Elliot Lake-Sudbury Group' or 'Elliot Lake Group and correlative rocks'.

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[1] It is taxonomically unfortunate that the name Bruce has been applied to a formation-Bruce Conglomerate – and a member-Bruce Limestone – of the Espanola Formation, as well as to a group and it would be well to eliminate the latter usage.

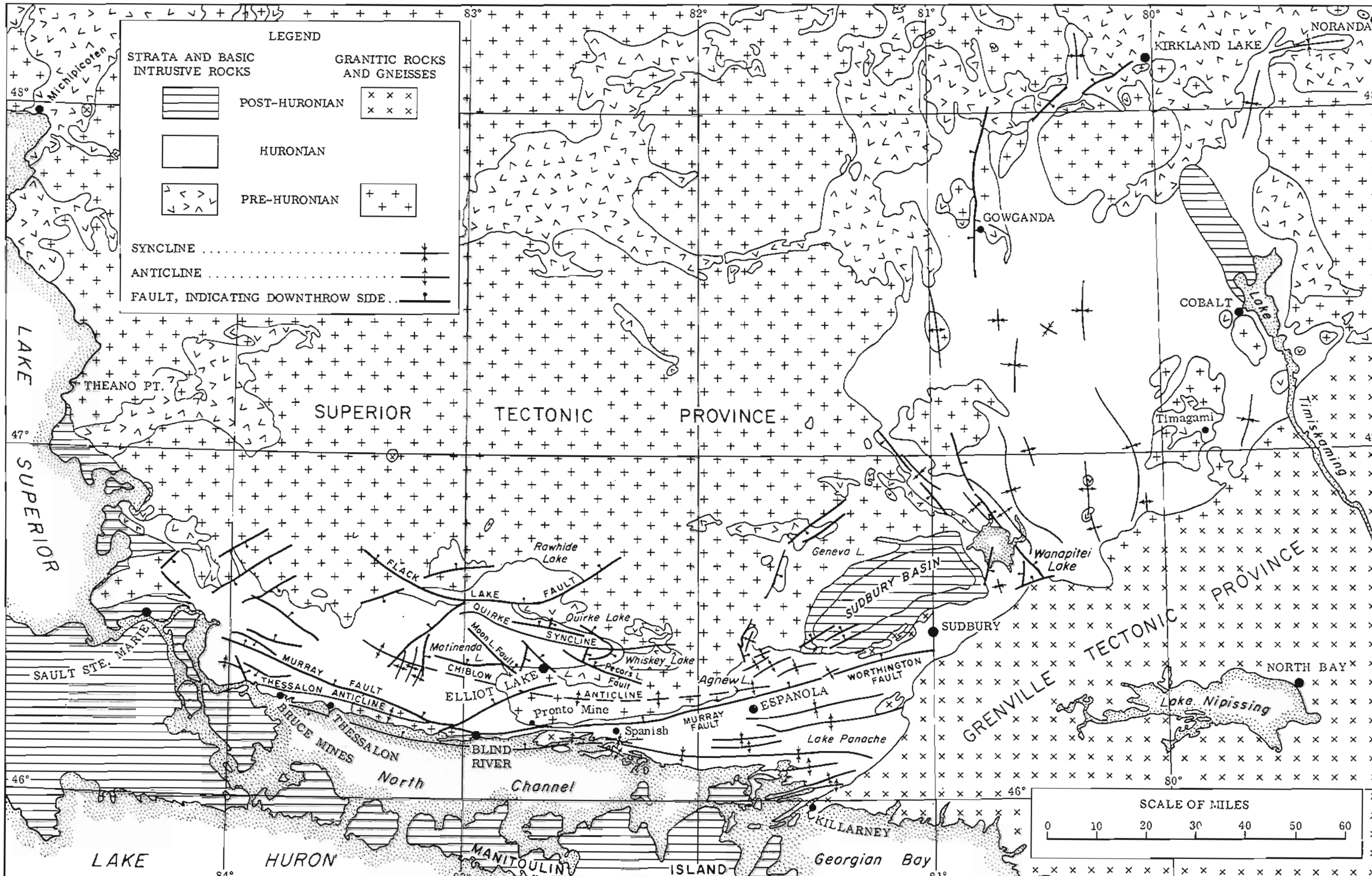

Figure 1. Distribution and structure of Huronian rocks.

DISTRIBUTION AND CORRELATIONS OF THE HURONIAN ROCKS

GENERAL

The Huronian rocks occur in a belt comprising three major sectors and a few outliers (Fig. 1). The western sector extends 100 miles eastward from Lake Superior to the Elliot Lake area. This includes the area referred to as the 'Original Huronian' area in recognition of the initial mapping in the area by Alexander Murray in 1858 and the description of the sequence therein as the Huronian series by William Logan (1863). The central sector extends about 100 miles west from Wanapitei Lake to Pronto Mine on the north side of the Murray Fault and to Killarney, Spanish, John Island, Blind River and the Mississagi River delta on the south side of the Murray Fault along the Lake Huron coast. The largest sector extends about 100 miles north and northeast of Lake Wanapitei. In addition to difficulties that arise in tracing deformed strata through the narrow necks that connect these sectors, the Murray Fault presents an obstacle to direct correlations of rocks on either side of it between Blind River and Espanola.

Many of the difficulties that have arisen in making correlations in the region apparently stem from presumptions that the nonconformity found in the 'Original Huronian' area can be treated as a stratigraphic plane, that the Mississagi Formation as mapped by Collins in the Blind River area is everywhere the lowest Huronian Formation and that the Huronian succession can be defined from the Mississagi Formation upwards. As a result of these assumptions, strata that are almost certainly correlative in different places have been variously included in the Mississagi Formation (Collins, 1925), the Sudbury series (Collins, 1925), and the Lower Mississagi Formation (Robertson, 1961-1967). In fact, deposition of Huronian rocks was transgressive from south to north over an irregular Archean surface so that different lithostratigraphic units overlie the basement rocks in different places and it is extremely awkward to discuss stratigraphy and correlations of Huronian rocks using the nonconformity as a primary reference plane. Some of these difficulties can be mitigated perhaps by describing the succession and distribution of major lithostratigraphic units in descending rather than in ascending order, reversing the normal procedure. Thus we shall examine the succession by lifting successive layers off the Huronian 'cake' rather than by attempting to slide them out from the bottom. The distribution of Huronian Groups is illustrated in Figure 2.

COBALT GROUP

General

The Cobalt Group lies directly on Archean basement rocks in the northeastern Huronian sector except near Lake Wanapitei where it overlies older Huronian rocks. The group also rests nonconformably on Archean rocks along the northern edge of the original Huronian area (Frarey, 1959, 1961a, b) – a relationship that led Emmons (in Collins, 1925, p. 33-38) to correlate these rocks erroneously with the Mississagi Formation. Farther south the group overlies older Huronian rocks which are exposed in relatively limited anticlinal or up-faulted areas. The Cobalt Group also covers an extensive area of older Huronian rock along Lake Huron south of the Murray-Worthington Fault in the central Huronian sector and occurs in small areas north of the fault in this sector. The exceedingly distinctive sequence of Cobalt Formations, is almost identical in each of the three segments and, includes in ascending order the Gowganda, Lorrain, Gordon Lake and Bar River Formations.

The group was evidently at least 10,000 feet thick over most of the region and may have exceeded 18,000 feet in the southern part. The primary inclination of crossbeds in the Lorrain Formation in each of the three major Huronian areas indicates a southerly direction of sedimentary transport according to measurements made by Pettijohn (1957) and by the writer and others. Inclinations of crossbeds in the Bar River Formation near Flack Lake and a few that have been measured in arkose within the Gowganda Formation, similarly indicate a southerly to southeasterly direction of current flow during deposition of fluviatile sediments of the Cobalt Group. The red coloration and presence of hematite in many beds within the various formations of the group are notable, as such coloration and occurrences of iron in the ferric state are lacking in subjacent Huronian successions.

FIGURE 2. DISTRIBUTION OF HURONIAN GROUPS

Outcrop areas of groups in A, B, C, and McKim Formation in D

Matinenda Formation

Volcanic rocks of Livingstone Creek, Pater, and Stobie Formations

Subsurface extent of groups

Paleolimits of groups . . . . — — —

Paleolimit of Gowganda Formation . . . . - - - - - - -

Predominent direction of primary inclination of crossbeds in major arenaceous units . . . . →

Estimated thickness of groups in hundreds of feet 12

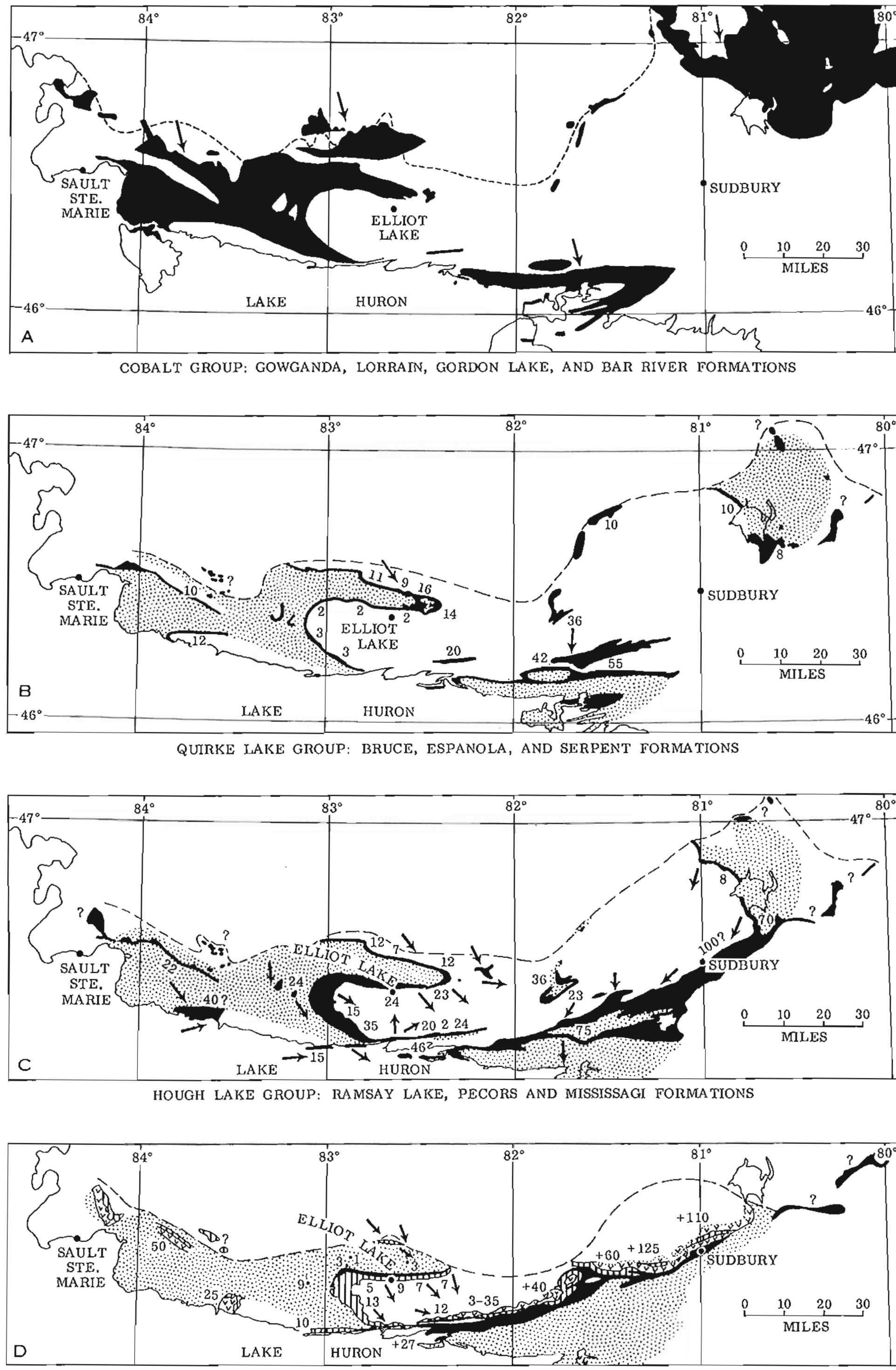

Figure 2. Distribution of Huronian Groups

Gowganda Formation

The Gowganda Formation is a heterogeneous assemblage of conglomeratic greywacke, sorted arkosic conglomerate, massive or laminated greywacke, siltstone and argillite, and arkose. The most characteristic rock, commonly referred to as tillite, consists of angular to rounded boulders, cobbles and pebbles of pink granite and a large variety of other Archean igneous and metamorphic rocks scattered in massive, fine grained, dark grey or greenish greywacke. Many layers of laminated greywacke-siltstone-argillite contain widely scattered to abundant rock clasts ranging in size from granules to small boulders; these resemble the fine grained sediments containing ice-rafted pebbles that are found in deposits of Pleistocene age. Thick conglomeratic layers are most abundant in the lower part of the formation, arkose and argillite in the upper part. A lower conglomeratic section and a thick, upper, nonconglomeratic section composed mainly of laminated argillite have been distinguished on some maps of parts of the northeastern Huronian area. Robert Thomson (1957) proposed that these extensive major units be named Coleman Formation and Firstbrook Formation. The latter name seems a useful addition to Huronian terminology but the well-known name Gowganda Formation should be retained for the conglomeratic rocks. The trend upwards from unsorted conglomeratic rocks to sorted fine-grained rocks is noteworthy as it is also shown by sequences overlying conglomeratic greywacke, i.e. the Ramsay Lake and Bruce Formations, at other stratigraphic levels within the Huronian succession.

Thickness

The Gowganda Formation is probably 2,000 to 4,000 feet thick through most of the 'Original Huronian' area according to estimates by Collins (1925), Robertson (1967) and Frarey (personal communication) but it thins abruptly along the northern fringe of the area where it is overlapped by the Lorrain Formation. The approximate position of the northern paleolimit of the Gowganda Formation is shown in Figure 2; north of this line it is absent and the Lorrain Formation rests directly on basement rocks. It is probably 3,000 to 5,000 feet thick in the southern part of the central Huronian area (Young, 1966; Young and Church, 1966; Frarey, personal communication). Thomson and Card (1963) estimated the formation to be as much as 9,000 feet thick in Davis Township 6 miles east of Lake Wanapitei. Simony (1964) estimated it to be 2,000 to 3,000 feet thick in the northern part of the Timagami Lake area with the variation due to local relief on the pre-Huronian surface. According to estimates given by Grant (1964), it was originally more than 4,500 feet thick and may have been as much as 7,000 feet thick in the southern part of the Timagami Lake area. Schenk (1960, p. 43) considered that the pre-Gowganda surface in this area was mountainous with a relief of almost 3,000 feet in a distance of 1 mile in one place. Drilling in Beachastel Township, Quebec, has indicated original pre-Gowganda basement slopes of at least 40 degrees (Ambrose and Ferguson, 1945, p. 13).

Lorrain Formation

The Lorrain Formation is characterized by thick-bedded, coarse-grained, white quartzite but it includes red arkose near the base, greenish feldspathic quartzite, orthoquartzite, jasper and quartz-pebble conglomerate and fine-grained red quartzite and siltstone. Frarey (1962a) recognized five members in the Bruce Mines area, in ascending order: (1) massive red arkose up to 2,000 feet thick, (2) purple siltstone and fine-grained quartzite up to 350 feet thick, (3) reddish and buff-coloured, crossbedded, pebbly, arkosic quartzite up to 2,000 feet thick, (4) conglomeratic white quartzite up to 850 feet thick containing abundant jasper as well as quartz and chert pebbles, (5) thick-bedded white quartzite up to 2,000 feet thick containing thin interbeds of quartz-pebble conglomerate. Units 1 and 2 have not been recognized in other parts of the region but they may have counterparts that have been included in the upper part of the Gowganda Formation in the north-eastern Huronian area. Where theLorrain Formation rests directly on pre-Huronian rocks north of Elliot Lake and in the northeastern area, the basal member resembles Frarey's member three, but is much less than 2,000 feet thick. It is relatively radioactive and at Kirkpatrick, Mount and Rawhide Lakes north of Elliot Lake contains thorium-bearing, black sand-type concentrations rich in hematite, monazite and zircon in quartz-pebble beds and along crossbedding and bedding planes in pebbly arkose. Near Mount Lake, such concentrations are also found higher in the formation within and above a conglomeratic section equivalent to Frarey's member four. The more abundant conglomerates in the formation contain quartz, chert and jasper pebbles in a well-sorted quartzose matrix and are not radioactive. This type of conglomerate is much less abundant and jasper pebbles are rare within it in the central and northeastern Huronian areas. Robertson (1963a) tentatively included arkose at Dunlop Lake in the Lorrain Formation but its stratigraphic position with respect to the radioactive arkosic quartzite at Mount Lake or with various units described by Frarey (1961a, b) is not known.

Gordon Lake Formation

The Gordon Lake Formation (Frarey, 1967) consists of varicoloured siltstone and corresponds to the unit designated as 'Banded Cherty quartzite' by Collins (1925). It is about 800 feet thick in the type area north of Bruce Mines. It is present in the Flack Lake area north of Elliot Lake, and near Killarney in the southern part of the central Huronian area where it is about 3,500 feet thick. It is also present in the northeastern area at Smoothwater Lake and along the Lady Evelyn River 40 miles north of Lake Wanapitei (Collins, 1917).

Bar River Formation

The Bar River Formation (Frarey, 1967) is composed of white quartzite. Thicknesses of up to 2,000 feet occur north of Bruce Mines and perhaps 6,000 feet near Killarney. In the latter area red hematitic siltstone occurs within the formation (Frarey, personal communication; Young, 1966). The formation is also present in synclinal basins at Smoothwater Lake and along the Lady Evelyn River in the northeastern Huronian area.

QUIRKE LAKE GROUP - BRUCE, ESPANOLA, AND SERPENT FORMATIONS

General

The Quirke Lake Group can be demonstrated to underlie the Cobalt Group in all of its outcrop areas with the exception of a synclinal area at Agnew Lake north of Espanola and another south of Espanola where the Cobalt Group has been removed by erosion. Formations of the Quirke Lake Group together comprise the most distinctive sequence within the Huronian Supergroup, and provide a most useful and positive stratigraphic reference for regional correlations. The area around Quirke Lake provides an excellent reference section for the group and for each of the component formations because the strata concerned have been studied there in considerable detail both in the excellent shoreline exposures and in numerous drillcores. Names and thicknesses of units beneath the west and southwest shores of Quirke Lake are tabulated in stratigraphic order below.

TABLE II

QUIRKE LAKE GROUP AT QUIRKE LAKE

GROUP (thickness in feet)	FORMATION (thickness in feet)	MEMBER (thickness in feet)
	Serpent (200-900)	
Quirke Lake (900-1, 700)	Espanola 650 (500-750)	Espanola Limestone ± 200 Espanola Siltstone ± 300 Bruce Limestone ± 140
	Bruce 120 (80-200)	

The Bruce Formation is composed of conglomeratic greywacke differing from most conglomeratic greywacke found in the Gowganda Formation insofar as most granitic clasts are grey rather than pink and the matrix is coarse, dark, quartzitic, and slightly pyritic.

The Espanola Formation consists of siltstone, limy siltstone, and subgreywacke, with a basal member of laminated pale grey limestone and an upper member characterized by the presence of rusty-weathering grey dolomite beds. Near Espanola and elsewhere east of the original Huronian area the basal banded (Bruce) limestone member of the Espanola Formation is rusty-weathering rather than white-weathering and the formation is not as readily subdivisible into members as it is at Quirke Lake. The Serpent Formation comprises white-weathering, grey, feldspathic quartzite generally finer grained, more arkosic and richer in plagioclase than other important Huronian quartzite formations.

Thickness Variations

The group and individual formations are relatively thick (2,000 to 3,500 feet) in the central Huronian segment north of the Murray Fault and still thicker (5,500 feet) in the southern part of this segment at Panache Lake. This general southerly thickening of the group as a whole is mainly due to thickening of the Serpent Formation which is as much as 3,000 feet thick in the Lake Panache area. The Bruce Formation is as much as 600 feet thick in this area - several times thicker than it is in Quirke Lake area.

Evidence of a disconformity between the Quirke Lake Group and the Cobalt Group has been given by Collins (1925), Frarey (1962a), Robertson (1963a, b) and others; this includes the presence of fragments of the Serpent Formation in basal Gowganda conglomerate. Pronounced local variations in the thickness of the Serpent Formation and the Quirke Lake Group as a whole are certainly due to erosion prior to deposition of the Cobalt Group. In the Denison Mine area, the contact between thin sections of Serpent Formation and the overlying Gowganda Formation is represented by a zone of interlayered Serpent-type quartzite and Gowganda-type conglomerate; perhaps a number of disconformities rather than a single erosion interval separate the two groups here. Polymictic conglomerate is also present above the Bruce Limestone Member north of Bruce Mines and in the Serpent Formation northwest of Sudbury. Layers of quartz and chert pebbles are not uncommon in the formation in other areas but these contain scarcely a trace of radioactivity.

Along the flanks and crest of the Chiblow Anticline, the entire Serpent Formation and much, perhaps locally all, of the Espanola Formation are absent beneath the Cobalt Group. The Bruce Formation is only about 60 feet thick along the north flank of the anticline. It is no more than 30 feet thick at Pecors Lake (Robertson, 1962, p. 33) and the overlying Espanola Formation is correspondingly thin. Along the south flank of the anticline, however, it thickens to 200 and 300 feet (Robertson, 1964a, p. 33). The present Chiblow Anticline was evidently not only a site of uplift and erosion prior to deposition of the Cobalt Group but also a positive tectonic zone during deposition of the Quirke Lake Group.

The Quirke Lake Group overlies the Hough Lake Group throughout most of the region, but 27 miles north-northwest of Blind River and 32 miles northwest of Sudbury, it overlaps the depositional or erosional edge of this lower group and rests nonconformably upon Archean rocks.

Correlation Problems Northeast of Sudbury

Rocks resembling those of the Quirke Lake Group underlie the Gowganda Formation northwest and south of Lake Wanapitei. In descending order these were mapped as Serpent, Espanola and Bruce Formations by Kindle (1932), Fairbairn (1939, 1941a, b), Cooke (1941) and, in part, by Quirke (1921). Thomson (1957b and 1961a) questioned these correlations in the area south of the lake and instead mapped most of the quartzite that directly underlies the Cobalt Group as Mississagi rather than as Serpent Formation. He referred underlying sequences containing limestone, siltstone, argillite, quartzite, greywacke and conglomerate to the 'Sudbury Group' rather than to the Espanola and Bruce Formation excepting at Ashigami Lake where he included similar rocks in the Gowganda Formation. Fairbairn (1939) considered that here, as at Elliot Lake, the Serpent Formation has been removed by erosion prior to deposition of the Gowganda Formation. Thomson believed that the quartzite and subjacent rocks mentioned above are separated by an unconformity south of Outlet Bay. Similar limy rocks underlie the quartzite in each of three widely separated places where relationships can be ascertained. This does not bespeak convincingly of a major angular unconformity. Bedding attitudes in the underlying limy rocks appear to diverge from the contact at considerable angles but this cannot be accepted as proof of an angular unconformity as bedding in the Bruce Limestone Member of the Espanola Formation characteristically shows spectacular crenulations. No strata resembling the Espanola Formation have been demonstrated to occur at any other stratigraphic position in the Huronian succession and the writer does not know of any in rocks of established Archean age in northeastern Ontario or western Quebec. The quartzite that overlies Espanola-like rocks and underlies the Gowganda Formation closely resembles the Serpent Formation, not the Mississagi Formation, of the western Huronian sector; the quartzite that underlies rocks resembling the Espanola and Bruce Formations at Ashagami Lake, on the other hand, does resemble the Mississagi Formation. These comparisons are based on observations by the writer as well as those published by Thomson and by Fairbairn and include consideration of grain size, sorting, constituent minerals, sedimentary structures, character of conglomeratic beds and rock clasts, radioactivity and chemical data (analyses published by Thomson, 1961a and by Pienaar, 1963).

Thomson (1961a) noted limestone within an extensive area of Gowganda Formation at Kukagami Lake 4 miles east of Wanapitei Lake. The mapping appears to permit the interpretation that this is exposed in an anticlinal structure and may therefore be correlative with the Espanola Formation as mapped by Fairbairn (1939) at Ashigami Lake.

Collins (1917, p. 69) found rocks resembling the Espanola Formation along the Sturgeon River in Demorest Township 18 miles north of Lake Wanapitei and considered these to be within the Gowganda Formation. The writer has visited this locality. The rocks are identical to those that comprise the upper part of the Espanola Formation at Quirke Lake and in other areas. They are overlain by quartzite that resembles the Serpent Formation as well as by the Gowganda Formation. No exposures of underlying rocks could be found so it is possible to assume that Quirke Lake Group rocks are exposed in a window eroded through the Cobalt Group in this area. A few miles to the north in Turner Township, quartzite and chert and quartz-pebble conglomerate, evidently overlying Archean rocks, are exposed in such a window or breached anticline. Some of the conglomerate is pyritic and radioactive and has been explored by pitting and diamond-drilling (Thomson, 1960a). Thomson assumed that the quartzite and conglomerate was correlative with the Mississagi Formation. This would require that the Quirke Lake Group, if originally present, was completely removed by erosion prior to deposition of the Cobalt Group. The paleolimit of the Quirke Lake Group extends further north than that of the Hough Lake Group in most places (Fig. 2) so it is possible that the quartzite in Turner Township is correlative with the Serpent Formation rather than with the Mississagi Formation.

Quartzite containing radioactive pyritic quartz-pebble conglomerate occurs beneath the Gowganda Formation and atop nonconformities in Pardo Township 18 miles east of Lake Wanapitei and 8 miles northeast of here at the south end of Vogt Township (Thomson, 1960a). These occurrences, like that in Turner Township, could be correlative with the Serpent Formation rather than with the Mississagi Formation.

At Emerald Lake in Afton Township 20 miles northeast of Lake Wanapitei, a window eroded through diabase and Gowganda Formation exposes Archean rocks and some limy rocks and polymictic conglomerates whose relationships to the Archean rocks are uncertain. Contorted, banded white rock covered by shallow water off a point in the southern part of the lake resembles the Bruce Limestone Member of the Espanola Formation.

Correlation Problem North of Thessalon

Isolated outcrop areas of quartzite containing slightly radioactive pyritic quartz-pebble conglomerate overlying Archean rocks and surrounded by Gowganda Formation 15 to 20 miles north of Thessalon in Houghton, Otter, Morin and Galbraith Townships, present difficulties in correlation similar to those posed by occurrences north and east of Lake Wanapitei described above.

Frarey (1959) mapped some of this quartzite as Serpent Formation because it appeared to underlie the Gowganda Formation and is not so coarse-grained as the Mississagi Formation is in other places near its northern limit. Later (1962), however, he considered it to be Mississagi as he found it overlain by conglomeratic greywacke resembling the Bruce Formation rather than conglomerate common in the Gowganda Formation. Some quartzite may be correlative with the Livingstone Creek or Matinenda Formations of the Elliot Lake Group. Uncertainties as to these correlations are indicated in Figures 2B, 2C and 2D.

HOUGH LAKE GROUP - RAMSAY LAKE, PECORS AND MISSISSAGI FORMATIONS

General

The Hough Lake Group underlies the Quirke Lake Group throughout the 'Original Huronian' area with exceptions, or possible exceptions, in the northern part of the area that have been mentioned previously. In ascending order, it comprises conglomeratic greywacke, fine-grained argillaceous quartzite and argillite, and coarse feldspathic quartzite. It has been traced eastward along the north side of the Murray Fault into the central Huronian segment by Robertson (1964, 1965a, b, 1966a, b) who referred to the above units as Middle Mississagi Conglomerate, Middle Mississagi Argillite, and Upper Mississagi Quartzite. This sequence underlies the Quirke Lake Group north and south of the Murray Fault near Spanish, north of Espanola, throughout an extensive belt south of Espanola, and in the Lake Wanapitei area. It extends continuously in a broad belt from Lake Wanapitei westward to Spanish, to islands in Lake Huron, to Blind River and to the mouth of the Mississagi River - a distance of 125 miles. The group overlies sedimentary rocks, herein classified as Elliot Lake Group in most of the region between Sault Ste. Marie and Lake Wanapitei. It overlies volcanic rocks considered part of the Elliot Lake Group in the Thessalon-Sault Ste. Marie area and, perhaps, south of Lake Wanapitei. It lies nonconformably upon Archean rocks north of the paleolimit of the Elliot Lake Group - as along the north limb of the Quirke Syncline, in Porter, Vernon and Ermatinger Townships north of Agnew Lake, and north of Lake Wanapitei, and in local areas where the Elliot Lake Group was either previously removed by erosion or not deposited atop hills on the pre-Huronian surface.

Roscoe (1957a) suggested that the lower units of the group, conglomerate and argillaceous rocks, be named the Whiskey Formation in the Elliot Lake area but later (1960b) recommended that the Whiskey Formation be considered to include only the conglomeratic rocks and that the overlying argillaceous rocks be designated as the Pecors Formation in order to facilitate correlations discussed below. The conglomeratic unit was mapped as Ramsay Lake Conglomerate in the Sudbury-Espanola area by Collins (1925, pp. 39, 40). He mapped overlying fine-grained argillaceous rocks and the coarse feldspathic quartzite, that constitutes the bulk of the group, as

Mississagi Formation. Mapping by Thomson (1953), Ginn (1960, 1961, 1965), Robertson (1961-1967), Frarey (1959-1962), Card (1965-1967), Young and Church (1966) and Casshyup (1966) has clearly established that regional correlations shown in Table III can be made.

TABLE III

EQUIVALENT FORMATIONAL NAMES, HOUGH LAKE GROUP

Collins (1925-1938)	Roscoe (1960b) - Elliot Lake	Robertson (1961-1967)	
Mississagi*	Mississagi*	Upper Mississagi	
	Pecors*	Middle Mississagi	Argillite
Ramsay Lake*	Whiskey		Conglomerate

* Names used in this report.

With uncertainties concerning correlations removed, the conglomeratic unit can be referred to by the same formational name throughout the region. The name Ramsay Lake (Coleman, 1914) has precedence over Whiskey. The name Pecors Formation should be applied to the fine-grained argillaceous sequence in the Espanola area, where it was previously mapped as part of the Mississagi Formation, as well as in the Elliot Lake area. The nane Mississagi Formation should be used only for the thick unit comprised dominantly of feldspathic quartzite that overlies the Pecors Formation and underlies the Bruce Formation of the Quirke Lake Group in the original Huronian area as well as in the Sudbury-Espanola area. It is emphasized that the definitions of formations recommended here negates the widespread concept that the Mississagi Formation is the basal unit of the Huronian succession and contains the important uraniferous conglomerate beds of the region.

Drillholes along the south limb of the Quirke Syncline provide better reference sections for the Hough Lake Group than surface exposures, as the lower formations are poorly exposed in most places. This paucity of exposures was probably largely responsible for Collins' (1925) conclusion that argillaceous units and conglomerates occurred as lenses at different stratigraphic levels within rocks that he mapped as Mississagi Formation in the Blind River area rather than as continuous lithostratigraphic units that underlie the Mississagi Formation as he mapped it in the Espanola area.

Quartzite underlies the Quirke Lake Group in the Thessalon Anticline between Bruce Mines and Thessalon and has been mapped as Mississagi Formation by Collins (1925) and Frarey (1962a). The base of this quartzite unit is not exposed but a few outcrops of fine-grained quartzite and conglomeratic greywacke intervene between it and volcanic rocks of the Thessalon Formation. A drillhole 5 miles west of Thessalon disclosed that the quartzite is underlain by about 700 feet of argillaceous rocks. The sequence Ramsay Lake, Pecors, and Mississagi Formations has been traced westward in drillholes from Elliot Lake to within 22 miles of Thessalon. It is not unreasonable therefore to correlate the conglomerate and argillite near Thessalon with the Ramsay Lake and Pecors Formations, and to seek equivalents of these formations still farther west beneath the Mississagi Formation and above the Thessalon Formation.

Conglomeratic greywacke occurs stratigraphically beneath a thick quartzite unit at Aberdeen and Madill Lakes 14 miles north of Bruce Mines. Collins (1925) and Frarey (1959) mapped the conglomerate as Bruce Formation and the overlying quartzite as Serpent Formation. Frarey (1962a) subsequently found that the quartzite was overlain by a normal Quirke Lake Group succession and therefore classified as Mississagi Formation. The conglomerate, like that at Thessalon, evidently overlies a thick sequence of volcanic rocks which Frarey has correlated with the Thessalon Formation. This conglomerate can also be correlated with the Ramsay Lake Formation. It may be overlain by the Pecors Formation but if this formation is present beneath drift it must be much thinner than it is at Thessalon.

Correlation Problem in Sault Ste. Marie Area

Volcanic rocks in Duncan, Jarvis and Aweres Townships, 8 miles northeast of Sault Ste. Marie, are correlated with those at Aberdeen Lake and Thessalon but are overlain by a sequence that does not so closely resemble the Hough Lake Group. Conglomerate composed of tightly-packed volcanic clasts overlie volcanic rocks in western Duncan Township 1 1/2 miles east of Trout Lake. A layer of thinly bedded, fine-grained sediments outcrops near the west shore of Alexander Lake. It dips gently west and would be no more than a few hundred feet stratigraphically above the volcanic rocks. This is overlain by massive polymictic conglomerate containing abundant volcanic clasts in a greywacke matrix. The volcanic clasts are less abundant relative to granite, quartz and other rock clasts in exposures farther west. Conglomerate at the west side of the conglomeratic belt at the east end of Trout Lake is not unlike conglomeratic greywacke of the Ramsay Lake Formation. A few feet of siltstone overlie conglomerate at this locality and is succeeded by coarse subarkose which is well exposed along the shores of Trout Lake in Aweres Township. The subarkose is crossbedded and contains layers with well-sorted pebbles of quartz and a few of granite. Some layers are faintly radioactive. Hay (1961) mapped a northwest-trending synclinal axis near the west end of Trout Lake. The sequence described above is not repeated on the west limb of the syncline and Hay (1961) mapped contacts between quartzite and granite west of Trout Lake as faults. Conglomerate containing cobbles of granite occurs in this vicinity and is slightly radioactive. McConnell (1926, p. 19) described a gradational contact between weathered granite and pebbly arkose near the southern shore of Lower Island Lake. Layers of quartz pebbles occur in subarkose along the northwestern shore of either Lower Island or Upper Island Lakes and are distinctly, although weakly, radioactive.

McConnell (1926) included all of the sedimentary rocks described above in a formation that he named the Aweres Formation and which he considered pre-Mississagi. Hay (1961) correlated the same rocks with the Serpent Formation. There is no justification for the latter correlation. The subarkose unit must be correlative with the Mississagi Formation or belong lower in the Huronian succession, as suggested by McConnell. The writer tentatively favours the former conclusion because of the apparent great thickness of the subarkose and the occurrence below it, at least locally, of siltstone and conglomeratic greywacke comparable to the Pecors and Ramsay Lake Formation. It must be noted, however, that the subarkose is very coarse and conglomeratic compared to the nearest occurrences of subarkose that is known to be stratigraphically equivalent to the Mississagi Formation.

Ramsay Lake Formation

The Ramsay Lake Formation, like the Bruce Formation, is essentially a homogeneous layer of conglomeratic greywacke in places, it contains sorted layers. It resembles the Bruce Formation more than it does most conglomeratic greywacke, or tilloid beds, in the Gowganda Formation, as it commonly has a gritty quartzose matrix, contains conspicuous pyrite and pyrrhotite, and contains grey and white rather than pink granitic pebbles. In most places it is distinguishable from the Bruce Conglomerate by the lighter coloured, grey, buff or greenish sericitic and feldspathic character of its matrix, a greater abundance of quartz pebbles and greenstone pebbles and cobbles in proportion to granitic clasts, and a relatively high though erratic radioactivity (due to monazite, zircon and rare highly radioactive minerals such as uraninite, thorite and thucolite). These characteristics appear to apply generally throughout the region as well as in the Elliot Lake area.

The Ramsay Lake Formation is 20 to 50 feet thick in most parts of the Elliot Lake area but varies in thickness from an inch or so in some drillcores to about 200 feet, and is generally thicker in the southern part of the Quirke Syncline than in the northern part. It is thinnest where it overlies the Algom-Quirke and Denison ore zones at Quirke Lake, in fact, it is locally absent or marked only by a thin layer of dark greywacke in some places in this area; local omissions, however, may be due to minor low angle faults rather than to non-deposition of the unit. The formation is as much as 200 feet thick in the Agnew Lake area but is considerably thicker a few miles farther south along its main belt of outcrop between Espanola and Sudbury. In Nairn Township, for example, Ginn (1965, p. 10) estimated it to be 600 feet thick.

Pecors Formation

The Pecors Formation is composed of interbedded subgreywacke (argillaceous, feldspathic quartzite) siltstone, and argillite. In the Quirke Lake Syncline, it is possible to subdivide the formation into a lower part that consists mainly of massive and laminated dark argillite, a medial section that is mainly subgreywacke and an upper part comprised of interbedded subgreywacke and siltstone. Banding in some of the Pecors argillite, like that in some Gowganda argillite, resembles varves. Along Panel Road near the inlet of the Serpent River into Quirke Lake, a few pebbles can be seen in banded argillite in the basal several inches of the formation. This is suggestive of ice rafting but the pebbles might have been washed onto the clay layers from an adjacent mound or bank of gravel. Ripple-marks and mudcracks are present in argillite at the base of formation along the north shore of Quirke Lake and have been noted elsewhere higher in the formation (Pienaar, 1963, p. 20).

The argillite is composed mainly of fine-grained white mica that gives a muscovite-illite X-ray pattern. It is highly aluminous and potash-rich approaching muscovite in chemical composition and is significantly radioactive compared to other Huronian formations, or to most shales in general. Pyrrhotite and pyrite are finely disseminated in the argillaceous rocks and also occur in concentrations along laminae. An analysis of dark, massive argillite from the base of the formation at Hough Lake shows 0.59 per cent carbon, 0.34 per cent sulphur (no sulphides were visible in the specimen), 0.0051 per cent ThO_2 and 0.0031 per cent U_3O_8.

The Pecors Formation thickens fromnorth to south. Its possible equivalent at the east end of Trout Lake near Sault Ste. Marie, is very thin. As mentioned above, it is thin, if present, at Aberdeen Lake 14 miles north of Bruce Mines but is 700 feet thick near Thessalon. It is 40 feet thick east of Ten Mile Lake, 100 feet or less at Quirke Mine and 100 to 250 feet elsewhere along the north limb of the Quirke Lake Syncline, whereas it is 600 to 720 feet thick 8 miles south of Quirke Mine and elsewhere along the south limb of the syncline excepting at Pecors Lake where it is locally only about 120 feet thick. The local thinning at Pecors Lake is coincident with a basement high (Fig. 3) and with thinning of the overlying Mississagi Formation and the thinning of the formations of the Quirke Lake Group that was mentioned previously. Where penetrated by drillholes in Montgomery Township and Township 167 near the crest of the Chiblow Anticline, it is 400 feet thick. Farther east at Emerald Lake and Lake of the Mountains, and also near the crest of the Chiblow Anticline, it is only about 40 feet thick according to Robertson (1964). Farther south along the north side of the Murray Fault near Pronto Mine and south of the fault near Blind River, it is about 800 feet thick. The formation is relatively coarse and contains little argillite in the zone of thickening south of the Chiblow Anticline (Robertson, 1964a, p. 25). Robertson(1964c, 1965b, 1966b, 1966c) has mapped this stratigraphic unit through a distance of 30 miles east of Pronto Mine along the north side of the

Murray Fault and also recognizes it south of the fault. It is 300 to 800 feet thick in most places north of the fault but it is locally missing over a basement high in western Lewis Township. The Pecors Formation extends eastward into the Agnew Lake, Espanola and Sudbury areas. In Porter Township (Ginn, 1961), northern Baldwin Township (Thomson, 1952 and Ginn, 1965) and in northern Hyman Township (Card, 1965), it is less than 200 feet thick. Farther south in Baldwin and Hyman Townships and in Drury Township it is perhaps 600 feet thick. It is about 1,600 feet thick in southeastern Nairn Township (Ginn, 1965) and is very thick still farther south at Lake Panache (Frarey, personal communication).

Mississagi Formation

The Mississagi Formation consists of grey, coarse-grained, argillaceous subarkose with minor interbedded subgreywacke, siltstone and argillite throughout most of the region. Robertson (1964a) has mapped siltstone and polymictic conglomerate members in the upper part of the formation between Matinenda and Lauzon Lakes near Blind River. The conglomerate unit, unlike others that occur at stratigraphic positions below the Cobalt Group, contains reddish granite clasts. In the Quirke Lake area and elsewhere near the northern paleolimit of the Hough Lake Group, green and buff-coloured sericitic gritty and pebbly subarkose beds comprise much of the formation (Pienaar, 1963, p. 27). The latter rocks are particularly radioactive but the less coarse-grained, more widespread, feldspathic quartzite of the formation is also distinctly radioactive compared to many other rocks of the region, such as pre-Huronian metavolcanic rocks, quartzite in the Lorrain and Serpent Formation and limestone, siltstone and greywacke in the Espanola and Gowganda Formations. This radioactivity is partly due to potassium in potash feldspar which is dominant over plagioclase but is also contributed by uranium and thorium in the argillaceous fraction and in heavy detrital minerals. Radioactive quartz and chert pebble layers are common in the formation and pyritic quartz-pebble beds in grit along the north limb of the Quirke Syncline are highly radioactive although thinner and less uraniferous than ore zones in the Matinenda Formation.

Most outcrops of the Mississagi Formation display excellent crossbedding which indicates southerly to easterly current directions corresponding with the direction of general thickening. Planar-type crossbedding is most characteristic but trough-type also occurs and is conspicuous in the coarse-grained facies in the Quirke Lake area. Ripple-marks have been noted in many areas but are not as common in the Mississagi Formation as in the Serpent Formation and in some Cobalt arenites.

The formation is probably about 2,000 feet thick at Aberdeen Lake 13 miles north of Bruce Mines and perhaps nearly 4,000 feet thick between Bruce Mines and Thessalon. It is 700 to 1,100 feet thick in most places along the north limb of the Quirke Syncline, 1,400 to 1,600 feet 8 miles to the south along the south limb of the syncline, and as much as 2,700 feet thick 12 or 15 miles farther south near Blind River. North of Agnew Lake, it is about 2,000 feet thick but 12 miles to the southeast in the Espanola-Sudbury area it is at least 8,000 feet thick and perhaps as much as 10,000 feet thick (Ginn, 1965). There are some interesting local variations in thickness in addition to the regional north to south thickening described above. It thins to as little as 600 feet at Quirke Mine from thicknesses of about 900 feet east and west of the mine the thinning being concomitant with thinning of the Whiskey and Pecors Formations over a thick zone in the underlying Matinenda Formation. This thinning of the Hough Lake Group formations may be due in part to their deposition atop an alluvial fan of coarse Matinenda sands and coarse pebble gravels.

Some variations in thicknesses of the Mississagi and other formations are doubtless related to pre-Huronian topographic features that controlled sediment-bearing streams, and differential compaction of sediments over buried hills and valleys. Others, however, are probably due to vertical movements in the basement during sedimentation that resulted in intraformational and intergroup erosion. As mentioned previously, the Pecors Formation and Quirke Lake Group formations are relatively thin over a basement high, at the north end of Pecors Lake. It is not certain that the Mississagi Formation is also thin in this area but it is apparent that the area was intermittently or continuously positive relative to adjacent areas during deposition of a great thickness of sediments. Northwest of Lake of the Mountains, the Mississagi Formation is only about 1,500 feet thick according to Robertson (1964a), whereas it is over 1,640 feet thick at Moon Lake farther north, 2,100 feet at Demorest Lake to the northwest and 2,700 feet thick at Thurston Lake a few miles southeast. These variations may be due to upwarp and erosion of the upper part of the Mississagi Formation along the ancestral Chiblow Anticline prior to deposition of the Quirke Lake Group which itself was deeply eroded in this area prior to deposition of the succeeding Cobalt Group. Robertson (1961, p. 17) cites the presence of quartzite boulders in the Bruce Formation as evidence of disconformity between the Mississagi Formation and the overlying Bruce Formation. The Bruce Formation appears to truncate bedding in the Mississagi Formation in some localities as at Chiblow Lake. At Quirke Lake the upper few feet of the Mississagi Formation is bleached in places suggesting that it may have been weathered prior to deposition of the Bruce Formation. Here and there the contact between the formations suggests that unconsolidated Mississagi sand was scoured and mixed with conglomeratic greywacke. Direct evidence of important erosion of the Mississagi Formation prior to deposition of the Quirke Lake Group is provided by variations in the stratigraphic position of siltstone and polymictic conglomerate in the upper part of the formation as mapped by Robertson (1964a) in the Lake Lauzon-Lake of the Mountains area. The quartzite overlying this band is as much as 800 feet thick at Lake Lauzon, whereas it is less than 200 feet thick near the northwest shore of Lake of the Mountains 6 miles to the northwest.

ELLIOT LAKE GROUP

General

The Elliot Lake Group includes sedimentary and volcanic rocks that concordantly underlie the Hough Lake Group as defined herein and nonconformably overlie Archean rocks, or are believed to be correlative with strata that show such relationships. The uranium ore-bearing, pyritic, quartz-pebble beds of the region are within this group. Stratigraphic successions within the Elliot Lake Group differ in different parts of the region (Table IV, Figs. 2d, 5). In the western part of the region, the group consists of subarkose overlain by a thick sequence of volcanic rocks through a distance of 50 miles. In the eastern part, subarkose and argillaceous sediments overlie volcanic rocks with apparent general concordance along a belt 100 miles long. In the Elliot Lake-Blind River area between these two sectors, subarkose lies nonconformably upon Archean granitic rocks and upon Archean metavolcanic and metasedimentary rocks.

The distribution of volcanic rocks intimately associated with sedimentary rocks that are definitely or probably referable to the Elliot Lake Group appears to conform with general concave-northward arcuate trends of stratigraphic overlaps, thickness and facies variations, the Murray Fault system and fold axes within the Huronian belt (Figs. 1, 2, and 5). The Elliot Lake Group was probably deposited along the north margin of an arcuate geosyncline that was the site of volcanism. The central area lacking volcanic rocks can be considered to have been a relatively broad part of the unstable marginal platform. Accordingly, the volcanic rocks west and east of Blind River are tentatively considered correlative. This, however, is far from established; in fact there is room for doubt as to whether volcanic rocks east of Elliot Lake are of Archean or Aphebian age or of both ages.

Livingstone Creek Formation

The lowermost known Huronian Formation in the western part of the Huronian belt has been termed Livingstone Creek Formation by M.J. Frarey (1967, p. 1). He states:

"The name Livingstone Creek Formation, derived from Livingstone Creek in the Thessalon area is proposed for the lowermost exposed Huronian Formation between Blind River and Sault Ste. Marie. It consists mainly of gently to moderately dipping, grey to flesh-coloured, fine- to coarse-grained feldspathic quartzite and subarkose, with grit, siltstone, and conglomerate as subordinate lithologies. Three miles east of Thessalon the Livingstone Creek Formation can be seen to overlie with great unconformity the metamorphic and igneous rocks of the pre-Huronian complex. An interesting gradational basal contact at one locality in the Thessalon area has been described in some detail by Collins (1925, pp. 31-32, Pl. IIIB). There the strike of the formation follows the course of Livingstone Creek for about 3 miles. The contact with the overlying Thessalon Formation is interbedded and locally there appears to be a slight erosional discontinuity. The Livingstone Creek Formation also outcrops in a belt a few miles long in Aberdeen and McMahon Townships about 15 miles north of Bruce Mines, where the lower boundary is a fault, as may be the case at a third locality in Duncan Township northeast of Sault Ste. Marie (Hay, 1964). The thickness of the formation varies from perhaps a few tens of feet near Thessalon to possibly

TABLE IV

FORMATIONS IN THE ELLIOT LAKE GROUP

Lithology	Localities					
	1	2a	2b	3a	3b	3c
subgreywacke argillite			McKim	McKim	McKim	McKim
subarkose grit*		Matinenda	Matinenda		Matinenda	
rhyolite						Copper Cliff
basalt minor rhyolite subgreywacke subarkose*	Thessalon			Pater	'Stobie' or probable equivalent	Stobie
subarkose*	Livingstone Creek					

*Uraniferous pyritic quartz-pebble conglomerate has been found in the Matinenda Formation, the upper part of the 'Stobie' Formation, near the base of the Thessalon Formation and near the top of the Livingstone Creek Formation.

1. Duncan Township (10 miles northeast of Sault Ste. Marie), Aberdeen Township (14 miles north of Bruce Mines) and Thessalon.

2a North flank of Quirke Syncline, Blind River (both north and south of the Murray Fault), northern Hyman Township (Agnew Lake area).

2b South flank of Quirke Syncline, Serpent River (10 miles east of Pronto Mine) to Denvic Lake (4 miles northeast of Spanish) along north side of Murray Fault, northern Hyman Township (Agnew Lake area).

3a Pronto Mine to Spanish (south of Murray Fault).

3b Victoria Township to Graham Township, Agnew Lake area excepting northern Hyman Township.

3c Graham Township to Falconbridge Township.

1,500 feet north of Bruce Mines. This unit was originally recognized and differentiated by A. Murray (1859), but was included in the Mississagi Formation of Collins (1925). The Livingstone Creek may be the stratigraphic equivalent of the Matinenda Formation (Roscoe, 1957)."

The present writer can add only a few notes to the foregoing description. The lower part of the formation in the type area east of Thessalon is composed of fine-grained, well-sorted, finely laminated, non-radioactive, grey subarkose. Southwest of Kirkwood Lake, this is overlain by a bed of ratioactive, pyritic quartz-pebble conglomerate that is several feet thick. Farther south near Highway 17, the railway, and the shore of Lake Huron, the fine-grained basal member is absent and the formation is represented by a few feet of radioactive, gritty, pebbly, sericitic subarkose and by basal conglomerate (Collins, 1925, pp. 31-32) between saprolitic (weathered) crystalline basement rocks and overlying lavas.

The formation outcrops along a belt 8 miles long in Aberdeen Township, 15 miles north of Bruce Mines. It dips about 45 degrees southwest and is overlain by volcanic rocks to the southwest. Volcanic and sedimentary rocks including uraniferous pyritic quartz-pebble conglomerate are interlayered along this contact. The formation is in fault contact with Gowganda Formation to the north and its base is not exposed. A minimum thickness of 1,500 feet is indicated near McMahon Lake. At the southeastern end of the belt near Havilah, the upper hundred feet or so of the formation is well-exposed and consists of well-sorted, medium- to coarse-grained subarkose that is not notably radioactive. Frarey (1959) has described the formation as composed of medium- to coarse-grained, crossbedded, feldspathic quartzite beds 1-foot to 3 feet thick, in places separated by argillite layers that may be several inches thick, and noted the presence of quartz-pebble conglomerate and pebbly quartzite 1 1/2 miles north of McMahon Lake.

In Duncan and Jarvis Townships 10 miles northeast of Sault Ste. Marie, the third locality mentioned by Frarey (1967), fine-grained subarkose underlies volcanic rocks along an 8 mile northwest-trending belt. Radioactive quartz-pebble conglomerate has been found in the volcanic rocks 100 feet above this contact at Maud Lake (Hay, 1964). Most contacts between subarkose and granitic rocks to the northeast were mapped as faults by Hay (1964) but he has described a number of places (Hay, 1963, p. 217) where conglomerate nonconformably overlies weathered granitic rocks north of Maud Lake and estimated the total thickness of sedimentary rocks in this area as 610 feet[1]. Greywacke and polymictic conglomerate mentioned by McConnell and Hay evidently form the lower part of the formation, and may occupy pre-Huronian valleys. It is possible that radioactive oligomictic conglomerates may be found at the base of thick (or 'valley') sections of the

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[1] McConnell (1926) estimated that 2,000 feet of quartzite overlies 400 feet of conglomerates south of Maud Lake. These thicknesses have not been confirmed.

formation. McConnell named the unit, Driving Creek Formation and placed it in his Soo series which he considered Huronian but older than the Bruce series. Hay (1964) correlated it with the Mississagi Formation. It is certainly correlative with the Livingstone Creek Formation as described by Frarey (1967).

Thessalon Formation

The Thessalon Formation is exposed in three belts, Thessalon, Aberdeen Township, and Duncan Township that correspond with the belts of Livingstone Creek Formation described above. In each area it is composed almost entirely of fine-grained, dark grey, dark green, or black basalt. Amygdaloidal layers and zones are common. Pillowed flows and flow breccia have been reported in the Aberdeen belt (Frarey, 1959). Rhyolite bands have been mapped in the upper and central part of the formation near Thessalon (Frarey, 1961b, 1962a) and are present in the Aberdeen belt (Knight, 1967). McConnell (1926) noted a porphyritic phase near the base of the formation northwest of Maud Lake in Duncan Township. Beds of quartzite, grit and quartz-pebble conglomerate, resembling strata of the underlying Livingstone Creek Formation, are interlayered with basalt mainly in the lower part of the formation in the Thessalon and Aberdeen belts (Frarey, 1959, 1961b, 1962a), and radioactive quartz-pebble conglomerate occurs 100 feet above the base of the formation both in the Aberdeen belt (Knight 1967, p. 41) and at Maud Lake in the Duncan belt (Frarey, personal communication). Frarey (1962a) has mapped a band of quartzite within the central part of the formation near Thessalon.

A uraniferous pyritic quartz-pebble conglomerate occurrence interbedded with lava in the Aberdeen belt has been investigated by pitting and drilling. Samples containing in the order of 0.1 per cent U_3O_8 were obtained but overall grades and thicknesses are submarginal. This conglomerate, like others near the contact between the Livingstone Creek and Thessalon Formations in the Thessalon and Duncan belts, differs slightly from those at Elliot Lake. It is darker and has a chloritic matrix. Pyrrhotite is abundant relative to pyrite and appreciable amounts of magnetite are present.

The formation is probably 2,000 to 3,000 feet thick in the Thessalon belt and 3,000 to 4,000 thick in the Aberdeen belt. The Duncan belt outcrops in a band 4,000 to 5,500 feet wide and the flows appear to dip 20 to 50 degrees southeast in concordance with underlying and overlying sedimentary strata northwest of Maud Lake. This suggests a thickness of 1,500 to 3,000 feet. Hay (1964), however estimated its thickness as only 200 to 300 feet southwest of Maud Lake where dips are gentle and undulating. McConnell (1926) considered that the basal contact was an unconformity in this area.

The lava flows were evidently very fluid and had remarkably level surfaces as indicated by occurrences of extensive sheets of coarse, presumably fluvial sediments between flows and by thin amygdaloidal layers that can be traced for considerable distances along strike (D. Sprague, personal communication).

Pater Formation

Basic metavolcanic rocks occur south of the Murray Fault near Spanish (Robertson, 1966b, c) and along the shore of Lake Huron near the Pronto uranium mine and at the Pater copper mine. They are associated with metasedimentary rocks and form part of an assemblage designated as 'Sudbury series' on Geological Survey of Canada, Map 155A and thereon shown as extending eastward to Sudbury. Collins (1925, p. 76) remarked on the resemblance of the volcanic rocks to the Thessalon Formation as did Robertson (1967, p. 6). Robertson (1965b) designated the volcanic rocks 'Pater volcanics' and included them in his 'Spragge Group' along with metasedimentary rocks which he correlated in part with the McKim Formation, and in part with the Ramsay Lake and Pecors Formations.

The Pater copper deposit is within the Pater Volcanics and may be genetically related to them or to metagabbro sills that are found in the area.

Stobie Formation and Probable Correlative Volcanic Rocks

Cooke (1946) applied the name Stobie Group to "a succession of lavas and sedimentary rocks that lie between the Norite Irruptive on the north and the McKim and Copper Cliff Formations on the south" in the Sudbury area. He used the term 'Upper Stobie' to distinguish sedimentary rocks with associated volcanic rocks just northeast of Sudbury from the adjacent but much more extensive 'Lower Stobie', comprised of volcanic rocks with subordinate intercalated sedimentary rocks. Yates (1948, pp. 597-598) applied the name 'Elsie Mountain Greenstone Formation' to most of the latter rocks and described them as "a series of very many narrow (andesitic and basaltic) flows with some interstratified thin beds of well bedded and crossbedded arkose". In addition, he used the name 'Snider Formation' for a "relatively narrow group of impure arkosic quartzites interlayered with thin flows of andesite and amygdaloidal basalt", that he considered to underlie and perhaps grade laterally into the 'Elsie Mountain Formation', and the name 'Frood Formation' for a transition zone of interbedded sedimentary and volcanic rocks between the 'Elsie Mountain Formation' and the overlying Copper Cliff Formation. The only one of these units that has been shown consistently on geological maps as extending for appreciable distances corresponds essentially with Cooke's 'Lower Stobie'. It is not readily subdivisible, so a designation of formational rank rather than one of group rank would be appropriate for it. The name Stobie Formation is tentatively used for this unit.

Local zones wherein sedimentary rocks are more abundant than volcanic rocks – i.e., 'Frood Formation' – are herein considered members of the Stobie Formation although it is realized that others may find it useful or necessary to consider such zones as separate formations.

The Stobie Formation outcrops in a belt that extends about 45 miles from Lake Wanapitei to Hyman Township and is 3,500 to 7,500 feet wide in most places. Interlayered metasedimentary strata resemble metamorphosed argillaceous quartzite, siltstone, argillite subarkose and quartz-pebble-bearing grit in sedimentary formations along the south side of the belt and, like the latter strata, dip steeply south. The formation is overlain by sedimentary-volcanic transitions ('Upper Stobie' and 'Frood' Formation) and the Copper Cliff Formation along the central part of the belt, by the McKim Formation farther east and west, by the Matinenda Formation at the west end of the belt and by the Hough Lake Group at the east end of the belt. Minor rhyolite is present, and is most common along the south side, or top, of the formation, particularly in the west end of the belt. This rhyolite may be correlative with that of the Copper Cliff Formation.

Basic volcanic rocks exposed beneath the Matinenda Formation in the core of an anticline in southwest Hyman Township and southeast Porter Township, and also basic volcanic rocks beneath the Matinenda Formation in Baldwin and Shakespeare Townships, are almost certainly correlative with the Stobie Volcanics. The volcanics in Baldwin Township probably extend to the west through Shakespeare and May Townships (Ont. Dept. Mines, Map P. 105) to form a continuous belt with igneous rocks mapped as volcanics in Victoria and Salter Townships by Robertson (1966b, c). This belt also contains intercalated sedimentary layers, including strata that resemble subarkose and grit in the overlying Matinenda Formation and, reportedly in May Township (Robertson, 1966c), radioactive quartz-pebble conglomerate. Robertson found evidence that these rocks are younger than Archean granitic rocks mantled by paleosol near Salmay Lake.

There are a number of copper deposits in the belt near Massey and it is possible that these are related genetically to the volcanic rocks.

Age relationship problems

The base of the Stobie Formation has not been recognized except possibly in western Drury Township where F.Q. Barnes (personal communication) considered that a volcanic flow nonconformably overlies granite. The volcanic sequence is very thin beneath the Matinenda Formation and wedges out between it and granite in this area. A short distance to the west in eastern Hyman Township, the Matinenda Formation rests directly on Archean granite (Card, 1965, p. 9). Card (1965, p. 8) cites evidence that granite intrudes volcanic rocks in Drury Township. The formation is intruded by the Sudbury Irruptive and the Creighton and Murray granites farther east along the belt so that the original nature of its north margin, or base, is obliterated. These relationships have lead Card (1965) and previous workers to believe that the volcanic rocks are pre-Huronian. An alternative possibility, however, is that there are post-Huronian as well as pre-Huronian granitic rocks in the Sudbury-Espanola area. This interpretation is consistent with, but not proven by geochronological data that will be reviewed later.

Most geological maps and reports published by the Ontario Department of Mines and by the Geological Survey of Canada designate the dominantly volcanic unit herein called Stobie Formation as Archean, Keewatin-type, or pre-Huronian. It is understandable that earlier workers (Coleman, 1913; Collins, 1925, 1936; Burrows and Rickaby, 1934; and Cooke, 1946) would have virtually automatically classified these volcanic rocks with those that are now known to be Archean - or more than 2.4×10^9 years old. Prior to recent work by Frarey, volcanic rocks were not known to be present and extensive within gently dipping, little metamorphosed, undoubted Huronian strata.

The Stobie Formation resembles metavolcanic rocks of known Archean age insofar as it dips nearly vertically. It is evident, however, that the volcanic rocks were folded and metamorphosed along with Huronian sedimentary rocks that lie to the south of it. If post-Huronian folding in the region between Blind River and Sudbury was similar in intensity to that west of Blind River in the 'Original Huronian' area, the Stobie volcanic belt would resemble the Thessalon Formation much more closely than it would resemble that of any of the Archean metavolcanic and metasedimentary belts. It would trend northeasterly through a distance of 100 miles (including volcanic rocks that are probably correlative with the Stobie Formation) and would dip gently to the south. In contrast, the Archean strata (Fig. 1) are isoclinally folded and occur in highly irregular belts and narrow septa that most commonly trend east or southeast and are surrounded and invaded by granitic rocks.

The Stobie Formation also appears to resemble the Thessalon Formation lithologically more closely than it resembles the belts of Archean strata. In contains thin massive flows with intercalated thin but extensive layers of sorted, potash-rich, argillaceous sediments and feldspathic quartzite-rocks that are abundant in overlying Huronian sedimentary formations but rare, if not absent, in nearby belts of Archean strata. The Archean volcanic rocks, including those in the Elliot Lake area, commonly contain thick flows with abundant pillows and breccia and intercalated layers and lenses of pyroclastic rocks, greywacke, iron-formation, chert, and cherty tuffaceous zones with abundant iron sulphides and, locally, sphalerite, chalcopyrite and galena.

Card (1965) considered that the granite which intrudes the Stobie Formation in Drury Township is the same granite that is nonconformably overlain by the Matinenda Formation in Hyman Township and therefore concludes that the Stobie Formation is Archean in age. If this were so, the contact between the Stobie Formation and the overlying Matinenda, McKim and Ramsay Lake Formations would be a regional nonconformity. No direct evidence for such a nonconformity is given in Cards' report (1965) or indicated on his detailed maps (Ont. Dept. Mines, Maps 2055 and 2119) that cover a 23 mile length of the volcanic-sedimentary contact zone. Evidence for a nonconformity along or near this contact has long been sought in vain. Interstratification of sedimentary and volcanic rocks along the contact, in fact, make it necessary to select an arbitrary boundary between the Stobie Formation and overlying formations in some places, near Sudbury in particular, as previously noted. Burrows and Rickaby (1934) included the Stobie Formation with the McKim and Copper Cliff Formations in the Sudbury series. Collins (1936, p. 1678; 1937, p. 1453) used the terms Keewatin and Sudbury series for the volcanic rocks and the overlying sediments, respectively, but agreed that the contact was transitional. Phemister (1956) also found that the volcanic and sedimentary strata in the Copper Cliff-Sudbury area were conformable. Cooke (1946) postulated that a "great fault" separated the Stobie Formation which he classified as pre-Huronian from the Copper Cliff and McKim Formations which he classified as Huronian. No evidence of such a regional fault was found by Phemister (1956), Thomson (1961b) or Card (1965, 1967). Thomson (1952) found no evidence of a nonconformity in Baldwin Township between presumed Archean volcanic rocks and overlying sedimentary rocks classified by Collins as Huronian on the Espanola (Geol. Surv. Can., Map 291A).

Ginn (1960, pp. 44-53; 1961, pp. 9, 11, 12) has presented evidence that the Matinenda Formation may nonconformably overlie metavolcanic rocks and associated metasedimentary rocks in southeastern Porter Township and overlie an older quartzite formation with angular unconformity in Baldwin Township. He stated that the evidence for an unconformity in Porter Township "is by no means conclusive" (1961, p. 9) and pointed out (1960, p. 52) that the Matinenda Formation is generally concordant with underlying strata in the Agnew Lake area and that angular discordances are uncommon. Knight (1967) has suggested that the local discordance in bedding found in Baldwin Township could be interpreted as large scale current bedding. At the principal locality in southeast Porter Township (Ginn, 1961, p. 11), garnet-quartz-biotite schist overlies metavolcanic rocks whereas sericite schist, interpreted as overlying an intervening band of quartzite, is found 140 feet to the north. Ginn considers that this apparent difference in grade of metamorphism of similar pelitic rocks may indicate that they are separated by a nonconformity. If this were so, the older rocks should have been obviously retrogressively metamorphosed during the second, lesser period of metamorphism. A fault along the valley that apparently separates the two exposures (Ont. Dept. Mines, Map 2011) would provide an alternative explanation. Ginn (1961, p. 12) discounted the possibility that such a fault is present but Card (1965, Ont. Dept. Mines, Map 2055) mapped a fault along the south margin of the pelitic rocks in adjacent southwestern Hyman Township and indicated that farther to the east these rocks (Ginn's sericite schist) contain biotite and garnet. Ginn, it should be noted, was careful to designate the underlying strata not as Archean but as pre-Bruce (pre-Matinenda in the context of terminalogy used in this report) and acknowledged the possibility that they may be equivalent to the Thessalon Formation.

In summary, the Stobie Formation appears to be concordantly overlain by Huronian strata; it contains intercalated beds of similar strata, and it resembles the Thessalon Formation of the Proterozoic Huronian succession more closely than it resembles known Archean metavolcanic rocks such as those that are non-conformably overlain by Huronian rocks in the Elliot Lake area. Present geological knowledge based on extensive detailed mapping dictates, therefore, that it be considered part of the Huronian Supergroup.

Copper Cliff Formation

The Copper Cliff Formation, initially named Copper Cliff Arkose by Coleman (1914), is shown on Geological Survey of Canada, Maps 292A, 871A and 872A as a band of rhyolite that extends 7 miles northeast and 11 miles southwest of Sudbury along the south margin of the Stobie Formation. The band is 1,000 to 2,000 feet wide in most places but at the northeast outskirts of Sudbury in McKim Township it is up to 4,000 feet wide. As previously mentioned, acidic volcanic rocks along the south side, or top, of the Stobie Formation in Graham, Denison and Hyman Townships, 14 to 28 miles west of Sudbury, are apparently at the same stratigraphic level as the Copper Cliff Formation and could be considered correlative with it.

Rhyolite flows and breccia are interlayered with sedimentary rocks and basalt in the Stobie Formation (Cooke's Lower Stobie, Yates' Frood Formation) immediately north of the Copper Cliff Formation and with argillaceous sedimentary rocks in the McKim Formation immediately south of it according to Cooke (1946) and Phemister (1956). Both these workers described the formation as massive or vaguely banded in most places but containing well-developed banding in the upper, or southernmost 100 feet and remarked on the somewhat coarse grain size of the rocks.

Cooke considered that flows and perhaps tuff layers were present in the formation and described amygdaloidal, flow-textured, and flow-brecciated units. Phemister (1956) concluded that the formation was probably an intrusive sill in McKim Township where he studied it in detail. The formation occurs at a horizon that contains definitely extrusive rhyolite and is fine-grained compared to granites of the area. If it is partly or largely of intrusive origin, as suggested by Phemister, the intrusions must have occurred at shallow depth during the closing, rhyolitic, stage of volcanism, and prior to the deposition of appreciable thicknesses of overlying sediments of the McKim Formation.

Matinenda Formation

The name Matinenda Formation was proposed by Roscoe (1957a) for the lowermost lithostratigraphic unit of the Huronian succession in the Quirke Syncline. This unit, composed mainly of subarkose, was mapped as part of the Mississagi Formation by Collins (1925) and designated 'Lower Mississagi quartzite' by Robertson (1961-1967) but, as previously explained, it is now known to be stratigraphically lower than the Mississagi Formation as mapped by Collins and others in Sudbury-Espanola area, the Bruce Mines area, and in the type locality of the Mississagi Formation at the mouth of the Mississagi River (Winchell, 1887, p. 168). The Matinenda Formation outcrops in a continuous belt along the flanks and crest of the Chiblow Anticline from Pecors Lake to Pronto Mine, and in separate belts at Whiskey Lake and between Quirke and Ten Mile Lakes along the nose and north flank of the Quirke Syncline. It also outcrops along a narrow belt that extends at least 30 miles eastward from Pronto Mine and in extensive areas in the Agnew Lake area, 40 to 65 miles east of Pronto.

The formation is most extensively exposed at the crest of the Chiblow Anticline in the vicinity of Matinenda Lake, a large lake 10 miles north of Blind River. Matinenda Lake is by far the most prominent geographic feature appropriate as a locality name for the formation. Drillholes through the formation have provided much more detailed sections than could be obtained from surface measurements at Matinenda Lake or in any other area and it is suggested that at least one drillcore section in the vicinity of the uranium mines east of Elliot Lake, and another in the Quirke Lake area, be preserved as primary reference sections for the formation.

Much of the Matinenda Formation consists of fairly homogeneous, coarse- to medium-grained, moderately well-sorted subarkose that is white, grey, buff, or pale yellow in colour. The ore zones and submarginal uraniferous quartz-pebble conglomerate beds, however, occur within extensive zones of distinctive subarkose that show considerable variation in grain size, sorting and colour but are characterized by an abundance of very coarse-grained, gritty, poorly-sorted subarkose, composed mainly of poorly rounded quartz and potash feldspar clasts in a sericitic matrix, that imparts a characteristic greenish to yellowish colour to the rock. This lithofacies can be referred to as grit, to contrast it with the more abundant subarkose lithofacies of the formation. It is essential to make this distinction and to attempt to determine the stratigraphic positions and areal extent of favourable grit zones as a guide to exploration. Scattered quartz, chert and greenstone pebbles, pebble beds, and even massive cobble conglomerate beds occur within the subarkose facies but, in contrast to quartz-pebble beds within grit zones, they have relatively little radioactivity associated with them.

Crossbedding, present throughout the formation, has been studied in detail by Pienaar (1963) and by McDowell (1957). These data indicate that

Matinenda sands and quartz-pebble gravels were deposited by southeasterly flowing streams. Trough-type crossbedding is particularly common in gritty subarkose.

Between Elliot Lake and Pecors Lake, the Matinenda Formation, up to 950 feet thick, is subdivisible into a lower gritty member up to 550 feet thick and an upper subarkose member up to 470 feet thick (Pienaar, 1963). The latter member may be divided into submembers including a basal conglomeratic zone and an upper fine-grained zone. Pienaar (1963, p. 46) recognized an unconformity between the two members. Review of drillhole data by the writer has shown further evidence for this unconformity. No less than 100 feet and perhaps as much as 300 feet of the lower member, containing pebble beds recognizable from one drillhole to another by their spacings and thicknesses, was evidently scoured in the vicinity of Stanleigh drillhole No. 9 prior to deposition of polymictic conglomerate at the base of the upper member.

Near the Quirke and Panel Mines on the north limb of the syncline, the entire Matinenda Formation, up to 300 feet thick, consists of radioactive pebbly grit containing quartz-pebble beds. Farther south and east, and locally at Quirke Mine, the grit rests on finer-grained subarkose. This subarkose thickens irregularly (due to basement irregularities) to the south and is more than 100 feet thick beneath the south end of the southwest arm of Quirke Lake. At Whiskey Lake, the Matinenda Formation is up to 750 feet thick (Fig. 3) and Pienaar classified this entire thickness as grit-type although it is less pebbly, generally finer-grained, and not so greenish in colour compared to the grit at Quirke Lake.

Grit may grade both laterally and vertically into coarse-grained, better sorted subarkose so it is difficult to place contacts, or even distinguish, between gritty and non-gritty facies in some drillcores - i.e., holes at May, Hough, and Gull Beak Lakes. The fact that such decisions may be rather arbitrary in some cases should not deter one from attempting to recognize and trace favourable gritty zones. Zones characterized by grit are by no means restricted to the Quirke Lake Syncline. They are present in the Matinenda Lake area, the Agnew Lake area, and along the south flank of the Chiblow Anticline between these two areas. They cannot be outlined for appreciable distances in these areas, however, on the basis of information presently available from surface mapping and drillhole records.

The basal part of the Matinenda Formation is coarser, grittier, and more pebbly than the upper part in most places, as for example at Elliot Lake, but this generalization should not be regarded as a rule. As previously noted, grit containing radioactive quartz-pebble conglomerate beds overlies thicker sections of relatively fine-grained, well-sorted subarkose near the south end of Quirke Lake. Fine-grained quartzite occurs at the base of the formation near the east arm of Matinenda Lake. At Copp Lake in Montgomery Township west of Matinenda Lake, coarse or gritty zones occur in several positions within an 883-foot core-section of the Matinenda Formation, ranging from 83 feet above the base of the formation to 100 feet below the top; the coarsest zone, about 170 feet thick, is 290 feet above the base and 425 feet below the top and contains several radioactive, small quartz-pebble beds up to 1-foot thick.

Subdivision of the Matinenda Formation in the Elliot Lake area

Pienaar (1963) considered that the upper subarkose member in the Elliot Lake-Pecors Lake area was deposited later than other Matinenda rocks in the Quirke Lake Syncline and therefore correlated grit at Whiskey Lake and grit and underlying subarkose at Quirke Lake with the lower grit member in the Elliot Lake area, although he specifically stated (op. cit. p. 44) that the "correlation is based entirely on lithological similarities and does not imply time-stratigraphic equivalence". A number of drillholes have been completed in deeper parts of the Quirke Syncline since Pienaar's field work, and restudy of all of the data recommends an alternative interpretation (Fig. 3). This cannot be clearly outlined using designations 'lower' and 'upper' for the members, so the name Ryan Member (after the small lake at the Nordic Mine townsite) is proposed for the grit lower member of the formation along the south limb of the syncline, the name Stinson Member (after another small lake 2 miles east of the Nordic Mine) for the better sorted upper part of the formation in the same area, and the name Manfred Member (after a lake 3,500 feet southwest of Quirke Mine) for the grit at Quirke Lake. The distribution and thicknesses of these members is shown in Figure 3. The writer considers that the Ryan Member was deposited, or has been preserved, only along the south limb of the syncline. The Stinson Member was deposited on the eroded surface of the Ryan Member along the south limb and on pre-Huronian rocks in the central part of the syncline north of the erosional edge of the Ryan Member. The Manfred Member was deposited on pre-Huronian rocks north of the depositional and/or erosional edge of the Stinson Member at Quirke Lake, and atop the Stinson Member farther south. The relatively fine-grained subarkose at the base of the formation in the Quirke Lake area is thus equated with fine-grained subarkose (Stinson) at the top of the formation on the south limb of the syncline. The nature of the southern boundary of the Manfred Member is in doubt due to scarcity of drillhole data. The member may thin abruptly to the south or it may interfinger with strata in the upper part of the Stinson Member and perhaps even be stratigraphically equivalent in part to fine-grained subarkose in the overlying McKim Formation. The foregoing interpretations agree basically with those given by D.S. Robertson and N.C. Steenland (1960, p. 663).

Isopachs of the Manfred Member (Pienaar, 1963) suggest that it was deposited as a lens with a long axis trending southeast towards the south end of Whiskey Lake prior to pre-Hough Lake Group erosion southeast of Quirke Lake. The grit at Whiskey Lake may be correlated tentatively, therefore, with the Manfred Member.

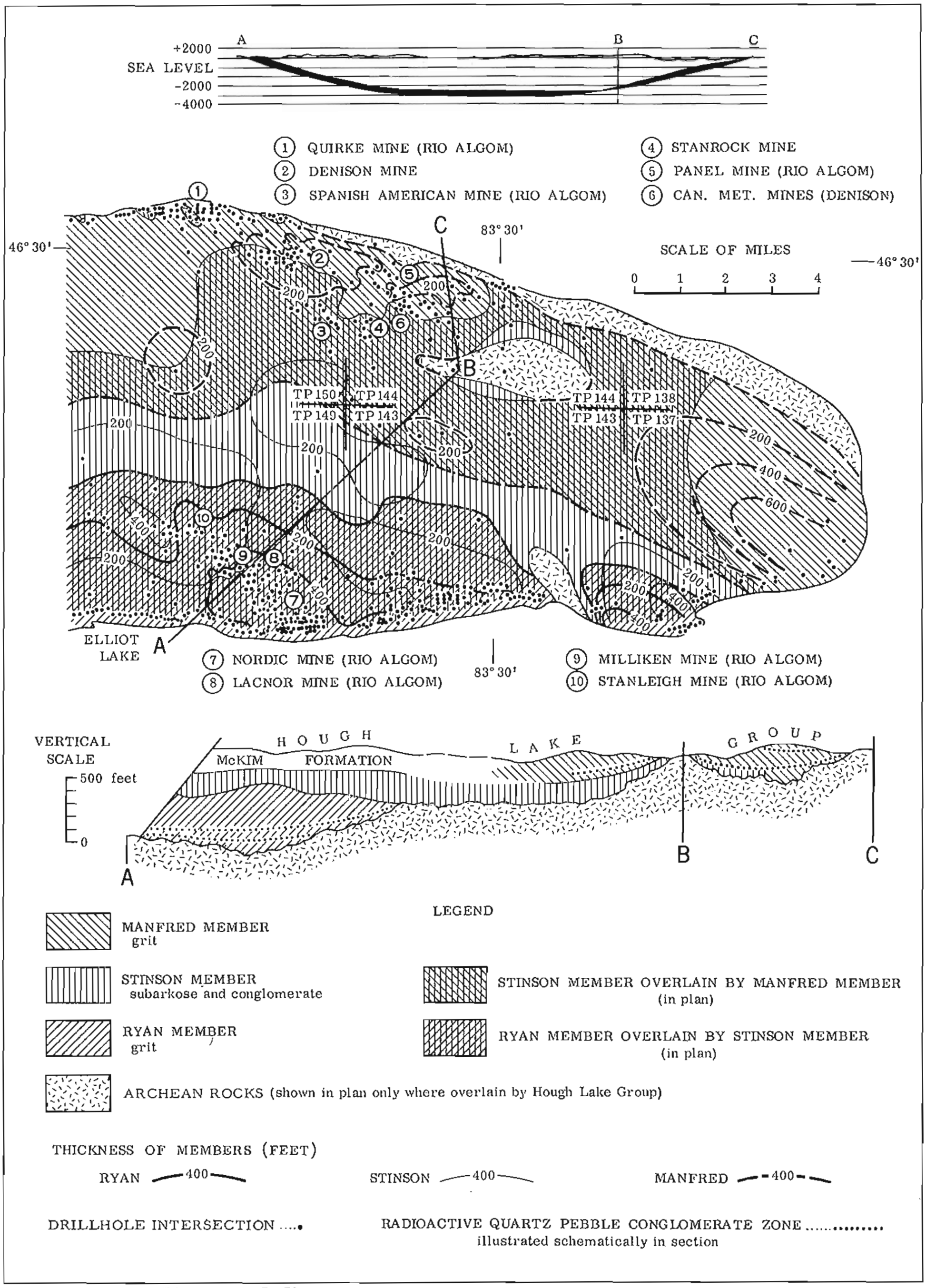


Figure 3. Stratigraphy of Matinenda Formation near Elliot Lake

The three members have not yet been traced westward beyond Townships 149 and 150. The Manfred Member probably continues westward for a considerable distance along the northern limit of the Matinenda Formation, however, and correlatives of the Ryan and Stinson Members are probably present in the Matinenda Lake area. At Moon Lake in the latter area, Robertson (1963a, p. 17) noted conglomerate that he considered resembled conglomerate found in the lower part of the Stinson Member east of Elliot Lake. There may also be units present in the Matinenda Lake area that have no stratigraphic equivalents in the Elliot Lake sector.

Evidence of Tectonic Movements during sedimentation

The disconformity, mentioned above, between the Elliot Lake Group and the Hough Lake Group has been well-substantiated by underground development at the Quirke, Denison, Panel and Stanrock Mines as well as by drillhole data. The Quirke 'reef' (ore-bearing conglomerate zone) is as much as 100 feet below the Ramsay Lake Formation in the central part of the Quirke Mine area; elsewhere on the Quirke and Denison properties, the Quirke reef is truncated by the Ramsay Lake Conglomerate. The Denison reef zone, stratigraphically as much as 150 feet below the Quirke reef zone, is also truncated by the Hough Lake Group near the north shore of Quirke Lake in Denison Mine underground workings. Ramsay Lake boulder conglomerate locally overlies the Denison reef near the Stanrock shaft. South and east of this shaft, it evidently truncates the reef and overlies the basal subarkose considered correlative with the Stinson Member.

Near Halfmoon Lake and the southeast end of Quirke Lake, several drillholes passed directly into pre-Huronian volcanic rocks beneath Ramsay Lake conglomerate. This area was formerly considered to represent a pre-Huronian topographic high that protruded through the Matinenda Formation (Roscoe, 1957a, p. 8; Pienaar, 1963, pp. 49, 127). The Stinson Member appears to thin beneath the Manfred Member at the margins of this area so a topographic high may have been present, but it is likely that the Halfmoon Lake area was also a site of pre-Hough Lake Group uplift during which as much as 300 feet of Matinenda Formation, including both Manfred and Stinson Members, were eroded. This feature can be referred to as the Halfmoon 'high'.

The Pecors Lake area, previously suggested to be a structurally positive area – a site of minimal deposition and of recurrent uplifts – during deposition of the Hough Lake and Quirke Lake Groups, was also evidently a positive area (Pecors 'high') during and immediately after deposition of the Elliot Lake Group. The McKim Formation and the Stinson Member as well as the Ryan Member thin towards the high and all are absent above its central part. At the flanks of the 'high', the Ryan Member contains relatively thick radioactive conglomerate beds whereas the Stinson Member is finer grained and less conglomeratic near the 'high' than it is away from it (Pienaar, 1963, Fig. 16). These variations cannot be explained as due simply to the presence of a ridge in the basement or to pre-Hough Lake Group erosion alone but must reflect both of these and additionally, most probably, vertical movements during deposition of the Matinenda Formation.

Drillcore data show that there are pronounced local thinnings and thickenings of sections between conglomerate or other distinctive beds within the Ryan and Manfred Members. These variations may be due in part to build-ups above base-level during formation of alluvial fans or to broad scour channels but they may also indicate uplifts of basement rocks immediately north and west of depositional areas and downwarps within the depositional areas during sedimentation. These movements would most likely have occurred along re-activated faults in basement rocks. Recurrent movements of this nature are postulated to have occurred during post-Matinenda sedimentation and to have produced the variations in thicknesses and facies of lithostratigraphic units and variations in stratigraphic magnitude of disconformities, noted previously, that occur well above the uranium ore-bearing units in the Huronian succession. Some of these loci of differential vertical movements were evidently ancestral to present structural features such as the uplifted basement area along the north side of the Quirke Syncline, the Chiblow Anticline, and the northerly trending cross-anticline (Robertson, 1961, p. 32 and 35) and northerly-trending fault in the Pecors Lake-Halfmoon Lake area.

The Matinenda Formation has been mapped as a continuous unit from Matinenda Lake to Pronto Mine and thence, with minor interruptions, 30 miles westward along the south limb of the Chiblow Anticline to May Township by Robertson (1961-1967) who has referred to it as Lower Mississagi quartzite. It is more than 1,000 feet thick west of Pronto (Robertson, 1964a, p. 21) but it is much thinner between Pronto and May Township, attaining maximum thicknesses of about 500 feet. It is absent in the western part of Lewis Township where the Mississagi Formation rests directly on Archean granitic rocks that contain inclusions of Archean metavolcanic and metasedimentary rocks according to Robertson (1964c). This section can be referred to as the Lewis 'high' as it was the site either of a local upland area that stood above the level of deposition of Matinenda sands or of an uplift that was swept clear of such detritus prior to deposition of the Mississagi sands. Anomalous northerly paleocurrent directions were measured in the Mississagi Formation at the east flank of the Lewis high by McDowell (1956, Fig. 5). These suggest that some of the Mississagi sands were derived from the Lewis 'high' rather than deposited by currents deflected around it. The Lewis 'high' might have been an actively rising area during Matinenda sedimentation as well as during Mississagi sedimentation.

The Lewis, Pecors and Halfmoon 'highs' are roughly aligned slightly east of north. This corresponds with a direction of faults in Huronian and pre-Huronian rocks (Fig. 1). The Pronto uranium deposit and the west ends of the Nordic-Stanleigh and Quirke Lake deposits show a similar alignment (as noted by Robertson and Steenland, 1960, p. 662, Fig. 2) approximately 7 miles west of the line joining these highs. It has been postulated, previously in this report that gritty zones at Quirke Lake and at Elliot Lake were deposited south of easterly-trending areas of uplift. It is now suggested that uplift also occurred along northerly-trending arches or fault lines during deposition of the Matinenda Formation. This would explain the north-south alignment of the three ore-bearing areas. The thickest, coarsest, and most conglomeratic zones would have been deposited south and east of north-south aligned nodes along easterly-trending lines of uplift. The individual nodes might have been uplifted edges of westerly-tilted fault blocks, or horsts (see Fig. 1).

The hypothesis outlined above is illustrated in Figure 4. The suggested positions and parallism of lines of uplift, other than the Halfmoon-Pecors-Lewis line, are largely conjectural although they are based on some evidence of the types presented above. They are shown only to underline the writer's conclusion that the Matinenda Formation was deposited on an unstable platform and that a consequent pattern of distribution of gritty zones likely to contain important radioactive conglomerate beds might be discerned through exhaustive studies of subtle stratigraphic variations and sedimentary structures.

Extension of Matinenda Formation eastward into the Espanola-Sudbury area

Quartzite formations interpreted as correlative with the Mississagi Formation were intensively prospected for radioactive conglomerate beds between 1952 and 1957. Many such beds were found north of Espanola in the vicinity of Agnew Lake, 40 to 60 miles east of the Pronto discovery, and a number were found at intervals between Pronto and Agnew Lake north of the Murray Fault. No significant discoveries have been made, however, in the Mississagi Formation south of the Murray-Worthington fault system or in many other areas of rocks corresponding to the Mississagi Formation as exposed in the type area at the mouth of the Mississagi River. These differences are not due to facies changes within the Mississagi Formation, although such changes do exist, but to the fact that the main host of uraniferous conglomerates is the lower of two quartzite, or subarkose, units of which only the upper should be called Mississagi Formation. Evidence for this was available in 1953 at the time of initial uranium prospecting in the Espanola area as Thomson (1952, pp. 15-18) had established that thick quartzite units occur in at least two widely separated stratigraphic positions in the sedimentary sequence in Baldwin Township rather than in one position corresponding to that of the Mississagi Formation as indicated on Geological Survey of Canada, Map 291A. He observed that quartzite of his group D – subsequently found to contain radioactive conglomerates – underlies argillaceous rocks correlated with the McKim Formation of Coleman's Sudbury series.

Similarities of pre-Bruce Formation sequences between Pronto and Sudbury to that at Elliot Lake were apparent to the writer during field work in 1954, 1955 and 1956. Proposals (Roscoe, 1957a, 1957b, 1960;

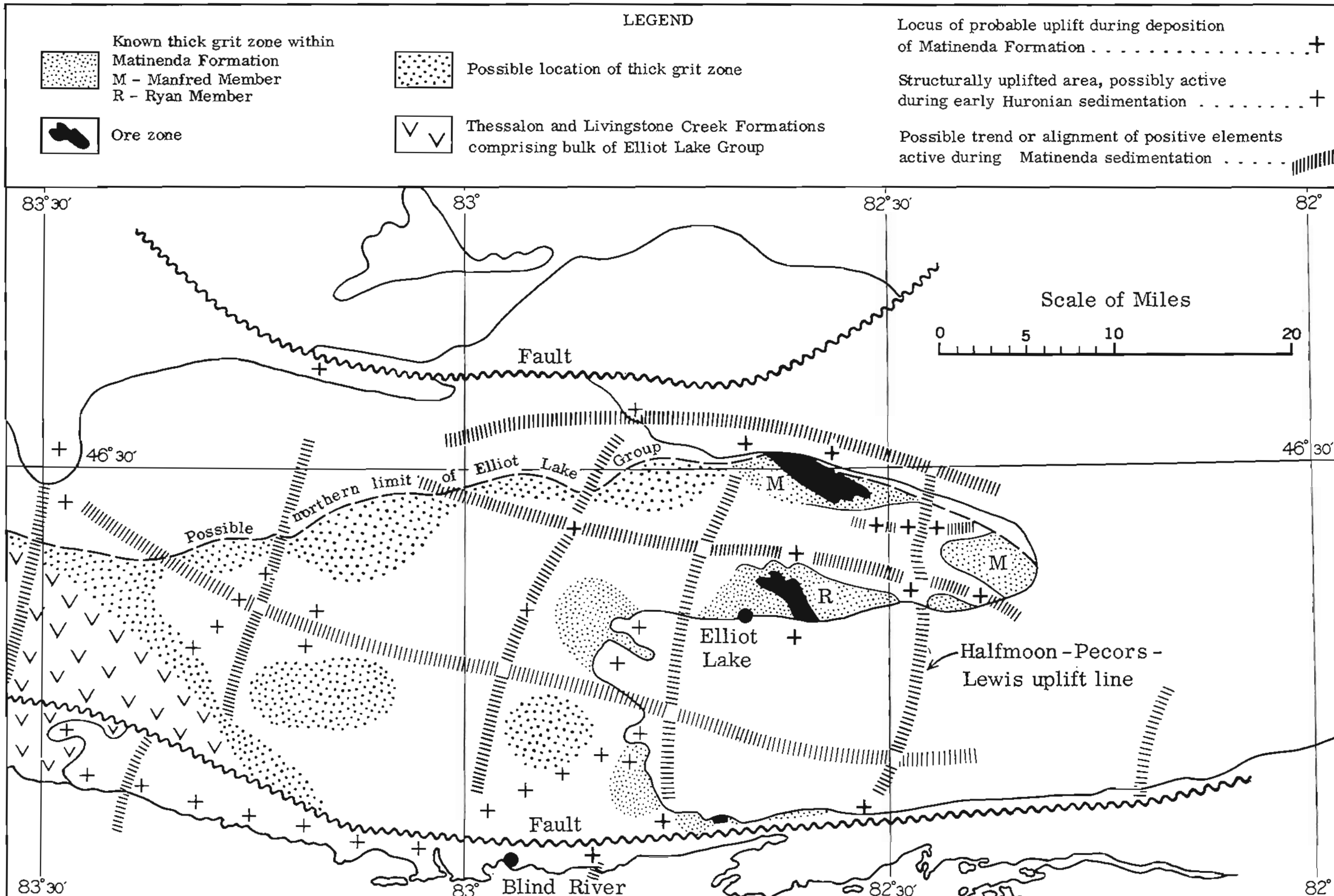


Figure 4. Relationships between distribution of thick grit zones in Matinenda Formation and structural uplifts during deposition.

Pienaar, 1963) that the lower subarkose unit at Elliot Lake be distinguished by a distinct formational name, Matinenda Formation, from a higher, separate subarkose unit and that the two be placed in separate Huronian groups were made, therefore, in cognizance of probable regional relationships as well as of relationships that had been established through an extensive area near Elliot Lake. Mapping by R.M. Ginn in the Espanola area during 1956, 1957 confirmed earlier work by Thomson and established that the sequence of pre-Bruce Formation sedimentary strata matched that at Elliot Lake (Ginn, 1960, 1961, 1965).

The sequence mapped by Thomson and Ginn in Baldwin, Nairn, and Porter Townships extends eastward through Hyman, Drury and Denison Townships into the Sudbury area as demonstrated by Card (1965, 1967). The lowermost sedimentary unit in these townships, referred to as 'the lower quartzite formation' by Card (1965), is composed mainly of feldspathic quartzite and contains radioactive quartz-pebble conglomerate beds including these now being developed for mining by Agnew Lake Mines Limited in Hyman Township. It nonconformably overlies Archean granitic rocks in northern Hyman Township but elsewhere, as in southwestern Hyman Township, southeastern Porter Township, Baldwin Township, Drury Township and Denison Township, it overlies Stobie or correlative volcanics with apparent conformity as previously discussed. It is overlain conformably by argillaceous sediments that are unquestionably correlative with the McKim Formation. It contains interbeds of similar argillaceous sediments. Such argillaceous strata form the basal part of the formation in places, as in central Drury Township (Card, 1965). Towards the east in eastern Denison and western Graham Townships the proportions of argillaceous to quartzose sediments increases to the point where it is no longer possible to separate a lower unit characterized by quartzite from the overlying McKim Formation. In other words, the quartzite formation interfingers with the lower part of the McKim Formation. As stated previously, Matinenda-type quartzite as well as McKim-type argillaceous sediments are interlayered with volcanic rocks in the Stobie Formation, and are abundant beneath the Copper Cliff Rhyolite near Copper Cliff and Sudbury, suggesting that the Matinenda-McKim sediments may interfinger with Stobie-Copper Cliff Volcanics.

The 'lower quartzite formation' of the Sudbury-Espanola area is clearly lithostratigraphically equivalent to the Matinenda Formation of the Elliot Lake area and should be referred to as Matinenda Formation. Matinenda sands and quartz-pebble gravels evidently once formed a continuous sheet extending southward from a line between Quirke Lake and northwestern Hyman Township interrupted perhaps by a few hills or small upland areas protruding through it.

McKim Formation

The argillaceous sedimentary rocks that outcrop at Sudbury in McKim Township were well described in 1914 by Coleman who called them McKim greywacke. They could be classified more specifically as argillaceous quartzites, siltstones and argillites as they are sorted rocks that do not possess the disrupted fabric that many consider diagnostic of greywackes The locality name McKim, however, is well established for the formation; it has been used by many workers, e.g., Coleman (1914), Collins (1925, 1936), Burrows and Rickaby (1934), Fairbairn (1941a, b), Cooke (1946), Yates (1948), in a consistent manner for the sequence of argillaceous sediments beneath, or north of, the Ramsay Lake Conglomerate and above, or south of the Copper Cliff Formation and lower volcanic rocks along the south side of the Sudbury Irruptive. The name McKim Formation should therefore be applied not only to all argillaceous strata that are in proven continuity with the type sequence in McKim Township but also to reasonably well-established lithostratigraphic equivalents.

The formation extends at least 5 miles northeast of Sudbury and has been mapped in detail from Sudbury westward 40 miles to Espanola (Ginn, 1961, 1964; Card, 1965, 1967). Lithostratigraphically equivalent rocks have long been known to extend at least 30 miles farther west through the Massey and Spanish areas (Collins, 1925, 1936; Geol. Surv. Can., Map 155A; Ont. Dept. Mines, Map, P.105; Ont. Dept. Mines, Map 2108). Recent detailed mapping by Robertson (1964c; 1965b, c; 1966b, c) in this area has confirmed this extension of the McKim Formation. Schists, lithologically similar to and contiguous with highly metamorphosed McKim strata near Spanish, extend 20 miles west of Spanish along the south side of the Murray Fault to Long Township. Robertson has designated strata south of the fault by names used in the Sudbury area as well as by names that he has used in the Elliot Lake-Blind River area and has stated (1966b, c) that the McKim Formation is equivalent to strata that he has termed the "argillaceous (Nordic) phase of the Lower Mississagi Formation", or "Lower Mississagi argillite". He has mapped the latter rocks north of the Murray Fault along the south flank of the Chiblow Anticline as far west as Lewis Township (10 miles east of Pronto Mine). Argillaceous strata occur in the same stratigraphic position (above Matinenda subarkose and below Ramsay Lake conglomerate) along the north flank of the Chiblow Anticline between Whiskey Lake and Chiblow Lake. Roscoe (1957a, b) and Pienaar (1963) referred to this unit as the Nordic Formation; Robertson (1961-1963, 1967) called it Lower Mississagi argillite. We now know that it is correlative with the McKim Formation and it is so called in this report. There is no longer any requirement or justification for either of the other recently introduced names and their use should be discontinued.

The McKim Formation was estimated to be 7,000 feet thick at Sudbury by Coleman (1914). It is probably several thousand feet thick throughout the broad main belt of the formation between Sudbury and Spanish.

It is difficult, however, to make even rough estimates of thicknesses along this belt as the argillaceous strata are highly deformed, metamorphosed, intruded by gabbro and truncated by the Murray-Worthington Fault and many lesser faults.

The formation thins rapidly to the north of its main outcrop belt. Ginn (1965, p. 23, Fig. 2) estimated that it was about 500 feet thick in northern Baldwin Township along the north limb of the Baldwin Anticline. A few miles farther northeast in northern Hyman Township, possible equivalent argillaceous layers are thin, interlayered with Matinenda-type subarkose and difficult to distinguish from Pecors argillite which is also thin in this area. This is probably very nearly the northern limit of deposition of the McKim Formation.

Northward thinning of the formation farther west has been illustrated by Robertson (1967a, Fig. 5) along a line of section that crosses the Murray Fault near Spanish and thence crosses the Chiblow Anticline to the Quirke Lake Syncline east of Elliot Lake. The formation is probably several thousand feet thick south of the Murray Fault but it is only about 600 feet thick just north of the fault and 0 to 280 feet thick, 13 miles north of the fault along the south flank of the Quirke Lake Syncline. Pienaar (1963, p. 85, Fig. 17) has drawn isopachs of the formation in the latter area. These, together with other drillcore data and mapping by Robertson (1963a) indicate that the formation was deposited as a tongue that trends slightly north of west across Townships 143, 149, and 155 and 'heads' near the northeastern corner of Township 161. Sand:shale ratios increase northwesterly from 2 to 3 through Townships 143 and 149 according to Pienaar. The tongue of argillaceous sediments therefore could have been deposited in a river estuary, or drowned Matinenda valley, that opened southeasterly into the McKim sea and owed its existence to downwarping north of the present position of the Chiblow Anticline. Vertical movements during and after deposition of the formation probably also affected the morphology and lithology of this tongue, however, and may have been the dominant influences. The formation was evidently eroded away entirely over the Pecors high prior to deposition of the Hough Lake Group.

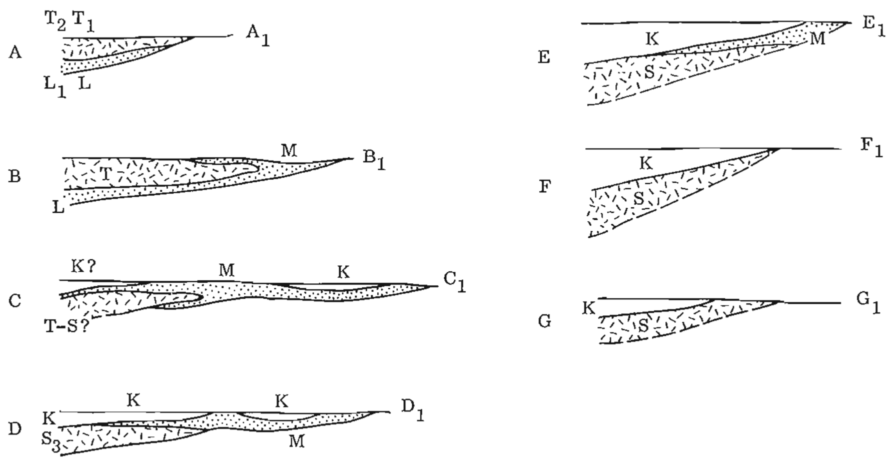
Occurrences of fine laminations, ripple-marks, small-scale cross-bedding, mud-cracks (Card, 1965, p. 12) and intercalations of coarser, crossbedded arenites indicate that the argillaceous rocks were deposited in shallow water, perhaps in a deltaic environment. The formation interfingers northward with coarse fluviatile subarkoses of the Matinenda Formation. It possibly also interfingers to the south and east with volcanic rocks. Card (1967) has mapped one locality in central Graham Township where such an interfingering certainly is present. Phemister (1956, p. 104) describes occurrences of rhyolite flow breccia and pillow lava interlayered with argillaceous sediments at the base of the formation where it overlies Copper Cliff Rhyolite in McKim Township. The McKim Formation thus can be interpreted as having been deposited during a period of marine transgression that began during volcanism and continued after cessation of volcanism. Apart from the tongue of argillaceous strata in the Elliot Lake area and other marginal areas of onlap over the Matinenda Formation, the distribution of the formation coincides with that of the Stobie and probable equivalent volcanic rocks. The volcanic and argillaceous strata were obviously deposited in a geosyncline; together they represent accumulations of perhaps as much as 15,000 feet of strata. These thicknesses are in pronounced contrast to thicknesses in the order of only hundreds of feet of coarse clastics and argillites deposited (evidently during the same time interval) a few miles to the north on the marginal platform.

Relationships Between Volcanic and Sedimentary Rocks

It has been postulated in this report that the Stobie Volcanics as well as the Thessalon Volcanics are coeval with the Elliot Lake Group sediments and that the volcanics were extruded in a belt peripheral to the main area of deposition of Matinenda sands and quartz-pebble gravels. If this were so, the build-up of the thick volcanic sequences must have had considerable influence on Matinenda sedimentation along and beyond the margins of the volcanic belt.

Suggested relationships between volcanic and sedimentary rocks are illustrated schematically in Figure 5. The Livingstone Creek Formation, together with subarkose and radioactive quartz-pebble conglomerate beds interlayered with volcanic flows in the overlying Thessalon Formation, probably represents the eastward extension of Matinenda beds. Although Matinenda sediments concordantly overlie Stobie Volcanics to the east, it seems unlikely that there are two separate thick successions of volcanic rocks, one older and one younger than the Matinenda Formation. More probably, the two volcanic formations are correlative, and are in part coeval with both the Matinenda Formation and the McKim Formation. Elliot Lake Group sediments are not known to overlie Thessalon Volcanics as they do Stobie Volcanics, but the top of the Thessalon Formation is deeply buried except in a few places and is poorly exposed in these. Arenites, like those in the Livingstone Creek Formation are not known to occur beneath the Stobie Volcanics but the base of this formation is obscured by intrusive rocks. The Snider Formation near Sudbury (Yates, 1948, p. 597) might represent an eastern counterpart of the Livingstone Creek Formation.

The lavas are postulated to have been extruded within an arcuate geosynclinal belt while Matinenda sands and gravels were deposited to the north on a marginal platform centred at Elliot Lake (Fig. 5). The principal volcanic vents must have been south of the northern limit of volcanic rocks so the northernmost lava flows along the periphery of the central platform area must have flowed towards the platform. The coarse Matinenda sediments, on the other hand, were deposited by southerly-flowing streams that carried much larger quantities of finer grained detritus farther south into the



K - McKim Formation, argillaceous rocks

M - Matinenda Formation, subarkose

S - Stobie Formation, volcanic rocks; Copper Cliff Formation, acid volcanics; Frood Formation, sedimentary rocks; volcanics in Porter and southwest Hyman Townships (S_1), Baldwin and Shakespeare Townships (S_2), and Salmay Lake area (S_3); Pater Formation (S_4)

T - Thessalon Formation, volcanic rocks

T_1 - formerly Aberdeen volcanics

T_2 - formerly Duncan greenstone

L - Livingstone Creek Formation, subarkose formerly mapped as Mississagi Formation

L_1 - formerly Driving Creek Formation

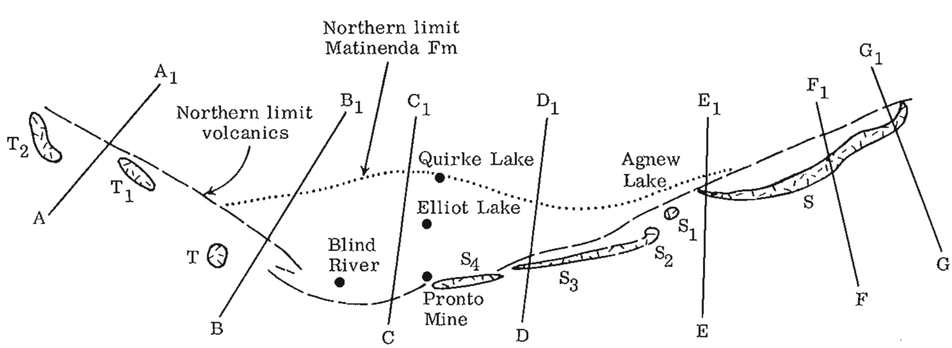


Figure 5. Schematic sections showing inferred stratigraphic relationships of volcanic rocks of the Thessalon and Stobie Formations and sedimentary rocks of the Elliot Lake Group.

geosyncline. The paucity of pillowed flows, particularly in the Thessalon Formation, and the presence of current-bedded sediments interlayered with some of the flows, indicates that much of the volcanism was subaerial. The volcanic eruptions in the peripheral geosyncline thus would have tended to obstruct drainage off the marginal platform. Fine-grained subarkose and argillaceous sediments found within and immediately adjacent to the Thessalon Stobie Formations may reflect local damming of drainage. Widespread damming was evidently averted by subsidence of the volcanic geosynclinal belt but there would likely have been considerable diversion of water-flow around areas of particularly rapid accumulation of volcanic strata.

A thick accumulation of volcanic rocks covered an extensive area east of Agnew Lake. Streams flowing south towards this volcanic centre would have been diverted towards the southwest along its northwestern margin. In this way, large volumes of moving water with high carrying capacity could have been concentrated or 'funneled' near the western margin of the positive volcanic area. The potential ore deposits of Lake Agnew Mines are just west of the northwestern wedge-out of the Stobie Formation (Fig. 5, section E-E). These deposits and numerous other radioactive quartz-pebble conglomerate beds in the thick sequence of Matinenda subarkoses in the Agnew Lake area may have been localized by the phenomenon of drainage diversion. The Thessalon volcanic belt may also have funneled drainage along its deeply buried and unexplored margin northwest of Blind River (Fig. 5, section B-B_1).

Conglomerate containing abundant volcanic clasts, possibly derived from Huronian rather than pre-Huronian volcanic rocks, is found at Pronto Mine. It appears to overlie granitic paleosol in remnants of two pre-Huronian valleys just north of the basal outcrop of the Matinenda Formation. Rounded cobbles and pebbles include granitoid rocks, gabbro, chert and quartz in addition to basic volcanic rocks and are fairly closely packed in a dark granular matrix. Many of the rock clasts have light-coloured rims that are doubtless the result of ancient weathering. Some of the volcanic clasts, however, have dark rims that resemble chilled borders. A few of these, moreover, have bomb-like forms.

This conglomerate resembles some that are found at or near contacts of Huronian volcanic rocks and sediments more closely than it resembles polymictic conglomerates found locally at the base of the Matinenda Formation in the Quirke Lake Syncline. Grossbedding in Matinenda subarkoses indicates that those at Pronto were transported from the northwest. There are no known extensive areas of pre-Huronian volcanic rocks northwest of Pronto that might have provided abundant volcanic clasts; the nearest such area is near Elliot Lake 13 miles north-northeast of Pronto Mine. Weathering of a mixed granitic and volcanic provenance and further weathering of debris derived therefrom would have resulted in a disproportionately large quantity of clasts of more resistant, fine-grained volcanic rocks. It seems likely, however, that such weathering would have also resulted in a greater abundance of chert and quartz clasts than are found in the conglomerate. There is reason to suspect, therefore, that Huronian volcanic rocks – perhaps the Pater Volcanics south of Pronto – contributed debris to the conglomerates. If this were established, it would demonstrate that Matinenda strata at Pronto are younger than the nearest volcanic rocks and in this respect resemble the Matinenda rocks at Agnew Lake more closely than they do the Livingstone Creek Formation at Thessalon.

Conglomerate beds at and near the base of the Stinson Member near Elliot Lake contain greenstone pebbles in addition to abundant quartz and chert pebbles. A remarkable development of this conglomeratic zone was intersected by drillholes on the Stanleigh property. Here the zone is about 350 feet thick and consists of well-sorted cobbles and large pebbles of volcanic rocks, argillaceous rocks, quartz, chert, and granite. It was evidently deposited as an open-work gravel in large part. Authigenic calcite and quartz (rare in Huronian clastic rocks) fills many of the interstices between pebbles and soft pebbles are commonly squeezed between harder pebbles. This local flooding of volcanic debris into the Matinenda Basin was probably the result of an uplift of pre-Huronian volcanic rocks somewhere to the west. It is possible, however, that an eruption of Thessalon volcanics contributed debris to the basin at this time.

The disconformity below the Stinson conglomerates, the evidence of vigourous washing of these conglomerates, and the comparatively well-washed character of Stinson arenites all suggest that a regionally important tectonic event followed deposition of the Ryan Member. The coarser Stinson subarkoses resemble subarkose in the Livingstone Creek Formation north of Bruce Mines. Fine-grained subarkose at the top of the Stinson Member and in the McKim Formation resembles the fine-grained arenite found in the Livingstone Creek Formation immediately beneath the Thessalon Volcanics near Thessalon and near Sault Ste. Marie. A persistent bed of distinctive olive green-coloured argillite, considered to mark the base of the McKim Formation at Elliot Lake, differs from the dark grey to dark green argillite that is abundant in the McKim and Pecors Formations. The writer suspects that it contains weathered tuffaceous or other volcanic material although petrographic study and chemical analyses do not show important differences between it and other argillites.

In summary, there are some reasons to suspect that the maximum northwesterly advance of Thessalon volcanism occurred subsequent to deposition of the Ryan Member and prior to deposition of the Manfred Member of the Matinenda Formation in the Elliot Lake area.

PRE-HURONIAN ROCKS

GENERAL

Huronian sediments including quartz-pebble conglomerates were derived from a pre-Huronian terrain that extended north of the present Huronian belt. Speculations on the composition of source rocks for Huronian sediments, the nature of weathering of these rocks during Huronian times, and the bulk composition of detritus and types of heavy detrital minerals supplied to the Huronian depositional area, are inevitably involved in this study. These things must be deduced mainly from study of the Huronian sediments themselves, but knowledge of the present distribution and general character of pre-Huronian rocks is helpful.

The region north of the Huronian belt is characterized by belts and small patches of metavolcanic and metasedimentary rocks intruded by granitic rocks (Fig. 1). The belts of metamorphic rocks, typically in the greenschist facies of metamorphism, are generally referred to as greenstone belts. They represent erosional remnants of tightly-folded and metamorphosed stratified rocks which must have been more extensive on the less deeply eroded surface that existed early in Huronian time. On the present surface, granitic rocks are by far the most important rock types. Most geological mapping has been designed to outline and map greenstone belts considered favourable prospecting areas. As a result, large areas believed to be underlain only by granitic rocks are little known.

The Huronian Groups nonconformably overlie granitoid rocks rather than greenstone in most places along the boundaries of the Huronian belt. There are some fairly extensive areas north of Lake Wanapetei where the Cobalt Group overlies greenstone, and the Hough Lake and Quirke Lake Groups overlie greenstone in several places near Lake Wanapetei. Apart from a small area near Sault Ste. Marie, however, the only place where the Elliot Lake Group overlies greenstone is along the eastern end and northern flank of the Quirke Syncline in the Elliot Lake area (Fig. 6). One is immediately compelled to search for factors that might couple the abundance of uraniferous conglomerates in the Elliot Lake area with the unique presence there of an extensive greenstone belt. Several possible factors are apparent: (1) the topography of the greenstone belt during Matinenda sedimentation would surely have been distinctive and might have directed transport and deposition of detritus in special ways; (2) crustal movements during sedimentation might have been more complex than in areas of more homogeneous granite basement rocks; (3) the greenstone belt could have provided a prolific local source for pebbles of chert and most probably vein quartz as well; (4) Archean granites that intrude the greenstone belt were likely 'higher level' intrusives, and hence perhaps more uraniferous than granitic rocks remote from the greenstone belt.

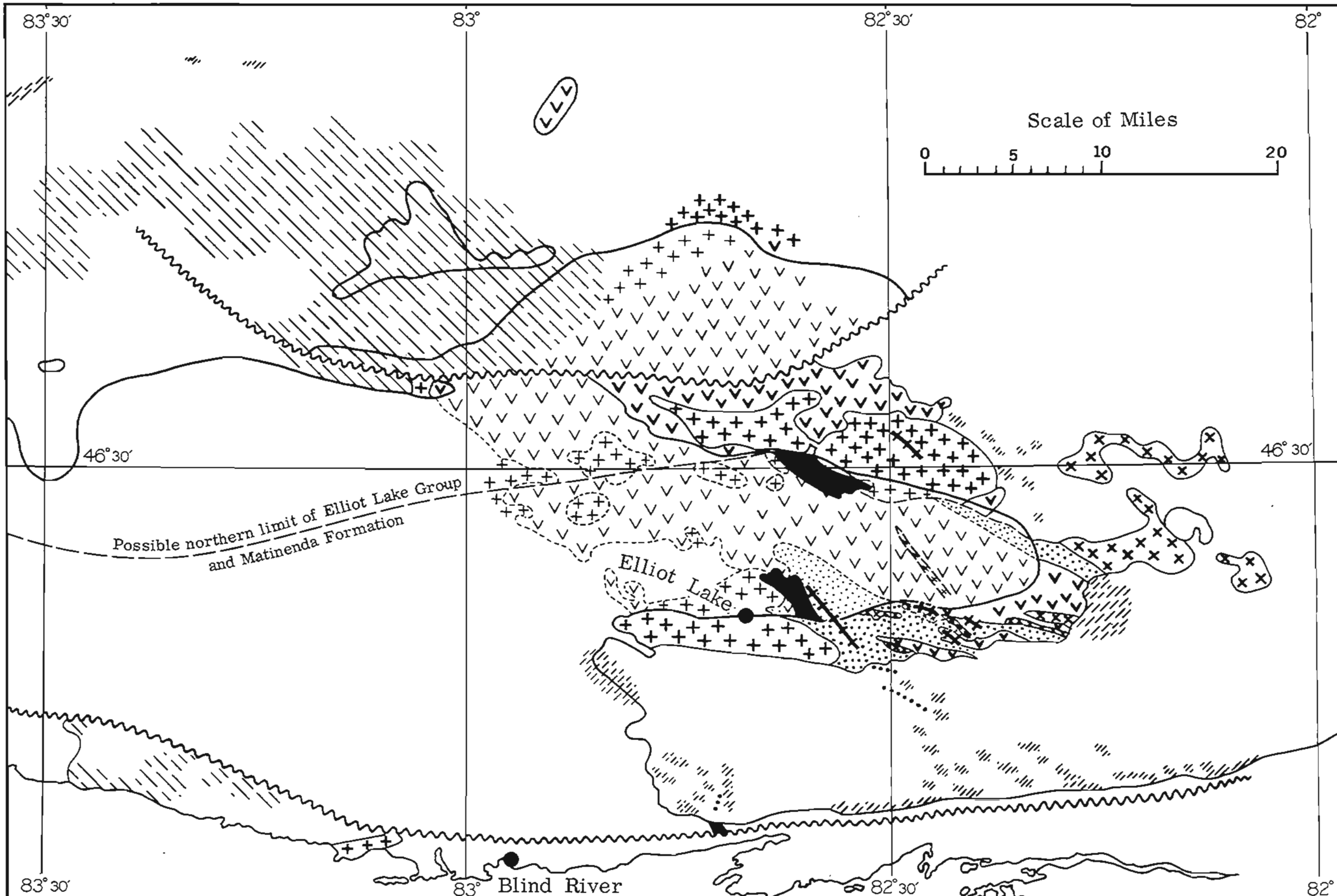


Figure 6. Distribution of Archean rocks beneath Huronian strata and ore zones.

LEGEND

ARCHEAN ROCKS

Massive red granitic rocks (exposed, covered by Huronian strata)

Grey granodioritic rocks and unclassified Archaean rocks

Amphibolite, migmatite and granitoid gneiss
(exposed, covered by Huronian strata)

Abundant inclusions of metavolcanic and metasedimentary rocks
(exposed, covered by Huronian strata)

Meta gabbro (exposed, covered by Huronian strata)

Metasedimentary rocks (exposed, covered by Huronian strata)

Metavolcanic rocks (exposed, covered by Huronian strata)

Iron formation

Giant quartz vein

Uranium ore zone in Matinenda Formation

Boundary of Huronian rocks . . . .

Possible northern limit of Elliot Lake Group
and Matinenda Formation . . . .

Fault . . . .

ARCHEAN METAVOLCANIC AND METASEDIMENTARY ROCKS

Basic volcanics, commonly pillowed, are the most common rocks in the greenstone belts but acidic volcanics, pyroclastic rocks, greywacke, conglomerate, iron-formation and intrusive rocks ranging from ultrabasic to acidic in composition are present in most belts. Iron-formation is found interbedded both with other sedimentary rocks and with volcanic rocks. The most common type is banded chert containing small amounts of fine-grained magnetite, but siderite, pyrite, jasper and hematite are important constituents of some iron-formations. The siliceous iron-formations were the source of chert, jasper and granular quartz found in all Huronian oligomictic conglomerates. Many of these pebbles contain magnetite, pyrite or hematite. The occurrence of jasper iron-formations 40 miles north and northeast of Sault Ste. Marie (Moore, 1925, 1926) is noteworthy as jasper pebbles are abundant in oligomictic conglomerates in the western part of the Huronian belt but are much less abundant near Elliot Lake and are rare farther east. Jasper iron-formation is also found 95 miles north of Elliot Lake (Goodwin, 1965) and in greenstone belts farther northwest.

The volcanic and sedimentary rocks were intruded by gabbro. This meta-gabbro is commonly difficult to distinguish from later Huronian, or post-Huronian, diabase. Other basic and ultrabasic intrusive rocks, norite, anorthosite, peridotite and serpentinite, are also found in some of the greenstone belts. Occurrences of pre-Huronian ultrabasic rocks are interesting because chromite is among detrital heavy minerals found in Elliot Lake quartz-pebble conglomerates.

Quartz and quartz-carbonate veins are abundant in the greenstone belts. Many veins contain pyrite or pyrrhotite; some contain base metal sulphides or gold. Occurrences of disseminated sulphides and masses of sulphides are also common in the metavolcanic rocks. Gold deposits are common through a belt extending east from Michipicoten which is about 100 miles north of Elliot Lake but are rare or absent in greenstone belts farther south nearer to Elliot Lake. The reported occurrence of gold in Huronian oligomictic conglomerate in Vogt Township (Thomson, 1960a) 22 miles southwest and 12 miles southeast of known Archean gold deposits near Timagami is interesting in view of the low tenor of gold that is present in the Elliot Lake uranium deposits which are farther away from known Archean gold occurrences.

Whiskey Lake Greenstone Belt

The Archean greenstone belt in the Elliot Lake area, previously mentioned, is referred to herein as the Whiskey Lake greenstone belt. It is an irregular, west-northwesterly trending belt about 40 miles long. Most of it is covered by Huronian rocks but parts are exposed east and south of Whiskey Lake and northwest of Quirke Lake. This greenstone belt and its probable extent beneath Huronian rocks are shown in Figure 6. The geology of Archean rocks exposed along the flanks of the Quirke Syncline and in the Chiblow Anticline is taken from work by Robertson (1961-1966); that of exposed Archean terrains elsewhere, from various sources including observations by the writer (Roscoe and Steacy, 1958, p. 475). Interpretations of Archean geology beneath Huronian cover are based on drillcore data and in part on aeromagnetic data[1]. The southwestern contact of the main metavolcanic-metasedimentary belt is shown as an irregular dashed line extending westward from the north end of the Elliot Lake ore zone to a point north of Matinenda Lake where an isolated drillhole intersected fresh-appearing volcanic rock[2], and thence northwestward to a small area of greenstone on the north flank of the Quirke Syncline. Continuity of volcanic rocks in these localities with those northwest of Quirke Lake, irregularities along the contact, and granitic bodies within the predominantly volcanic belt are suggested by aeromagnetic data (Geol. Surv. Can., Geophys., Paper 7068 G). Aeromagnetic contours are generally higher and show more intricate patterns in the areas believed to be underlain by volcanic rocks than in those believed to be underlain by granitic rocks. The differences, however, are slight and it is difficult to assess effects of gabbro bodies and apparently magnetic arkose beds in the Gowganda Formation, so sub-Huronian Archean geology northwest of Elliot Lake cannot be regarded as more than schematically illustrated in Figure 6.

Basic volcanic rocks in the belt are massive to highly schistose. Breccia structure and amygdules can be recognized in many surface outcrops and in drillholes. Ellipsoidal structure is well shown in lavas on the east shore of Whiskey Lake and has been reported elsewhere in the belt. Under the microscope the fine-grained volcanic rocks are seen to be composed of altered feldspar laths intergrown with chlorite, epidote, quartz, sericite, leucoxene, black opaque material and sulphides. The volcanic rocks are commonly, if not typically porphyritic.

'Acidic volcanic rocks' are found immediately northwest of Quirke Lake and have been reported by Robertson (1961, 1962) south of Pecors Lake and Hart Lake. Those near Quirke Lake are buff-weathering, fine-grained, banded rocks containing abundant quartz 'eyes' and much sericite. Acidic fragments are found in a pyroclastic breccia at the bottom of a drillhole on the northeast shore of Pecors Lake.

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[1]Pienaar (1963, Fig. 6) mapped buried contacts between Archean greenstone and granitic rocks in the eastern part of the Quirke Syncline from drillcore data. Steenland and Brod (1960) have made some interpretations of basement geology, structure and depths in a small part of the Quirke Syncline from aeromagnetic data.

[2]There is a possibility that this volcanic rock is Huronian in age (equivalent to the Thessalon Volcanics) rather than Archean.

Metasedimentary rocks form a large proportion of the pre-Huronian rocks east of Elliot Lake and south of Pecors Lake. The most abundant types are fine-grained, dark grey sericitic schists and green chloritic schists, locally referred to as 'argillite'. They are probably of tuffaceous origin. Meta-greywacke with definite clastic grains, as described by Pienaar (1958, p. 20), is associated with the fine-grained metasedimentary rocks. According to Peinaar, meta-greywacke is particularly common in drillholes around Stinson Lake and pre-Huronian polymictic boulder conglomerate has also been intersected in a few holes in this area. He also reported that pre-Huronian polymictic boulder conglomerate was encountered in the Can Met Shafts at Quirke Lake.

Lean cherty iron-formation is found in several places in the southern parts of Townships 143 and 138. There are also several small occurrences of iron-formation north of Quirke Lake. One, 6 miles northwest of the Quirke Mine, is rich in pyrrhotite and pyrite (Friedman, 1958b).

Meta-gabbro has been intersected under Huronian rocks in a number of drillholes, and of course is found in a great many outcrops. It can generally, but not always, be distinguished from the later diabasic intrusives which cut granitic rocks and Huronian rocks as well as greenstone by its more irregular contacts and altered appearance. The largest pre-Huronian, pre-granite basic intrusive body in the area is the East Bull Lake gabbro at the east end of the Whiskey Lake greenstone belt. It has been described by Moore and Armstrong (1943) as containing facies of anorthosite, norite and amphibolite. Some sulphide mineralization containing a little copper and nickel has been found in several places in sheared or fractured East Bull Lake gabbro. Rock with composition approaching quartz diorite is common along greenstone – 'granite' contacts. It is difficult in many cases to ascertain whether the rock is an altered border of the greenstone, a basic border of the granitic intrusives, or part of a meta-diorite intrusive that happens to be near the contact.

The internal structure of the Whiskey Lake greenstone belt is not known but Robertson (1962) has found evidence that the belt is an easterly-trending syncline wherein metavolcanic rocks overlie metasedimentary rocks. In most places stratification and foliation dip steeply and strike west or northwest. Northerly strikes were noted in one place immediately northwest of Quirke Lake. At the Quirke Mine, northwest of Quirke Lake, a granite-greenstone contact locally parallels the contact between the greenstone and the overlying Huronian rocks both in strike and dip. In the Algom-Nordic Mine, foliation and probably stratification in pre-Huronian metasedimentary rocks strikes northwest and dips as little as 30 degrees north, thus locally approaching parallelism with overlying Huronian strata which strike west and dip 15 to 20 degrees north.

GRANITIC ROCKS NEAR ELLIOT LAKE

The term 'granitic rock' is used for quartzo-feldspathic rocks which include granite, quartz monzonite, granodiorite, and quartz diorite. These pre-Huronian rocks are commonly referred to as 'Algoman granite'. Quartz monzonite is the most abundant compositional variety. It is medium to coarse grained, massive to faintly gneissic, pale grey, white, or pale pink in colour. The potash feldspar is microcline; perthite is common but no orthoclose was seen in any of the specimens studied.

Microcline, commonly 2 to 6 millimetres in size, forms the largest mineral grains in most rocks. A common variety of quartz monzonite contains porphyroblasts (or phenocrysts) of microcline, up to 10 by 20 millimetres in size, in a matrix that contains considerably more plagioclase than microcline. Anhedral quartz grains or aggregates range from 1 to 6 millimetres in size; plagioclase (oligoclase) grains are commonly smaller and subhedral in shape. Hornblende is the most abundant mafic mineral but lesser amounts of biotite are commonly present and many rocks contain biotite with little or no amphibole. In most specimens the mafic minerals, particularly hornblende, are altered to chlorite, epidote, leucoxene, and ferric oxide. Plagioclase has been highly altered, mainly to white mica. Alteration of microcline to sericite is much less extensive.

Chemical and spectrographic analyses of 7 granitic rocks are listed by Pienaar (1963, pp. 12, 13, Tables V, VI). These analyses, and several others obtained by the writer, resemble those of normal granites, quartz monzonites and granodiorites so there is no reason to list them here. Contents of copper, nickel, cobalt, tin, boron, beryllium, and molybdenum are very low.

Granites, granodiorites and quartz diorites appear to be particularly common adjacent to the Whiskey Lake greenstone belt. Pink and red granites are found in a number of places. There are bodies of red hornblende granite north of Ten Mile Lake that appear to have sharp contacts with greenstone. Brick-red granite, intruding greenstone some distance south of the main contact of the greenstone belt, was encountered at the bottom of a Can Met Shaft at Quirke Lake. Red and pink coloration in granites, quartz monzonites, and rarely granodiorites is due to ferric oxide in feldspar, generally in the microcline. The microcline in many rocks however, is greyish, and in some the plagioclase as well as microcline is stained red. Red and pink rocks generally contain more microcline than plagioclase, however, and the writer agrees with Robertson (1960-1964) that it is useful to distinguish between the generally more potash-rich reddish granitic rocks and the more sodic and mafic grey granitic rocks. This distinction, following Robertson (1960, Ont. Dept. Mines, Map 2032), is made in Figure 6. Robertson (1960-1964) believed that the grey granitic rocks, which are commonly gneissic, heterogeneous in character and veined by aplites, are older then the more massive, commonly porphyritic, reddish granitic rocks.

The apparent concentration of the latter rocks along and within the greenstone belt suggests that they are relatively high level intrusives. They are more radioactive (due partly to their higher potassium contents) than the grey rocks, and contain a somewhat different suite of accessory minerals from that found in the latter rocks (Roscoe and Steacy, 1958; Robertson, 1962); zircon and monazite are relatively abundant in this suite.

Grey quartz diorite and granodiorite along the northern contact zone near Quirke Mine and along the southern contact zone near Nordic Lake are finer grained than the more normal acidic igneous rocks and commonly have a granoblastic texture. A body of coarse-grained, red, porphyritic biotite-hornblende syenite intrudes greenstone and also intrudes the East Bull Lake gabbro mass east of Whiskey Lake.

Gneissic rocks of granodioritic and quartz dioritic composition are found throughout an extensive area south of Rocky Island Lake and 20 to 40 miles northwest of Elliot Lake. The foliation strikes northwest and west, dipping steeply to the southwest and forms an arcuate pattern concave towards the southwest. North and northeast of these rocks, the granitic pre-Huronian rocks appear to be more massive, more uniform, perhaps coarser grained, and perhaps more radioactive than those elsewhere in the region near Elliot Lake. Faint foliation dipping gently north was noted in places at Rocky Island Lake. Small patches of unusually radioactive granite, generally red, are found in granite and quartz monzonite near Rocky Island Lake (Roscoe and Steacy, 1958, Fig. 5, sample 31) and Rangers Lake.

Some thin radioactive veins have been found along faults and fractures in granitic rocks and along contacts of diabase dykes near Aubrey Falls (Harding, 1950) and Rangers Lake about 60 miles northwest of Elliot Lake. They resemble pitchblende occurrences 60 miles farther west on the east shore of Lake Superior near Montreal River, and they may well be post-Huronian in age. Weak radioactivity probably due to thorium has been found along fractures in granitic rocks near Blind River and southeast of Whiskey Lake; this mineralization is probably pre-Huronian in age.

Thin granite pegmatite dykes, fine-grained aplitic dykes, and quartz veins are found cutting granitic rocks. Some aplitic and pegmatitic dykes are slightly more radioactive than the granitic rocks. Pegmatite dykes, however, are commonly less radioactive than adjacent granitic rocks. Several 'hot spots' were noted in a pegmatite on an island in Rocky Island Lake. One of these was attributed to a grey metallic mineral; another to an earthy greenish mineral. The grains were small, highly weathered, and were not identified. Pegmatite would form a very small proportion of the total pre-Huronian terrain; in fact, pegmatite dykes are perhaps unusually rare in this particular granitic terrain.

Quartz veinlets are probably fairly abundant in granitic rocks but thicker veins that might be sources of large pebbles and cobbles of quartz are not widespread. Giant quartz veins have been mapped by Robertson (1964c, 1965a) and by Abraham (1953), however, in granitic rocks southeast of Elliot Lake and north of Pronto Mine.

Heavy Accessory Minerals

Heavy accessory minerals of 23 granitic rocks were reported by Roscoe and Steacy (1958). The heavy minerals were separated from 50 grams of the 100-150 mesh size-fractions of samples of granulated rock. The smallest quantity of a heavy mineral species that could be estimated under the procedure was about 10 ppm in terms of amount (by weight) present in the rock but the minimal detectable amount, indicated by the presence of a few grains and reported as a trace, might be as low as 1 ppm. The results of this study are summarized below. Robertson (1960-1964) found very similar suites of heavy accessory minerals he noted in addition, chalcopyrite, pyrrhotite and galena in some samples, and malcon zircon in red granites. The proportions and sizes of the heavy minerals are worth brief consideration because any placer deposits derived from the granitic terrain must contain many of them or their altered equivalents.

The opaque iron minerals, hematite, magnetite, ilmenite and pyrite, are the most abundant group of heavy accessory minerals. Most specimens contain nearly one half of 1 per cent of these minerals. One granodiorite (Roscoe and Steacy, 1958, Fig. 1, No. 20) contains 2 per cent magnetite. A granite nearby (19) contains about 1 per cent hematite. The opaque minerals range in size from less than 0.03 millimetres to 0.7 millimetres; most are less than 0.4 millimetres. The titanium minerals, sphene, rutile and anatase, were found in most samples. They are of special interest as they are at least feebly radioactive and may in some way be related to radioactive titaniferous grains important in ore conglomerates. Some sphene is particularly radioactive. One sample of granodiorite (Roscoe and Steacy, 1958, Fig. 1, No. 20) contained about 1 per cent sphene which typically occurs as rhombic shaped euhedral grains up to 4 millimetres long. Most specimens, however, contain only about 0.1 per cent sphene in grains commonly about 0.3 millimetres by 0.6 millimetres in size. Zircon (hyacinth) and apatite are probably ubiquitous in these granitic rocks. A zircon content of up to 0.1 per cent was found in some granite samples but about 0.01 per cent is most common in the quartz monzonites and granodiorites and is compatible with zirconium contents of about 0.01 per cent found in spectroscopic analyses. Most zircons are about 0.05 by 0.1 millimetres in size but rare crystals up to 0.4 millimetres in length were noted. Monazite, a mineral of major importance in radioactive conglomerates, was found in amounts up to 0.06 per cent in mineral separates of 4 of the granitic rocks and was noted in thin sections of several additional samples. It occurs in grains 0.1 to 0.4 millimetres in diameter. Allanite, a radioactive mineral of the epidote group, was found in 5 heavy mineral separates. A few grains about 0.15 millimetres in diameter were recognized in thin sections. Other epidote group minerals are found in most of the rocks studied but, like chlorite, muscovite, amphibole and biotite, they are not included in this tabulation of heavy accessory minerals. Abundant thorite 0.2 to 0.5 millimetres in diameter was found in one, very radioactive, granite sample (Roscoe and Steacy, 1958, Fig. 1, No. 31). A single grain was noted in each of two sections of other samples. Beryl attached to biotite was found in heavy mineral separates of three samples (28, 29, 30) collected near Algom-Quirke Mine. No beryl was seen in thin sections nor was beryllium found in spectrographic analyses of the other heavy mineral concentrates.

Thorium and Uranium Contents

Thorium and uranium oxide contents of 27 granitic rocks were reported by Roscoe and Steacy (1958). The most common analysis (7 out of 27) is about 0.0016 per cent (16 parts per million) ThO_2 and 0.0006 per cent (6 parts per million) U_3O_8 - a $ThO_2:U_3O_8$ ratio of 2.7. Many rocks, however, are much more radioactive and contain up to 100 ppm ThO_2 and 30 ppm U_3O_8. A few samples are less radioactive and contain as little as 5 ppm ThO_2 and 3 ppm U_3O_8. The average of all samples is 27 ppm ThO_2 and 11 ppm U_3O_8 – a $ThO_2:U_3O_8$ ratio of 2.5. It is probable that more samples with abnormally high radioactivities than with abnormally low radioactivities were taken. The median contents of 19 ppm ThO_2 and 8 1/2 ppm U_3O_8 – a $ThO_2:U_3O_8$ ratio of 2.25 – would perhaps be more closely representative of the granitic rocks in the area. These thorium and uranium contents, while not abnormally high, are considerably higher than those cited as averages for acidic and intermediate igneous rocks (Larsen, 1954; Whitfield et al., 1959). The thorium to uranium ratio (2.25) is certainly lower than that believed normal for acidic to intermediate igneous rocks (3 to 4).

It is difficult to conclude whether or not variations in radioelement contents show any definite systematic relationships with either rock composition or geographic position. A group of radioactive samples (Roscoe and Steacy, 1958, Fig. 1, Nos. 1, 2, 3, 4, 5) with the highest $ThO_2:U_3O_8$ ratios (3 1/2 to 5) were taken from granites and quartz monzonites remote from Elliot Lake. Another group of relatively radioactive samples (Nos. 10, 11, 12, 32) with low $ThO_2:U_3O_8$ ratios (0.8 to 1.8) are from red granites both near and remote from Elliot Lake. Two analyses (16, 17) with low radioactivity but extremely low Th:U ratios are granodiorite and quartz diorite in basement rocks very close to the Quirke ore zone. Other samples with low radioelement contents have average to high Th:U ratios. These are (22) biotite granodiorite very close to the southern (Nordic) ore zone, grey granite (26) beneath radioactive conglomerate at the outlet of Elliot Lake, grey granitic rock (24) immediately below a radioactive pebble bed near the town of Spanish, and (20) hornblende granodiorite gneiss 40 miles northwest of Elliot Lake. The variations are normal inasmuch as radioelements are most concentrated in some of the more potassic rocks, but the extremely low Th:U ratios found in two intermediate rocks near Quirke Mine are unusual.

The data do not in any way suggest that uranium was introduced into the basement rocks near ore zones, nor do they suggest that uranium may have migrated from the granitic rocks near the Huronian contact and so have been available for concentration in overlying Huronian rocks. There is no evidence, either in these analyses or in microscopic studies of distribution of radioactivity, that the radioelements are other than normal syngenetic constituents of the pre-Huronian rocks. A number of samples Roscoe and Steacy, 1958, Fig. 1, Nos. 10, 13, 16, 17, 25, 32), close to contacts with Huronian rocks and therefore little eroded since the time of Matinenda sedimentation, have unusually low Th:U ratios (as low as 0.6). Farther north much erosion has taken place since early Huronian time. It is possible that rocks with very low Th:U ratios, particularly red granites were more abundant on early Huronian surfaces than they are on present surfaces.

Distribution of Radioactivity in Granitic Rocks

Distribution of radioactivity in granitic rocks was studied by means of autoradiographs of thin sections. Some radioactivity is distributed along grain boundaries or associated with secondary minerals, particularly those formed by alteration of mafic minerals, but in most sections a larger proportion of the radioactivity seems to be contained in sparsely distributed heavy accessory minerals, monazite, zircon, allanite, sphene and thorite. Heavy mineral separates, which contained common mafic minerals and secondary minerals as well as the heavy accessory minerals listed in the table, are more radioactive than their parent rocks. Six of them showed more than 0.01 per cent U_3O_8 equivalent. Natural concentrations of heavy minerals in coarse-grained sediments (or placer deposits) derived from pre-Huronian rocks would similarly be relatively radioactive; in fact they would be much more radioactive if the mafic minerals had been destroyed by weathering or hydraulically removed from heavier, more radioactive, accessory mineral assemblages. Monazite concentrations are in fact found in sands in the valley of the Au Sable River 25 miles east of Elliot Lake.

INFLUENCE OF ARCHEAN BASEMENT ROCKS AND TOPOGRAPHY ON MATINENDA SEDIMENTATION

General

The topography of the Archean surface over which the Matinenda sediments were carried and upon which they were deposited was probably the main factor controlling local facies and thickness variations within the formation. At an early stage in the exploration of the two main conglomeratic zones, Hart, Harper *et al*. (1955, p. 129) concluded that the Quirke and Nordic orebodies lie largely "within pronounced depression(s) on the pre-Huronian surface", that the "thickest beds of conglomerate occur in the lowest parts of the depressions" and that "the depressions were caused by the differential erosion of pre-Huronian green schists and granitic rocks". Subsequent reports by others – (Roscoe, 1957a, pp. 8, 17; Roscoe and Steacy, 1958, p. 478; Derry, 1960, p. 913; Pienaar, 1963, pp. 8, 44, 49, 127, Fig. 32; Robertson, 1960, 1966a, pp. 127, 132) have also stressed the important influence that basement lithology and topography had in controlling the locales of deposition of thick and abundant quartz-pebble conglomerate beds.

Variations in thicknesses of strata underlying ore zones establish that local relief must have been as great as 100 feet in lateral distances of less than 1,000 feet. Maximum differences in elevation were probably much greater than that and highlands may have risen fairly abruptly north of the depositional platform. The total thickness of the Matinenda Formation varies by as much as 700 feet within a lateral distance of 1 mile (Pienaar, 1963, Fig. 8) but such differences cannot be attributed solely to basement relief. They are also due to irregularities on the upper surface of the formation, that are attributable in part to fan-like build-ups of coarse sediments deposited at the mouths of valleys and in part to erosion of that surface prior to deposition of overlying rocks.

Nordic Area

The ore zone near Elliot Lake overlies a northwesterly-trending zone of metasedimentary schists bordered to the southwest by granite and to the northeast by iron-formation (Fig. 6). The iron-formation forms a distinct ridge that rises some 100 feet above the deepest part of the depression beneath the central part of the ore zone. Conglomerate beds, including the main ore reef, abut against the iron-formation ridge and only the uppermost beds of the thick conglomeratic zone pass eastward over its crest. Pebbles of chert, doubtless derived from this ridge, are unusually abundant in the basal conglomeratic beds. The granitic basement to the southwest also rises slightly above the valley floor but the southwestern margin of the ore zone is marked by a feathering-out of the reefs rather than by their abutment against the hillside.

Pardee Area

Conglomeratic beds containing potential ore of marginal grade extend 4 miles east of the iron-formation ridge to the Pecors 'high' at Pecors Lake. These beds overlie a basement composed of metasediments, metavolcanics, and meta-gabbro. Several valleys carved into this lowland area are overlain by thicker, more uraniferous conglomerates. Uraniferous conglomerate beds are also present in the lowland area east of the Pecors high. This zone and the entire Ryan Member wedges out beneath the Stinson Member (Fig. 3) to the northeast and north and probably also along the Pecors 'high'. The northern extensions of all of the conglomeratic zones along the south limb of the Quirke Syncline are similarly limited by the truncation of of the Ryan Member by the Stinson Member.

Quirke Lake Area

The extensive ore deposit at Quirke Lake overlies metavolcanic rocks just south of their contact with reddish quartz monzonites, except near the east end of the zone where they overlie a granite embayment into the metavolcanics. A valley structure is well defined where the Matinenda Formation outcrops at Quirke Mine and its continuation southeast is suggested by isopach maps of the Matinenda Formation and of strata beneath ore-bearing reefs (Fig. 3). The compound reef mined at Denison abuts against basement that rises towards the west and northwest headward in the valley toward the Quirke No. 1 shaft zone, where a reef about 100 feet higher in the Manfred Member was mined. Local basement hills rise up into the ore-bearing conglomerate at Panel, Can Met and Stanrock Mines. The ore mined in these properties and in Spanish American Mine probably represents eastward and southward extensions of the reef that has been mined at Denison. A ridge between Stanrock and Can Met Mines extends northward beneath the central part of Quirke Lake almost bisecting the ore zone. Parts of the ridge evidently stood above the level of deposition of the most important conglomerate beds. For the most part, the Quirke Lake ore zone is limited by the disconformity below the Ramsay Lake conglomerate and by southward and eastward decreases in thicknesses and uranium content of conglomerate beds rather than by bounding hillsides.

It is well to bear in mind that the distribution, abundance and thickness of conglomerate beds, other than those that lie upon basement rocks, was not controlled directly by the form of the valley floor buried beneath them but by the position of the main source of the pebbles (i.e. - the yet-unburied, headward extension of the valley) and the direction of current flow.

Whiskey Lake Area

A very thick zone of Matinenda Formation outcrops along the southeast side of Whiskey Lake near the trough of the Quirke Syncline. It doubtless indicates the presence of an important valley, likely to trend northwest and 'head' somewhere southeast of the Halfmoon 'high'.

Area West of Quirke Lake

The Matinenda Formation has not been explored west of Quirke Mine[1]. There should be valleys and ridges on the greenstone surface in this area as there are elsewhere. The western border of the greenstone belt, at depths of 3,000 to 6,000 feet, 8 to 18 miles west of Quirke Lake just south of the line of wedge-out of the formation, would be a logical place to seek a major valley. This area, in fact, is the only place where we can hope to find a coincidence of all the geological elements common to both of the major ore zones; in particular: an edge of an extensive Archean greenstone belt, and an 'upstream' depositional edge of a thick gritty unit within the Matinenda Formation.

Many of the occurrences of radioactive quartz-pebble conglomerate that have been found in quartzite units stratigraphically higher than the Matinenda Formation are above Archean greenstone. One of the thickest, largest pebbled, and most uraniferous conglomerate beds known in the Mississagi Formation (Upper Mississagi Formation of Robertson, 1961-1967) is exposed near the Little White River in the eastern part of Township 169, 21 miles northwest of Elliot Lake. Just west of this occurrence, Ramsay Lake conglomerate overlies greenstone that is believed to represent the western edge of the Whiskey Lake greenstone belt. West of this, the Bruce Conglomerate overlaps the paleolimit of the Hough Lake Group and rests directly upon granitic rocks; this was perhaps an upland area during Mississagi sedimentation. It was suggested above that a valley should be sought beneath the Matinenda Formation farther southeast along this margin of the greenstone belt. The uraniferous conglomerate in the Mississagi Formation may have been deposited in the northwestern extension of such a valley. There are radioactive, pyritic, quartz-pebble beds in gritty Mississagi subarkose everywhere along the north limb of the Quirke Syncline from the Little White River eastward to Whiskey Lake. Most individual beds are only a few inches thick, and pebbles are generally less than 3/4 inch in diameter. These beds are not impressive compared to ore-bearing conglomeratic zones in the underlying Matinenda Formation but it is noteworthy that they are more abundant in this area of greenstone basement than they are elsewhere.

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[1] A considerable amount of shallow drilling was done at the edge of Huronian rocks along the north flank of the Quirke Syncline west of Quirke Mine. Some holes, up to 2 miles west of Quirke No. 1 shaft, intersected thin layers of Matinenda Formation; others passed directly into basement rocks beneath the Ramsay Lake Formation. Farther west in Township 156 no holes have intersected the Matinenda Formation beneath the Ramsay Lake Formation. The northern depositional or erosional edge of the Matinenda Formation thus trends west to southwest from Quirke Mine as suggested in Figure 6. Its projection would cross beneath the synclinal axis somewhere near the west end of Dunlop Lake in Township 156 at a depth of about 5,000 feet.

Wanapitei Area

There are extensive areas of Archean greenstone beneath Huronian rocks north of Lake Wanapitei. Radioactive occurrences in this area have attracted considerable attention. Most of these are pyritic quartz-pebble conglomerate beds in the Mississagi Formation; the Matinenda Formation is not known to occur in the area. One occurrence, near Anstice in Creelman Township (Thomson, 1960a, pp. 16, 18, 30) consists of concentrations of tiny uraninite grains with abundant grains of ilmenite, zircon, monazite, magnetite, apatite, sphene and tourmaline in fine-grained, dark, argillaceous quartzite or siltstone that is interbedded with radioactive quartz-pebble conglomerate. The heavy minerals are concentrated at the bases of graded laminae that may be crossbeds. Northwestward in Grigg Township along the Wanapitei River, there are occurrences of radioactivity in somewhat similar, though coarser, argillaceous rocks interbedded with quartz pebble-bearing polymictic conglomerate at the base of the Mississagi Formation (M. J. Frarey, H.W. Little, and H.K. Conn, personal communications, 1967).

In Pardo, Vogt and Turner Townships, respectively 19 miles east, 25 miles east and 21 miles north of Lake Wanapitei, radioactive pyritic quartz-pebble conglomerate beds are associated with quartzite (Serpent?) at the base of the Gowganda Formation. The Vogt and Turner Township occurrences overlie metavolcanic rocks near occurrences of iron-formation in the basement rocks. The Pardo occurrences nonconformably overlie quartz-biotite-staurite schist. Company records, according to Thomson (1960a, p. 34), show that drillholes intersected 'greenstone', as well as highly metamorphosed pelitic quartzite, beneath quartz-pebble conglomerate.

Mount Lake Area

The abundant, thorium-bearing, hematitic quartz-pebble conglomerate beds at the base of the Lorrain Formation in the vicinity of Mount and Rawhide Lakes 19 miles north of Elliot Lake overlie the northern extremity of the Whiskey Lake greenstone belt, according to the interpretation of the extent of that belt shown in Figure 6.

Areas with Granitic Basement Rocks

Radioactive conglomerate beds are apparently more abundant in Huronian rocks that overlie greenstone basement than they are in the much more extensive areas of granitic basement but numerous occurrences of conglomerate beds and two important uranium deposits have been discovered in the latter environment. The ore-bearing bed at Pronto rested directly upon granitic rocks, granitic paleosol, or locally upon a thin layer of massive dark argillite that overlies paleosol. The ore layer was probably deposited in a shallow valley on the granitic surface according to Derry (1960, p. 913).

A remarkably deep channel was evidently present in the granitic basement beneath extensive highly radioactive conglomerate zones of mineable thickness at the Agnew Lake Uranium Mines (formerly Canadian Thorium Corporation - see Thomson, 1960a, p. 22) and Kerr Addison Mines properties 49 miles east of Elliot Lake in Hyman Township.

Depressions on the surface of granitic terrains would have been controlled by slight differences in rock composition, by joints, by fractured zones and by faults. Of course all of these features must have had different patterns of distribution than the zones of soft rocks within, and at the margins of, greenstone belts. It seems likely that post-Huronian tectonic movements would have included adjustments along pre-Huronian faults and the consequent extension of these older structures through Huronian rocks. If this is so, many of the faults that cut Huronian rocks may mark positions of narrow fault-controlled valleys in basement rocks.

It was postulated earlier in this report that positions of widespread zones of gritty, pebbly subarkose were controlled by differential vertical movements of sectors of basement rocks during sedimentation and also by volcanic eruptions. The emphasis given here to the more passive influence of basement topography upon deposition of conglomeratic zones should not be construed as a negation of the importance of tectonic controls.

RESIDUAL DEPOSITS ON THE PRE-HURONIAN SURFACE

Mineralogy

The contact between pre-Huronian rocks and stratified Huronian rocks is commonly gradational. The transition zone may be only a few inches thick or it may be as much as 50 feet thick. These gradational contacts have been interpreted by Collins (1925), Roscoe (1957a), McDowell (1957), Pienaar (1963), Robertson (1961-1966) and others as due to weathering of pre-Huronian rocks prior to deposition of the overlying Huronian sediments. No other possible explanation has been offered or need be considered here.

The thickest residual deposits (saprolite or paleosol) overlie granitic rocks. The nature of the transition from granitic rocks to feldspathic quartzite is best seen in core from many drillholes, but transitional zones of granitic saprolite can readily be seen on surface outcrops in many places and may even be mapped, e.g. along the pre-Huronian contact at Pronto Mine, and northwest of Pronto Mine. A transition zone was examined underground at Pronto Mine. In these zones, granitic rock, for example a pink biotite, granite, grades upwards into a white rock with recognizable granitic texture, but containing highly altered mafic minerals and plagioclase almost entirely altered to sericite. Inclusions of unaltered rock are found in the white-altered granitic material. Higher in the section the granitic texture disappears, microcline is partly replaced by sericite that commonly divides individual grains into fragments. The quartz grains alone remain similar in shape and size to those in the original granite. The ultimate development is a greenish rock containing quartz grains and relatively few, smaller, irregular grains of microcline 'floating' in a structureless mass of sericite[1]. The microcline is fresher than most of that in the original granite. The quartz grains are less strained than those in the overlying clastic sedimentary rocks, and also appear to be less strained than those in the underlying granite. Apparently the sericite matrix protected the grains from deformation during folding of the adjacent rocks. No doubt the original products of weathering of the feldspars were clay minerals which were converted to mica-illite (or sericite) during subsequent deep burial. Small grains of hematite, magnetite, pyrite, rutile, zircon, monazite, thorogummite (probably originally thorite), garnet and amphibole have been recognized in samples of granitic saprolite. The passage upwards from granitic saprolite to overlying transported sandy sediments is clearly marked by a sharp reduction in the amount of interstitial sericite, a sorted appearance, stratification, and commonly quartz pebbles. Where boulder conglomerate rather than subarkose is the lowermost Huronian Formation, the saprolite is generally very thin or even absent altogether. This suggests that deposition of the boulder conglomerate was preceded by extensive scouring of the surface.

The ancient weathered zone is much thinner above greenstone than above granite and is much more difficult to recognize. The altered greenstone is greenish, grey, or pale yellowish in colour and has a high sericite content not found in normal greenstone. The most altered phase is yellowish in colour and probably contains little other than sericite. Altered greenstone at the nonconformity is commonly called 'argillite' and can be confused with pre-Huronian metasediments or Huronian argillite. Basal Huronian conglomerates contain pebbles of altered greenstone and greenstone pebbles with altered rims. The writer has noted altered rims around fragments of many types of rocks in various Huronian conglomerates. Pyrrhotite is typically abundant in altered greenstone immediately beneath the nonconformity. Commonly there is a thin layer (as much as 1-inch thick) consisting mainly of pyrrhotite immediately above the altered greenstone and below impure coarse Huronian clastic sediments. Very small amounts of chalcopyrite are associated with the pyrrhotite. Magnetite was noted in some samples. In a few places pyrite rather than pyrrhotite was noted along the nonconformity.

The relatively thin, altered zone above greenstones as compared to those above granite and the extreme rarity of granite pebbles compared to greenstone pebble in quartz-pebble conglomerates suggest that coarse granular rocks were more readily disaggregated than fine grained igneous rocks during weathering. This does not necessarily mean, however, that granitic surfaces were lowered more rapidly than greenstone surfaces during erosion.

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[1]Mica-illite, according to X-ray determinations.

More likely, the clayey soils developed above greenstone would have been easily washed away exposing the rock to continued attack by weathering agents whereas quartz granules in soils above granitic rocks would have tended to armour these soils allowing thicker mantles to accumulate.

Chemical Variations

Variations in thorium and uranium content through two saprolitic transition zones were studied by Roscoe and Steacy (1958). These data suggest that relatively little uranium and even less thorium was lost during the weathering; thorium may in fact be concentrated in the weathered rock. It must be pointed out that the original granite probably did not have absolutely uniform thorium and uranium contents so that samples of the altered rocks may reflect original variations as well as variations due to early Huronian weathering.

Pienaar (1963, pp. 14-16) has compared the chemical composition of saprolite with that of underlying fresh granite in the Quirke Lake area and reached conclusions concerning the nature of early Aphebian weathering that are fully in accord with results of later studies by Robertson (1964, pp. 16-18) and unpublished work by Rice (1958) and by Roscoe. The latter work included analyses of paleosol developed on basic volcanic rocks and of rocks that represent various intermediate stages in the development of granitic saprolite. The ancient weathering evidently resulted in leaching of most of the CaO, SrO_2 and MnO_2 and appreciable amounts of the MgO, Na_2O, FeO, and Fe_2O_3 originally present in the rocks. Loss of Fe_2O_3 exceeds that of FeO in most of the suites studied but there are some inconsistencies in this regard which may in part be related to the formation of some magnetite at the top of the saprolite. Water, Rb_2O_3, and variable amounts of K_2O (dependant on the amount originally present) were added. Small amounts of SiO_2 and perhaps a little Al_2O_3 may have been leached from some of the rocks, if the ZrO_2 or TiO_2 contents are considered to have remained constant.

Apart from the loss of iron, the reduction rather than an increase of Fe_2O_3:FeO ratios and perhaps the extreme loss of MnO_2, the alterations resemble those that occur under normal, present-day weathering conditions. As pointed out by Pienaar and re-stated by Robertson, the decrease in oxidation state and the leaching of iron could hardly have occurred in the presence of free oxygen. It is difficult to envisage this regional alteration of rocks immediately beneath a nonconformity as due to any process other than subaerial weathering, and to avoid the conclusion that soil waters and hence the atmosphere lacked free oxygen in early Aphebian time. This problem will be discussed further.

The reduction of strontium and augmentation of rubidium content of the paleosol indicates that the weathering of the Archean rocks could be dated by Rb:Sr isotopic analyses.

Significance

Some important conclusions, applied later in this report, are drawn from studies of these ancient weathering profiles and comparisons with normal, present-day erosion surfaces:

1. Prior to deposition of Huronian rocks, the pre-Huronian surface was mantled with residual debris. This is normal for present-day erosion surfaces in unglaciated regions. The weathering profiles, as far as is known, are not diagnostic of any particular climatic conditions or topographic conditions. Similar profiles are most rapidly developed and attain their greatest depth (hundreds of feet in some cases) in hot humid climates but they are also found in cold and semi-arid climates.

2. The bulk of sediments carried to the Huronian depositional area were derived from weathered rock debris rather than directly from the rocks themselves.

3. The composition of the weathered debris was more uniform than that of underlying rocks from which it was derived.

4. The proportions of different materials – clay, silt, quartz granules, feldspar granules, and rock fragments – available for transportation to the depositional area at any one time was largely dependant on the average depth of erosion of the mantle and the balance between rate of erosion of surficial material and rate of weathering of the underlying parent rocks. The composition of the sediments deposited from such detritus depended additionally upon their sorting and sizing. The corroded potash feldspar grains, for example, are concentrated in the coarsest sediments whereas more weathered – hence smaller – plagioclase grains are relatively more abundant in finer-grained arenites. There is no reason to suppose, as Pienaar (1963, pp. 123-125) has done, that some of the differences in potash and soda contents of various arenites may indicate that they were derived from different source rocks.

5. Many chemically stable heavy accessory minerals (resistates) survived the weathering process and some, such as zircon, rutile and monazite, were concentrated in the residuum. Concentration of elements, such as Ti, Zr, Hf, Th, Nb, Ta, Be and Ce, that occur in resistates is characteristic of residual deposits, even such an extreme product of chemical weathering as bauxite (Adams and Richardson, 1960). Uranium is not greatly depleted during the weathering and may even by concentrated. Such concentrations are probably generally due to uranium contained in zircon (Adams and Weaver, 1958).

6. If the principal ore minerals (uraninite and brannerite) in quartz-pebble conglomerates were original detrital minerals, they must have acted as resistates and survived at least the initial stages of weathering

(corresponding to the stage where granite is disaggregated into an arkosic sand). Both uraninite (Steacy, 1953; Zeschke, 1960) and brannerite are known to occur as detrital minerals but it is generally considered unlikely that much uraninite survives normal, present-day weathering processes. They would have been more likely to have survived under the non-oxidizing conditions that appear to have prevailed during early Aphebian weathering.

DISCUSSION OF SPECIAL CHARACTERISTICS OF HURONIAN ROCKS

POSSIBLE GLACIAL ORIGIN OF CONGLOMERATIC GREYWACKE UNITS

The Huronian succession has been best known, beyond the circle of those concerned specifically with Canadian Shield geology or, more recently, with uranium deposits, for the occurrence of till-like conglomeratic greywacke units within the Gowganda Formation. Similar units comprise the Bruce and Ramsay Lake Formations lower in the succession. Uraniferous, pyritic, quartz-pebble conglomerate beds are found in places immediately beneath the Bruce, Gowganda and Ramsay Lake Formations. Such conglomerates also occur a short distance above the Ramsay Lake Formation along the north limb of the Quirke Syncline. Farther north, radioactive, hematitic, quartz-pebble conglomerates occur above the Gowganda Formation in the basal part of the overlying Lorrain Formation. Clearly, it is important to seek an understanding of the environmental significance of the conglomeratic greywacke (or paraconglomerate) units beyond the fact that they are products of mass transport and mass deposition of unsorted or mixed sediments.

The Ramsay Lake, Bruce and Gowganda Formations are components of a sequence that is up to 40,000 feet thick. These sediments, deposited in a geosyncline and presumably derived from a complementary geanticlinal welt, are the products of a long-lived orogenic process. The conglomeratic greywacke units reflect a recurrent element in the tectonic pattern. Each is succeeded by fine-grained, subaqueous sediments that are in turn succeeded by coarse fluvial sediments. Thus, they appear to represent integral parts of cyclical sequences that are the major units of the thick geosynclinal succession, rather than extraneous deposits related solely to epochs of continental glaciation.

Gowganda Formation

The paraconglomerates in common with other Huronian sediments, were derived from a highland north of the geosyncline. During deposition of the Gowganda Formation this highland was mountainous or, at least, deeply incised in many places. Glaciation would not necessarily be required to produce and transport the chemically immature debris that filled valleys, buried high hills and spread out over older Huronian sediments in the geosyncline to the south. The Gowganda Formation is over 4,000 feet thick in many places and consists of a heterogeneous assemblage of greywacke, sorted conglomerate, arkose, quartzite, siltstone and argillite layers in addition to, and commonly greatly in excess of, massive conglomeratic greywacke beds. It is unfortunate that the term 'Gowganda tillite' has commonly been applied to the whole formation and that there has been a tendency to ascribe a glacial and periglacial origin to all of its rocks on the basis of features that may be absent through much of the formation. Deposition of sediments by a variety of agencies would normally occur within and along the flank of a mountainous region. It is possible that glaciation was only one of several processes responsible for the formation of Gowganda sediments. Subaqueous turbidity currents, slides, torrential sheet flows are all believed capable of producing paraconglomerates. Penecontemporaneous deformational structures, well described by Casshyap (1966), are common in Gowganda rocks. Mixing of layers of gravel, and clayey silts in mudslides could produce till-like units. Near Matachewan and Gowganda, for example, it is possible to find gradations from greenish greywacke containing thin interlayers of red mudstone, through greywacke containing layers of red mudstone clasts, into units comprised of greywacke with dispersed red clasts.

Ovenshine (1965) has studied the Gowganda Formation in the North Shore area and concluded that most of the features of the formation could be ascribed to glacial and periglacial phenomena, but pointed out that none of the criteria for such an origin are unequivocal. Schenk (1965) has described an exposure of a striated and grooved surface of Archean basement rocks south of Timagami Lake in Vogt Township (see Grant, 1964). The writer has visited this occurrence in company with M.J. Frarey. A thin bed of argillite overlies the Archean rocks and has been weathered out in places, resulting in Gowganda paraconglomerate overhanging the smooth surface of the Archean rocks. The grooves had been filled with argillite; they were certainly not produced by Pleistocene ice and it is difficult to imagine that they could have been produced by shearing along the unconformity. Cooke (1922) had previously described an occurrence of this sort near Lake Dassarat in Quebec. The writer has not seen the latter occurrence. Exposures of contacts of the Gowganda Formation with underlying Archean rocks are by no means rare and many of them are extensive. The underlying surface of Archean rocks varies from smooth, to hackly, to irregular in exposures seen by the writer. Gowganda sediments commonly extend down into fractures in the Archean rock. In most cases there is some evidence that the surface of the Archean rock was weathered prior to deposition of the Gowganda Formation although the alteration rarely exceeds an inch. At the north end of Duval Lake, 30 miles northwest of Elliot Lake, fractured granite with greywacke in the fractures grades upward into a basal Gowganda conglomerate with angular granite fragments. Somewhat similar contacts may be seen underground in some of the silver mines of Cobalt. These observations lead the writer to believe that in most places the Gowganda Formation was not deposited upon a freshly glaciated surface. It is noteworthy also that sorted rocks - conglomerates, arkose, and argillite (ripple-marked in places) - rather than tilloid rocks, form the basal unit of the formation in many if not most places.

Striae considered to be of glacial origin have been found on rock clasts in Gowganda conglomerates (Coleman, 1907; Collins, 1914; Wilson, 1913). Ovenshine (1965) points out that such striated clasts must be very rare in the Gowganda Formation compared to those in Pleistocene boulder clays but he shows a photograph of one (op. cit. Pl. 30, p. 174). This occurrence has been shown to many geologists on field trips led by James Robertson and the writer. Some, the writer included, are not satisfied that the striae were present on the surface of the boulder when it was deposited.

The most convincing evidence that important glaciation occurred during deposition of the Gowganda Formation is the presence in many laminated siltstones of rock clasts that were evidently ice-rafted. McConnell (1926, p. 35), however, in effect suggested that they could be accounted for by bergs calved from local (valley) glaciers.

If glacial phenomena were of major importance during the deposition of thousands of feet of Gowganda sediments, there would likely have been prolonged interglacial periods as well as many individual ice advances and retreats. Alternate growth and melting of extensive ice-sheets would have resulted in changes of land and sea-levels. The only hope of discerning such changes and of distinguishing between glacial continental and marine deposits on the one hand and non-glacial continental and marine deposits on the other hand lies in regional stratigraphic studies. Some details of stratigraphy through thick parts of the Gowganda Formation have been established locally (i.e. - Casshyup, 1966) but the task of obtaining such knowledge regionally is formidable. Uranium exploration activity, however, should produce abundant, useful drillcore data.

Ramsay Lake Formation

Pienaar (1963, p. 19) considered that the Ramsay Lake paraconglomerate was more likely deposited by mudflows than by a glacier. This mechanism would require the simultaneous triggering of a single series of mudflows along a 150-mile front and the spreading out of the coalesced flows over an apron that extended at least 30 miles from the front and thickened away from it. The flows would have consisted of regolithic material that had mantled extensive slopes north of the depositional platform. The release of the mudflows would have resulted in the exposure of unaltered rocks in broad areas along the slopes. Unweathered detritus such as rock pebbles, arkosic sand, and greywacke washed from these slopes should have been deposited in layers atop the paraconglomerate. Beds of immature sediments of this type are abundant in the Gowganda Formation but they do not occur in association with the Ramsay Lake or Bruce paraconglomerates. Alumina-rich clay, the product of prolonged weathering, was deposited in shallow water atop the Ramsay Lake Formation. The regolithic cover had evidently been restored to the slopes north of the depositional basin and only the finest grained material was washed down into the basin. This environment and sequence of events does not seem to fit the mudflow hypothesis very well. It is easier to imagine the formation to have been deposited by a glacier. The thinning and more weathered character of the paraconglomerate above thick accumulations of Matinenda sediments at Quirke Lake could be accounted for by erosion and weathering of the till after the ice receded. Sea-level rise due to melting of extensive ice-sheets may have given rise to deposition of argillites and siltstones of the Pecors Formation immediately above the till. After deglaciation the depressed land area would have risen, resulting in the migration of sandy deltas over the clayey, silty lower part of the Pecors Formation and perhaps culminating in the deposition of fluvial sands and fine gravels of the base of the thick sequence of Mississagi sands. It would hardly be reasonable to attribute deposition of the entire Mississagi Formation to differential uplift related to deglaciation. The required uplift of the source area to the north and downsinking of the depositional area were most likely part of a pattern of tectonic movements that continued throughout Huronian time, although periodically interrupted or modified by glacial loading and unloading.

Bruce Formation

The possibility that the Bruce paraconglomerate represents a till has been considered by a number of geologists including Collins (1925), Pienaar (1963) and Casshyap (1966). Although unable to find any satisfactory alternative explanation, Collins (1925, p. 61) was reluctant to accept the glacial hypothesis fully. Pienaar (1963, p. 31) thought that a mudflow origin was more likely. Casshyap (1966, p. 220) pointed out that the absence of associated beds of immature sediments (the same argument used above by the writer in the case of the Ramsay Lake Formation), and the texture and fabric of the Bruce conglomeratic greywacke militate against a mudflow origin.

The same pattern of sea-level rise followed by general land rise, related to widespread deglaciation, postulated to explain the Ramsay Lake – Pecors sequence could also be applied to the Bruce-Espanola sequence. The Espanola Formation, particularly its basal beds, are limy in contrast to the Pecors Formation. One can find a ready source of lime in the leaching evident in regoliths beneath Huronian rocks. The precipitation of this lime in the case of the Espanola Formation but not in Pecors Formation is a problem, however. The answer must lie in differences in circulation, salinity, carbon dioxide content, temperature, or supply of argillaceous material. The uppermost part of the Bruce paraconglomerate, moreover, is limy whereas that of the Ramsay Lake is not. It is possible that a crude layered zone commonly found in the central part of the Bruce Formation near Elliot Lake separates two types of paraconglomerate. The lower part may have been a till deposited by a continental ice-sheet, the medial banded zone may have resulted from sorting that occurred during rapid marine transgression, whereas the upper zone may represent unsorted debris dropped from melting icebergs. The limy zone can then be explained as due to the onset of carbonate deposition prior to cessation of glacial calving.

Significance of Association of Oligomictic Conglomerates with Tilloids

If the glacial origin of the Ramsay Lake and Bruce paraconglomerates is accepted, it is probable, but by no means certain, that at least some of the feldspathic quartzite and quartz-pebble conglomerate in the Matinenda and Mississagi Formations were deposited in a cold climate. Paleosol found directly beneath the Ramsay Lake Formation at Quirke Lake might also have been developed under cold climatic conditions. The beginning of a period of glaciation might have been a time of high precipitation. The sea-level and base-level of streams might have been lowered due to growth of vast ice-caps. These phenomena would result in an increase in stream competence. This may explain occurrences of coarse pebbly zones in the upper part of the Matinenda Formation (Manfred Member) immediately beneath the Ramsay Lake paraconglomerate, quartz-pebble beds near the top of the Mississagi Formation beneath the Bruce paraconglomerate, and occurrences of radioactive oligomictic conglomerate beneath Gowganda paraconglomerate in the Timagami Lake area. Deglaciation would result in general uplift. This uplift, perhaps reinforcing the general tectonic uplift of the source region evident throughout Huronian time, would be most rapid in early stages. It is interesting therefore that quartz-pebble beds occur near the base of the Mississagi Formation above the Pecors Formation, and at the base of the Lorrain Formation above the Gowganda Formation.

Tilloid units also occur in the Witwatersrand succession in South Africa and it has been suggested that there might be a connection between ancient glaciations and the formation of ore-bearing reefs (Wiebols, 1955). Morainal material containing rock debris formed through mechanical rather than chemical processes of rock disintegration is postulated as a source for pyrite and other supposedly reactive minerals found as detrital-appearing grains in the conglomerates. Cold temperatures, moreover, might have inhibited chemical activity during transport and deposition of the debris. There is little merit in this suggestion. The quartz pebbles are not concentrated along with immature arkosic debris but with weathered, leached detritus like that found in the ancient regoliths described above. This conclusive evidence of deep weathering does not disprove the possibility of a cold climate at the time of deposition of quartz-pebble conglomerate beds, but neither would stratigraphic proximity of tilloid beds substantiate such a climate. The presence or absence of tilloid beds evidently cannot be considered important criteria in selecting successions worth prospecting for conglomeratic uranium deposits. It could be argued, however, that early Aphebian time represents an unusual period in the earth's history when conditions were particularly propitious for both widespread glaciation and formation of pyritic, radioactive, auriferous, quartz-pebble conglomerate beds. If this were so, the association of tillites and oligomictic conglomerates within successions might be useful for long range correlations. In this connection, it is interesting to note that paraconglomerate occurs near Padlei, Northwest Territories, probably within the same Hurwitz succession that contains weakly radioactive, pyritic quartz-pebble conglomerate beds (Heywood and Roscoe, 1967). As previously mentioned, the Witwatersrand succession of early Aphebien or older age contains tilloids. No mention is made in the literature of tilloids at Serra de Jocobina, Brazil, where radioactive auriferous conglomerates have also been found in Proterozoic rocks.

ANOXIC CHARACTER OF HURONIAN ROCKS

Lack of Red Beds in Pre-Cobalt Rocks

Huronian sediments, particularly those in pre-Cobalt groups, are characteristically greyish, greenish, white, cream, or buff-coloured on fresh surfaces. The lack of pink, red, orange and brown coloration in most of these beds requires examination as they are dominantly continental sediments derived from sources that included red granites, transported in swift, shallow, aerated water, periodically exposed to the atmosphere during deposition, and lacking in organic debris derived from land plants. It is doubtful that the reduced state of iron in the rocks can be attributed to metamorphism or diagenesis. Some of the rocks in question have not been regionally metamorphosed to greenschist rank and diagenetic effects attendant upon deep burial would not necessarily effect extensive reduction. The Triassic Newark red beds, for example, are up to 25,000 feet thick in New Jersey and Pennsylvania (Dunbar and Rodgers, 1957, p. 213). Metamorphic and other alterations in Huronian rocks will be described later in this report.

Reddish coloration is common, if not typical in continental sediments deposited in tectonically active belts. The coloration is commonly due partly to hematite dust in reddish feldspar clasts derived from red or pink granitic rocks and to alteration of detrital mafic minerals as well as to minute hematite particles in shale and in matrices of siltstones and sandstones. Such pigmentation implies that ferric oxide in the detritus was not reduced to the ferrous state during erosion, transport and diagenesis, or alternately that ferrous oxide was oxidized to the ferric state during these processes. Marine sediments and continental sediments rich in organic material are commonly drab coloured. They are deposited in oxygen deficient environments where biogenic processes result in reducing conditions. As a result, the sediments have low ferric:ferrous ratios and lack red or brown pigmentation due to ferric oxide. The iron that might have been present as hematite is incorporated in magnetite, iron sulphide, siderite, or in silicates in the non-oxidized or reduced sediments. In the Huronian rocks some, but by no means all, of the ferrous iron is in pyrite. The term anoxic is used in this report to characterize non-oxidized or apparently reduced Huronian sediments that are in an environment where oxidation would be expected and reduction not expected according to the concepts outlined above.

Colours of Rock Clasts

There are some exceptions to the generalization that Huronian rocks lack reddish coloration. Clasts of red jasper and pink felsite are found in various types of conglomerates throughout the succession. Red or pink granite clasts are abundant only in the Gowganda Formation but they also occur in the Serpent Formation and in polymictic conglomerate in the Mississagi Formation (Robertson, 1964a, p. 29). A huge pink granite boulder with a broad white rim is present in intraformational breccia in the Mississagi Formation near Tube Lake in Victoria Township and pale pink boulders and cobbles, some of which have white rims, are present locally in the Bruce Formation although they are outnumbered by white granitic clasts. Pink and red arkose is abundant in the Gowganda Formation and the lower part of the Lorrain Formation and occurs in the upper part of the Serpent Formation. Some of the red arkose is mineralogically similar to red granite. Stratigraphically lower arkoses and subarkoses in the Serpent, Mississagi and Matinenda Formations are white, grey, or greenish apart from the occurrence of rare granules and small pebbles of pink feldspar. Such clasts are fairly abundant in some places within coarse grit zones in the latter two formations.

The differences in abundance of red granite and feldspar clasts in different stratigraphic horizons cannot be attributed to differences in source rocks. Red granitic rocks of the sort found north of Quirke Lake must have been at least as abundant on the erosion surfaces that contributed abundant white clasts to the Ramsay Lake and Bruce conglomerates as on the deeper erosion surfaces that contributed abundant red clasts to the Cobalt Group. Scarcity of red clasts in the pre-Cobalt rocks is evidently due to their derivation from regolithic material and underlying rock surfaces that were leached under reducing conditions, as discussed previously. Rare red clasts in the lower strata were derived from material that had escaped leaching in areas of more rapid erosion. Their presence is evidence that the anoxic character of many Huronian rocks is not due to metamorphism or to extraordinarily intensive reducing condition during diagenesis.

There are some rocks in the Cobalt Group whose reddish colour does not appear to have been inherited from primary source rocks. It may be due, that is, to disseminated hematite in the rock matrices rather than to hematite dust in feldspar grains. The Firstbrook Formation of Robert Thomson (1957), which overlies the Gowganda Formation near Cobalt, is composed of siltstone and argillite that is characterized by chocolate-coloured layers. Red siltstone and shale found at the top of the Gowganda Formation 30 miles northwest of Elliot Lake and in the Matachewan-Gowganda-Elk Lake area as well as purple and reddish siltstone in the lower part of the Lorrain Formation near Bruce Mines are roughly within the same stratigraphic zone as the Firstbrook Formation. There is a fine-grained pink quartzite unit in the Lorrain Formation west of Timagami Lake. Red siltstone layers are common in the varicoloured Gordon Lake Formation. A hematitic red siltstone unit is present in the upper part of the Bar River Formation (Young, 1966; Frarey, 1967). In addition, specular hematite occurs in the Lorrain and Gordon Lake Formations in various different ways, analogous to the modes of occurrence of pyrite in the Mississagi and Matinenda Formations.

Evidently, fine-grained hematite formed in situ or survived transportation and diagenesis in these Cobalt rocks, whereas it did not in the pre-Cobalt rocks that were described above as anoxic in character. There is evidence as well, however, of anoxic conditions during Cobalt sedimentation. Paleosol developed on the Lorrain granite beneath the Lorrain Formation in its type area, Lorrain Township, on the west shore of Lake Temiskaming, is not particularly reddish. Its chemistry should be studied and compared to the anoxic paleosol found beneath lower formations. Greenish, silty layers in coarse-grained Lorrain and Gordon Lake quartzite must contain some ferrous iron but little ferric iron. Their environment was hardly one that would have been conducive to biogenic reduction of iron, but it is one that should have favoured oxidation as many of these layers show ripple-marks and dessication cracks or both.

Comparison of Pyritic and Hematitic Conglomerates

Quartz-pebble conglomerates will be described later but it is appropriate here to contrast uraninite-bearing pyritic conglomerates in the Matinenda Formation with monazite-rich hematitic conglomerates in the Lorrain Formation. Quartz pebbles containing coarse pyrite and siliceous pebbles rich in iron sulphides have been found near the base of the Matinenda Formation. These are considered to have been derived from pyritic quartz veins and sulphide-rich siliceous Archean strata or iron-formation. The sulphides evidently survived weathering, transport and diagenesis after burial. They are coexistent with magnetite in iron-formation pebbles that show little evidence of sulphidization. Evidence that some of the interstitial granular pyrite is allogenic and some of it authigenic will be presented later. The radioactive conglomerates in the Lorrain Formation contain interstitial grains of hematite in the place of pyrite. There is no doubt that most of the hematite, together with associated ilmenite and magnetite, is allogenic or pseudomorphous after titaniferous magnetite. Authigenic hematite also occurs in these conglomerates. The two types of radioactive conglomerates apparently do not grade one into the other. The rocks are very similar texturally and chemically (except for the sulphur and higher uranium content in the pyritic ones) but there is no evidence that the pyritic variety formed through alteration of originally non-pyritic, hematitic conglomerates, or vice versa[1]. The pyritic type evidently occurs only in anoxic continental sequences. The hematitic type occurs in continental sequences that are more normal insofar as

[1]The pyrite contains considerably more cobalt, nickel and other trace elements and less titanium, maganese, vanadium and chromium than the iron oxides.

they contain reddish beds. They are simply monazite-rich, black-sand placers and are common compared to pyritic conglomerates.

The relationships described above are puzzling and difficult to present clearly but they lead to some rather important suggestions relevant to exploration for uraniferous conglomerates. It is obvious that any sequence of fluvial sediments showing anoxic characteristics should be prospected. Normal sequences containing oxidized rocks are probably unlikely to contain conglomeratic uranium ore deposits although other types of uranium deposits may be present. One should not be misled in this respect by the presence of radioactive black-sands. The anoxic character of pre-Lorrain Huronian sediments may be related to the existence of an anoxic atmosphere at that time rather than to metamorphic reactions in deeply buried sediments. Furthermore, it is possible that the composition of the atmosphere was changing so that it contained sufficient free oxygen after deposition of the Gowganda Formation to produce some oxidation of iron in sediments. If this were true, there would be good reason to postulate that important conglomeratic uranium deposits, so far found only in rocks more than 2 billion years old, will not be found in any strata younger than the Gowganda Formation.

Concepts of Evolution of the Earth's Atmosphere

The suggestion that anoxic features in Huronian regoliths and sediments may indicate an anoxic Precambrian atmosphere is in keeping with well-known concepts that the earth's atmosphere has developed from a primitive atmosphere that lacked free oxygen. These concepts have been considerably refined in recent years by biochemists, biologists, and paleontologists as well as by geologists, chemists and physicists. Important papers on the subject have been published by Oparin (1938), Urey (1952), Rubey (1955), Rankama (1955), Sokolov (1957), Rutten (1962), Berkner and Marshall (1965), Cloud (1965), Holland (1965), Commoner (1965), Fischer (1965), and others.

There is general agreement that the primitive atmosphere could not have contained free oxygen. Degassing of the earth's interior through volcanism has been a major factor in development of the atmosphere and hydrosphere but did not contribute free oxygen. Life likely originated from complex abiotic organic compounds that were formed by the action of intense ultraviolet radiation upon mixtures of compounds such as CH_4, CO_2, H_2, H_2S and N_2 that would be dominant constituents of the primitive atmosphere postulated by Urey (1952). Loss of hydrogen from the atmosphere and oxidation of chemically active gases by oxygen created by photodissociation of water in the upper atmosphere has been postulated to have produced a transitional atmosphere characterized by N_2 and CO_2 but the appearance and accumulation of free oxygen would probably have had to await the development and proliferation of organisms such as blue-green algae that produce it through photosynthetic dissociation of water and carbon dioxide. Oxidation of ferrous iron to ferric iron and oxidation of volcanic and biogenic hydrogen sulphide would postpone significant build-up of free oxygen in the atmosphere but eventually it would begin to accumulate and environments favourable for life would expand offering increased opportunities for evolution.

Some peculiarities of Precambrian rocks, it has been suggested, may reflect these changes in the atmosphere and associated changes in the hydrosphere and biosphere. Limestone, for example, might be rare in Archean rocks because of lack of lime-secreting organisms in Archean time; the principal lime-collecting agent in Aphebian seas, as evidenced by an abundance of stromatolitic carbonates, may have been algae, whereas hard-shelled animals were major collectors in Paleozoic and later seas. High ferrous:ferric ratios have been cited by Rankama (1955) as evidence of a reducing atmosphere in Precambrian time. In the absence of oxidizing agents, ferrous iron of both volcanogenic and terrestial origin could become concentrated in sea water. This may explain the abundance of siliceous iron-formations in Archean and Aphebian strata.

The presence of some jasper-hematite and even the presence of chert-magnetite iron-formation (Davidson, 1965b) in Archean rocks has been cited as an argument against the existence of a reducing atmosphere in Archean time and its persistence into early Aphebian time when pyritic conglomerates were deposited. Hematite may form under the most weakly oxidizing conditions, however, and it has been pointed out by Cloud (1965) that restricted oxidizing realms would likely have been produced by algae prior to the development of an oxidizing atmosphere that would result in widespread aeration of waters. Chert-magnetite, pyrite and siderite iron-formations are much more abundant than jasper-hematite iron-formations in Archean strata whereas the reverse is generally believed to be the case in Aphebian strata. The higher ferric:ferrous ratios of Aphebian iron-formations could be interpreted as indicating that oxygenated sites of iron deposition were more abundant in Aphebian time than in Archean time but G.A. Gross (personal communication, 1967) has pointed out that this may merely mean that shallow water sites of iron deposition are less commonly preserved in Archean rocks than in Aphebian rocks.

DIAGENESIS, REGIONAL METAMORPHISM AND METASOMATIC ALTERATION

GENERAL

Huronian rocks in the Elliot Lake area and throughout large contiguous parts of the region should be considered as essentially unmetamorphosed. This conclusion has not been stated by any previous writer and requires considerable elaboration because it has an important bearing on problems of origin of various minerals in the radioactive conglomerates. Previous writers have either concluded or seem to have tacitly assumed that the ancient rocks were regionally metamorphosed and that the metamorphism was sufficiently intense to convert even the most gently folded rocks to the greenschist facies.

Robertson and Steenland (1960) remarked that the rocks have been "soaked with late sulphides". Davidson (1957) speculated on the occurrence in the region of a late period of granitization to which the uranium-sulphide mineralization may be linked. Pettijohn and Bastron (1959) have suggested that soda metasomatism may account for the high soda content of some Cobalt argillites. Heinrich (1958) described some specimens of albitized uranium ore from the Pronto Mine and considered that this locally albitized material, together with other evidence, supports a high temperature hydrothermal (hypothermal) origin for the uranium mineralization. Davidson (1960), in support of his conclusion that the uranium minerals were hypothermal, or mesothermal near hypothermal, cited these occurrences as examples of "widespread albitization with removal of lime and addition of soda" in Huronian sediments and "extensive albitization" of ore-bearing rocks. He has also stated (with reference to the Witwatersrand not Blind River), "The criticism of Basazzo (1959) that the gold mineralization cannot be hydrothermal because there is no wall-rock alteration becomes meaningless once it is accepted that there is hydrothermal alteration throughout the whole sequence of strata".

It has been suggested (Derry, 1960) that uranium and thorium dissolved in surface waters were carried and precipitated along underground water courses in lightly buried gravels. Another possible type of epigenetic origin for uranium in the conglomerates might involve concentration from connate solutions that migrated through the sedimentary rocks during diagenesis at depth. This hypothesis was espoused by Davidson (1965a), who had previously considered the uranium to be of igneous-hydrothermal origin.

Any hypothesis of epigenetic origin requires movements of large volumes of reactive solutions through the rocks. Alterations, varying in intensity in different rock types and strata, would surely have been produced by such solutions. The nature of mineralogical and chemical alterations produced by groundwater in aquifers, diagenetic connate waters, low temperature hydrothermal solutions, high temperature hydrothermal fluids, and igneous emanations are not totally unknown. It is incumbent on anyone who either proposes or denies an epigenetic origin for the Elliot Lake deposits to consider the precise nature of alterations that affected Huronian rocks, both in the vicinity of uranium ore zones and regionally. These alterations are important consideration not only with regard to the question of whether or not temperatures were sufficient to permit crystallization of uranium-thorium minerals in the conglomerates but also have a bearing on the permeability of strata at the time of any such hypothetical hydrothermal introductions.

DISCUSSION OF DIAGENETIC AND METAMORPHIC PROCESSES

Pre-depositional Alteration

Sedimentary materials in transit from source areas to depositional sites may be weathered to varying degrees. Altered rims on many greenstone pebbles in Huronian conglomerates attest that pre-depositional weathering effects can be recognized in these rocks. Some minerals such as quartz and zircon are highly resistant to weathering and are referred to as resistates. Others, notably potash feldspar, are unstable under weathering conditions, forming clay minerals, soluble salts, and ferric hydroxide, but nevertheless are commonly found in abundance as detrital grains in sedimentary rocks. Many of the rock-forming minerals in igneous and metamorphic rocks for example, biotite, hornblende, pyroxene, and calcic plagioclase, are highly unstable under weathering conditions. Their presence as detrital grains in a sedimentary rock indicates rapid erosion and lack of severe weathering conditions in the source area, rapid transport, and rapid burial. The absence or rarity of such 'metastable' minerals however does not necessarily imply severe weathering conditions. A source terrain (such as the present pre-Huronian terrain) containing rocks that are mainly in the greenschist facies of metamorphism could not provide an abundance of the metastable minerals mentioned above. Furthermore, the minerals most susceptible to destruction by weathering are also among those that are highly metastable under diagenetic conditions.

Diagenesis

Sediments undergo diagenetic changes during their burial and compaction. Compaction involves reduction of pore spaces. Grains are dislocated, repacked, and even crushed and some water is forced out of the sediment. The amount of water driven out and the amount of crushing increases with depth. Emery and Rittenberg (1952) have pointed out that the very large volumes of water forced upwards to the surface by compaction of a thick sedimentary pile provide a means of selective solution at depth and deposition above. It is illuminating to consider that 10,000 cc of water may have passed upwards through 1 square centimetre of sediment at the top of a column 3,000 feet high if there has been a total volume reduction of 10 per cent in this column due to load. Some of the displaced water may, of course, be diverted laterally into permeable beds or fractures that have access to the surface, but it is clear that the very nature of the compaction process demands that appreciable water is forced through even the most impermeable beds.

Cementation is the most conspicuous diagenetic phenomenon to be observed in sandstones. Some sands contain a primary clayey matrix (Huronian arenites are in this group). Recrystallization of the matrix may form a primary cement. In other sands the voids between sand grains, initially filled with water, became filled with a secondary mineral cement of calcite, quartz, chert or ferric oxide. If the mineral cement was derived from surficial waters it can be referred to as exogenic (Packham and Crook, 1960) to distinguish it from an endogenic cement derived from solution of materials within the sedimentary pile. Detrital grains of feldspar and mafic minerals may be altered or partially replaced during cementation of the rock. Cementation may take place and reach completion at any depth of burial, or stage of compaction. Cementation reduces the amount of compaction, or further compaction, that the sediment can undergo when it is buried to greater depths.

Deep Diagenesis

At great depths diagenetic alterations are greatly expedited by high temperatures and pressures. Metastable detrital minerals tend to be destroyed and stable ones produced. Mineralogical reconstitutions occur, in other words, to form equilibrium assemblages. The suite of secondary minerals that form under such conditions resembles that which characterizes the lowest rank of regionally metamorphosed rocks as they include quartz, albite, secondary white mica, chlorite, and epidote. Diagenetic facies have been discussed by Packham and Crook (1960) who described several depth sequences. There seems to be some evidence that the more extensive diagenetic alterations do not normally occur at depths of less than 15,000 feet. The aggregate thickness of the Huronian strata that can be assumed to have been present near Elliot Lake is less than 15,000 feet, although the same sequence is probably over 30,000 feet thick in some parts of the region. Some rocks diagenetically altered at depth (Packham and Crook, 1960) contain exotic minerals - pumpellyite, prehnite, laumontite, heulandite and an analcite. Turner (1958) recognized a zeolitic facies that he considered transitional between diagenesis and metamorphism.

Distinction between Diagenesis and Metamorphism

The distinction between diagenetic alterations and metamorphism is an arbitrary one. Turner (1958) classified an alteration as metamorphic rather than diagenetic when coarse clastic grains, as well as fine-grained materials, have become so extensively reconstituted that the rock has been substantially recrystallized and an equilibrium assemblage formed. Packham and Crook (1960) considered that alterations are diagenetic if the original fabric is not appreciably modified. Thus a rock containing an equilibrium assemblage of quartz, albite, muscovite, chlorite and epidote, with no metastable minerals, would be considered diagenetically altered if the original texture is intact, a contact metamorphosed rock if it has a hornfelsic texture, and a regionally metamorphosed rock if it has a schistose texture.

Most of the Huronian rocks in the Elliot Lake area must be considered unmetamorphosed according to either definition. Disequilibrium assemblages can be recognized. Original fabrics and textures have remained intact. Moreover, the 'greenschist minerals', chlorite and epidote seem to be rare in rocks whose chemical composition would demand their development under regional metamorphic and perhaps even under intensive diagenetic conditions. Widely scattered, small round grains of epidote and clinozoisite are found in Huronian arenites and are interpreted as detrital grains. Secondary epidote and chlorite (typically stilpnomelane) minerals, locally developed in arenites that are highly deformed or adjacent to diabase dykes, can be distinguished from detrital minerals by their uniform distribution, abundance, and textural relationships.

There is one feature that does not appear to be entirely in accord with the thesis that the minor recrystallizations noted in gently-dipping sedimentary rocks near Elliot Lake are diagenetic rather than metamorphic. This is a potassium argon date of 1.6×10^9 years on mica-illite in Pecors argillite in that area. Deposition and diagenesis of the Huronian sequence must have occurred prior to intrusion of Nipissing diabase sills more than 2.1×10^9 years ago. Evidently, the mica-illite lost argon during the Hudsonian Orogeny. This does not necessarily indicate, however, that the more important modifications occurred at this time rather than during earlier diagenesis.

DISEQUILIBRIUM ASSEMBLAGES OF DETRITAL MINERALS IN HURONIAN ROCKS

The most common metastable mineral in detrital sedimentary rocks is plagioclase (other than albite, which is stable under low rank metamorphic conditions and under 'normal' diagenetic conditions). Plagioclase is abundant in Huronian greywackes but occurs only sparingly as small grains in most of the coarse subarkose formations. Some of the plagioclase seems to be in the albite range but a great deal is definitely more calcic. Pienaar found plagioclase (oligoclase) compositions ranging from An_{10} to An_{26} in the Mississagi and Serpent Formations. Ginn (1960) found anorthite contents up to An_{20} in plagioclase in the Serpent Formation in the Espanola area. The plagioclase in Huronian rocks, like that in Archean rocks, is much more altered than associated potash feldspar. Grains within the same thin section vary in appearance. An almost entirely altered grain may be adjacent to a grain that is little altered, indicating that the alteration was pre-depositional. Matrix mica-illite invades plagioclase as well as potash feldspar. No other definite in situ alteration effects such as overgrowths of albite or replacement of altered oligoclase by clear albite were identified although they would be expected in diagenetically altered rocks.

Biotite, amphibole and other metastable minerals also occur as detrital grains in Huronian arenites. They are most common in greywackes, particularly in Gowganda, Bruce, and Ramsay Lake conglomeratic greywackes. They are rarest in coarse-grained subarkoses. It is necessary only to consider the occurrence of biotite in the polymictic conglomerates. Granitic pebbles contain biotite that is chloritized to varying degrees. Grains of biotite are also found in the greywacke between pebbles. They are also chloritized but rare grains are fresh. Some have a bleached appearance that may have been produced by pre-depositional weathering. Both types of alterations must be pre-depositional features.

The presence of metastable minerals in different types of Huronian arenites at all stratigraphic horizons indicates conclusively that the Huronian rocks near Elliot Lake have not been regionally metamorphosed. It also suggests that diagenetic alterations were not particularly intensive. Perhaps the relative impermeability of many of the Huronian arenites inhibited their diagenetic alteration. This would imply that the warm water forced out of (and through) the rocks during compaction was channelled into the least impermeable beds (subarkoses and conglomerates) and migrated laterally along such beds towards areas of lower pressure; alternatively, escape may have been through fissures.

Small amounts of biotite and many other 'high rank' metastable minerals are found in ore-bearing and other radioactive conglomerates together with low rank minerals such as chlorite, white mica and albite. Many heavy minerals, separated from ore-bearing conglomerates have been positively identified by X-ray diffraction patterns. Non-radioactive ones that are most significant as indicators of disequilibrium assemblages include: biotite, hornblende, clinopyroxene, orthopyroxene[1], greenalite[1], chamosite[1], grunerite[1], garnet, tourmaline, ilmenite, chromite, apatite, epidote, and sphene. Most of these minerals could not have survived metamorphism or intensive hydrothermal alteration. The higher rank minerals could hardly have been formed in situ except under conditions that would have produced reconstitutions of the lower rank minerals. The lower rank minerals could not have been formed in place except under conditions that would have destroyed some of the higher rank ones - biotite, hornblende and pyroxene, for example, would have almost certainly been completely altered to chlorite and other low rank secondary minerals. The recognition of disequilibrium assemblages of metastable minerals in ore-bearing conglomerates is thus,

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[1]Reported by Milne (1958).

in itself, direct evidence that the minerals are of detrital origin, and that the rock has never been subjected to the type of alterations that have occurred in epigenetic deposits classified as hydrothermal, particularly those considered mesothermal or hypothermal.

PRESERVATION OF SEDIMENTARY TEXTURES

All original structures, fabrics and textures are so faithfully preserved in most Huronian rocks in the Elliot Lake area, that they can be readily compared with their counterparts in more recent, unmetamorphosed, sedimentary rocks. Variations in grain size and degree of sorting can be compared from bed to bed, in fact from lamella to lamella, and can be confidently ascribed to variations in depositional conditions with no recognizable modifications by metamorphic processes. Greywackes in the Whiskey, Bruce and Gowganda Formations show typical disrupted fabrics with sizes of fragments from boulders down to the minimum size that can be resolved by the petrographic microscope. There is no reason to believe that these silt size fragments, whose abundance and distribution are typical of normal greywackes, are other than detrital grains that have been little modified by diagenetic or metamorphic processes. Many argillite and siltstone specimens from the McKim, Pecors, Espanola, and Gowganda Formations show delicate lamellae as thin as 0.1 millimetre. Some show gradations in size of fine sand and silt sized particles through the lamellae; some contain lenticular crosslaminations of the sort that is produced by migration of small ripple-marks. Fine-grained calcarenites of the Bruce Limestone and Espanola Formations show similar delicate structures. Minute styolites were recognized in one specimen. Recrystallizations, related perhaps to dolomitization, can, however, be recognized in the calcareous rocks. Patchy development of coarser carbonate obliterates laminations in places.

Pienaar (1963, p. 20) recognized grains of unzoned tourmaline in Pecors argillite and considered it to be an authigenic product.

SECONDARY MINERAL CEMENT

Secondary mineral cement is rare in Huronian clastic rocks. The well-packed conglomerate in the Stinson Member of the Matinenda Formation, probably originally an open-work gravel, contains some quartz and carbonate cement between pebbles and cobbles. Similar conglomerate with carbonate cement is present near the base of the Gowganda Formation at Stanrock Mine. Some carbonate cement was noted in subarkose in the Serpent Formation in the same locality. Secondary quartz overgrowths in optical continuity with detrital quartz grains was noted in one thin section of Serpent subarkose and they are common in Lorrain quartzite. Irregular outlines of some pebbles in various oligomictic conglomerates are suggestive, but are not conclusive evidence, of overgrowths of secondary quartz.

ARGILLACEOUS CONSTITUENTS

Mineralogical adjustments in response to elevated temperatures would be most complete in the finest grained rock components. The mineralogical composition of lutites (argillites) and the fine-grained components (matrix) of arenites and rudites should provide the most sensitive index of the degree of metamorphic or diagenetic alteration that has occurred in the rocks. These fine-grained materials consist principally of a fine-grained aggregate of flakes that resemble muscovite optically and is identified as mica-illite by X-ray studies. Chemical analyses show compositions similar to those that would be found for a mixture of muscovite with varying minor amounts of quartz and microcline. A few analyses by Pienaar (1958) and Rice (1959) of rocks containing a high proportion of argillaceous material contained a higher ratio of alumina to alkalis than is found in micas or feldspars. This suggests that clay minerals such as illite and kaolinite are present. Kaolinite was identified by X-ray techniques in one sample of conglomerate. The presence of clay minerals could be considered diagnostic of lack of regional metamorphism, but their absence (if all of the mica-illite is actually fine-grained muscovite) does not imply that the rocks have been metamorphosed rather than mildly diagenetically altered.

Previous descriptions of the matrix of arenites and rudites near Elliot Lake mention the presence of chlorite as well as sericite (or secondary white mica). Some of these descriptions imply that chlorite is an important constituent of the matrix of all quartz-pebble conglomerates. This is incorrect, although chlorite is not uncommon within detrital grains. X-ray studies were made of fine-grained flakey components in a number of samples of various types of rocks. Chlorite, in addition to mica-illite, is present in residual argillite derived from pre-Huronian rocks and in greywackes. No chlorite was detected in argillite from either the McKim or Pecors Formations in the Elliot Lake area. None of the coarse-grained subarkoses tested contained detectable matrix chlorite. Several ore-bearing quartz-pebble conglomerate samples contained traces of matrix chlorite but most did not. The absence of chlorite in the fine-grained components of many Huronian rocks may be very significant as many of them contain sufficient iron and magnesia (as much as the residual argillites) to have required formation of chlorite, or related minerals, has the rocks been metamorphosed. The chlorite in greywackes and residual argillites is, therefore, probably an allogenic constituent, not a secondary mineral. Kaolinite was detected in a specimen of quartz-pebble conglomerate from the Stanrock Mine which also contained a trace of chlorite. The kaolinite is probably an unaltered original, or early diagenetic, constituent but perhaps it might have been formed subsequent to opening of the mine workings.

INCIPIENT RECRYSTALLIZATIONS

One inconspicuous modification of original texture is found in all of the Huronian arenites. The margins of clastic grains are commonly serrated where they are in contact with fine-grained 'micaceous' matrix material. Tiny flakes of 'white mica' project into the clastic grains producing the serrated appearance. This is not a rare phenomenon in arenaceous rocks with a primary argillaceous cement and it can readily be attributed to reaction under diagenetic conditions. This has been pointed out by Pienaar (1963, p. 28) but he prefers to consider that the modifications took place under low grade metamorphic conditions, a possibility that the present writer discounts in the absence of other evidence of low grade metamorphism. Quartz pebbles and granules separated from the rocks have a frosted appearance that is clearly due to this reaction with the matrix, not as might be supposed to sand blasting in a desert environment of deposition.

Argillites and other fine-grained rocks, where they are deformed more than is usual in the Elliot Lake area, locally show cleavage or incipient foliation that may cut across bedding. The bedding is commonly crenulated in such places. The foliation is clearly produced by realignment or crystallization of fine-grained secondary white mica along shear planes. Such rocks could properly be called phyllites but not sericite schists.

CATACLASIS

Coarse-grained subarkoses and well-packed quartz-pebble conglomerates show evidence of cataclastic deformation particularly where the beds are relatively steeply dipping as at Quirke Mine. Arnold (1954) emphasized the prominence of cataclastic deformation at Quirke Mine and suggested that the 'sericite' matrix of quartz-pebble conglomerates was originally an illite-type clay altered by potassium and sulphur-bearing hydrothermal solutions which migrated into rocks that dilated during deformation. The present writer stated in a previous report (Roscoe, 1957a, p. 15):

"The more competent clastic sedimentary rocks have been deformed cataclastically. The following effects of such deformation in varying degrees of intensity are observable in thin sections: undulatory extinction of quartz grains; marginal granulation and even complete fragmentation of grains; fractures with displacements; rotation of grains; comminution of matrix material in grit and conglomerate. The crushed rocks have been rehealed by secondary quartz, mica and other minerals. Serrated boundaries between grains and granular texture within quartz pebbles (giving the pebble the false appearance of a pebble of quartzite) are common. The effects of cataclastic deformation are most obvious, if not most intense, within massive, poorly bedded coarse-grained quartzite, grit and conglomerate in the Matinenda Formation."

It is by no means certain that all of the effects described above should be attributed to cataclastic deformation during folding. The same features can be developed to some degree in sandstones during compaction under load (Maxwell, 1960). Solution and recrystallization of minerals are promoted by the elevated temperatures at depth as well as by load pressures so their recognition in cataclastically deformed rocks does not necessarily mean that the cataclasis was related to tectonism. Some specimens from the Quirke Mine, however, show unusually extensive recrystallization with development of coarse intergrowths of secondary quartz, muscovite, epidote and sphene. There seems little doubt that these particular, relatively steeply-dipping rocks were subjected to strong internal rotational strain during folding. The Matinenda Formation is rather massive and thus strains developed during folding would not be as readily dissipated by bedding plane movements as they would in well-bedded formations. Petrofabric studies (Borg et al., 1960) could probably be used to distinguish cataclasis produced under differential strain from that produced by homogeneous load pressure. This distinction is particularly important because radioactive minerals, including brannerite and uraninite, as well as the main rock components, have been displaced, squeezed and fractured (Pl. IIIB). If their deformation was effected during compaction, as would seem likely in the case of flat-lying beds in the central parts of the syncline, then the grains must be of detrital origin. If, on the other hand, the deformation took place during folding, it can only be concluded that the minerals are pre-orogenic in age.

DYNAMICALLY AND THERMALLY METAMORPHOSED ROCKS

The most highly deformed rocks of known Huronian age near Elliot Lake are adjacent to the Flack Lake Fault to the north and the Murray Fault system to the south. Mississagi subarkoses along the Flack Lake Fault at the Little White River 20 miles northwest of Quirke Lake could locally be described as quartz-sericite schists and contain metamorphic clinozoisite and other clearly secondary minerals. A veinlet of radioactive clinozoisite was also noted transecting radioactive conglomerate. Steeply-dipping strata east of Pronto are probably in the greenschist facies of metamorphism. Mica-staurolite schists are found nearby on the south side of the fault.

Huronian rocks in the Espanola-Sudbury area have been much more intensely deformed than those in the Elliot Lake area, and in places they are highly metamorphosed. Card (1965) recognized chlorite-biotite, garnet, chloritoid and staurolite zones in Hyman and Drury Townships. Radioactive conglomerates along the south shore of Agnew Lake in Baldwin and Shakespeare Townships have been deformed and recrystallized with development of greenschist minerals - muscovite, chlorite, stilpnomelane, clinozoisite and albite so that most original sedimentary textures other than pebble outlines have been obliterated. These 'greenschist' minerals are also found in radioactive conglomerates and other rocks on the Agnew Lake Uranium Mines property in northern Hyman Township, but original sedimentary textures in these rocks are little modified. Some conglomerates along the north shore of Agnew Lake are completely recrystallized so that the 'matrix' between 'pebbles' comprises a foliated crystalloblastic intergrowth principally of quartz, muscovite and biotite. The biotite in the metaconglomerate is notably radioactive, that in adjacent other rocks is not. There can be no doubt that the conglomerates were radioactive rocks prior to the metamorphism.

Metamorphic micas have yielded potassium-argon dates between 1.5 and 1.7 x 10^9 years. Similar Hudsonian dates have been obtained on little-metamorphosed Whitewater strata, on the Sudbury Irruptive, on mica-illite in 'unmetamorphosed, Pecors argillite, and on some samples of Archean granite. There is considerable evidence of retrograde metamorphism in areas of higher grade rocks so it is possible that, like the Archean granite samples, they lost argon during a minor metamorphic event. The most important period of metamorphism of Huronian rocks, that is, may have been prior to the Hudsonian Orogeny.

CONTACT METAMORPHIC ROCKS

Contact metamorphic alteration rarely extends more than a few inches from contacts of basic intrusives in the Elliot Lake area. The altered rocks have a bleached, darkened, or reddened appearance. Coarse-grained subarkoses are commonly recrystallized to a fine-grained rock. Secondary minerals developed in the altered zones include stilpnomelane, chlorite, albite, epidote group minerals, carbonate, quartz, magnetite, hematite, and sulphides. Lime silicate minerals occur in Bruce Limestone immediately under the contact of a diabase sill exposed in a rock cut on the highway north of Elliot Lake. Skarn-type deposits containing magnetite, chalcopyrite, cobaltite sphalerite and galena are found in similar situations in Aberdeen, Additional and Hart Townships.

Some extensive albitized and chloritized zones have been intersected in mine workings and drillholes and albitite veinlets are abundant along joints in some parts of the area. In many, but not all, cases these alterations are spatially associated with known diabase intrusives. They will be considered separately from the normal contact alterations, however, because they are local phenomena involving important metasomatic changes in bulk chemical composition of the altered rocks.

METASOMATICALLY ALTERED ROCKS

General

Intensely altered rocks have been intersected locally in mine workings along ore zones. The alterations involved addition of soda and magnesia and removal of silica and potash; they include: albitization with little chloritization, chloritization with little albitization, and, most commonly, a mixture of the two. A genetic relationship with diabase dykes is indicated. The only altered zones that have been studied are within ore zones but metasomatically altered rocks are by no means restricted to radioactive conglomeratic beds. Pienaar (1963, p. 39) described a zone 4 feet thick south of Stinson Lake, wherein subarkose near diabase has been altered to a rock composed of 60 per cent fresh albite with quartz and antiperthite. Red altered zones noted in subarkose adjacent to diabase intrusives at Whiskey, Pecors and Quirke Lakes, and many other places, are probably similar to the Stinson Lake occurrence. Albitite veinlets along fractures and joints in subarkose may extend appreciable distances from diabase intrusives. In places, for example at Matinenda Lake, albitized subarkose may be remote from any exposed diabase contact. This does not disprove a genetic connection between the alteration and diabase; the responsible agent may have been an overlying sill removed by erosion or an underlying sill not exposed. The altered rocks do not contain any more (or any less) uranium than adjacent unaltered rocks.

In the Algom Nordic Mine and the Denison Mine, a number of altered zones have been found immediately adjacent to east-west trending steeply-dipping diabase dykes; chloritization is dominant. The most extensive albitized zones in the area are in the deeper levels of the Pronto Mine, where the alteration bears no obvious relationship to diabase dykes but does seem to be related to fractured zones. In the Can Met Mine, an appreciable proportion of the ore zone has been chloritized, albitized and carbonatized. Altered rocks are also found in the adjacent Panel Mine but were seen only in drillcore by the writer. Some of the alteration is adjacent to a steep, east-west trending dyke, about 100 feet thick. Highly chloritized ore was intersected in Denison's drillhole No. 29 a few thousand feet west of Can Met workings; the altered rock is adjacent to a dyke, presumably the same one that is associated with altered rocks on Panel and Can Met ground. The pattern and character of the widespread alteration at Can Met is complex, however, and much of it is along faults and fractures a considerable distance from any intrusive rocks.

Deleterious Effects of Altered Ores on Milling Operations

Chloritic ore creates difficulties in the mills due to sliming and high acid consumption. Calcite and pyrrhotite, common in chloritic sections, are also acid consumers. Highly chloritic rocks therefore must either be left unmined or milled in very small amounts diluted with normal mill feed. This applies to diabase and lamprophyre waste rock as well as to ore grade material. Large parts of the uranium-bearing zone at Can Met are despoiled by chlorite and carbonate; discovery of this during underground development necessitated a downward revision of ore reserves originally estimated from widely-spaced drillholes. No serious difficulties of this nature have been encountered in other mines. Considerable albitized ore was mined and milled at Pronto but there is relatively little chlorite in the altered rock there.

Albitization

Albitization evidently preceded chloritization in the altered zones and is the more extensive and more pervasive of the two forms of alteration. In altered zones adjacent to diabase dykes, incipient replacements of matrix and finer clastic grains in subarkose and conglomerate by clear albite (An_{3-6} according to Pienaar (1958, p. 133)) may be found 40 feet or more from the dyke. Closer to the dyke, most of the clastic grains of quartz and microcline may be replaced by albite but outlines of quartz pebbles, pyrite, and radioactive minerals in conglomerates remain substantially intact. At the contact, both subarkose and conglomerate are converted to albitite. Varying amounts of chlorite and small amounts of stilpnomelane, carbonate, epidote, rutile, sphene, leucoxene, and hematite are commonly present in the albitite and the rock is typically reddish in colour. Chlorite invades albite. Sulphides are less abundant than in unaltered rocks; in fact they may not be visible megascopically. Pyrrhotite, rather than pyrite, is commonly the sulphide present. Radioactive minerals present include monazite, brannerite, uraninite and zircon. The radioactive grains, however, differ in shapes and sizes from their counterparts in unaltered rock and are commonly too small to be identified. A pale yellow mineral abundant in some radioactive albitite, has not been identified.

Chlorite-free albitite ore in the Pronto ore zone was logged as radioactive 'quartzite' in exploration drillholes (Holmes, 1956). However, in underground exposures it is obvious, that the pink albitite is a metasomatic rock that has replaced normal quartz-pebble conglomerates and subarkoses. Chloritic albitite has a grey granular appearance, like greywacke, and has been referred to as 'grit' (Holmes, 1956). Previous reports, wherein albitites at Pronto are considered to be sedimentary 'radioactive quartzites' and 'radioactive grits' that grade laterally into radioactive conglomerates, might give the impression that the albitization is controlled by primary sedimentary features. This would imply that the conglomerates, and perhaps the unconformity below the ore zone, acted as channelways for the ingress of albitizing fluids. Such a conclusion does not appear to be justified. Albitized rocks are by no means restricted to the basal, ore-bearing zone although underground workings do not provide any opportunity to gauge their abundance in higher strata.

Holmes (1957, p. 21) stated that the 'radioactive grits' occur close to a pronounced 'drop-off' on the pre-Huronian surface. He considered the 'drop-off' to be a scarp controlled by a pre-Huronian Fault, along which there was recurrent movement during Huronian sedimentation, resulting in accumulation of the grits as slump material along the scarp. According to his description, relationships are obscured by "brecciation and feldspathization of overlying quartzites", and a "heterogeneous mixture of grits, pebbles, and quartzites" is present.

It is now apparently agreed among mining geologists that the 'radioactive grits' and radioactive quartzites are metasomites, not sedimentary rocks. Derry (1960) described alteration at Pronto as follows:

"(1) The alteration, in which albitization plays a major part but which also includes carbonate replacement has the effect of changing the yellowish quartzite into a salmon pink mass resembling a syenite intrusive. The ore-bearing conglomerate is also affected, first the matrix being replaced and in the more advanced stages even the quartz-pebbles being completely obliterated. (2) Surprisingly enough the uranium values have not been removed, but remain in the original stratigraphic position although in places compressed into a smaller thickness than maintained in the adjoining unaltered conglomerates. (3) The alteration is clearly related to faulting and fracturing, certain 'panels', defined by near vertical fractures, being altered while adjoining 'panels' are left relatively unchanged from their normal appearance."

Chloritization

Chloritization is the most conspicuous form of alteration in zones bordering diabase dykes. At Denison Mine (in 1958) altered zones were exposed in mine workings on both sides of a steep, 100-foot thick diabase dyke that strikes north 74 degrees west and crosses the main conveyor haulage-way 200 feet north of No. 2 shaft. Conglomerate and subarkose beds immediately adjacent to the dyke have been completely replaced by chlorite and extensive chloritization extends locally as much as 100 feet from the dyke along zones presumably controlled by fractures and bedding planes. These chloritic apopheses, bands, and thin seams invade and cross a zone that is albitized to varying degrees. Some of the chlorite bands have well-defined contacts with albitized rocks or unaltered rocks; others have gradational contacts. Pebble-bearing beds can be traced from unaltered rocks into altered rocks that contain remnants of pebbles in a black chloritic matrix. Pyrite-bearing layers with associated radioactive minerals in unaltered rocks can be similarly traced into the altered zones.

The chloritic alteration appears to have preferentially advanced into conglomerate beds rather than subarkose beds in some places, suggesting that the conglomerate was more easily permeated by the chloritizing fluids. Altered conglomerate, however, with remnants of white quartz pebbles and yellow pyrite grains standing out in strong contrast to the black chloritic material, is a much more conspicuous rock than the altered subarkose so this impression of preferential chloritization is partly, or perhaps entirely, illusionary.

Two chloritized zones seen by the writer at Algom Nordic Mine are very similar to that at Consolidated Denison, but neither is as extensive. One of them was studied by Pienaar (1963, pp. 73-80). It is at the south side of a steep, southerly-dipping, east-west, 60-foot thick dyke near the intersection of the 4th level crosscut and east drift. The other is along the north side of the same dyke, 2,000 feet to the west. Neither continues far along strike. It was not possible to examine both sides of the dyke at the first locality, but at the second locality it is obvious that there is little alteration on the south side of the dyke, so it can be concluded that the altered zones are not necessarily everywhere developed on both sides of a dyke. There is a few feet of vertical separation of the ore zone at opposite sides of the dyke (after allowing for the normal effect of displacement of the walls of the fissure by the dyke) suggesting that the dyke may have occupied a pre-diabase fault.

The chloritic rock is commonly schistose, suggesting that some deformation occurred contemporaneously with the alteration. Compressional structures were noted in an altered zone at Algom Nordic. The altered section of the ore zone there, and in many places at Pronto, is thinner than the ore in adjacent unaltered sections. It is suggested that the rock was softened during alteration adjacent to the diabase, that the alteration involved a decrease in volume, and that the incompetent altered material was compressed plastically.

Diabase and quartz diabase adjacent to the altered zones do not appear to be significantly more altered than basic intrusive rocks in other places, nor have they any other obvious unique compositional features. Pyroxene and calcic plagioclase are present in the interior of the Denison dyke, mentioned above, and typical diabasic textures can be recognized within an inch of the chilled contact of the dyke against chloritic rocks. The alteration must have either preceded or accompanied the emplacement of the dyke.

Alterations are found at Can Met along faults that cut and displace the main diabase dyke. Pienaar considered that some minor faults with chloritized walls at Algom Nordic cut the diabase dyke, there. It is possible that later movement occurred along faults whose walls had previously been chloritized. More likely, perhaps, intrusion of diabase dykes, alteration of fractured wall rocks, and faulting may have occurred almost contemporaneously. The alteration may have been initiated by hot fluids rising through fissures in advance of magma and have continued during emplacement and faulting of the hot dykes. The writer would also suggest that the abnormal abundance of faults at Can Met might be related in part to volume decreases that accompanied the widespread alteration found in the ore zone on that property.

INTRUSIVE ROCKS

GABBRO

General

The Huronian rocks and adjacent rocks throughout the region are intruded by sill-like bodies and dykes of gabbro. These intrusives were classified as Keweenawan in older reports but at least three different ages of post-Huronian gabbroic rocks are present.

The oldest gabbroic bodies are principally extensive, thick, sill-like masses that are abundant throughout the Huronian region. The term 'Nipissing diabase' was applied to sills in the Cobalt and Gowganda silver mining areas and has been used for post-Huronian gabbro sheets elsewhere in the region. The term 'Sudbury gabbro' has been used for similar bodies in the Sudbury area, where they have been tightly folded and metamorphosed along with their Huronian host rocks. These gabbroic sheets are older than the Sudbury Irruptive (norite-micropegmatite) and the Whitewater Group which forms the roof of the irruptive. The Whitewater Group inside the basin is much less metamorphosed than Huronian strata south of the basin. Moreover, it lacks gabbroic intrusives comparable to those found in any equivalent-sized area of Huronian rocks outside the basin. The intrusion of the norite-micropegmatite must post-date metamorphism of strata south of the irruptive as quartz diorite dykes ('offsets') radiating out from the irruptive cut across the folded, metamorphosed Huronian sediments and gabbroic sills. Northwesterly-striking olivine diabase dykes cut all of the rocks mentioned but are displaced along some faults. These dykes are few in number and regular in habit compared to abundant older dykes that are presumed to be associated with the same period of igneous intrusion as the gabbro sills.

Isotopic ages

A date of 2.15×10^9 years has been obtained on gabbro and gabbro-granophyre bodies in the Thessalon-Elliot Lake area by the whole rock Rb/Sr isochron method (Van Schmus, 1965). A biotite K-Ar date of 2.1×10^9 years has been obtained for Nipissing diabase at Cobalt. A number of lower K-Ar dates have been obtained on similar gabbro bodies in the Sudbury and Bruce Mines area but it is believed that these rocks have lost argon, most likely during the Hudsonian Orogeny about 1.6×10^9 years ago. Isotopic compositions of leads in galena-bearing silver veins that cut Nipissing diabase at Cobalt and outlying districts have model ages of 2.2 to 2.3×10^9 years.

The Sudbury norite-micropegmatite irruptive and also the Whitewater rocks in the Sudbury Basin have been dated as 1.7×10^9 years old by the whole rock Rb-Sr isochron method (Fairbairn _et al._, 1966). Lead isotope data (Kanasevich and Farguhar, 1965; Ulrych and Russell, 1964) indicate that leads in lead-zinc deposits in the basin, in micropegmatite, and in nickel-copper deposits along the base of the norite are at least 200 million years younger than those in Nipissing diabase. Kanasevich (1962) concluded that data on isotopically abnormal leads were consistent with a date of 1.7 x 10^9 years for the time of intrusion of the irruptive.

Northwesterly-striking olivine diabase dykes near Sudbury and some northeasterly-striking dykes are probably about 1.1 x 10^9 years old according to K-Ar data. A uranium-lead age of 1.15 x 10^9 years has been obtained (Collins et al., 1954) on pitchblende in a fracture along a diabase dyke near Theano point.

The gabbroic rocks are considered to fall into the following age categories: older Aphebian – 2.1 to 2.4 x 10^9 years; younger Aphebian – 1.7 to 2.1 x 10^9 years; and Neohelikian – 1.0 to 1.3 x 10^9 years.

Nipissing Diabase

The distribution of the larger bodies of Nipissing diabase in the region is shown on various small scale maps – i.e. Ont. Dept. Mines Maps 2108, 2046, 2032, P. 387, P. 301, P. 321 and Geological Survey of Canada Map 1063A – as well as on the more detailed geological maps from which these compilations were made. This distribution and the thicknesses of the diabase sheets is a matter of concern to those searching for conglomeratic uranium deposits, as estimates of depths to favourable target zones must include allowances for such diabase bodies. Some may be as much as 1,000 feet thick, although none so thick have been intersected in drillholes near Elliot Lake. Diabase sheets are stacked in some places. The bodies dip more steeply than bedding in most places so vertical drillholes may miss part of the stratigraphic sequence in passing through them. It is important, therefore, but very difficult, to project diabase sheets from known positions in upper strata to their probable positions in lower strata likely to contain radioactive conglomerates. More than a few exploration drillholes have yielded inconclusive results due to intersecting diabase in the Matinenda Formation. A more satisfactory intersection may be sought in such cases by wedging an offset from higher in the hole.

Gabbro bodies near Elliot Lake have been described by Robertson (1961-1964). These sills and dykes are probably typical of those throughout the region. The larger ones are differentiated and have granophyric zones in the upper parts; concentrations of hypersthene and olivine reported in the lower part of Nipissing diabase sheets at Cobalt and Gowganda (Robert Thomson, 1957) are probably common in sills throughout the region. Some of the gabbroic dykes are evidently younger than some of the sills; others may represent feeders. Some of the folding and faulting took place in Huronian rocks prior to intrusion of the gabbro. Robertson (1962) believed that some sills were injected into dilatant zones in the troughs of actively developing folds. Many dykes were injected into faults along which later movement occurred. The dykes and sills were faulted and folded along with Huronian rocks during the continuing tectonic activity or during a later period of deformation.

Rock and ore alterations along margins of diabase dykes have been described above.

Associated Mineral Deposits

The widespread diabase bodies are the only igneous rocks that might be suspect as sources for epigenetic mineralization in conglomerates. It has been suggested (e.g. Joubin, 1954) that the pyritic uranium deposits might be related to other types of mineral deposits in the region. The types of deposits associated with diabase are therefore of some interest. The best known of these are the native silver-bearing veins of the Cobalt and Gowganda areas. In these areas, diabase sheets about 600 to 1,000 feet thick cut across the nonconformable contact between Archean greenstone and the overlying Gowganda Formation. The veins occur in diabase as well as in Archean rocks and in the Gowganda Formation below or above the diabase sheets. In addition to native silver, the narrow veins characteristically contain abundant cobalt-nickel-iron arsenides and sulpharsenides, various antimonides and arsenides, sulphides, and calcite. Bismuth sulphide and native bismuth are not uncommon. Sulphides include bornite, chalcopyrite, pyrrhotite, galena, and sphalerite. Small amounts of uranium, reportedly, have been found in veins in Cane Township (Lang, 1952, p. 150). Mineral occurrences similar to the Cobalt type, but containing little silver, have been found in diabase bodies near Lake Huron 12 miles northwest of Bruce Mines, 15 miles southwest of Espanola, 24 miles north of Thessalon and 9 miles northeast of Thessalon. The latter occurrence contains pitchblende in addition to cobalt-nickel arsenides. Cobaltite has been found in a number of other occurrences, one is reported from near Espanola, another along the shore of Lake Huron near Killarney, still another is in Hart Township northwest of the Sudbury Basin.

Chalcopyrite occurrences are found within or near all diabase bodies. It occurs in veinlets, in disseminated form and not uncommonly in quartz-carbonate veins several feet thick. Such veins were mined for many years at Bruce Mines, the site of one of the earliest mining operations of any type in Canada. Bornite and specularite are common associates of chalcopyrite. Galena and gold are associated with chalcopyrite in quartz veins east of Lake Wanapetei and northwest of Timagami; sphalerite-chalcopyrite-galena occurrence are also found. Disseminated chalcopyrite occurs in granophyre at the top of some thick diabase sills and also in some small granophyric segregations within diabase. Two occurrences of the latter type north of Quirke Lake contain appreciable amounts of finely disseminated uranium (but no thorium).

Auriferous quartz-carbonate veins along a contact between the Gowganda Formation and diabase have been mined at the Crystal Mine on the east shore of Lake Wanapetei. Attempts were made to exploit similar veins in a diabase body near its contact with Mississagi quartzite at the Havilah Mine 13 miles north of Bruce Mines. Gold-bearing quartz veins occur in the Pecors Formation near a diabase sill at Whiskey Lake. Other post-Huronian gold deposits, characterized by arsenopyrite, have been found 13 miles southwest of Sudbury and 8 miles south of Espanola. The orebody at the Long Lake Mine near Sudbury consisted of arsenopyrite and pyrite disseminated in Mississagi quartzite. The gold-arsenopyrite occurrences south of Espanola are in quartz veins in Gowganda quartzite and conglomerate and in diabase.

There are also some interesting mineral deposits associated with younger diabase dykes. The best-known of these are pitchblende-bearing veins along diabase dykes near Theano Point on Lake Superior 50 miles north of Sault Ste. Marie. These have been described by Nuffield (1955). Similar occurrences are present at Rangers Lake 55 miles northwest of Elliot Lake. Traces of pitchblende are associated with chalcopyrite in fractures along the margin of a northeasterly-trending diabase dyke 25 miles east of Gowganda near Elk Lake. Digenite and sooty pitchblende occur in jasperoid along the margin of a diabase dyke 8 miles northeast of Bruce Mines. Many of the numerous galena-sphalerite occurrences northeast of Sault Ste. Marie (Ont. Dept. Mines, Map 2108) are veins in Archean granite near narrow diabase dykes or within the dykes themselves.

It is hardly necessary to point out that the post-Huronian mineral deposits do not resemble mineral assemblages found in the matrices of radioactive conglomerates. A little pyrrhotite with some associated cubanite and traces of millerite occur in some conglomerates but the amounts of such minerals are very small compared to the amount of pyrite present. Lead is mainly radiogenic. Pyrite in conglomerates contains much less cobalt than pyrite in veins in diabase bodies at Elliot Lake. Uranium is invariably associated with thorium in the conglomeratic deposits; it is associated with copper, or cobalt and arsenic in post-Huronian deposits. Deposits associated with diabase bodies are not notably rich in pyrite; in fact there is a tendency toward low sulphur mineral assemblages in these deposits - e.g., bornite, pyrrhotite, hematite, native metals. The pyritic uranium deposits are obviously much older than mineral deposits associated with the younger diabase dykes. Ore is altered in places along margins of diabase dykes believed to be coeval with larger (Nipissing) gabbroic bodies. This indicates that the pyritic uranium ores are probably older than any known post-Huronian mineral deposits. There is no hint whatever of any variations in tenor or mineralogy of uraniferous conglomerate beds that may be related to distribution of diabase bodies.

GRANITIC ROCKS

Cutler Granite

The Cutler batholith south of the Murray Fault east of Pronto may be of post-Huronian age according to Robertson (1967a). Certainly it intrudes metamorphosed strata that are correlated with the Elliot Lake Group in this report. Isotopic age dates ranging from 1.1 to 2.0 x 10^9 years have been reported from this batholith and associated pegmatite dykes. Discordant lead dates on zircon indicate that the batholith is more than 1.5 x 10^9 years old. Perhaps the oldest date, a whole rock Rb-Sr date of 2.0 x 10^9 years (Fairbairn et al., 1960, pp. 41-66), is close to the actual age of the granite.

Murray-Creighton Granite

The Murray-Creighton granite south of the Sudbury Irruptive in Snider, Waters and Graham Townships, together with granite in Drury Township, intrudes metavolcanic rocks of the Stobie Formation according to Card (1965) and is intruded by the Sudbury Irruptive. Card (1965) mapped the granite in Drury Township as part of the same body that is overlain non-conformably by the Elliot Lake Group farther west in Hyman Township. As pointed out earlier in this report, however, there is no evidence that the Stobie Formation is pre-Huronian; in fact, like the Thessalon Formation, it appears to be part of the Elliot Lake Group. If this were so, post-Huronian as well as pre-Huronian granite must be present in the Agnew Lake-Sudbury area. A whole rock Rb-Sr isochron date of 2.1^4 x 10^9 years has been reported for Murray-Creighton granite by Fairbairn et al. (1965. This is consistent with a hypothesis that granites, including the Murray-Creighton and Cutler granites, were emplaced during a major orogenic episode that took place in mid-Aphebian time prior to deposition of the Whitewater Group and intrusion of the Sudbury Irruptive. Some important objections to this interpretation can be raised, however; these are discussed below.

It has generally been supposed that the main period of deformation and metamorphism of Huronian rocks took place, not in mid-Aphebian time, but at the end of Aphebian time and corresponded to the 1.6-1.8 x 10^9 years Hudsonian Orogeny (Stockwell, 1964, p. 6) and Penokean Orogeny (Goldich et al., 1961, pp. 6, 118-120, 156) of other areas. This would seem to be supported by the fact that most K-Ar dates on metamorphic micas in Huronian rocks are near 1.6 x 10^9 years (some are as low as 1.4 x 10^9 years). The Murray-Creighton granite, however, has yielded K-Ar dates of 1.4 and 1.7 x 10^9 years despite its Rb-Sr date of 2.1 x 10^9 years, so it is probable that the apparent K-Ar ages of micas in both the metamorphic and granitic rocks were reduced through loss of argon. This loss might have occurred during a milder 1.6 x 10^9 metamorphism that affected the later Aphebian Whitewater Group and Sudbury Irruptive as well as Huronian rocks and Archean rocks that underlay them. Some additional loss of argon doubtless occurred during the Grenville Orogeny as well. These later alterations evidently also resulted in modifications of apparent Rb-Sr mineral dates in various rocks.

It is possible that not only K-Ar but also Rb-Sr isotopic dates have been down-graded, so the Murray-Creighton granite could be Archean rather than mid-Aphebian in age. Such down-grading of apparent Rb-Sr ages of Archean granitic rocks is demonstrated by Aphebian dates obtained for a boulder in Gowganda conglomerate and for basement granite collected underground in the Panel Mine (Fairbairn et al., 1960). The downgrading in these two cases could have been due to leaching of strontium during early Aphebian weathering and addition of rubidium during diagenesis. Analyses of paleosols, discussed previously, demonstrate that such subtractions and additions did occur. This particular process of Rb-Sr downgrading, would not have affected the Murray-Creighton granite samples that were analysed to obtain the 2.14×10^9 year isochron.

Work by Knight (1967) indicates that metamorphic downgrading of Rb-Sr whole rock isochron dates may occur. He obtained an isochron date of $2.0-2.4 \times 10^9$ years on pre-Kenoran metavolcanic rocks that must be more than 2.5×10^9 years old. A date of 1.9-2.1 years was obtained on Stobie volcanics which cannot be younger than Copper Cliff rhyolite dated as 2.35 $\times 10^9$ years old by whole rock Rb-Sr analyses on two samples (Fairbairn et al., 1965). Neither the Stobie volcanics nor the Copper Cliff rhyolite can be younger than the Murray-Creighton granite dated at 2.14×10^9 years as mentioned above. Knight also obtained a date of 1.9 to 2.0×10^9 years for Thessalon Volcanics which cannot be younger than the Nipissing diabase dated as 2.15×10^9 years old by Van Schmus (1965).

There are other problems involved in the interpretation of the Murray-Creighton granite and granite in Drury Township as post-Huronian rather than Archean in age. They differ from the Cutler granite in that they lack abundant associated pegmatites. They contain tabular bodies of metamorphosed basic rocks that could be interpreted as Sudbury gabbro (or Nipissing diabase) dykes. Their contacts with the Stobie Formation appear to be stratigraphically controlled, or restricted, insofar as this formation maintains a fairly constant width south of the granitic rocks. Granite bodies invade the lower parts of the Stobie Formation, according to mapping by Card (1965a, 1967) but do not transect the entire formation and have not been found intruding the McKim Formation which concordantly overlies the Stobie Formation. Remobilization of Archean granite nonconformably overlain by Stobie lavas, during mid-Aphebian Orogeny, could have produced the relationships described. This explanation seems contrived but it is at least as credible as the alternative suggestion (Card, 1965a) that the Stobie Formation is Archean despite the fact that mapping has not demonstrated the existence of a nonconformity between it and the overlying McKim Formation.

Croker Island Complex

The Croker Island Complex in the North Channel of Lake Huron 10 miles southeast of Spanish has been described by Card (1965b). It is a circular body about 6 miles in diameter with a core of biotite-rich syenite, diorite and gabbro and outer parts composed mainly of quartz monzonite. The pluton, which intrudes Mississagi quartzite (Robertson, 1967b) and post-Huronian gabbro, is mainly covered by water and Paleozoic strata but its outline is clearly shown by contours on aeromagnetic maps. Several other circular aeromagnetic anomalies found over Manitoulin Island are probably due to similar intrusive complexes beneath Paleozoic strata. The Croker Island Complex has been dated as 1.4 to 1.5 x 10^9 years old by Van Schmus (1964).

Wavy Lake Granite

A number of small granitic bodies intrude Huronian metasedimentary rocks near the southeastern margin of the Huronian belt along the Grenville Front south of Sudbury. The largest of these is known as the Wavy Lake Granite. A Rb-Sr date of 1.4 x 10^9 years has been obtained on biotite from this granite (Fairbairn et al., 1960, p. 58). Like other mineral dates, this may be a minimum date. Thus it is not adequate as evidence that the Huronian rocks were intruded by granites younger than the Murray-Creighton granite apart from the granitic phases of post-orogenic complexes like the Croker Island Complex.

MONGOWIN ULTRABASIC BODY

A very small body of ultrabasic rocks intrudes the Cobalt Group in Mongowin Township 6 miles south of Espanola. There is an occurrence of nickeliferous pyrrhotite along its north border, an interesting occurrence of sepiolite and colloform magnetite with a radiating crystal structure near the centre of the body (Moore, 1932) and a coarse muscovite-orthoclase-rich granophyric zone along its south border. A K-Ar age determination on muscovite in the granophyre gave 1.5 x 10^9 years (Lowdon, 1963, p. 71). Card (1965b) has pointed out that this is about the same age as the Croker Island Complex.

LAMPROPHYRE DYKES

Lamprophyric intrusives have been intersected in many, if not most, drillholes in Huronian rocks. They weather readily so they are rarely seen in outcrop and little is known about their habit or abundance throughout the region. Core lengths approaching 100 feet have been intersected but true thickness of the tabular bodies of micaceous, hornblendic rock probably rarely exceed a few feet. Sills of minette-type lamprophyre a few inches thick are not uncommon in underground workings in Elliot Lake area mines.

Some of these sills are sheared and altered and may be a nuisance to mining operations. Moreover, inclusion of lamprophyre in mill feed increases acid consumption as do chloritized rocks and diabase.

Robertson (1961, p. 47) considered that the lamprophyre dykes and sills occur mainly within or near the larger bodies of post-Huronian gabbro (Nipissing diabase) and suggested that they represent a late stage differentiate of the gabbroic magma. It is difficult, however, to judge how closely they are related spatially to diabase. Moreover, an age date of 1.4×10^9 years (Lowdon, 1962, p. 87) on biotite-rich lamprophyre intersected in a drillhole at Rangers Lake in Township 138, 12 miles northeast of Elliot Lake indicates that the lamprophyre is probably much younger than the diabase. This K-Ar date is less likely to be downgraded than most K-Ar dates in the region as the unaltered biotite analyzed comprised most of the rock. The lamprophyre dykes thus appear to be about the same age as the Croker Island Complex and are petrologically somewhat similar to biotite-rich mafic rocks in that complex.

GRENVILLE ROCKS

The folded Huronian metasedimentary rocks south of Sudbury abut against the Grenville Structural Province which is characterized by high-grade gneisses that yield K-Ar isotopic dates of about 10^9 years or slightly less. South of Timagami, the Grenville gneisses are in contact with Archean, or at least pre-Cobalt, granitic and gneissic basement rocks. Cobalt strata near the Grenville Front in this area are not greatly deformed or metamorphosed. Contacts between Grenville gneisses and less metamorphosed Aphebian and Archean rocks are faulted in some places and are broad mylonitized zones in other areas. The front is evidently a zone along which deep-seated rocks were brought into juxtaposition 10^9 years ago with Aphebian and Archean rocks that retain argon generated more than 10^9 years ago.

Recent geochronological studies of Grenville rocks (Krogh et al., 1968) have disclosed that many give Rb-Sr dates appreciably older than 10^9 years. It has long been considered probable that the Grenville Province includes highly metamorphosed equivalents of Aphebian and Archean rocks (Quirke and Collins, 1930; Stockwell, 1965). There is a possibility that some of the radioactive occurrences in the Grenville Province may represent redistributions of uranium and thorium that were originally present in Huronian or other sediments of Aphebian age. Occurrences of uraninite and gold in metaquartzite in the Grenville Province 25 miles southeast of the front east of Lake Temiskaming in Atwater and Pomeroy Townships, Quebec, are particularly interesting in this respect. It may be significant also that the pegmatitic and granitic uranium deposits of the Johan Beetz area near Havre St. Pierre along the north shore of the St. Lawrence River are within a very extensive belt of quartzite, paragneiss, and sill-like bodies of metagabbro (Claveau, 1949; Grenier, 1957; Cooper, 1957). Quartz-pebble conglomerates are found within the quartzite.

STRUCTURE

FOLDS

Major structural features that involve Huronian rocks in the region are shown in Figure 1. In most parts of the eastern sector, the structure is that of a block-faulted homocline with gentle southerly dips rarely as great as 45 degrees. This pattern is broken by the Chiblow Anticline and Thessalon Anticline. Strata along the north flanks of these structures dip gently north. In the more tightly-folded central sector, beds dip more steeply than 45 degrees in most places and southerly-facing strata along the south side of the Sudbury Irruptive are vertical or overturned in many places. The north-easterly sector, commonly but erroneously considered to be unfolded, is characterized by northerly-trending basins and domes. Dips along the flanks of these structures are generally less than 25 degrees but steep dips are found locally in the more tightly folded area north of Lake Wanapetei.

FAULTS

Classification

It is difficult to classify faults throughout so large a region in terms of their attitudes and directions of displacement but the following groupings may be useful for descriptive purposes: (1) Major east-trending, steeply dipping, reverse faults; north sides moved down and to the east with respect to the south sides. (2) Northwesterly trending faults with north sides moved down. (3) Northeasterly trending faults with north sides moved down. (4) North to northeasterly trending, faults with east sides moved down with respect to west sides. (5) Reverse faults that dip slightly more steeply than Huronian strata.

The Murray-Worthington Fault system and the Flack Lake Fault are the most important faults in the region. They are classified as east-west faults (group 1) although both are curvilinear, trending north of west at their west ends and north of east at their eastern ends.

Murray Fault

Vertical stratigraphic separation along the Murray Fault near Thessalon may be as great as 10,000 feet. Contacts of Huronian strata are displaced to the east along the north side of the Murray-Worthington Fault in the Espanola-Sudbury area. Right-hand strike separations in the order of 5,000 feet are apparent in this area (Thomson, 1952) but the actual horizontal component of movement was probably much greater than this as many of the contacts displaced to the right would have easterly-pitching traces on the fault plane. Late diabase dykes are displaced along the fault (Robertson, 1967, p. 14). It is difficult to match dykes on either side of the fault but it appears that considerable right-handed movement may have occurred at a relatively late date, perhaps during the Grenville orogeny.

Flack Lake Fault

Cobalt Formations are downfaulted against Archean basement rocks to the south along the Flack Lake Fault 5 miles north of Quirke Lake. Vertical stratigraphic separation along the fault is probably at least 6,000 feet. If the Whiskey Lake greenstone belt extends north of the fault beneath Huronian rocks as shown in Figure 6, the north block must be displaced to the east. Roscoe and Pienaar confirmed the existence of this steep south-dipping reverse fault in 1956 and traced it as shown on Roscoe and Steacy's Figure 1 (1958, p. 476), Ont. Dept. Mines, Map 2108, and in Figure 1 and other figures in this report. Strata are deformed and probably somewhat metamorphosed along the fault west of Flack Lake.

Northwesterly and Northeasterly Trending Faults

Most of the northwesterly trending faults (group 2) in the Bruce Mines area and northeasterly trending faults (group 3) in the Espanola-Sudbury area are either branches off the Murray-Worthington fault system or closely related faults. Others near Elliot Lake have similar displacements of the north-side down and may represent conjugate fractures with a history similar to that of the Murray Fault, Flack Lake Fault and other less important east-west faults. Robertson (1964a, p. 51) noted that the Lake of the Mountains Fault is younger than other faults near Blind River.

North-Northeasterly Trending Faults

North to northeasterly striking normal faults (group 4) separate westerly tilted fault blocks and are probably tensional faults with a different history to that of previously mentioned faults (groups 1 to 3).

Gently-Dipping Reverse Faults

A major low angle reverse fault (group 5) repeats conglomeratic zones and higher formations in the Quirke Lake area (Roscoe, 1957a, p. 16). Vertical stratigraphic separation along this fault is as great as 400 feet on the Denison property. Total displacement along the fault is in the order of 1,200 feet in the vicinity of the Stanrock and Spanish American mines. Dip of the fault decreases to the south and it is possible that the faulting does not involve basement rocks. Curvilinear reverse faults have been mapped by Robertson (1962) around the nose of the Quirke Syncline near Whiskey Lake. Diabase dykes have been displaced by the reverse faults and by bedding plane faults and slips. Movements along these structures are in the same sense as adjustments that must have taken place during folding; upper strata are moved upward and outward away from the synclinal axis.

RELATIONSHIP OF FAULTING TO HURONIAN SEDIMENTATION

The rupture of the gently-dipping reverse faults, as well as the displacement along them, was doubtless related to the development of east-west folds but this seems unlikely to be true of the steeply-dipping reverse faults. More likely they are old normal faults along which reverse movement took place during folding. It was suggested previously in this report that some thickness and facies changes within Huronian strata are related to crustal movements that occurred during their deposition. Warping of the basement between the area of uplift to the north and the downsinking geosynclinal area to the south would have produced tensional strain in the zone marginal to the geosyncline. Normal faulting would have occurred along pre-existing fractures in this zone.

Southerly-facing fault scarps can thus be envisaged as prominent features of the Archean landscape at the time of deposition of the lowermost Huronian strata. These would have influenced sedimentation and eventually would have become buried as sedimentation encroached sourceward toward the north. Recurrent movement along the faults would have resulted in development of flexures in the overlying strata and in extension of faults upwards from the basement through the strata. In both cases, the up-dip side of the fault would be a site of erosion or minimal deposition whereas the down-dip side would be a site of maximal deposition or minimal erosion. This phenomenon has been invoked previously in this report to explain variations in facies, in thicknesses of units, and in amounts of interformational erosion as well as the alignment of the Pronto, Nordic and Quirke Lake ore zones (Fig. 4). It must be pointed out, however, that this explanation is hypothetical as none of the variations noted can be shown to be related definitely to specific faults. Moreover, significant differences in thickness and grades of ore have not been found (to this writer's knowledge) on opposite sides of minor faults in stoped areas.

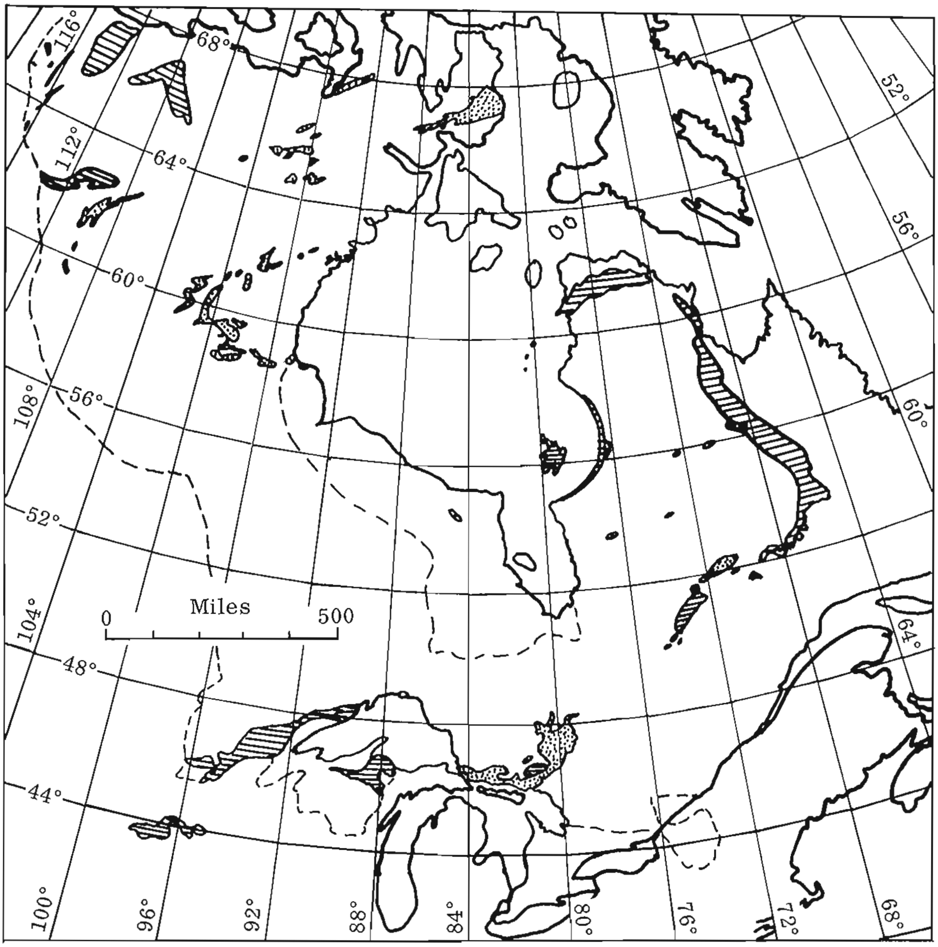
COMPARISON OF HURONIAN AND OTHER APHEBIAN ROCKS

GENERAL

The Huronian Supergroup is one of many successions 1.6 to 2.5 x 10^9 years old, or Aphebian in age (Stockwell, 1964, pp. 13-14), that are found in separate belts along the margins of the Superior Province. Most of these belts, like many belts of similar age in other parts of the world, contain extensive, thick units of iron-formation, characteristically the jasper-hematite variety. Other strata abundant in most of the belts include shale, dolomite, quartzite and volcanic rocks. Belts of similar strata are found at the perimeter of the Slave Province in the northwestern part of the shield but these lack iron-formations, apart from minor occurrences in the Great Slave Group and the Hurwitz Group. Gneissic rocks in the Churchill and Grenville Provinces probably include highly metamorphosed Aphebian strata equivalent to the less deformed strata known to non-conformably overlie Archean rocks at the margins of the two ancient structural provinces.

It is important to emphasize that the Huronian Supergroup, together with similar strata in the Mistassini region in central Quebec, and perhaps some units presently included in the Hurwitz Group and other groups west of Hudson Bay differ from other Aphebian successions (Fig. 7). Thick arenaceous units dominate the Huronian succession and most of these are coarse to very coarse grained, feldspathic and argillaceous. Arenites are much less abundant and are relatively fine-grained, well-sorted, and siliceous in most other Aphebian successions. Most of the argillaceous material is present in the matrix of argillaceous quartzites or subgreywackes in Huronian rocks whereas thick shale formations form the main units of other successions. The latter units are commonly highly carbonaceous whereas the darkest Huronian argillites contain less than 1 per cent carbon. Carbonaceous arenites also occur in some Aphebian successions but not in Huronian rocks. Limestone occurs in one Huronian Formation, the Espanola Formation, but most of the lime in this formation is in limy siltstone rather than in well-defined limestone beds; stromatolitic structures are lacking in this formation. In contrast, other Aphebian successions contain thick formations of stromatolitic and oolitic dolomite. Biogenic structures and microstructures have also been found in Aphebian cherts. The Huronian Supergroup lacks the iron-formations and cherts that are found in most other belts of Aphebian rocks but contains a great abundance of various types of conglomeratic rocks including radioactive and non-radioactive quartz-pebble conglomerates and thick tillite-like units. Relatively rapid facies changes are another characteristic of Huronian rocks. Moreover, there is reason to believe that they were deposited on a much more irregular surface than were other Aphebian successions.

It is obvious that the Huronian succession was deposited in a very different environment than most other Aphebian successions. It can be considered to be characterized by chemically and texturally submature, fluvial



Stipples - indicate sequences characterized by clastic rocks, including coarse arkosic and argillaceous varieties.

Ruling - indicates sequences characterized by well-sorted sedimentary rocks, including shale dolomite and iron formations and lacking coarse arkosic and argillaceous clastic rocks

Figure 7. Distribution of Aphebian rocks in Canadian Shield

sediments and other continental and marginal marine sediments deposited upon an irregular, unstable platform adjacent to a rising highland source area. Most other Aphebian sediments, on the other hand, were deposited in a marine or marginal marine environment on a relatively smooth, stable shelf and were evidently derived from extensive, deeply-weathered source areas of low relief.

RELATIONSHIPS BETWEEN HURONIAN AND ANIMIKIE ROCKS

Acceptable correlations can evidently be made between Aphebian belts in the Lake Superior region. James (1958) concluded that all these belts should be considered as part of the Animikie 'series' rather than the Huronian 'series' or 'system'. It is unfortunate that the term Huronian became widely applied to strata in the Lake Superior area as this usage, in the context of modern stratigraphic nomenclature, implies that they were deposited at the same time as strata of the Huronian Supergroup north of Lake Huron. This is unlikely. The Animikie belts and the Huronian belt, following roughly the same east-west trend along the south margin of the Superior Province, are separated by only 150 miles of Paleozoic cover between Marquette and Sault Ste. Marie. This distance is only a fraction of the known extents of the two dissimilar successions. It is difficult to visualize the one passing into the other through abrupt facies changes, or the two having been deposited simultaneously in separate adjacent basins under dissimilar tectonic conditions. Aphebian time (2.5 to 1.6 x 10^9 years) is much greater than all Paleozoic, Mesozoic and Tertiary time put together. There is no need to assume that deposition of Huronian and Animikie rocks overlapped in time or followed one immediately after the other.

So many suggestions concerning relationships of Huronian and Animikie rocks have been made, the latest by Young and Church (1966), that perhaps yet another can do little harm. Animikie rocks nonconformably overlie arkose and other highly metamorphosed strata called the Dickenson Group south of Marquette (see James, 1958). The presence of arkose containing clasts of older granite as well as abundant pebbles of granular quartz suggests that the Dickenson Group may be early Aphebian rather than Archean in age. Huronian rocks are older than 2.1 x 10^9 years and were involved in a mid-Aphebian orogeny in the Sudbury area according to evidence reviewed in this paper. There is no evidence that the Animikie rocks are as much as 2.1 x 10^9 years old. It is possible therefore that the Animikie rocks are late Aphebian and nonconformably overlie remnants of early Aphebian rocks correlative with Huronian rocks.

WHITEWATER GROUP

Relationships of the Whitewater Group to other rocks in the Sudbury area are illustrated in Figure 8. Thomson (1957) correlated the group with metavolcanic and metasedimentary rocks immediately south of

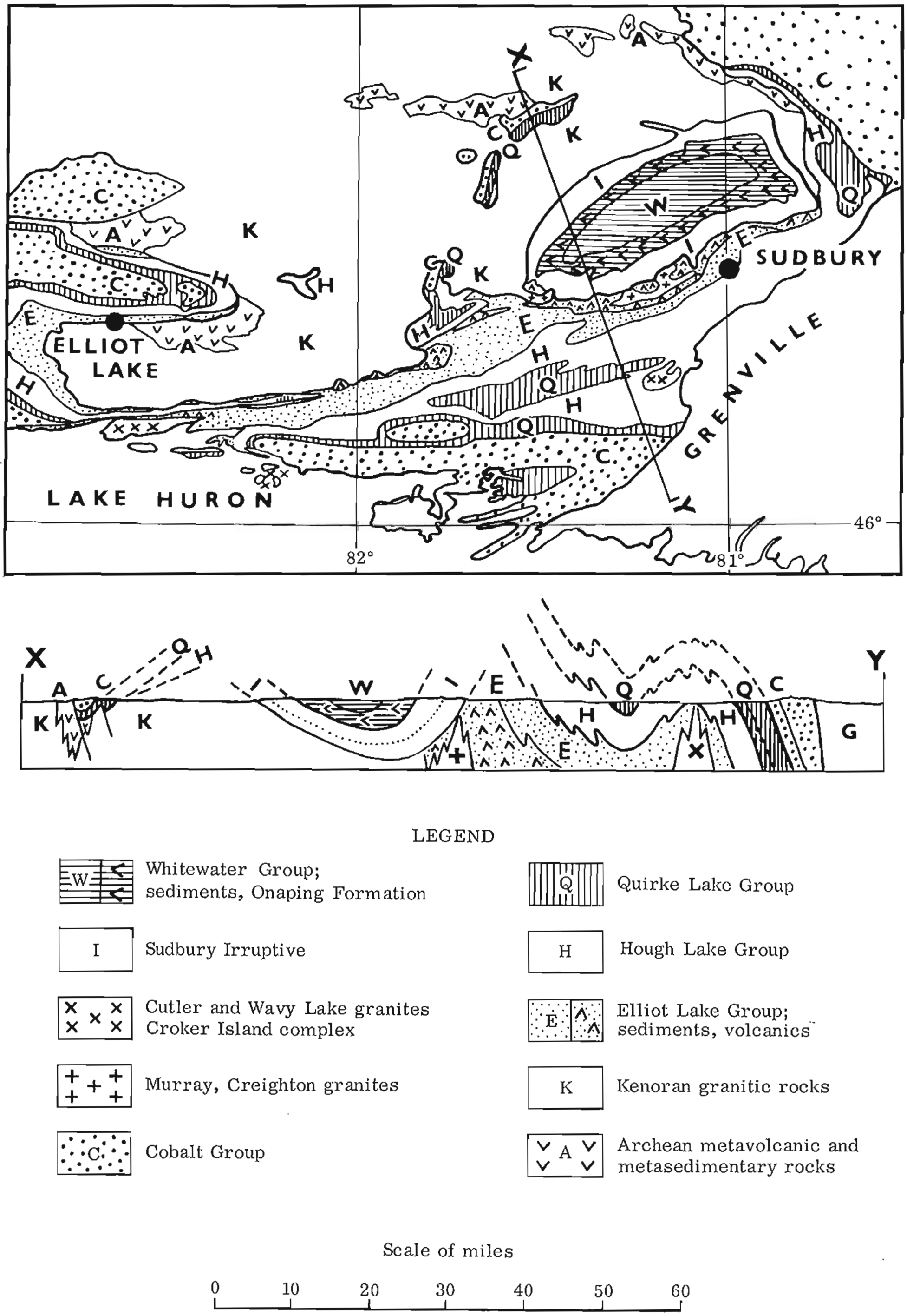


Figure 8. Relationships of Whitewater Group to Huronian rocks in the Sudbury-Elliot Lake Area.

the Sudbury Basin. Other workers, however, have believed that the group comprises the youngest Precambrian strata in the area and that the Sudbury Irruptive was intruded along a nonconformity beneath the group. Isotopic dating, reviewed previously, supports this conclusion as granite beneath the south rim of the irruptive has been dated as about 2.1 x 10^9 years old whereas the Whitewater rocks and the Sudbury Irruptive have been dated as about 1.7 x 10^9 years old (Fairbairn et al., 1964). Huronian strata, intruded by gabbro about 2.15 x 10^9 years old (Van Schmus, 1965), were evidently folded into a great domal structure that coincides approximately with the position of the Whitewater (Sudbury) basin structure (Fig. 8). Cooke (1946) previously noted this evidence of angular unconformity. Huronian strata south of the basin are highly deformed and metamorphosed compared to the Whitewater Group and, if the writer's interpretation that the Stobie Volcanics are Huronian in age is correct, they are intruded by granite about 2.1 x 10^9 years old. A mid-Aphebian orogeny and a period of deep erosion of folded, metamorphosed Huronian rocks and granite evidently separated the periods of deposition of Huronian rocks and Whitewater rocks.

Quartzite breccia at the base of the Whitewater Group (or at the top of the irruptive) has been described by Stevenson (1961). This breccia is of particular interest as it contains quartzite fragments, some of which are huge, that resemble quartzite in Huronian Formations. Greenish, sericitic, coarse-grained, feldspathic quartzite clasts containing layers of quartz pebbles, for example, resembles quartzite found in the Matinenda, Mississagi and Lorrain Formations. Finer grained varieties, some of which show crossbedding, resemble quartzite found in the Livingstone Creek, Matinenda, Mississagi and Serpent Formations. Perhaps there are Huronian quartzites beneath the irruptive. It may have lifted off 'skins' of such quartzite when it was intruded beneath the Whitewater Group, or blocks of quartzite may have floated up through the intrusive. Alternatively, and perhaps more likely, the rock clasts may have been sloughed off Huronian cliff-sides just outside the present basin area or to have resulted from a gigantic explosion (Dietz, 1964).

MISTASSINI REGION

The Chibougamau Group, the Papaskwasati Formation and the Otish Mountain Group in the Mistassini region of central Quebec resemble Huronian rocks whereas the Mistassini Group and Matonipi rocks in the same region resemble Animikie and Kaniapiskau rocks (Fig. 9).

Many workers, e.g. Retty (1929, p. 58), Mawdsley and Norman (1935, p. 43), have commented on the close resemblance of the Chibougamau Group to the Gowganda Formation. No one familiar with the Cobalt Group could fail to be impressed by the very close resemblance of rock types in the Chibougamau Group and Otish Mountain Group to those in the Gowganda Formation and Lorrain Formations respectively. The Papaskwasati

Formation resembles the Mississagi Formation somewhat in its white and greenish coloration, feldspathic and sericitic character, crossbedding, radioactive quartz-pebble layers and general anoxic character (lack of ferric oxide). It could, however, represent an upper part of the Chibougamau Group or a lower, local, facies of the Otish Mountain Group.

The Cobalt Group, over 10,000 feet thick extends nearly 300 miles northeastward from the Sault Ste. Marie area with little change in character. It is not unlikely, therefore, that it once extended another 300 miles to the

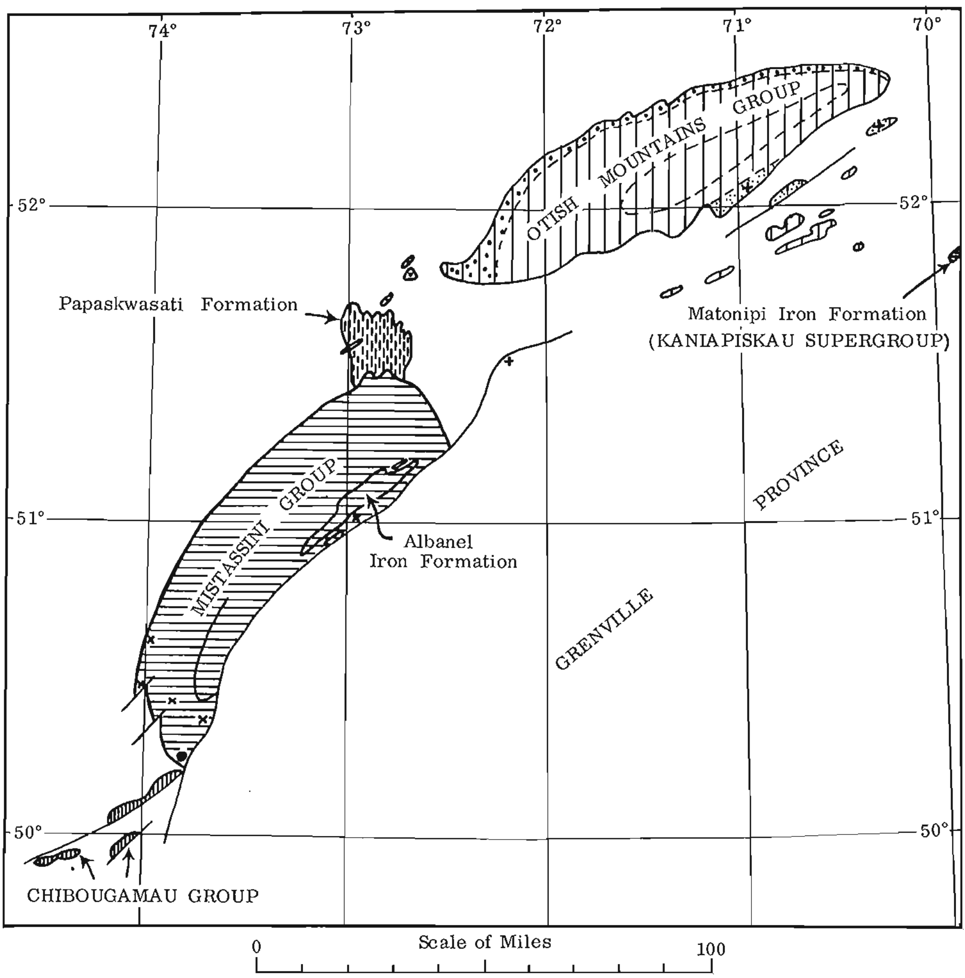


Figure 9. Aphebian strata in the Mistassini Region, central Quebec

Mistassini region. Relationships in this region suggest that the Chibougamau Group and the Papaskwasati Formation might have been overlapped to the north by the Otish Mountain Group in the same way as the Lorrain Formation overlaps older Huronian Formations in the Lake Huron-Lake Temiskaming region. Outliers of distinctive basal conglomeratic arkose of the Otish Mountain Group are found west of the Otish Mountain Basin (Chown, 1960a); one of these is only a few miles north of the Papaskawasati Formation. Crossbedding is inclined to the south in these outliers indicating that the Otish Mountain Group must have extended some distance in that direction. It is not found beneath the Papaskwasati Formation so it is reasonable to suppose that it once extended over that formation.

The Huronian-like units in the Mistassini region were evidently deposited on irregular surfaces, and were probably deformed and deeply eroded prior to deposition of the Mistassini Group on a smooth surface. Unfortunately, there is only indirect evidence for this unconformity. The Mistassini Group is not found in contact with the Chibougamau Group, although the southern end of the Mistassini Basin is within a half mile of one trough of Chibougamau rocks. The Papaskwasati-Mistassini contact is not well exposed.

The Chibougamau Group, like the Gowganda Formation, was deposited on an irregular surface. This surface had a local relief of at least 300 feet in Bay Township (Duquette, 1964) where as much as 2,500 feet of strata including 700 feet of conglomeratic rocks overlain by 1,800 feet of arkose are found in a syncline overturned to the northwest (Mathieu, 1966). In contrast the Mistassini sediments characterized by marine sediments - stromatolitic dolomite, carbonaceous shale and iron-formation - were deposited on a very smooth surface as evidenced by the regular outline of the northwest border of the Mistassini Basin and by drillhole data. The Papaskwasati Formation is open-folded along southerly trending fold axis whereas overlying Mistassini strata dip gently south (Neilson, 1951; Chown, 1960a).

Hematitic, monazite-bearing quartz-pebble conglomerate layers are found in pebbly arkose near the base of the Otish Mountain Group. These are similar in character and in association to thorium-bearing conglomerates in the Lorrain Formation north of Quirke Lake where the latter formation lies on granitic basement rocks. Radioactive conglomerates in the Papaskwasati Formation differ in that they have a greenish sericitic matrix and contain little if any hematite. They contain little or no pyrite as far as the writer is aware, however, so it is not certain that they can be compared with pyritic conglomerates in Huronian rocks.

METAQUARTZITE IN THE GRENVILLE PROVINCE EAST OF LAKE TEMISKAMING

A band of metaquartzite in Grenville gneisses at Hunters Point, Quebec, 50 miles east of Timagami contains concentrations of uraninite and gold in a very narrow zone that parallels thin bands of garnetiferous mica schist and thus can be considered concordant with bedding. One may speculate as to whether this occurrence could have been produced through metamorphism of a uraniferous, auriferous quartz-pebble bed such as those that are found in Huronian quartzite in the Timagami area. The metaquartzite is micaceous and shows crossbedding. No definite pebbles are present but vague outlines suggest granulated streaked-out quartz pebbles. Some hematite, and needle-like crystals possibly rutile, are associated with the uranium-gold concentration but no sulphides were noted by the writer. This interesting deposit should be studied in detail.

WAKEHAM GROUP

The Wakeham Group, near Johan Beetz on the north shore of the Gulf of St. Lawrence opposite Anticosti Island, is composed of metaquartzites with minor meta-argillite and conglomerate intruded by meta-gabbro and by later-granite and pegmatite. Radioactive occurrences in the latter rocks have recently attracted the attention of a number of exploration companies. The group resembles early Aphebian, Huronian-type sequences, such as the Otish Mountain Group 350 miles to the northwest, more than it does the more widespread Animikie-Kaniapiskau type sequences. It contains feldspathic quartzite, micaceous quartzite, concentrates of heavy resistates including rutile, zircon and hematite, and quartz-pebble conglomerate beds. It has been mapped by Claveau (1949), Grenier (1957), and Cooper (1957).

CONTINENTAL CLASTIC SEDIMENTS IN NORTHERN QUEBEC

A very thick succession of reddish arkoses, conglomerates, siltstones and stromatolitic dolomites underlies the normal succession of Kaniapiskau rocks in the Cambrian Lake area about midway along the Labrador Trough (Roscoe, 1957c). Fahrig (1957) noted that these predominantly terrestrial sediments filled a great depression that trends westerly across and beyond the western border of the overlying marine Kaniapiskau rocks which were evidently deposited on a fairly smooth surface.

Similar relationships are found near the mouth of the Little Whale River at Richmond Gulf along the east side of Hudson Bay. Coarse, ferruginous arkoses, red argillite and volcanic rocks deposited on an irregular surface (Eade, 1966a, p. 54) are intruded by gabbro and are unconformably overlain by dolomite and other marine strata of the Manitounuk Group. This group, and the Belcher Group, resemble Animikie and Kaniapiskau rocks.

Eade (1966a) has mapped a number of small easterly trending belts of coarse continental sediments between Hudson Bay and James Bay on the west and the Labrador Trough to the east. He referred to these rocks as the Sakami Formation. The various separate belts contain sequences as much as 3,400 feet thick, composed of granite and quartz conglomerates, red and green arkose, red mudstone and overlying beds of quartzose sandstone.

These ancient red beds are not dissimilar to younger continental sediments that contain uraninite impregnation deposits, or to sediments found in some areas of pitchblende deposits, and they likely contain radioactive conglomerates of the black sand type. They differ, however, from Huronian fluvial sediments in their oxidized condition and therefore probably do not contain uraniferous pyritic conglomerates.

APHEBIAN ROCKS WEST OF HUDSON BAY

Strata of probable Aphebian age west of Hudson Bay include some clastic sediments that resemble Huronian subarkoses, siltstones, and conglomeratic greywacke. Slightly radioactive, slightly auriferous, pyritic quartz-pebble conglomerate beds (Heywood and Roscoe, 1967) have been found in such strata near Padlei, District of Keewatin, beneath or in the basal part of the Hurwitz Group. In order to show that some favourable, coarse, drab-coloured arkosic and argillaceous rocks occur within some of the Aphebian belts in this region, these belts have been outlined in Figure 7 by the same stippled pattern used for Huronian rocks. This could be misleading, however, because the most extensive and best exposed Aphebian rocks west of Hudson Bay more closely resemble the relatively abundant Animikie-like successions than the Huronian succession. The main unit of the Hurwitz Group, composed of distinctive, fine-grained, white and pink orthoquartzite unlike any Huronian quartzite formation, is probably of transgressive marine origin rather than of fluviatile origin. This unit is overlain by argillaceous rocks and locally by stromatolitic carbonate rocks, rare iron-formation lenses, and volcanic rocks (Eade, 1964, 1966; Bell, 1968). In places, the orthoquartzite grades downwards into poorly-exposed arkosic rocks that non-conformably overlie 'basement' rocks. It is not clear whether the radioactive quartz-pebble conglomerate beds described by Heywood and Roscoe (1967) are within a thick section of this basal arkosic zone or whether they are within a separate pre-Hurwitz group.

RADIOACTIVE QUARTZ-PEBBLE CONGLOMERATES

INTRODUCTION

Information pertaining to the distribution and geological environment of occurrences of uraniferous conglomerates is dispersed throughout this report. This chapter summarizes such information and other information based on laboratory studies. More complete descriptions of individual uranium ore deposits and mineralogy of ores may be found in the literature.

As far as the writer can determine, all features of radioactive conglomerates are consistent with the theory that they are essentially placer deposits. Certainly there is no evidence that any other theory would be useful to exploration. There are two types of radioactive conglomerates, one contains abundant iron oxides such as hematite; the other, pyrite. Both types contain concentrations of monazite, zircon and other radioactive and nonradioactive heavy detrital minerals. Concentrations of uranium-rich minerals, particularly uraninite, resulting in low thorium to uranium ratios and economically interesting deposits, are evidently restricted to the pyritic type but even this most commonly contains more thorium than uranium. Both types occur in Huronian rocks, but not together. The hematitic type may be found in rocks of any age and is comparable to recently-formed placer deposits. Pebbles other than quartz and chert may be abundant or even dominant in some radioactive conglomerates of this type. Important occurrences of the pyritic type have been found only in rocks of approximately the same age as Huronian rocks, that is not younger than Aphebian or perhaps mid-Aphebian (about 2×10^9 years) in age.

DISTRIBUTION

Occurrences of radioactive quartz-pebble conglomerate are found in many places and at a number of stratigraphic positions in Huronian rocks through a distance of 200 miles between Sault Ste. Marie and Timagami. These conglomerates are within very coarse-grained, argillaceous, feldspathic quartzites or grits deposited along the northern margin of the Huronian geosyncline by southerly flowing streams. The most important occurrences and the only ore deposits or deposits approaching ore grade found so far, are in the Matinenda Formation where this formation rests nonconformably on granitic and metamorphic rocks of the Superior Province. Beds of radioactive conglomerate are also interlayered with volcanic rocks at roughly the same stratigraphic level as the Matinenda Formation and within higher feldspathic quartzite units, particularly where these overlap older Huronian strata and lie directly on basement rocks at the margin of the geosyncline. These units include in ascending order the Mississagi Formation, possibly the Serpent Formation, and the Lorrain Formation. Radioactive conglomerates in the Lorrain Formation contain hematite rather than pyrite as their most abundant heavy mineral.

Radioactive, pyritic, quartz-pebble beds have been found in the Matinenda Formation in most places where this formation outcrops (Fig. 2). They also occur interbedded with volcanic rocks near the base of the Thessalon Formation in the three areas where that formation outcrops i.e., near Thessalon, north of Bruce Mines, and near Sault Ste. Marie. The most extensive, thickest and most uraniferous conglomeratic zones are in the Elliot Lake area and near Agnew Lake. The Quirke ore zone 8 miles north of Elliot Lake is about 9 square miles in extent. The Nordic ore zone just east of Elliot Lake is about 3 square miles in extent. The Pronto deposit 12 miles south of Elliot Lake, now largely mined out, was much smaller. Griffith and Roscoe (1964) estimated in 1964 that about 200,000 tons of recoverable U_3O_8 remained in the main ore zones at Elliot Lake and that a like amount was probably present in lower grade conglomeratic zones above and below the ore zones and east of these zones.

Occurrences of radioactive conglomerates have been found in the Wanapetei-Timagami area in the Mississagi Formation and immediately beneath the Gowganda Formation in quartzite that may be correlative with either the Mississagi Formation or the Serpent Formation. Unlike the Elliot Lake area, this is an area where gold deposits occur in Archean basement rocks so it is interesting that some thin beds of auriferous pyritic quartz-pebble conglomerates have been found there. Unusual occurrences of uraninite associated with ilmenite have been found in the fine-grained, argillaceous quartzites in Hough Lake Group north of Lake Wanapetei.

Numerous occurrences of thorium-rich hematitic quartz-pebble conglomerate are found in the lower, arkosic part of the Lorrain Formation near Kirkpatrick, Mount, and Rawhide Lakes north of Elliot Lake. Similar conglomerates occur near the base of the Otish Mountain Group northwest of Lake Mistassini in central Quebec. The Otish Mountain Group is lithologically identical to the Lorrain Formation and may well be correlative with it.

The Papaskwasati Formation, just north of Lake Mistassini contains radioactive pebble beds that may be of the pyritic type rather than the hematitic type (Roscoe, 1967). The formation is a coarse-grained feldspathic quartzite. It is crossbedded, white and green coloured and resembles the Mississagi and Matinenda Formations in these respects and in its 'anoxic appearance'.

Occurrences of very slightly auriferous and radioactive, pyritic quartz-pebble conglomerate have been found in the Hurwitz Group east of Hudson Bay in the Northwest Territories (Heywood and Roscoe, 1967).

CHARACTER OF ORE ZONES

Pronto Zone

The deposit worked by Pronto Uranium Mine - a 1,500 tons per day operation between 1955 and 1960 - 12 miles south of Elliot Lake, was a

[1] Extensive drilling programs, were carried out in 1967 and 1968 but no uraniferous beds were reported.

single layer of conglomerate (with minor lenses of quartzite) averaging about 7 1/2 feet in thickness. The ore zone, now substantially extracted, is at the base of the Matinenda Formation and nonconformably overlies granite or altered granite. It dips 15 to 20 degrees south and is truncated at a depth of about 1,000 feet by a major, southerly dipping reverse fault related to the Murray Fault which is a short distance farther south. Quartz and chert clasts (many of them cobble size i.e., greater than 2 1/2 inches in diameter) are larger than those in most conglomerate beds in other ore zones. They are also relatively well-rounded and include a notable abundance of pebbles and cobbles of pink chert. Pyrite grains are more abundant (perhaps up to 20 per cent of the ore) and are coarser (commonly about 1/8 inch in diameter) than in most other ore zones.

Local alterations of the ore to a pink feldspathic rock and a greyish chloritic rock gave rise to early reports of facies changes from uraniferous conglomerate to uraniferous quartzite and grit. A later report (Heinrich, 1958) cited these intense alterations as evidence that the ores were introduced by hydrothermal solutions. It is now understood that all of the ore was originally pyritic conglomerate and that it pre-dated the alterations which are associated with intrusive diabase and fractures.

A widespread misconception concerning surface leaching of uranium from pyritic conglomerates have grown up around the circumstances of early exploration of the Pronto deposit which was the first to be discovered. Samples taken from the surface exposures around 1949 contained 0.05 to 0.1 per cent U_3O_8 according to chemical as well as radiometric analyses; two samples contained 0.2 per cent (Kesten, 1950, p. 49; Lang, 1952, p. 124). These samples were considered discouraging as in those days even 0.2 per cent let alone 0.1 per cent U_3O_8 was considered sub-ore grade. A theory that the zone may have been leached at the surface (Joubin, 1954, p. 1) reportedly led to the 1953 drilling program that outlined the deposit and established that it contained about 0.13 per cent U_3O_8 and was remarkably uniform. This grade is not much higher than the uranium content of many of the surface samples. The main sites of surface sampling, moreover, were not directly up dip from ore. The deposit was in fact mined to surface in most places east of the main old pits. It does not seem likely, therefore, that important leaching of uranium occurred at Pronto despite the success that followed the testing of this reasonable theory. The writer is not aware of any evidence of uranium or uranium daughter product leaching, or disequilibrium effects, that could be grossly misleading to exploration work in Huronian rocks.

Nordic Zone

The Nordic ore zone just east of Elliot Lake is about 1 mile wide and 3 1/2 miles long. It trends northwesterly, dips about 16 degrees north, and extends from surface to a depth of about 3,700 feet. Four mines, each with its own treatment plant, were established on the zone. From southeast to northwest, these are the Algom Nordic Mine, the Lacnor Mine, the Milliken Lake Mine and the Stanleigh Mine, all of which are now controlled by the Rio Algom-Rio Tinto organization. The Algom Nordic Mine with a capacity to treat 3,000 tons of ore per day has been the only one in operation on this zone since 1964.

The ore occurs in a conglomeratic zone some 70 feet thick, 0 to 50 feet above the base of the Ryan Member of the Matinenda Formation. Two subarkose units separate the conglomeratic zone into three sections or 'reefs': the lower reef, the main reef, and the upper, or Pardee reef. Each of these are complex assemblages of individual lenticular beds of conglomerate, pebbly subarkose, and subarkose or grit a few inches to a few feet thick. The main reef contains the thickest, most persistant and, in most places, the richest ore but considerable mining has been done in the lower reef and the upper reef also contains ore in places. The latter has a much greater lateral extent than the main and lower reefs; in fact it extends 6 miles east of the ore zone and contains marginal to submarginal material through extensive areas.

The average grade of ore mined in the ore zone has been about 0.12 per cent U_3O_8; thicknesses are about 10 feet in most places. Relatively high grade and thick sections have been found in the Algom Nordic, or southeastern, part of the zone. Pyrite may also be a little more abundant in ore in this part of the zone than in other parts. The zone in general contains less pyrite than other zones, perhaps as little as 5 per cent in some ore. Most pebbles are between 1 and 4 inches in diameter. The largest are in the lower conglomerate beds. Pienaar (1963, p. 69) detected a southward and an eastward decrease in pebble size in the southeastern part of the ore zone.

Quirke Zone

The Quirke ore zone extends about 6 miles in a southwesterly direction from its outcrop on the Algom Quirke property 8 miles north of Elliot Lake. It has a maximum width of nearly 2 miles beneath the west end of Quirke Lake and has been developed and mined from shafts around the periphery of the lake on the Denison, Spanish American (Rio Algom), Stanrock, Panel (Rio Algom) and Can Met (Denison) properties, as well as on the Algom Quirke property 2 1/2 miles west of the lake. Each of these properties had their own treatment plants (most with a capacity of 3,000 tons per day) but several have been dismantled since their shut-downs between 1959 and 1961. The Denison Mine with a milling capacity of 6,000 tons per day has been the only mine operating on a standard basis since 1964, although Stanrock Uranium Mine has been recovering uranium from underground leaching operations. Rio Algom plans to begin operations at a new mine on the Algom Quirke property in mid-1968.

The northernmost part of the zone dips as steeply as 45 degrees locally but the dip flattens rapidly to the south and is less than 20 degrees through most of the ore zone. The deepest part of the zone is 3,100 feet below the surface of Quirke Lake.

Most of the ore occurs in a conglomerate zone that may be referred to as the Denison reef. This reef lies at the base of the Manfred Member of the Matinenda Formation atop greenstone west of Quirke Lake and does not extend up dip to the outcrop of the formation on the Algom-Quirke property. The ore that outcrops and that has been mined to date on this property occurs in a reef some 80 to 140 feet above the Denison reef. Several additional conglomeratic zones are present in the northwestern part of the ore-bearing zone. The Quirke and Denison reefs, like reefs in the Nordic ore zone, are multiple units containing sections of interlayered, or interlenticulated, conglomerate and quartzite separated by extensive well-defined quartzite layers that contain little conglomerate. There are three such conglomeratic sections in the Quirke reef, of which the central section is the thickest and most uraniferous. The Denison reef, within the Denison property, is a double reef with upper and lower conglomeratic sections that are separated by a quartzite section up to 15 feet thick but commonly only a few feet thick. Both contain relatively high-grade ore through extensive areas and in many places both are mined together with the intervening quartzite in stopes as much as 30 feet high. In other places dilution of ore with the intervening quartzite must be avoided so that the two are not mined together. The lower reef is characterized by quartz-cobble conglomerate and relatively coarse, abundant pyrite.

Total thicknesses of the Denison reef zone are much less toward the southern and eastern margins of the ore zone than in the vicinity of Denison No. 1 shaft. This decrease in thickness coincides with a decrease in numbers and thicknesses of individual conglomeratic layers within the zone and within the Manfred Member as a whole. Pebble sizes also decrease rapidly towards the south and are much smaller in the ore zone in the Spanish American Mine and in the southeastern part of the Stanrock Mine than in most conglomerates in the northern and central Denison workings. Pienaar (1963, p. 68) found that the median size of pebbles and cobbles through the reef near Denison No. 1 shaft is about 2 1/2 inches whereas it is less than 1 inch in the Can Met Mine. Related changes in uranium content, thorium: uranium ratios and in heavy minerals will be discussed in a subsequent section.

The Quirke reef appears to change in a similar manner towards the southeast. Pienaar found that pebbles in the Quirke reef had a median diameter of 2 1/2 inches near the Algom-Quirke No. 1 shaft, 1 1/2 inches 2,000 feet east of the shaft and less than 1 inch 1,000 feet west of the shaft. One to 3 miles southeast of this shaft the reef overlaps the Denison reef. The belt of overlap is limited to the southeast (see Derry 1960, p. 918 and Fig. 3) as the Quirke reef is truncated by an unconformity at beneath the Hough Lake Group (Ramsay Lake Conglomerate). Where intersected by drillholes near this eastern limit zone is thinner, much lower grade and contains much smaller pebbles than 'upstream' near the Quirke shaft.

The Denison reef is also truncated in places by the unconformity beneath the Hough Lake Group; in places it abuts against basement highs, but the southern and eastern limit of the ore zone is mainly an economic one controlled by diminution of uranium content and thinning of the reef.

MINERALOGY

Minerals Present

All of the radioactive pyritic conglomerates consist essentially of quartz and chert pebbles in a matrix of sericitic, feldspathic quartzite that contains grains of pyrite, titanium minerals, monazite and zircon. Conglomerates in ore zones near Elliot Lake contain a variety of radioactive minerals including uraninite, brannerite, thucolite, uranothorite, uranothorianite, coffinite, allanite, xenotime and gummite. Uraninite, highly radioactive material (including brannerite) associated with anatase and rutile, radioactive material (possibly uranothorite) admixed with monazite, and brannerite appear to be the most important ore minerals in Elliot Lake ores. Uranothorite is probably the most important ore mineral in the conglomeratic ores at Agnew Lake Uranium Mines (D. S. Robertson, personal communication). Thucolite is abundant in some of the other conglomerate occurrences in the Agnew Lake area and may be important locally at Quirke Lake.

A large variety of other minerals have been reported by Roscoe and Steacy (1958) and by Milne (1958). These include garnet, spinel, chromite, cassiterite, tourmaline, niobium-bearing rutile, magnetite, hematite, ilmenite, sphene, apatite, fluorite, barite, muscovite, phlogopite, biotite, hornblende, clinopyroxene, orthopyroxene, greenalite, chamosite, grunerite, epidote and zoisite. Individual grains of the same mineral species (i.e., monazite or zircon) occurring together in the same specimen commonly vary in colour or in other characteristics.

Gold is concentrated in the conglomerates but the amounts present are close to the limit that can be detected by normal assay methods and relatively few assays have been made. Most samples assayed have been reported to contain 'trace' or 'nil' or 0.005 ounces a ton. Many samples from ore zones contain about 0.01 ounces, a few contain up to 0.04 ounces a ton. Higher gold contents have been found in pebble beds in the Timagami area where, unlike Elliot Lake, gold deposits occur in pre-Huronian rocks.

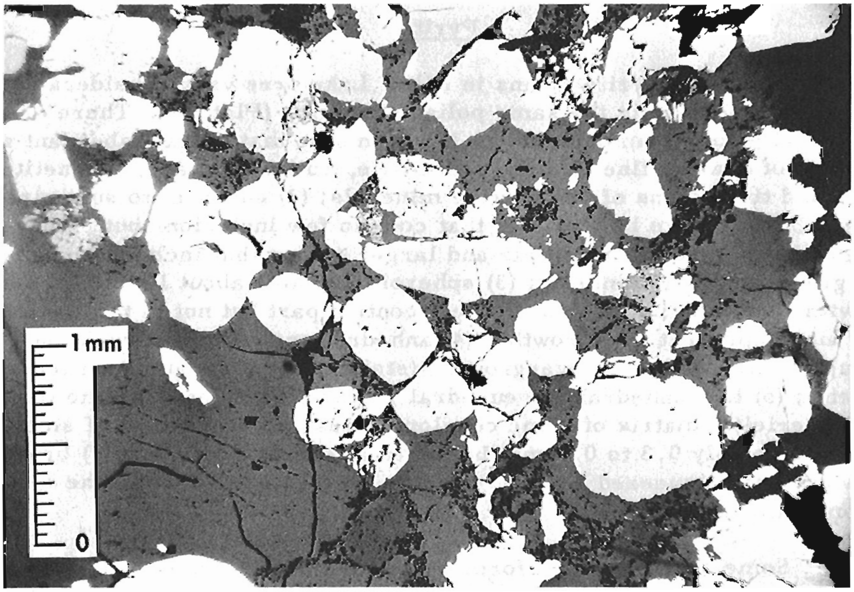
Minor amounts of pyrrhotite, chalcopyrite or cubanite, and millerite are associated with pyrite in some specimens. Tiny grains and veinlets of galena containing highly radiogenic lead are common in uraninite-rich ores and within individual uraninite grains, particularly in the Quirke zone. Thin calcite and quartz-calcite veins containing marcasite, pyrrhotite, sphalerite, galena and hydrocarbon cut ore. These are most common in the Quirke zone. Molybdenite and also hydrocarbon coat walls of some fractures.

PLATE III.

A. Pyrite grains (white) in matrix of conglomerate, Lacnor Mine. Several small grains of monazite and brannerite (light grey) are present. Dark grey areas are quartz, sericite and feldspar. Times 25. 200888-E.

PLATE III.

B. X-ray micrograph, base of Pronto ore. Tiny, brilliant white grains are uraninite; large white grains, pyrite; black, quartz; grey, feldspar, sericite, and rutile-antase-brannerite grains. Uraninite grains are concentrated at base of conglomerate layer and two have been pressed down beneath a quartz granule into underlying argillite.
Times 11. 200888-F.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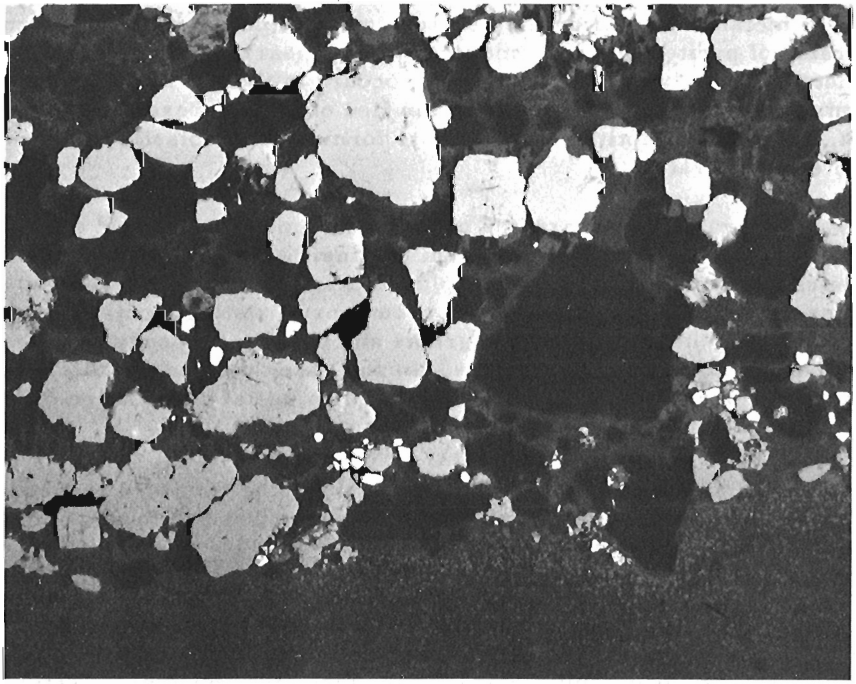


Pyrite

Individual pyrite grains in Elliot Lake ores vary considerably in appearance, even within the same polished section (Plate I). There are: (1) anhedral grains commonly about 1 mm in size that contain abundant small inclusions of quartz, fine-grained muscovite, rutile, anatase, magnetite, spinel, and tiny grains of radioactive minerals; (2) euhedral to subhedral grains 0.3 to 0.6 mm in diameter that contain few inclusions but embay quartz-pebbles or other minerals and larger grains that include normal sized grains of other minerals; (3) spheroidal grains about 1/2 mm in diameter with abundant inclusions in their control part but not in their rims which may represent overgrowths; (4) anhedral grains with curved markings that suggest boundaries of overgrowths (staining makes many such features apparent); (5) tiny anhedral and euhedral grains disseminated in the fine-grained sericitic matrix of some conglomerates; (6) aggregates of small grains, commonly 0.3 to 0.6 mm but up to 12 mm in diameter; (7) brecciated grains evidently squeezed between pebbles during compaction of the conglomerate.

Some structurally deformed conglomerates contain large aggregates of coarse pyrite intergrown with secondary quartz showing flamboyant structure and with muscovite, epidote, and rutile. Other dynamically and thermally metamorphosed conglomerates contain smaller euhedral or anhedral grains of pyrite that are homogeneous in appearance and are intergrown with metamorphic minerals. Pyrrhotite occurs in the most metamorphosed conglomerates in the Agnew Lake area in lieu of or in excess of pyrite. Quartz, muscovite, biotite and pyrrhotite form crystalloblastic intergrowths in such conglomerates.

The variety in character of pyrite in unmetamorphosed ores suggests that it may be of several different origins. Much of the pyrite may have been detrital; some of it may have replaced detrital iron-rich minerals; some, doubtless formed in situ, crystallized around pre-existing pyrite grains and was deposited in the matrix as tiny grains and in larger 'spongy' masses that included and replaced other minerals. In any case, the present distribution of most of the pyrite evidently corresponds to an initial distribution of detrital mineral grains that were about 0.3 to 0.5 mm in diameter.

The sulphides in radioactive conglomerates may be compared with the several different types of sulphide occurrences that are found near conglomeratic ores. These are: (1) pre-Huronian sulphides in Archean strata, in veins that do not extend up into Huronian rocks, and in pebbles in Huronian rocks; (2) indiginous sulphides in Huronian argillites and argillaceous greywackes; (3) sulphides in Huronian arenites and basal conglomerates that show little relationship either to argillaceous material or to radioactivity or to abundance of other heavy minerals; (4) sulphides along post-ore fractures; (5) post-Huronian epigenetic sulphides associated with diabase intrusions, and younger sulphide occurrences.

Work by Pienaar (1958) and the writer has shown that there are differences in contents of selenium, cobalt, nickel, and other elements and in the isotopic composition of sulphur in these various types of sulphide occurrences and in pyrite in ores, in less radioactive conglomerates, and in conglomerates interbedded with volcanic rocks (Table V). The data indicate that it is unlikely that the pyrite in radioactive conglomerates (1) is related to post-Huronian epigenetic processes that produced other types of sulphide concentrations or (2) that it is entirely detrital in origin although partially redistributed, or (3) that the sulphur was entirely of biogenic origin or (4) that the trace elements in the pyrite could have been inherited entirely from pre-existing magnetite. An hypothesis that the conglomerates contain a mixture of detrital pyrite, and pyrite formed through diagenetic processes is therefore tenable. This should be tested by analyzing individual grains and parts of grains of pyrite in the conglomerates and comparing pyrites that occur near argillaceous rocks, where biogenic generation of H_2S might have been at a maximum, with those that are more remote from such rocks - i.e., in conglomerates interbedded with volcanic rocks.

Uraninite

Uraninite occurs as subhedral grains most commonly about 0.1 mm in diameter, rarely as large as 0.2 mm or as small as 0.05 mm. Its size-range appears to be less than that of other heavy minerals. The largest grains are found in uraninite-rich conglomerates that are generally large-pebbled and contain relatively large, and relatively sparse grains of other heavy minerals. Concentrations of uraninite grains are commonly found at the base of conglomerate layers. Striking examples of such concentrations in the Pronto mine have been described by Holmes (1956). The writer has noted and photographed a uraninite grain that was pressed down beneath a quartz pebble into argillite that locally underlies the Pronto reef (Plate IIIB). The uraninite must have been present prior to compaction of Huronian sediments.

The most spectacular concentrations of uraninite are laminae of tightly-packed grains found along bedding and crossbedding planes in thin lenses of coarse-grained subarkose within uraninite-rich conglomerates in the Quirke and Denison Mines. The thicker laminae appear to show gradations in grain size and this was confirmed in the case of one specimen that contained a succession of laminae through a thickness of more than one-half inch (Plate IV). Grain size varies from as much as 0.2 mm at the base of laminae to as little as 0.1 mm at their tops. Other minerals, such as zircon, monazite, rutile, pyrite and quartz, within and between uraninite laminae are consistently larger than the uraninite. Small scale crossbedding is also found within multiple layers of uraninite grains. Layers of uraninite grains are deformed in places where they have been pressed down over quartz pebbles or where pebbles have been pressed down into them during compaction.

TABLE V

MINOR ELEMENTS AND ISOTOPIC COMPOSITION
OF SULPHUR IN SULPHIDES

A. radioactive quartz-pebble conglomerates

				ppm.				
		n	δS^{34}	Se	Ti	Co	Ni	Co/Ni
Stanleigh, Milliken, Lacnor,	min.			16	100	380	150	1.9
Nordic, Quirke, Denison,	med.	14		24	310	540	200	3.2
Panel, Pronto ores	max.			32	880	930	300	3.8
	min.		+1.1					
	med.	10	+1.9					
	max.		+2.4					
	min.			23	400	560	180	2.7
Spanish American ores	med.	3		20	730	720	210	3.1
	max.			34	1550	770	290	3.4
		1	+2.7					
Stanrock, Can. Met. ores,	min.			26	590	480	220	1.0
marginal and submarginal	med.	13		32	1200	680	420	2.0
conglomerates with high Th:U	max.			39	4700	1070	570	2.3
ratios in Matinenda Formation,								
Elliot Lake area	min.		+0.0					
	med.	8	+1.0					
	max.		+1.8					
Kamis hole north of Elliot Lake		1		<15	3400	920	330	2.6
Mississagi Formation (Stanrock)		1		<15	7300	430	210	2.1
Mississagi Formation (Stanleigh)		1	+1.8					
Mississagi Formation (Wanapetei Lake)		1	+0.7					
Mississagi ? (Turner Township)		1	+1.6					
	(c)	1	+1.6					
Interbedded with Thessalon volcanics, Aberdeen Township		1	+3.6					
Altered ore, Nordic		1		19	220	420	230	1.9
Altered ore, Panel		1		33	260	650	260	2.3
	min.		0.0					
Altered ore, Can. Met.	med.	4	1.3					
	max.		2.7					
Metamorphosed conglomerate	min.		0.6					
Agnew Lake area	med. (a)	6	1.5					
	max. (c)		5.1					

Notes: Sulphides analysed are pyrites excepting: (a) pyrite and pyrrhotite; (b) pyrite, pyrrhotite and chalcopyrite; (c) pyrrhotite; (d) pyrrhotite and chalcopyrite; (e) chalcopyrite; (f) sphalerite.

Analyses for Se, Ti, Co, and Ni are compiled from Pienaar (1958, appendix page 13, Table VIII). Sulphur isotope analyses were made under supervision of R.K. Wanless, Geological Survey of Canada.

B. 'non-radioactive' rocks

		n	δS^{34}	Se	Ti	Co	Ni	Co/Ni
Archean greenstone, Denison		1		47	1060	940	330	2.8
greenstone, Pecors Lake		1		36	3500	6200	860	7.2
greenstone, Nasco		1	3.8					
greenstone, San Antonio		1	1.8					
sulphide 'bed' Samreid Lake		1	1.3					
	(c)	1	2.7					
	(c)	1	3.1					
	min.		2.7					
sulphide-rich pebbles, Matinenda	med.	4	2.9					
	max.		3.3					
	(c)	1	0.9					
	min.			36	450	560	1130	0.11
Huronian argillaceous rocks	med.	6		47	980	800	2020	0.33
Ramsay Lake, Pecors, Bruce,	max.			63	1800	1440	4400	0.65
Espanola Formations								
	min.		2.7					
	med. (a)	7	5.6					
	max. (c)		8.9					
	min.			15	90	480	170	2.2
'non-argillaceous' Huronian	med.	4		17	260	1120	270	4.2
sediments, argillaceous basal	max.			23	1030	1920	400	6.4
conglomerate and paleosol								
	min.		-1.3					
	med.	8	0.0					
	max.		+1.2					
Mississagi Formation, Stinson Lake		1		22	1020	1350	1140	1.2
veins cutting conglomerate		1	-17.2					
ore		1	+ 4.2					
	(f)	1	+ 6.0					
Post-Huronian diabase		1		41	8000	1860	440	4.3
		1		43	160	7000	840	8.3
	min.		1.9					
	med.	10	4.4					
	max.		5.3					
Bruce Mines copper ore	(e)	1	-2.2					
Pater copper ore	(e)	1	0.0					
	(d)	1	+2.9					

n – number of samples,

$$\delta S^{34}\text{‰} = \left[\frac{S^{34}/S^{32}\ \text{sample} - S^{34}/S^{32}\ \text{standard} \times 1000}{S^{34}/S^{32}\ \text{standard}} \right]$$

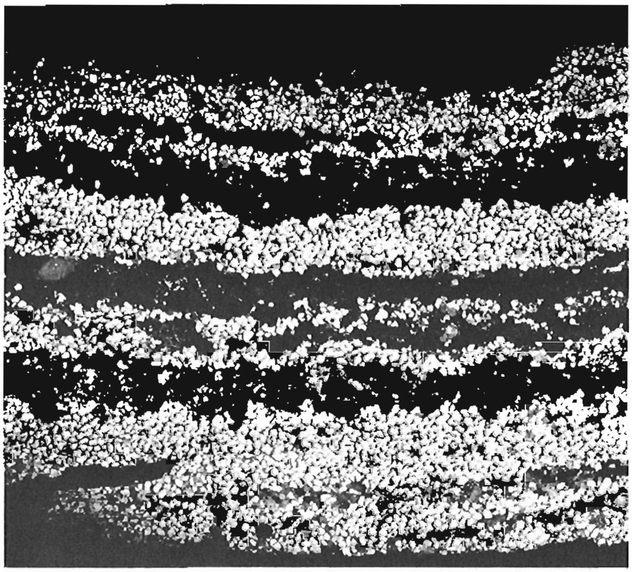
standard used here is Cañon Diablo meteorite with $S^{32}/S^{34} = 22.22$

min. max. – minimum and maximum individual values
med. – median value of n samples.

PLATE IV. Uraninite-rich layers in thin, crossbedded subarkose lens within ore, Quirke Mine (Sample 58-RF-8).

A. X-ray micrograph of a thin section. Individual uraninite layers have flat bases and irregular tops. A few of the largest white grains are pyrite rather than uraninite. Large, grey grain at left centre is zircon. Other grey grains, slightly larger than uraninite grains include uranothorite, brannerite and monazite. 200888-G.

B. Photomicrograph of lower uraninite layer on a surface adjacent to thin section A. There is an upward gradational decrease in size of uraninite grains in this and other layers. Tiny brilliant white grains are galena. 200888-H.



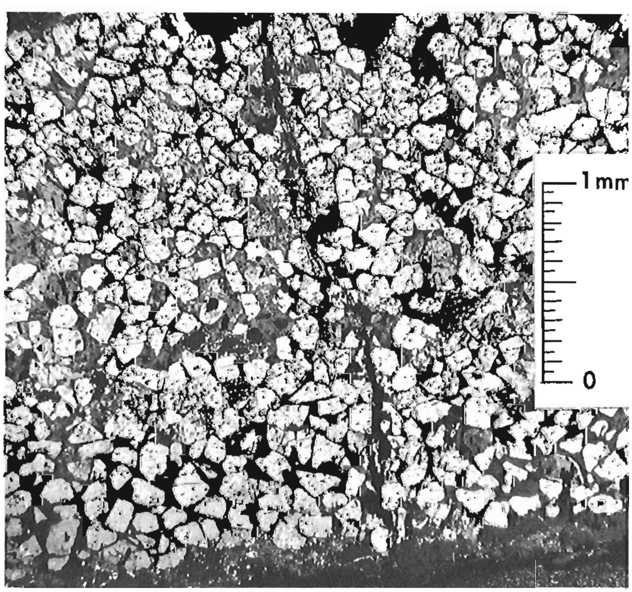

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TABLE VI

PARTIAL ANALYSES OF URANINITES

	uranium	thorium	rare earth oxides	lead	Th/U	U/Th	R.E./Th	Pb/Th	Pb/U
1	44.51	4.93	5.92*		0.111	9.05	1.20		
2	41.12			13.93					0.312
3	50.15	5.35	5.93*	14.31	0.106	9.45	1.11	2.68	0.283
4	55.13	6.02	5.69*	14.09	0.109	9.15	0.95	2.24	0.256
5	43.8	3.6		10.7	0.082	12.1		2.9	0.244
6	48.3	4.5		5.2	0.093	10.7		1.2	0.108
A	51	5.2			0.10	10			
B	55	5.5			0.10	10			
C	41.1	4.91	8.4 ?	25.2	0.119	8.37		5.13	0.613
D	47.1	4.73	+4.4 ?	23.5	0.100	10.0		5.01	0.503
E	46.8	5.50	6.2	19.7	0.117	8.50	1.13	3.58	0.421
F	55	6.0	6.5	24	0.108	9.25	1.08	4.0	0.436
G	63.23	6.52	2.87*	9.50	0.103-	9.57	0.44	1.46	0.150
H	63.74	6.37	2.93*	9.57	0.100	10.0	0.46	1.50	0.150

*3b Analyses of precipates of total rare earths

	Y_2O_3	Nd_2O_3	CeO_2	Dy_2O_3	Sm_2O_3	Er_2O_3	Pr_2O_3	La_2O_3	Gd_2O_3
1	38.1	14.1	14.5	9.1	6.0	5.0	3.0	3.0	7.2
3	37.8	14.1	12.4	10.1	6.6	5.2	2.5	2.5	7.8
4	40.7	12.1	10.6	12.4	6.4	6.1	3.1	1.2	7.8
G	50.4	13.4	10.1	9.1	5.2	6.9	1.8	1.1	5.9
H	46.6	13.6	10.2	8.6	5.1	5.8	2.3	1.0	5.9

Description and location of specimens, sources of analyses.

1. Sample 58 RF-8 - uraninite rich layer, 4 level E, Quirke Mine (plate IV), contains 10-15 per cent SiO_2; mineral impurities apart from abundant galena include quartz, minor feldspar, sericite, brannerite, pyrite, monazite and zircon. A single lump of the natural specimen was crushed and analyzed; no mineral separation was made.

2. Sample 58 RF-8 - a lump adjacent, and similar to 1. This was taken because lead was lost from No. 1 during analytical work; Th:U, R.E.:Th ratios can be assumed to be similar to those in 1.

3. Uraninite concentrate separated from other fragments of 58 RF-8.

4. Uraninite concentrate, Denison Mine, separated from a large sample of high grade ore. Hand picked, it contained no recognizable mineral impurities.

5. Uraninite concentrate, Nordic Mine, Wanless and Trail (1956).

6. Uraninite concentrate, Pronto Mine, Wanless and Trail (1956).

A. Uraninite concentrate, Denison Mine, Roscoe (1959).

B. Uraninite concentrate, Nordic Mine, Roscoe (1959).

C. Uraninite concentrate, Denison Mine, uraninite laminae in cross-bedded quartzite, Pienaar (1958).

D. Uraninite concentrate, Denison Mine, Pienaar (1958).

E. Uraninite concentrate, Nordic Mine, Pienaar (1958).

F. Calculated composition of a uraninite 2.4 b.y. old having Th:U and R.E.:Th ratios, as indicated, similar to those in above uraninites.

G. Uraninite (58 RC-9), Halo Mine, Bancroft area, Haliburton Co., Ontario, 102 W.x-cut, in pyroxenite that also contains molybdenite. Collected by S.C. Robinson.

H. Uraninite (56 RC-24), Halo Mine, Bancroft area, Haliburton Co., Ontario, 102 E.x-cut, in granite pegmatite containing abundant sulphides. Collected by S.C. Robinson.

Chemical compositions of uraninites from various parts of the Elliot Lake area are very similar and closely resemble the compositions of thorium and rare earth-bearing uraninites found in the Bancroft area and in other high temperature or pegmatitic deposits (Table VI). It is unlikely that such uraninite could have been formed in unmetamorphosed, unaltered Huronian rocks. Lower temperature uraninites, such as those found in sandstone impregnation deposits in the western United States and in vein-type deposits, contain very little thorium and rare earths. Even these deposits have some rock alteration associated with them.

The uraninite is evidently of detrital origin. The only other possibility would be that it is pseudomorphic after some detrital mineral about as heavy as uraninite, and there is no evidence whatever that this is the case. Thorianite, uranothorianite, and perhaps galena are practically the only possible choices for an antecedent, very heavy, detrital mineral and none of these appear to be any more likely than uraninite itself. Patchett (1959) reported that some uraninite grains have carbonaceous cores and considered this to be evidence that the uraninite was epigenetic. The carbonaceous material could represent inclusions that were present in detrital grains, however, and in any case there is no evidence that it is commonly present. The writer has never noted any such carbon cores, nor were any reported by Ramdohr. Epigenetic hydrocarbon is locally associated with uraninite and gradations are found between uraninite-rich layers such as those shown in Plate IV, layers of uraninite grains with interstitial radioactive hydrocarbon, and tucholite seams that contain remnants of uraninite grains.

Titania-rich Grains or Aggregates

Most of the rutile, anatase and brannerite in radioactive conglomerates occur in ovoid grains or aggregates about 1/4 to 1 1/2 mm in diameter (Plate III). Individual grains differ in character. Some are composed of massive rutile or anatase but the most common types are composed of needles of rutile intergrown with quartz (Plate V). Sericite, carbonate, chlorite, pyrite and pyrrhotite also occur in many of these grains. In some grains, the needles or prisms of rutile are aligned in one, two, or (most commonly) three directions. Ramdohr (1958b, p. 18) has interpreted examples of the latter type as relic structures of unmixed titaniferous magnetite.

All of the rutile and anatase is weakly radioactive but most of the composite grains contain a separate, much more radioactive phase. Most commonly, this occurs as a rim of fine-grained material around the titaneferous grains (Plate V). Needles or 'feathery' intergrowths of brannerite are present in many grains. These are commonly concentrated near the margins of the grains and may have been formed through recrystallization of the fine-grained uraniferous material that rims grains. The most uraniferous conglomerates contain grains that consist of brannerite, quartz, and pyrrhotite with little or no rutile or anatase. Grains of massive or nearly massive

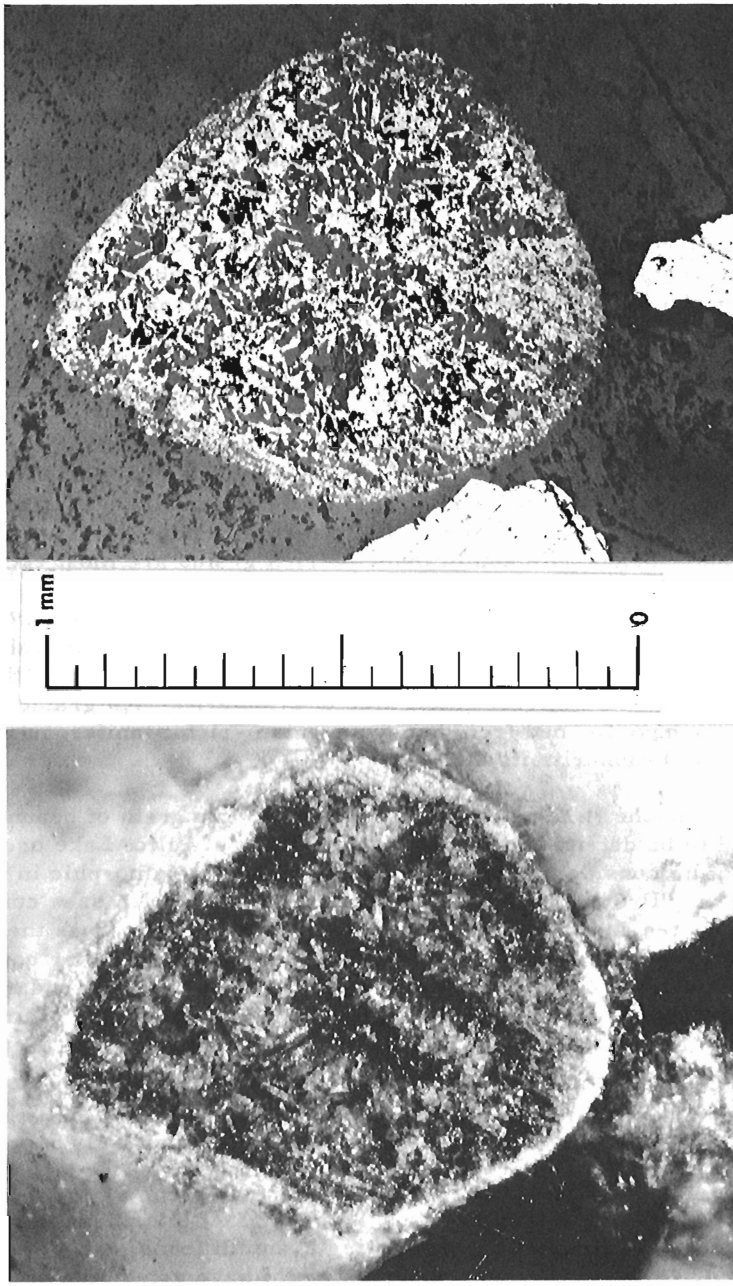

PLATE V. Large composite grain of rutile-anatase-quartz-brannerite. Top, reflected light; bottom, oblique illumination. Brannerite and radioactivity is concentrated at altered rim of composite grain. 200888-I, 200888-J.

brannerite are found in some samples. Weakly radioactive titaniferous grains occur in conglomerates that contain brannerite-rich grains as well as in conglomerates that contain little or no brannerite.

In addition to the ovoid grains discussed above, there are wispy streaks of anatase in the matrix of conglomerates and many prismatic, wedge-shaped, and platy grains that contain abundant anatase or rutile. Some of these also contain brannerite, or supposed brannerite, most commonly along their margins. The various distinctively shaped titaniferous grains are partially or completely altered remnants of detrital sphene, amphibole, biotite, and (probably) pyroxene. Many of the ovoid aggregates are doubtless of similar origin.

There are some interesting size relationships amongst the titaniferous grains. The largest and least titaniferous are those derived or probably derived from chloritic mafic minerals. The more titaniferous relics of sphene are smaller. Massive or near-massive rutile grains that might have been derived from detrital ilmenite and rutile grains are still smaller - about 0.3 mm in diameter, comparable to many 'rounded' detrital appearing pyrite grains. Brannerite and brannerite-rich grains are most commonly still smaller but are larger than associated uraninite grains. The sizes of different types of grains thus appear to be inversely proportional to their specific gravities or to the specific gravities of antecedent minerals. The larger, lighter, heavy minerals were evidently deposited along with smaller, heavier ones. The relatively small size of brannerite-rich grains suggests that they may have formed from heavy, uranium-rich titaniferous grains, most logically brannerite itself.

Ramdohr (1958a, pp. 17-18) observed one grain of brannerite that he believed to be detrital in the polished sections of Elliot Lake ores that he studied, but he considered that most brannerite is metamorphic in origin, formed by the "Pronto-Reaktion" between TiO_2 and UO_2 in ores containing rutile aggregates and uraninite. The interpretations as well as the observations and microphotographs of this outstanding mineralographer command respect. There is no doubt that much of the brannerite is secondary but the writer has found no evidence that it has formed at the expense of uraninite as suggested by Ramdohr and would prefer to consider it a diagenetic mineral in most places rather than a metamorphic mineral which it may be at Pronto.

The secondary brannerite was probably formed in two stages, an early stage wherein uranium was extracted from solution and absorbed by TiO_2, and a later stage wherein much of the uraniferous TiO_2 crystallized to form brannerite. Hydrated titanium oxide is known to be a most effective collector of uranium (Loskorin _et al._, 1958), in fact this phenomenon is the basis of a proposed process for extracting uranium from sea water (Davies _et al._, 1964). Altered titanium minerals might have acted as a collector of uranium through a history that began as early as the weathering of their parent rocks, and continued during their sojourn in paleosol, and during their transport, burial and diagenetic alteration.

Monazite

Rounded grains of monazite about 0.3 mm in diameter are abundant in most ores and smaller grains are common in less radioactive conglomerates, grit, and subarkose. Red, orange, yellow and grey monazite grains have been found together in a single ore sample. The grey variety is the most abundant type in ores. It contains a little finely disseminated pyrite and 'inclusions' of a relatively radioactive material, possibly uranothorite, that results in a higher thorium and much higher uranium content than is present in other monazites. It has been shown (Roscoe, 1959b) that excess uranium and thorium is dissolved from the mineral during ore treatment and that monazite is an important ore mineral in ores that have ThO_2:U_3O_8 ratios greater than 0.5.

The relatively radioactive phase present in grey monazite appears to have been an integral part of the original detrital grains. There is a possibility, however, that this phase was introduced into certain types of monazite grains but not into others subsequent to the deposition of the conglomerates.

Zircon

Violet, pale mauve, and brownish zircons occur as rounded elongate grains in conglomerates and subarkoses. They are less abundant in large pebble, uraninite-rich conglomerates than in small-pebble, weakly radioactive conglomerates. The relatively small size of most zircon grains appears to offer an explanation for this phenomenon. Zircons should be about 0.2 by 0.4 mm in size in order to be hydraulically equivalent (Sundborg, 1956) to 0.1 mm uraninite grains and 0.3 mm monazite grains found in rich conglomerates. A few grains this large are found associated with abundant uraninite but most zircon grains are considerably smaller (0.1 to 0.2 mm long) and hence were swept farther downstream.

Thucholite

Little is known about the distribution, importance, or significance of tucholite in Elliot Lake ores and other ratioactive conglomerates. It occurs most commonly in thin seams along bedding in relatively rich sections within ore zones. The hydrocarbon evidently derived its radioactivity from the radioactive minerals that it has replaced locally.

CHEMICAL-MINERALOGICAL CLASSIFICATION

Proportions of heavy minerals in conglomerates vary greatly not only from area to area but laterally, and even vertically from bed to bed, within the same ore zone. It is extremely difficult and tedious to make modal analyses of radioactive conglomerates so a chemical classification is presented here. The distinctive elements of the heavy mineral assemblages are iron, sulphur, titanium, rare earth elements, thorium, phosphorus, uranium, and zirconium. A summary of results of analyses of 66 conglomerate specimens for these elements, excepting sulphur, phosphorus, and rare earths, is given in Table VII.[1] The specimens were collected from drillcores and include conglomerate well above ore zones and remote from ore zones as well as samples from all parts of the Quirke and Nordic zones. The analyses were divided into five groups on the basis of relative abundances of the elements Ti, Zr, Th (as ThO_2) and U (as U_3O_8).

Type 1, with $U_3O_8 > Ti > ThO_2 > Zr$, are uraninite-rich conglomerates. They have the lowest ThO_2:U_3O_8 ratios, approaching 0.10 - the ratio in uraninite - in the richest specimens. There is a direct correlation between U_3O_8 and ThO_2 as both are mainly in the same mineral, uraninite. Correlations between other sets of elements, such as Ti and Zr, however, are poorer than in other groups. Pyrite contents and pyrite:uraninite ratios vary widely. The conglomerates contain relatively little monazite, hence their rare earth contents, particularly Ce and La, are low. They are slightly richer in rare earths than they are in thorium, however, as the uraninite contains almost equal amounts of thorium and rare earths that include a higher proportion of Y and Yb than is present in the rare earths in monazite. The heavy mineral suite is simple compared to that of other groups. The rarer heavy minerals are not likely to be found in it, although cassiterite was found in such a suite and the highest gold assays in Elliot Lake uranium ores have been obtained on conglomerates of this group. The median uranium content of this group is much higher than average ore grade, probably because the samples were selected from the most radioactive sections of well-packed pebble beds. Such sections contain a large part of the uranium in ore zones but are admixed with much larger quantities of lower grade, poorly-packed conglomerate and nearly barren pebbly subarkose.

Type 2, with $Ti > U_3O_8 > ThO_2 > Zr$, contains abundant grains of radioactive rutile and anatase that commonly have a more radioactive rim as well as grains that contain intergrowths of titanium oxide, brannerite, and quartz. Grains of pure brannerite are rare. Variable amounts of uraninite are present and it is probably the main ore mineral in many cases. Monazite is considerably more abundant than in type 1 conglomerates, consequently the content of rare earth elements is higher. Correlations between U_3O_8 and ThO_2 are poorer than in type 1 but correlations between ThO_2, Ti and Zr are better. Given samples of equal uranium content, it is easier to find a large variety of minerals in heavy mineral concentrates of samples in this group than in samples of type 1.

Type 3, with $Ti > ThO_2 > U_3O_8 > Zr$, are monazite-rich conglomerates that also contain abundant titaniferous grains of the types found in type 2. Brannerite, or at least recognizable brannerite grains or crystals

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[1] Individual analyses are listed in Appendix Table B.

TABLE VII

CHEMICAL CLASSIFICATION AND ANALYSES OF PYRITIC QUARTZ-PEBBLE CONGLOMERATES

conglomerate type	order of abundance of diagnostic elements	No. of samples		% U_3O_8	% ThO_2	% Zr	% Ti	% Fe
			minimum	0.19	0.038	0.011	0.06	3.8
1	Fe > U > Ti > Th > Zr	14	median	0.47	0.071	0.025	0.16	5.8
			maximum	1.8	0.19	0.09	0.45	18.0
			minimum	0.047	0.016	0.010	0.12	4.0
2	Fe > Ti > U > Th > Zr	14	median	0.16	0.07	0.024	0.40	8.2
			maximum	0.36	0.16	0.082	0.44	11.0
			minimum	0.025	0.04	0.008	0.15	3.8
3	Fe > Ti > Th > U > Zr	24	median	0.07	0.12	0.023	0.44	6.4
			maximum	0.19	0.30	0.060	1.0	13.0
			minimum	0.012	0.06	0.013	0.35	4.5
4	Fe > Ti > Th > Zr > U	6	median	0.018	0.12	0.035	0.50	6.2
			maximum	0.052	0.17	0.063	1.3	18.0
			minimum					
5	Fe > Ti > Zr > Th > U	1	median	0.007	0.012	0.035	0.27	1.4
			maximum					

intergrown with rutile, is less abundant than it is in either of the preceding types. Uranothorite is not uncommon but uraninite is fairly rare. Radioactive rims on titaniferous grains, and grey monazite are the main ore minerals in conglomerates of this type. There is excellent correlation between Ti, ThO_2, U_3O_8 and Zr in this group and correlations of these elements with iron is better than in other types.

Type 4, with Ti > ThO_2 > Zr > U_3O_8, is characterized by abundant rutile, monazite and zircon. The titaniferous grains and monazite grains do not appear to contain as many highly radioactive inclusions, rims or patches as they do in type 3 conglomerates but this is not certain. Individual grains of highly radioactive minerals – uraninite, uranothorite and brannerite are rare. There is excellent correlation between abundances of Ti, ThO_2, Zr and U_3O_8 in these conglomerates but, as in type 1, little correlation between them and iron. Pyrite is very abundant in some samples of this type despite their low radio-element contents.

The group was undersampled in this study. One of the six samples is from a conglomerate bed in the Mississagi Formation and had a ThO_2:U_3O_8 ratio of 10. If this sample were omitted, the median ThO_2 and U_3O_8 contents for the type would be 0.10 per cent and 0.02 per cent respectively. The highest uranium content found was 0.052 per cent. Many other conglomerates that the writer believes to belong to this group (on the basis of their mineralogy) have U_3O_8 contents as high as 0.1 per cent and ThO_2:U_3O_8 ratios as low as 1.5. In some conglomerates ThO_2 contents as high as 0.5 per cent may exceed Ti contents.

<u>Type 5</u>, with Ti > Zr > ThO_2 > U_3O_8, is represented by only one sample of the 79 analyzed for all five elements, but it is nevertheless of great interest as it is in this group alone that abundance of all of the definitive elements are in the same relative order as they are in pre-Huronian granites, paleosols developed on granites, and in common Huronian subarkoses, siltstones and argillites. This group may in fact represent a common type of radioactive concentration in Huronian rocks. Most radioactive grit, pebbly subarkose beds, and thin layers of small pebble conglomerate throughout the region may belong to this group rather than to type 4. The writer's sampling was concentrated in ore zones and special attention was paid to well-packed conglomerates and to intervening pebble-free subarkose beds whereas intermediate rocks such as pebbly subarkose and layers of single pebbles were ignored on the supposition that they likely represented hybrid mineralogical types. Such rocks commonly contain concentrations of rutile or anatase, zircon, some monazite and relatively sparse, fine-grained pyrite. They lack highly radioactive minerals.

The classification was developed to simplify descriptions of mineralogical variations in this report but it might be of more general use. For example, the weakly radioactive pyrite conglomerate in the Hurwitz Group west of Hudson Bay (Heywood and Roscoe, 1967) can be compared to Elliot

Lake conglomerates by categorizing it as a type 5 conglomerate. The conglomerates at Lake Agnew Mines resemble types 3 and 4. The Witwatersrand conglomerates are more similar to type 2. The radioactive conglomerates in the Lorrain Formation and in the Otish Mountain Group are somewhat analogous to type 4 but contain hematite and other black opaques in lieu of pyrite and have higher ThO_2:U_3O_8 ratios probably because their monazite does not include the uranium-rich variety found at Elliot Lake.

The scheme makes it possible to classify conglomerates precisely if analyses for the four diagnostic constituents are available, but approximate classifications can be made with less information. It is possible to distinguish minerals under a hand lens in many specimens, particularly sections of drill-core. Mineralogical differences between type 1 and types 2 or 3, and between types 2 or 3 and types 4 or 5 can be recognized in this way excepting where pyrite is so abundant that it tends to hide other minerals. In addition, a high uranium analysis, or even very high radioactivity, will eliminate the possibility that the specimen is type 4 or 5 and knowledge of the Th:U ratio will serve to separate types 1 and 2 from types 3, 4 and 5.

MINERALOGICAL ZONATIONS

The variations in ThO_2:U_3O_8 ratios in Elliot Lake ores and conglomerates that have been described by Roscoe and Steacy (1958), by D.S. Robertson and N.C. Steenland (1960), and particularly well documented by D.S. Robertson (1962) reflect variations in mineralogical character of conglomerates. Such variations are best illustrated in the Quirke ore zone and its southeastern, sub-ore grade fringes which contains all of the mineralogical types described above. In most parts of the zone, two or more of these types are interbedded. Type 1 (or uraninite-rich) conglomerate is most abundant near the 'upstream head' of the Denison reef on the Algom-Quirke and Denison properties. Farther southeast, type 2 (brannerite-rich) conglomerate is probably the dominant type but type 1 and type 3 (monazite-brannerite) conglomerates also occur. Still farther 'downstream' to the southeast on the Spanish American, Stanrock and Can Met properties, type 1 is absent and type 4 (monazite-zircon) conglomerate appears.

These mineralogical changes in the downstream direction are accompanied by decreases in pebble sizes, in sizes of heavy mineral grains, in thicknesses of individual conglomerate beds and in total thicknesses of the reef. The latter two factors are as important as mineralogical changes in controlling the downstream and lateral limits of the ore zone. In some places the limit is reached within material dominated by conglomerates of type 2 and having a ThO_2:U_3O_8 ratio less than 1. In other places the extremity of the ore zone is within conglomerate of type 3 and, near the east side of Quirke Lake, it may extend into type 4 material with a ThO_2:U_3O_8 ratio as high as 4:1.

The main reef in the Nordic zone does not show pronounced downstream mineralogical and other variations comparable to those in the Quirke zone. The zone contains type 1 (uraninite-rich) conglomerate throughout its length but grades laterally into type 2 conglomerate along its southwest and northeast margins. The mean ThO_2:U_3O_8 ratio of 2,000,000 tons of ore at Stanleigh Mine near the head of the zone was 0.15, whereas that in 100,000 tons of ore from each the 3 'downstream' mines was 0.18 according to D.S. Robertson (1962). The overlying, more extensive, Pardee reef is probably composed mainly of type 2 conglomerate in the ore zone area and type 3 conglomerate east of the ore zone. Conglomerate beds above the Pardee reef in the ore zone area are type 3 conglomerates with Th:U ratios between 1 and 2. Subarkose and grit in the same stratigraphic zone have Th:U ratios between 1.4 and 2.7.

The Whiskey Lake submarginal zone contains type 4 conglomerates. These may change sourceward towards the northwest into more uraniferous types.

Successively higher conglomerate beds at any given place within the Matinenda Formation are successively farther 'downstream' from their heads. For this reason, we find the same trend upwards through the section from type 1 to type 5 conglomerates that is found in the downstream direction within a given reef. The upward increase in ThO_2:U_3O_8 ratios in successions of conglomerate beds is apparent even within ore zones, although reversals are common and beds below the ore zone have ThO_2:U_3O_8 ratios higher than that in the ore.

Exploration possibilities within an area should not be evaluated solely on the basis of the most radioactive conglomerate beds within the section. Consider, for example, a section of Matinenda Formation that contains a marginal type 2 conglomerate zone at its base and a submarginal type 4 conglomerate bed 200 feet above its base. The type 2 conglomerate may not extend far enough sourceward to improve appreciably in grade or thickness but the type 4 conglomerate 200 feet above the base may extend miles headward, thickening and changing in this direction to types 3, 2 and, finally 1.

Variations in mineralogy and ThO_2:U_3O_8 ratios in subarkose and grit are not so pronounced as those in conglomerates. The lowest ratios - about 0.5 - are found in subarkose interbedded with type 1 ore, but there is no close correlation between ratios in conglomerates and associated subarkose and grit. In one case - Quirke drillhole No. 63 - for example, grit with a ratio of 3.5 is associated with conglomerate, in the main ore zone, which has a ratio of 0.26 whereas a higher conglomerate bed with a ratio of 3.5 is associated with grit that has a ThO_2:U_3O_8 ratio of 1.4.

Well-packed conglomerate layers commonly contain 20 to 100 times more uranium, and in some cases contain as much as 400 times more uranium, than adjacent subarkose layers.

The mineralogical zoning of conglomerate 'reefs' is demonstrated in a different way in Table VIII. The median concentrations of U_3O_8, ThO_2, Zr, Ti, and Fe in some Archean granites and granitic paleosols near the east side of Quirke Lake are arbitrarily taken as representative of amounts present in the source detritus for the Elliot Lake Group. The concentration ratios of these elements in type 1 conglomerate at the head of a reef zone, in conglomerate types 2, 3, 4 and 5, in 'non-radioactive' coarse-grained subarkose, and finally in argillite, each progressively farther downstream, are shown as factors of their concentrations in the hypothetical average source material.

TABLE VIII

RATIOS OF CONCENTRATION OF DIAGNOSTIC ELEMENTS

	U_3O_8	ThO_2	Zr	Ti	Fe
granite and granitic paleosol	1	1	1	1	1
conglomerates					
type 1	250	17	5	4	4
type 2	85	17	5	10	6 1/2
type 3	37	29	5	11	5
type 4	9 1/2	29	7	12	5
type 5	4	3	7	6 1/2	1
subarkoses	.4	.4	1 1/2	1.3	.7
argillites	4	2 1/2	2 1/2	1	3

Uranium, largely in uraninite, was enriched 250 times in type 1 conglomerate in the upstream part of our model quartz pebble gravel deposit. The bulk of the uraninite grains, which were 0.05 to 0.2 mm in diameter, were entrapped in this part of the deposit, whereas the bulk of other, more abundant, lighter types of heavy minerals were carried farther downstream. Some grains of iron and titanium minerals, monazite and zircon were sufficiently large to be hydraulically equivalent to 0.1 mm uraninite grains and were therefore deposited along with the uraninite. Larger quantities of smaller grains of these minerals, however, were accidentally entrapped despite their non-equivalence hydraulically to uraninite. This would account for the poor correlations amongst Fe, Ti, Zr and Th in type 1 conglomerate.

The sizes of most heavy minerals were largely controlled by their sizes as accessory minerals in igneous rocks. Zircons are amongst the smallest accessory minerals in granitic rocks in the region so it is not surprising that most were carried farther downstream than monazite grains. Grains of titanium minerals evidently occurred in a wide range of grain sizes but many were of a hydraulic equivalent size similar to zircon grains and were concentrated along with zircon in the smallest pebble conglomerates and in coarse subarkose. The original iron minerals probably occurred in a great range of sizes in the source detritus but there appears to be a significantly greater concentration of iron in type 2 conglomerate than in other types.

Uranium is more concentrated in argillites, particularly black argillite, than in clean, well-washed subarkoses away from the ore zones. This indicates that significant quantities of uranium were carried in solution along with the detritus and became absorbed in clay minerals. It has been postulated above that altered titanium minerals were particularly efficient absorbents of uranium and that this process may account for some of the uranium concentrated in types 2 and 3 conglomerates.

ISOTOPIC AGE OF LEAD IN RADIOACTIVE AND NON-RADIOACTIVE MINERALS

General

Isotopic compositions of leads in Huronian rocks provide a means of testing various hypotheses concerning the ages and origins of radioactive minerals and of lead-bearing non-radioactive minerals in Huronian ores and rocks. Radiogenic lead has leaked from radioactive minerals and has become incorporated in non-radioactive minerals. Hence the isotopic compositions of leads in non-radioactive minerals as well as daughter-parent ratios and Pb_{207}:Pb_{206} ratios in radioactive minerals should be considered if one is to seek an estimate of the time of formation of the Huronian ores. The isotopic compositions of radiogenic lead in non-radioactive minerals can provide considerable information concerning the character and age of its radioactive parental material. Such data establish that dates obtained on uraninite concentrates are minimum dates and that the oldest of them – about 2.2×10^9 years – postdates the actual time of formation of the mineral and the time of formation of ore-like concentrations in Huronian rocks. Discussions of the available lead isotope data may be better or more widely understood if some principles of lead isotope geology are reviewed briefly.

Significance of Variations in Isotopic Compositions of Leads

Ordinary lead correction

Natural uranium contains a mixture of uranium isotopes U_{238} and U_{235} which disintegrate to form lead isotopes Pb_{206} and Pb_{207} respectively. As a result of the much more rapid decay rate of U_{235} as compared to that of U_{238}, the U_{235}:U_{238} ratio, at present 1:137.8, has been decreasing through geological time and there has been a corresponding decrease in the ratios of Pb_{207}:Pb_{206} produced by decay of uranium. Thorium disintegrates to form Pb_{208}. Lead isotope Pb_{204} has no radioactive parent. Leads extracted from large volumes of geologic material with 'normal' contents of lead, uranium and thorium have Pb_{206}:Pb_{204}, Pb_{207}:Pb_{204} and Pb_{208}:Pb_{204} ratios that vary systematically with age (due to additions of uranium and thorium daughter leads) through a narrow range. Such leads are termed ordinary leads. Ordinary lead in potash feldspar and in other non-radioactive minerals in Archean granites and older rocks must have been incorporated in Huronian sediments. Various data – e.g. Russell and Farquhar, 1960; Tilton and Stieger, 1965 – suggest that this lead should have had isotopic ratios that are not appreciably greater than the following: Pb_{206}:Pb_{204}-14.05, Pb_{207}:Pb_{204}-14.85, Pb_{208}:Pb_{204}-33.90. All leads in Huronian rocks have ratios greater than this and can be considered to contain mixtures of radiogenic lead (Pb_r) generated subsequent to the crystallization of Archean granites and ordinary lead (Pb_o) resembling that specified above. The composition of the radiogenic leads can be obtained by subtracting ordinary lead isotope ratios from the ratios present in the mixture. The porportion of radiogenic lead to ordinary lead and the ratios of Pb_{207} to Pb_{206} and Pb_{208} to Pb_{206} in the radiogenic lead can then be calculated. The latter two ratios in various leads from the Elliot Lake area are plotted in Figure 11.

Ratios of radiogenic lead to ordinary lead

If we assume that ordinary lead was fairly uniformly distributed in Huronian subarkoses and associated quartz-pebble conglomerates, the Pb_r:Pb_o ratios of leads in non-radioactive minerals reflects the abundance of radiogenic lead in the rocks. This abundance is a measure of the concentration of radioelements in the source of the radiogenic lead and the size and proximity of this source; it is also a measure of the time during which the lead was generated in the source. Abundant radiogenic lead may have been generated, for example, during a short period in an extensive very radioactive source or during a longer period in a less radioactive source.

Ratio of Pb_{207} to Pb_{206}

The ratio of Pb_{207} to Pb_{206} generated in uranium has been decreasing through geological time and the ratio at any given time may be calculated from the decay constants of U_{235} and U_{238}. The ratio 2.5×10^9 years ago, for example, was 0.36 whereas it is 0.046 at present. The ratio in lead generated during any given interval can also be calculated (see Russell and Farquhar, 1960) or we may calculate a series of intervals during which lead a given Pb_{207}:Pb_{206} ratio might have been generated. Radiogenic lead with a ratio of 0.2, for example, could have been separated 1.6 x 10^9 years ago (t_s) from a radioactive mineral that formed 2.0 x 10^9 years ago (t_m); some alternative possibilities for the interval t_m-t_s, expressed in 10^9 years include 1.9-1.7, 2.1-1.5, 2.4-1.0, 2.7-0.5 and 2.87-0. Note that the ratio 0.2 in this example establishes that the lead could not have been removed more than 1.8 x 10^9 years ago from a source that was formed no less than 1.8 x 10^9 years ago and no more than 2.87 x 10^9 years ago. Independant geochronological considerations and Pb_r:Pb_o ratios may place further limitations on possible combinations of t_m and t_s. Various possible combinations of t_m and t_s for Elliot Lake leads are indicated in Figure 11. In the special case of leads in radioactive minerals, t_s must be equated to zero (or present time) but, if there has been loss of lead from the mineral, t_m will be a minimum date.

Ratio of Pb_{208} to Pb_{206}

The ratio of thorium daughter lead, Pb_{208}, to the principal uranium daughter, Pb_{206}, in a radiogenic lead with a known Pb_{207}:Pb_{206} ratio establishes the Th:U ratio of the radioactive source. This enables leads derived from normal sources with high Th:U ratios, such as granitic, arkosic or shaly rocks to be distinguished, from leads derived from uranium concentrations that have low Th:U ratios comparable to most of the conglomeratic ores. Thorium to uranium ratios of 0.125, 0.25, 0.5, 1.0, 2.0 and 4 are indicated in the plot of isotopic ratios of Elliot Lake leads (Fig. 11).

Loss of lead from radioactive minerals

Lead atoms produced by disintegration of radioelements in radioactive minerals tend to migrate out of the crystal lattices; they are 'foreigners' there. Different radioactive species differ in their abilities to retain lead. Zircon is generally considered to have a high lead retentivity. Uraninite and other uranium-rich minerals are likely to have lower retentivities. This is apparently the case in Elliot Lake ores. The main thorium mineral in these ores, the highly radioactive phase (Th:U~2) present in much of the monazite, may also have a low lead retentivity. The rate of lead loss depends upon mineral grain size, the abundance of fractures in the grains, and upon temperature as well as the mineral species (Tilton, 1960).

Lead that has diffused out of the lattices of radioactive minerals presumably diffuses at a slower rate through the radioactive rocks and will become temporarily or permanently attached to or incorporated in lead-bearing non-radioactive minerals such as the galena, pyrite, pyrrhotite, sericite and feldspar that occur in Huronian ores and rocks. The isotopic composition of this lead must change with time in the same manner as the composition of lead retained within the radioactive mineral changes. If radioactive minerals lost lead at a constant rate throughout their history, the average composition of lead now found in non-radioactive minerals would be similar (although not identical) to that in the radioactive minerals. Some of the lead lost early in this history, however, may have migrated out of the rocks and some may have become locked in early-formed, non-ratioactive minerals. The latter lead would have had higher Pb_{207}:Pb_{206} ratios than the average for all of the lead that had been generated. The remaining lead attached to non-radioactive minerals then would have correspondingly lower Pb_{207}:Pb_{206} ratios. Pyrite in Elliot Lake ores (e.g. Nos. 9, 11, 15 and 17, Table X) contains easily leached lead with higher Pb_r:Pb_o and lower Pb_{207}:Pb_{206} ratios than 'older' lead that is tightly bound in the pyrite.

The rate of diffusion of radiogenic lead from radioactive minerals would have been drastically accelerated 'episoidically' during periods when the host environment of the minerals was modified. Lead would have been separated from radioactive minerals in Archean rocks during the weathering of these rocks and from radioactive detrital minerals during their transport and burial as well as during folding, intrusion of diabase, further folding and metamorphism or incipient metamorphism of Huronian rocks. This sequence of events may be postulated to have occurred about 2.3 to 2.1 x 10^9 years ago. Later thermal events evidently occurred about 1.6 x 10^9 years ago (K-Ar analyses of mica-illite in the Pecors Formation), perhaps about 1.4 x 10^9 years ago (lamprophyre dykes), and about 1.0 x 10^9 years ago (late diabase dykes and Grenville orogeny). Burial of the region under Paleozoic cover rocks may also have had a significant influence on thermal gradients in the Huronian rocks. The thermal events suggested above may also have been the main periods during which the fugitive lead was incorporated in non-radioactive minerals.

Lead Contents of Conglomerate Ores

Lead, U_3O_8, and ThO_2 contents of 7 specimens of conglomerate ore from various mining properties (compiled from Pienaar, 1958, Table XXX, p. 275) are tabulated below.

	Pb%	U_3O_8 %	ThO^2%	$\frac{ThO_2}{U_3O_8}$	$\frac{Pb}{U+0.26\,Th}$
Quirke (1177)	0.078	0.15	0.049	0.31	0.57
Spanish American (497)	0.046	0.13	0.072	0.55	0.36
Panel (131)	0.094	0.15	0.115	0.77	0.61
Stanleigh (443)	0.048	0.108	0.018	0.17	0.50
Lacnor (493)	0.107	0.275	0.044	0.16	0.44
Nordic (1171)	0.056	0.189	0.038	0.20	0.33
Pecors (26)	0.086	0.156	0.235	1.5	0.47

If all of the lead were radiogenic and derived from radioactive minerals 2.5×10^9 years old, the thorium in the samples would have produced 0.26 times as much lead as an equivalent amount of uranium and the ratio Pb:(U+0.26 Th) would be 0.47 in all samples. The median and mean ratio of the group is 0.47 and individual samples have ratios within 34 per cent of this value despite the fact that both Pb contents and U+0.26 Th values vary by a factor of 2. Isotopic analyses of lead in radioactive minerals (Table IX) and in non-radioactive minerals (Table X) in several ores indicate that over 90 per cent of the lead in these ores is radiogenic. The samples listed above differ appreciably in their mineralogy. Uraninite is the principal radioactive mineral in the Stanleigh, Lacnor, and Nordic samples. The Pecors sample contained abundant monazite with little or no uraninite, and the other samples various mixtures of brannerite, monazite and uraninite. There is no evident trend in ratios related to these differences in mineralogy (or ThO_2:U_3O_8 ratios). This suggests that there are probably no major differences in age amongst the various radioactive minerals present.

The purest uraninite concentrates from ores in the Quirke Lake area (27, 28, Table 10) have Pb:(U+0.26 Th) ratios of 0.28 and 0.25. If the average ratio in Quirke ores is 0.47, 40 to 50 per cent of the lead generated in the uraninite has migrated out of this parent mineral and is present in other associations in the ores. This deduction is consistent with the abundance of lead in pyrite (Pienaar, 1958, Appendix Table VIII, p. 13) and other non-radioactive minerals and with the isotopic composition of this lead (Table X). The abundance of fugitive radiogenic lead relative to that of parental radioelements in Quirke ores then might be in the order of 0.2. This lead has higher Pb_{207}:Pb_{206} ratios than lead that has been retained within the parent minerals (Fig. 11) indicating that the Pb_{207}:Pb_{206} ages of the uraninites are minimum ages. The abundance of the older fugitive lead indicates that the actual age of the uraninite may be much greater than these minimum ages. This may be demonstrated qualitatively as follows:

About 3/4 of the fugitive lead in Quirke ores is Pb_{206} (Table X) so the ratio of fugitive Pb_{206} to U_{238} in the ore is probably no less than 0.15 (by comparison, the Pb_{206}:U_{238} ratio in uraninite 27, Table IX, is 0.325). Ratios of radiogenic Pb_{207}:Pb_{206} in leads in non-radioactive minerals in Quirke ores range from about 0.15 to 0.26 and the average ratio must be greater than 0.18 (the Pb_{207}:Pb_{206} ratio in uraninite 27 is 0.116 corresponding to an apparent age of 1.93×10^9 years). The uranium in the ore could not have generated the estimated amount of fugitive lead in the ores in less than (a) 0.9×10^9 years and the lead might represent say (b) one half of the lead generated in 1.7×10^9 years or (c) one third of the lead generated in 2.4×10^9 years. Generative periods (t_m-t_s) of these durations for lead with a Pb_{207}:Pb_{206} ratio of 0.18 can be calculated as (a) $2.2\text{-}1.3 \times 10^9$ years, (b) $2.4\text{-}0.7 \times 10^9$ years or (c) $2.6\text{-}0.2 \times 10^9$ years. The Pb_{207}:Pb_{206} date of 1.93 for lead in the uraninite indicates that only a portion of the lead generated prior to 1.3×10^9 years (case a) was lost; moreover there is some fugitive lead with very low Pb_{207}:Pb_{206} ratios in the ores. Thus the uraninite is certainly more than 2.2×10^9 years old and may well be more than 2.4×10^9 years old if the ratios of fugitive $Pb_{206}:U_{238}$ and $Pb_{207}:Pb_{206}$ used here are minimum ratios as believed.

Apparent Isotopic Ages of Radioactive Minerals

Analyses made for the purpose of radioactive dating of Huronian uranium ores are listed in Table IX. Some of these have been published previously (Wanless and Traill, 1956; Mair et al., 1960). Calculated $Pb_{207}:Pb_{206}$ ages of Nordic uraninites (35, 36), brannerites (37, 38), monazite (39) and zircon (40) (Mair et al., 1960) together with other geochronological data have been cited (e.g. Davidson, 1965a) as evidence that the uranium deposits are not of detrital origin. Unfortunately, the uranium contents of the samples were not determined so that daughter-parent ages are unknown and consequently the reliability of the lead ratio age cannot be appraised directly. Lead contents were determined, however, and it is clear that the ages would be discordant and hence the ratio ages unreliable, unless the concentrates contained very much less uranium than similar concentrates that have been prepared at the Geological Survey (some of them by J. E. Patchett who made the separations used by the Toronto workers). Daughter-parent ratios of analyses 26-34 are plotted in Figure 10, and may be compared to combinations of ratios that give concordant $Pb_{207}:U_{235}$ and $Pb_{206}:U_{238}$ dates. Ratios for samples 35-38, based on the assumption that the uraninites contained 45 per cent and the brannerites 32 per cent uranium, are also plotted. The apparent ages of all samples excepting 29 are very discordant with $Pb_{207}:Pb_{206}$ ages greater than $Pb_{207}:U_{235}$ ages which are in turn greater than $Pb_{206}:U_{238}$ ages. This type of discordant age pattern can be produced by loss of lead relative to uranium and is generally so interpreted. Other, more complicated, interpretations such as recent addition of uranium or of an ancient radiogenic lead to the minerals are possible (see Stief et al., 1956) but do not appear to be acceptable in this case. The uranium deposits evidently pre-date diabase dykes believed to be about 2.1×10^9 years old. There is no evidence that more than one type or age of uraninite is present. The amount and the $Pb_{208}:Pb_{206}$ ratios of radiogenic lead present in the ores and rocks appear to be closely dependant on their radioelement contents and thorium:uranium ratios.

If the pattern of discordant ages is entirely due to loss of lead, the $Pb_{207}:Pb_{206}$ date of about 2.2×10^9 years given by analysis 34 must be closest to the actual age but must be a minimum age. Analyses 26, 27 and 28 from the Quirke Lake area plot along a line that has a $Pb_{207}:Pb_{206}$ slope of about 0.2 and intersects the concordia curve at about 2.3×10^9 years. The significance of this alignment is not clear. Loss of lead with an average $Pb_{207}:Pb_{206}$ ratio of 0.2 from uraninites 2.3×10^9 years old would yield analyses like 26, 27 and 28 but leads with ratios appreciably greater than 0.2, derived from a uranium rich source, are present in Quirke Lake ores and in Nordic ore so it is possible that the uraninite is as old as the definitely detrital monazite (39) and zircon (40).

TABLE IX

ISOTOPIC ANALYSES OF LEADS IN RADIOACTIVE MINERALS

	anal. ref. no.	% U	% Th	% Pb	lead isotope analyses			
					204	206	207	208
GEOL. SURV. CAN.								
uraninites	25	44.51	4.93		0.187	81.48	11.36	6.97
Quirke	26	44.11		13.93	0.070	82.93	11.37	5.63
	27	50.51	5.35	14.31	0.043	85.70	10.55	3.71
Denison	28	55.14	6.02	14.09	0.223	81.20	11.06	7.52
Nordic[1]	29	43.8	3.6	10.7	0.10	86.15	8.19	5.59
Pronto[1]	30	48.3	4.5	5.2	0.33	81.42	9.82	8.43
U.S. GEOL. SURV.[2]								
uraninites, Pronto A	31	23.9	2.79	1.27	0.010	88.13	7.91	5.95
	32	9.26	1.31	0.64	0.012	88.14	7.40	4.15
Pronto B	33	2.68	0.30	0.175	0.035	86.98	8.01	4.98
Quirke	34	27.00	2.20	12.27	0.07	80.91	12.04	6.98
UNIV. TORONTO[3]								
uraninites, Nordic	35			8.5	0.010	87.39	9.98	3.60
	36			6.3	0.012	86.49	9.23	4.28
brannerites, Nordic	37			3.3	0.025	84.96	10.21	4.80
	38			3.9	0.035	85.48	10.80	3.35
monazite Nordic (amber)	39			0.31	0.026	13.12	2.48	84.37
zircon Quirke	40			0.019	0.055	70.48	11.56	17.90

[1] Wanless and Traill (1956); [2] Courtesy of L.R. Stieff, T.W. Stern, C.M. Cialella, and J.J. Warr, published by permission of the Director, U.S. Geological Survey; [3] Mair *et al*. (1960).

Analyses 25, 26, 27 were made on material from three matched pieces of a 1/2-inch thick uraninite-rich layer; uraninite was separated for analysis 27; natural material was used for 25 and 26.

Analysis 34 was made on a galena and pyrite-bearing uraninite concentrate; analysis 18, Table X, was made on galena from the same sample.

Analyses 31, 32 and 33 were made on impure concentrates that contained pyrite.

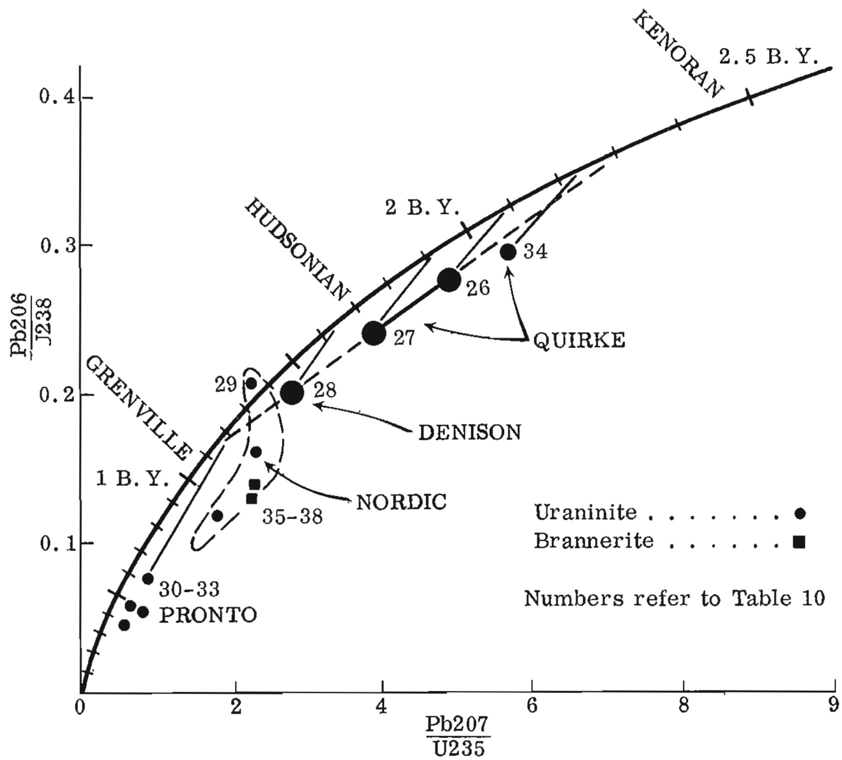
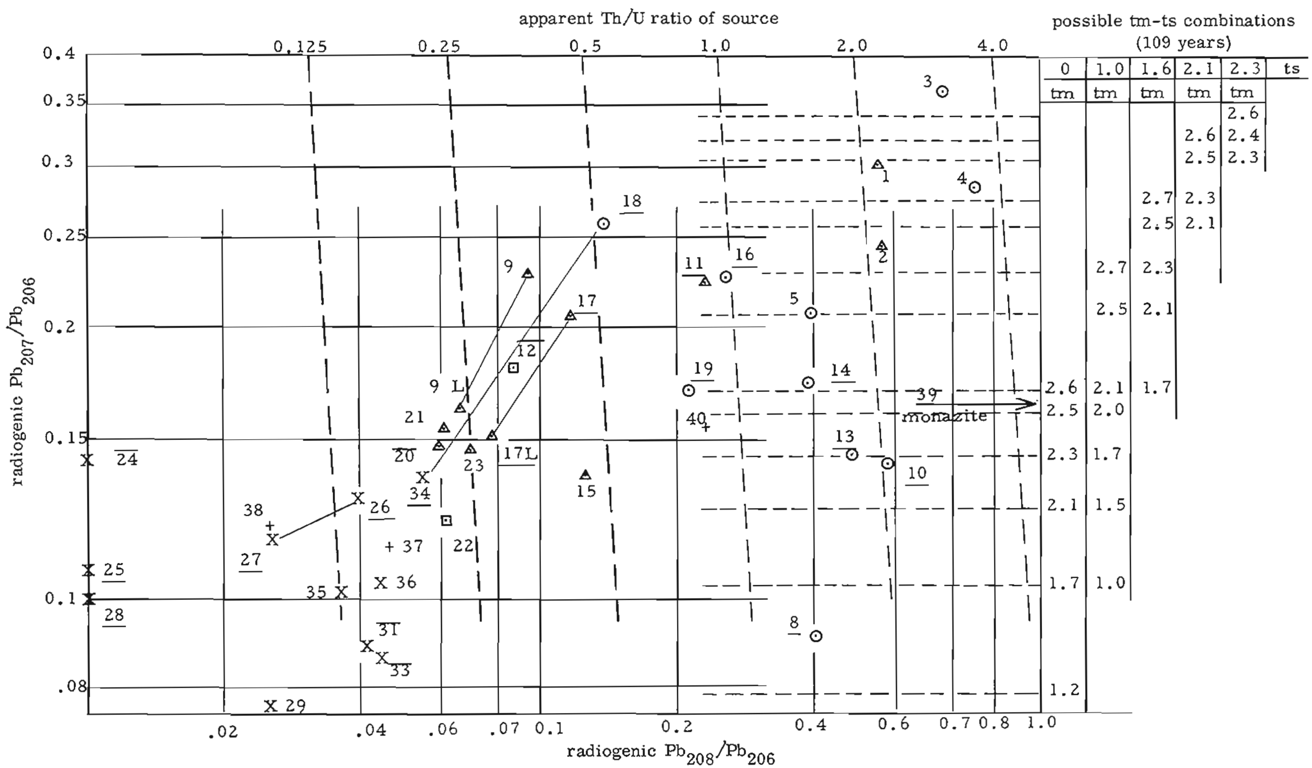


Figure 10. Lead: Uranium isotopic ratios in ore minerals

Isotopic Composition of Leads in Non-Radioactive Minerals

Isotopic analyses of leads in galena, pyrite, pyrrhotite and sericite in ores and in Huronian rocks are listed in Table X. Isotopic ratios of radiogenic components of these leads and leads in radioactive minerals are shown graphically in Figure 11 and therein compared with ratios of leads generated during various periods, t_m-t_s, in sources with various Th:U ratios. The primary and derivative data have also been plotted on various other types of diagrams that are not reproduced in this report. Analyses 10, 11, 13, 14, 16, and 18 of leads from the Quirke Lake area have Pb_{207}:Pb_{204} and Pb_{206}:Pb_{204} ratios that plot along a line that has a Pb_{207}:Pb_{206} slope of 0.32.



Galena . . . . ⊙
Pyrite, pyrrhotite . . . . . △
Feldspar, sericite . . . . . ⊡
Uraninite X
Brannerite (or zircon
where so indicated) . . . +

Numbers refer to samples listed in tables 9 and 10; those underlined (18) ore from Quirke or Denison mines, those overlined (31) from Pronto mine.

Figure 11. Lead isotope ratios in radiogenic leads.

As noted by Mair et al. (1960) many analyses have ratios that plot along a line with a $Pb_{207}:Pb_{206}$ ratio of about 0.15. Most leads from the Nordic area and leads easily leached from pyrite in the Quirke area plot near this line but pyrite leads (9) from Nordic, (17) from Quirke and feldspar lead (12) from Pronto contain radiogenic lead with $Pb_{207}:Pb_{206}$ ratios significantly higher than 0.15. Several galena leads plot near the intersection of the lines with 0.15 and 0.32 slopes and two (6, 7) have anomalously high Pb_{206} contents. The latter are galenas in vuggy, hydrocarbon-bearing veinlets. The least radiogenic leads are in 'indiginous' pyrite and pyrrhotite (1, 2) in argillaceous strata above and below the Mississagi Formation and in galena (3, 4) in the Mississagi Formation remote from ore deposits. Errors in analyses and in selection of a composition for the ordinary lead component of these leads - particularly 1 and 2 - would affect the computed composition of radiogenic lead considerably but not that in other samples. The ordinary lead composition (Kenoran) that was used for the computations of all of the radiogenic lead compositions involved in Figures 10 and 11 is one that gives a minimum spread in the $Pb_{207}:Pb_{206}$ and $Pb_{208}:Pb_{206}$ ratios for radiogenic lead in 1, 2, 3 and 4. This lead, like some of the radiogenic lead in Quirke Lake ores, evidently has a $Pb_{207}:Pb_{206}$ ratio of about 0.3. The $Pb_{208}:Pb_{206}$ ratios of these leads indicate sources with Th:U ratios of 1 to 4 which are consistent with ratios that are found in their host rocks.

It is evident that most of the leads are complex mixtures. There may be 5 end members represented in these mixtures: (1) lead with a $Pb_{207}:Pb_{206}$ ratio of about 0.3 generated in weakly radioactive rocks with Th:U ratios of 1 to 4; (2) lead with a $Pb_{207}:Pb_{206}$ ratio of 0.32 generated in ores with Th:U ratios of 0.2 to 0.5; (3) lead with a $Pb_{207}:Pb_{206}$ ratio of about 0.15 generated in ores over a longer period of time than leads 2 (they occur in mixtures with considerably higher $Pb_r:Pb_o$ ratios); (4) lead with a $Pb_{207}:Pb_{206}$ ratio of 0.15 generated in rocks with Th:U ratios of about 2; (5) lead formed from radon that had escaped from radioactive minerals.

A radiogenic lead with a given $Pb_{207}:Pb_{206}$ ratio may have been generated during a short interval, t_m-t_s, or during a long interval as indicated in Figure 11. If the ratio of uranium to non-radiogenic lead (hence the $U_{238}:Pb_{204}$ ratio) in the system were known, it would be possible to calculate $Pb_{206}:U_{238}$ ratios, and from these the durations of the generative periods, as the ratios of Pb_{206} to Pb_{204} are known from the analyses. There is one, very tenuous, way of estimating a possible value for the required $U_{238}:Pb_{204}$ ratio. It is unlikely to have been any greater than the lowest ratio found in any uraninite-rich sample. The lowest $U_{238}:Pb_{204}$ ratio found in 5 mineral separates and natural concentrates from Quirke Lake ores (Table IX) are 1800 in analyses 25 and 28 (others are No. 34-3100, No. 26-4400, and No. 27-8400). A ratio of 1800 would be equivalent to an ordinary lead concentration of 35 ppm in average grade ore. This is higher than the probable concentration of lead in Archean granitic source rocks and in sericite, potash feldspar and quartz within the conglomerates but it is likely that heavy detrital minerals concentrated in the conglomerates contained considerable ordinary lead. If lead 18 (Table X) with a ratio of radiogenic lead Pb_{206} to Pb_{204} of 215 less 14, was generated in a system that had a U_{238}:Pb_{204} ratio of 1800 the Pb_{206}:U_{238} ratio for this lead would be 0.11 and would indicate a generative period that lasted 700 million years. Its Pb_{207}:Pb_{206r} ratio of 0.26 indicates that its generative period must have begun more than 2.1 x 10^9 years ago and the choice of t_m and t_s for a 700 million year generative period would be 2.45 and 1.75 x 10^9 years respectively. If the lead were removed from uraninite 1.6 x 10^9 years ago at the K-Ar indicated date of orogeny or of a thermal event, the uraninite would be 2.55 x 10^9 years old.

The lead (18) used in the above example, like other leads in non-radioactive minerals that are intimately associated with Quirke Lake ore minerals (as opposed to lead easily leached from pyrite and lead in galena that occurs in fissures in rocks as well as ores), is probably a mixture that contains considerable lead with a Pb_{207}:Pb_{206} ratio of 0.32 and lead with a ratio of 0.15. The 0.32 ratio lead must have begun its generative period more than 2.35 x 10^9 years ago. The considerable amounts evidently present suggest that its parental uranium-rich minerals are more than 2.5 x 10^9 years old. A possible combination of t_m and t_s would be 2.6 and 2.1 x 10^9 years. The latter figure for t_s corresponds roughly to the probable date for the culmination of a series of events-diagenesis of Huronian sediments, structural deformation, intrusion of diabase and incipient (or locally appreciable) metamorphism. This is a likely date, then, both for excessive loss of lead from uraninite and for incorporation of lead in pyrite.

It should be borne in mind that if the uranium minerals were detrital, they likely lost some of their earliest-generated lead at the time of initial erosion of their hostrocks, most probably about 2.3 x 10^9 years ago. Some of this lead should have been deposited with argillaceous sediments and the relatively high (although not firmly established) Pb_{207r}:Pb_{206r} ratios in samples 1, 2, 3 and 4 are consistent with this thesis.

Most leads with a Pb_{207}:Pb_{206} ratio around 0.15 have much higher Pb_{206}:Pb_{204} ratios than lead 18 used in the computation given above. This indicates that such lead was probably generated through a much longer period than the older lead. Much of it is associated with pyrite but is easily leached from this pyrite. It is possible that most of it represents an accumulation of lead that has been leaking out of 2.5 x 10^9 years old radioactive minerals subsequent to the 1.6 x 10^9 orogenic event during which earlier fugitive lead had become incorporated in pyrite and other minerals.

Radiogenic lead tightly-bound in pyrite (9) in Nordic ore has a Pb_{207}:Pb_{206} ratio of 0.23 and feldspar in Pronto ore (12) contains radiogenic lead with a ratio of 0.18. Other leads in the Nordic area, however, and most pronouncedly those in Pronto ores have lower Pb_{207}:Pb_{206} ratios and lower ordinary lead contents than leads in the Quirke Lake area. There is a corresponding southward decrease in apparent daughter-parent ages of uraninites (Fig. 10). If all of the uraninite is 2.5 x 10^9 years old, that at Quirke Lake

TABLE X: ISOTOPIC COMPOSITION OF LEADS IN NON-RADIOACTIVE MINERALS

	Sample description	lead isotope analyses			
		204	206	207	208
1	Pyrite in Bruce conglomerate (RF 4)	1.00	16.00	15.44	34.96
2	Pyrrhotite in Nordic argillite (56 RF 9)	1.00	16.04	15.34	35.01
3	Galena in Mississagi quartzite (55 WT 301)	1.00	17.11	15.96	36.35
4	Galena, Agnew Lake	1.00	19.95	16.52	39.46
5	Galena, Rangers Lake (57 PH 294)	1.00	29.68	18.09	40.04
6	Galena, Quirke Mine	1.00	34.00	15.08	44.26
7	Galena, Mississagi quartzite (57 PH 429)	1.00	55.94	15.39	41.31
8	Galena, Quirke Mine in cross fracture	1.00	59.49	18.61	52.49
9	Pyrite, Nordic Mine in high-grade ore (RF 8)	1.00	66.46	26.94	38.58
9L	Acid leached lead from pyrite 9	1.00	236.53	50.77	48.72
10	Galena, Quirke Mine	1.00	79.81	24.25	71.31
11	Pyrite, Quirke Mine (56 RF 462) lower reef	1.00	84.23	30.68	49.93
11L	Lead leached from pyrite 11	1.00	91.82	31.87	51.69
12	Feldspar, Pronto Mine in ore	1.00	89.09	28.46	40.46
13	Galena, Quirke Mine in fracture (56 RF 15)	1.00	95.43	26.41	73.27
14	Galena, Denison ore (56 RF 415)	1.00	118.36	32.98	74.93
15	Pyrite, radioactive layer in Stinson quartzite (RF 168)	1.00	156.11	34.48	51.73
15L	Lead leached from pyrite 15	1.00	225.15	43.26	62.86
16	Galena, Denison ore (55 GS 550)	1.00	142.20	43.77	66.20
17	Pyrite, Quirke ore (56 RF 463)	1.00	192.95	52.41	54.82
17L	Lead leached from pyrite 17	1.00	805.00	136.15	99.48
18	Galena, Quirke ore (55 GS 549)	1.00	215.14	67.38	61.31
19	Galena, Quirke Mine in fracture (55 GS 549)	1.00	246.92	54.77	81.88
20	Pyrite, Pronto ore (55 GS 476)	1.00	337.59	62.77	53.23
21	Pyrite, Nordic ore	1.00	463.90	84.09	60.73
22	Sericite, Nordic ore	1.00	542.28	79.86	66.34
23	Pyrrhotite, Nordic ore	1.00	1187.76	187.16	116.72
24	Pyrite, Pronto (55 GS 477)	1.00	5109.41	735.88	36.47

Sources of data:

3, 6, 8 – Wanless and Traill (1956); 10, 12, 21, 22, 23 – Mair, Maynes, Patchett, and Russell (1960).

16, 18, 19, 20, 24 – unpublished data from L.R. Stieff, T.W. Stern, C.M. Cialella and J.J. Warr, used herein with the permission of the Director, U.S. Geological Survey.

1, 2, 4, 5, 7, 11, 13, 14, 15, 17 – analyzed by W.D. Loveridge and others in the isotope geology laboratory of the Geological Survey of Canada under the supervision of R.K. Wanless.

has lost 1/3 to 1/2 of its lead, that at Nordic about 1/2 and that at Pronto as much as 90 per cent. Corresponding losses of lead from the ore as a whole during 2.1, 1.6 and 1.0 orogenic events that were more intensive at Pronto than at Quirke would have reduced the average Pb_{207}:Pb_{206} ratios in Pronto ores relative to those in Quirke Lake ores.

Discussion

Lead isotope data have been interpreted herein in a manner that is consistent with the proposition that the uraninite is of detrital origin. The fact that this can be done does not constitute evidence that the uranium ores are placers but it does demonstrate that isotopic data cannot be used to refute textural and other evidence for such an origin. The writer is much more impressed, frankly, by the fact that the mode of occurrence of uraninite cannot be distinguished from that of unquestionably detrital zircon in the conglomerates than he would be by similarities or differences in isotopic compositions of leads in the two minerals. Different interpretations of these lead isotope data are possible but it is doubtful that any such interpretations could yield a uraninite age of less than 2.25×10^9 years and at the same time be in accord with established geological relationships. Other evidence indicates that the ores as well as the Matinenda Formation must be older than diabase that has been dated as 2.15×10^9 years by Rb:Sr analyses. The isotopic composition of some lead in the ores permits an interpretation that the uraninite may be as much as 2.6×10^9 years old. The age of the youngest source rocks of detrital minerals in Huronian source rocks can only be estimated as greater than 2.4×10^9 years from K-Ar analyses of Archean granitic rocks, greater than 2.45×10^9 from Pb_{207}:Pb_{206} ratios in detrital zircon in the conglomerates, and perhaps less than 2.7×10^9 years from other geochronological data (e.g. Tilton and Stieger, 1965). The age of the conglomerates (2.15 to 2.7×10^9 years) is not known any more precisely than the age of the uraninite (2.25 - 2.6×10^9 years within it). There is no possibility therefore that the epigenetic or placer origin of ore minerals could be established through additional isotopic analyses on them alone. If Huronian sedimentation closely followed Kenoran orogeny, as seems possible, it would be doubtful if a detrital mineral derived from Huronian granite could be distinguished isotopically from a mineral formed, perhaps less than 100 million years later, in Huronian gravels.

If further lead isotope studies are undertaken they should include analyses of total lead, uranium, and thorium contents and isotopic compositions of leads in large samples of ores. The advantage of this approach, advocated by Nicolysen _et al_. (1962a), is shown by the fact that uraninite sample No. 26 yielded greater and more concordant apparent ages than a uraninite concentrate No. 27 from the same specimen. The extra lead in sample 26 is very similar to that found in galena and pyrite concentrates and has clearly been generated in the uraninite. The efforts made in this report to reconstruct the daughter-parent ratios and lead isotope ratios that have been modified by lead diffusion are beset with uncertainties that could have been mitigated if analyses had been made on the ore samples rather than minerals separated from them. One might even consider using mill head, mill solution, and tailings effluent samples that would represent large volumes of ore.

DISCUSSION OF GENESIS

General

Certain arguments that have been raised against the placer hypothesis were not explicitly outlined in the foregoing descriptions and discussions of the uraniferous conglomerates because they involve considerations that are largely extraneous to the conglomerates themselves. The late C. F. Davidson, for example, was compelled to take a position of vigorous opposition to the placer hypothesis not by weight of evidence directly favouring an alternative epigenetic origin but rather because he doubted the adequacy of detrital processes, as he understood them to operate under present day conditions, to produce the Witwatersrand and Elliot Lake deposits. Such critiques have had a salutory influence on research and it cannot be claimed that satisfactory answers have yet been found and documented for all of the objections to the placer hypothesis that have been pointed out. This in itself, however, does not constitute evidence for any alternative epigenetic hypothesis. It should also be realized that theories of epigenetic origin of the conglomeratic deposits have been advocated mainly in review articles rather than in publications by persons who have been deeply involved personally in studies of the geological environment and character of the deposits.

Theories of Epigenetic Origin

Most publications relating to placer as opposed to epigenetic origins of conglomeratic gold and uranium deposits have been concerned with the Witwatersrand deposits or Witwatersrand deposits plus other deposits rather than specifically with deposits in Huronian rocks. The principal arguments for an epigenetic origin of the South African deposits have been aptly reviewed by Nel (1958) but it may be useful to summarize some of them very briefly here in order to bring them into context with Huronian deposits.

The concept that the Witwatersrand deposits were formed through the introduction of gold, sulphur and other elements into transmissive zones containing highly permeable conglomerates was expounded in greatest detail by L. C. Graton in 1930. He believed that the ore-forming solutions were introduced into the conglomeratic zones at depths after the strata had been folded and that these solutions travelled great distances through the zones depositing minerals in pore spaces. Later exponents of epigenetic hypotheses have uncritically accepted Graton's careful explanations (Graton, 1930, p. 64) as to why the ore-bearing conglomerates were likely to have been much more permeable than other rocks and considered that this alleged superior permeability was the major factor in the localization of the ores.

Davidson (1953) postulated that the ores were derived from an unknown granitic source at depth but evidence that radioactivity was not confined to conglomerate beds (Simpson, 1951) and perhaps doubts concerning the efficacy of conglomerate beds as through-going conduits led him to state that "it would appear that the mineralizing fluids have soaked upwards throughout the entire sedimentary sequence, deposition of heavy elements in sufficient quantities to form ore being confined to the beds or horizons of greatest permeability."

In 1965, Davidson (1965a) outlined a different hypothesis of epigenetic origin for the Witwatersrand, Huronian and Sierra de Jacobina conglomeratic deposits. Unfortunately this publication proved to be his last pronouncement on the subject. The hypothesis may be summarized in his own words (Davidson, 1965b, p. 1197) as follows:

"The occurrence of these uraniferous conglomerates close to major unconformities within or bottoming deep confined basins of Proterozoic sediments is compatible with the view that the uranium has been leached by ground waters from the overlying stratigraphical sequences, the bankets marking the mature end-phase of a prolonged series of interstratal migrations which the mineralization has undergone. Auriferous uranium deposits have been derived from the lixivation of acid-intermediate volcanic-pyroclastic rocks and uranium deposits devoid of workable gold from the leaching of granitic detritus. In each case groundwaters have gradually and intermittently carried a load of mineralization downward to the lowest permeable horizon; and where there was a depth-source of heat they have moved outward, principally along the open conglomeratic channels, to deposit the metals toward the cooler marginal zones."

He attributed this change in his views to new geochronological data (Burger, Nicolaysen and de Villiers, 1962) and to a realization that epigenesis need not necessarily be attributed to plutonism. It was his view that the deposits in ancient conglomerates had an origin very similar to that of deposits in Mesozoic and Tertiary continental sandstones and associated rocks in the western United States.

In a discussion of Davidson's paper, Rice (1965) pointed out that the argillite above the Elliot Lake uranium deposits would have acted as an impermeable barrier to descending uranium-bearing solutions. He suggested that water trapped in the wedge of strata between the argillite and the basement dissolved uranium from these strata and precipitated it as uraninite in quartz-pebble conglomerate layers. The present writer, if concerned with a source for epigenetic uranium, would add that uranium-bearing connate waters might have been squeezed out of the very extensive McKim Formation during compaction and entrapped up-dip in the conglomerate-bearing wedge between the impermeable Pecors Formation and the basement.

Derry (1960) concluded an excellent description of the Elliot Lake uranium deposits with a discussion of the opinions of various workers concerning their genesis. Lack of unanimity concerning the origins of uraninite and brannerite in the ores, lack of identification of these minerals in Archean source rocks, lead isotope date (Mair, et al., 1960) and his suspicion that the deposits may have formed through processes akin to those that formed the important uranium deposits in sedimentary rocks in the western United States, led him to suggest an hypothesis which is not unlike 'precipitation' hypotheses that have been suggested for South African ores (Du Toit, 1953; Macgregor, 1953). He theorized that the quartz-pebble gravels initially contained heavy detrital minerals but little uranium; groundwater containing uranium and a little thorium dissolved from weathered Archean rocks seeped slowly through the porous gravels; uranium minerals were deposited and pyrite formed in the gravels under reducing conditions which prevailed during initial burial of the gravels; deeper burial resulted in diagenetic alterations which produced the minerals and textures now seen in the ores.

Weaknesses in the Concept of Permeability Control

All of the foregoing 'models' for the formation of the conglomeratic ores mainly by epigenetic processes have weaknesses apart from the fact that there is excellent evidence that uraninite, uranothorite, and other minerals are present as detrital grains. One weakness common to all is the requirement that quartz-pebble conglomerate beds were much more permeable than any other rocks. There are cogent reasons for doubting this alleged superior permeability. Nel (1958, p. 78) pointed out that the numerous noneconomic conglomerates in the Witwatersrand succession actually must have been more permeable initially than the much less abundant ore-bearing conglomerates which had matrices filled with poorly-sorted detrital particles, and that it is unlikely that this relationship would have become reversed at any stage of diagenesis or metamorphism that might correspond with a hypothetical period of epigenetic mineralization. The permeability of sediments in the Huronian and Witwatersrand sequences would have depended at least as much upon the size distribution (or sorting) of granules, silt particles and clay-sized particles as upon features such as the presence or absence of pebbles and types, shapes, and spacings of pebbles. Like Nel and others, Roscoe and Steacy (1958, p. 482) considered the effect of sorting upon permeability of sediments and concluded that "sharp, very large, contrasts in uranium content cannot be correlated with large differences in permeability, insofar as permeability can be deduced from grain sizes and degree of sorting of the allogenic constituents of the rocks. Rocks with much fine-grained material in their matrices may contain more uranium or less uranium than adjacent better sorted rocks. Moreover, many well-sorted Huronian conglomerates contain very little uranium."

Petrographic evidence mitigating against permeability control of uranium concentrations in the Elliot Lake area evidently has not been advanced forcefully enough to elicit consideration by exponents of epigenetic hypotheses. Davidson (1960, p. 224) stated "Surely it need only be remarked that oligomictic conglomerates, typically the product of marine transgression, are almost invariably characterized by good sorting and ipso facto have a particularly high permeability?" Certainly, oligomict conglomerates may form as the product of marine transgression, perhaps most are formed in this manner, but all who have studied Huronian uraniferous conglomerates and associated rocks in detail have agreed that they must be fluviatile in origin. The same view is widely held in the case of the South African auriferous, uraniferous, pyritic, oligomic conglomerates. We need not depend upon a theory of origin of the conglomerates (in this case an erroneous one) in order to evaluate their sorting. Anyone who takes the trouble to look at them will find that not all of their constituents are well-sorted. The quartz pebbles or cobbles, whether scattered or closely packed, are generally rounded and sized; there is an upper limit to the sizes of quartz and feldspar granules associated with the quartz and chert clasts, some of the heaviest minerals have limited size ranges, but the smaller sand-sized, silt-sized, and clay-sized light particles are characteristically poorly-sorted. This is exactly what one would expect where pebbles were being rolled and coarse sand and heavy minerals moved by saltation along the bed of a swift, turbid stream that carried a heavy load of fine sand, silt and clay in suspension. Wherever movement of the larger and heavier particles was arrested, their interstices would become clogged with the ubiquitous finer-grained material. The difficulty of washing this material from the coarse gravels may be likened to that of laundering white socks in muddy water.

The coarse, feldspathic, argillaceous (or sericitic) quartzites that characterize the Huronian succession display pronounced differences in sorting. Some are well-sorted and contain little interstitial argillaceous material; authigenic quartz and carbonate is present locally. These 'clean' arenites were 'washed' in relatively clear water. At the other extreme, we find gritty, argillaceous subarkoses whose finer grained allogenic constituents were obviously very poorly-sorted. These rocks should have been less permeable than cleaner arenites, yet they are invariably more radioactive than the latter. Where there are scattered quartz pebbles in the poorly-sorted grit, it is more radioactive and commonly more pyritic than grit that lacks pebbles. The highly radioactive conglomeratic zones that contain the ore deposits comprise layers and lenses of grit with dispersed to tightly-packed pebbles or cobbles interlayered with poorly-washed to well-washed beds that contain few pebbles. Lenses with large, closely-packed pebbles are generally the most radioactive and pyritic rocks but most of the grains of pyrite, radioactive minerals, and other heavy minerals are imbedded in poorly-sorted material that fills the interstices between pebbles. Other oligomict as well as polymict conglomerates associated with 'clean' arenites rather than with argillaceous grit are not particularly radioactive. Beds of quartz- chert- and jasper- pebble conglomerate in the lower part of the Lorrain Formation, for example, are amongst the least radioactive of Huronian rocks. Near Mount Lake, beds of this type of oligomict conglomerate are interlayered with beds of quartz-pebble conglomerate and pebbly argillaceous arkose that contain abundant radioactive black sands. Layers of well-sorted cobbles, pebbles and boulders of granite and other rocks in arkosic sections of the Gowganda Formation and in the Serpent Formation are not abnormally radioactive. Thin, radioactive, pyritic layers are found in relatively well-washed, coarse-grained subarkose in the Stinson Member of the Matinenda Formation but conglomerates in the basal part of this member, which unconformably overlies the gritty, radioactive, Ryan Member, are remarkably barren. These conglomerates contain clasts of greenstone and a few of granite and other rocks in addition to abundant well-rounded, well-sorted clasts of quartz and chert. Near the Stanleigh Mine, a channel several hundred feet deep filled with cobble conglomerate truncates beds of radioactive pyritic quartz-pebble conglomerate. The cobble conglomerate contains little interstitial fine-grained allogenic material and was probably deposited in large part as an open-work gravel, for soft pebbles are squeezed into interstitial spaces that also contain authigenic quartz and carbonate but not uranium minerals or appreciable amounts of pyrite. Any solutions that passed through the conglomerate beds that contain pyrite and uranium minerals would have had ready access to this much more transmissive barren conglomerate zone.

Comparison of Conglomeratic Deposits with known Epigenetic Deposits

If the conglomeratic deposits were epigenetic in origin, one would expect to find some features that would link them with known epigenetic deposits. The relatively widespread class of deposits found in continental sediments in the western United States and elsewhere provide an excellent 'model' to illustrate features likely to characterize concentrations of uranium minerals precipitated from solutions that percolated through transmissive strata. Both Derry and Davidson indicated that they believed that the conglomeratic deposits were analogous to the epigenetic deposits in continental sandstones and associated rocks, but they did not describe any important features common to the two categories of deposits excepting their association with terrestial clastic sediments. The deposits are compared in Table XI. They are strikingly dissimilar morphologically, geologically, mineralogically and chemically.

The restriction of Huronian uranium deposits to a particular type of conglomerate must be ascribed to some unique characteristic of this conglomerate that is not possessed in any important degree by any of the varied host rocks of peneconcordant 'sandstone-type' deposits. It is apparently not valid to consider that this attribute was an extraordinarily superior transmissivity to uranium-bearing solutions. The conglomerates are most unlikely to have contained concentrations of reducing agents that were rare or absent in other Huronian rocks. Most of the Huronian Supergroup is in a reduced state and contains pyrite. Free carbon is more abundant in argillites than in coarse arenites and conglomerates. The one unique characteristic of the ore-bearing conglomerates is that they contain placer concentrations of heavy

TABLE XI: COMPARISON OF SANDSTONE-TYPE AND CONGLOMERATIC-TYPE URANIUM DEPOSITS

	Sandstone-type deposits in United States[1] (including lignitic deposits)	Deposits in ancient quartz-pebble conglomerates
Host rocks	sandstones of continental origin; red, brown, buff, grey, or white; quartzose to arkosic or tuffaceous; clean to highly argillaceous; fine-grained to very coarse grained; also: polymict and oligomict conglomerates, siltstone, mudstone, tuff, calcarenite, limestone, and lignite; not normally appreciably radioactive. age: mid-Paleozoic to recent ($0.3\text{-}0 \times 10^9$ yrs.)	layers and lenses of well-packed to sparse quartz pebbles in coarse greenish, argillaceous subarkose; these rocks are radioactive on a regional scale and are the only ore hosts; they are in successions that are continental in origin, but lack red coloration normally found in such strata.
Shape of deposits	peneconcordant tabular bodies, irregular elongate bodies and swarms of bodies that commonly have C-shaped cross-sections and sharp boundaries which cut smoothly across bedding; minor tabular bodies along fractures.	stratiform, concordant in detail with sedimentary features.
Controls of localization	facies variations and large scale sedimentary features that affected transmissivity of sediments and disposition of organic material in host formations; tectonic structures (in some cases) including fractures, faults and brecciated zones.	primary features favourable for concentration of detrital heavy minerals and quartz pebbles; paleotopography of underlying surface; no direct relationships to secondary structures.
Main uranium minerals	uraninite, lacking thorium and rare earths, as in vein deposits; coffinite, secondary uranium minerals.	uraninite, with thorium and rare earth elements, as in pegmatites; brannerite; uranothorite.
Ore mineral textures	very fine grained, impregnations of pore spaces, local replacements of allogenic constituents, and fissure fillings.	small, discrete, subrounded to rounded grains that appear to be detrital or pseudomorphous after heavy detrital minerals.
Elements recovered from deposits	uranium, vanadium, copper, molybdenum.	uranium, thorium, yttrium, rare earths, gold (S. Africa), also osmium and iridium in S. Africa.
Other elements concentrated in ores	selenium, arsenic, sulphur, nickel, cobalt, iron.	phosphorous, titanium, zirconium sulphur, iron, cobalt, nickel.
sulphur	extreme isotopic fractionation	little isotopic fractionation.
Rock alteration	bleaching of host rocks due to reduction of ferric iron; many deposits are at contacts between altered and 'unaltered' rocks; pyrite, limonite, hematite, carbonates, silica, and sulphates, have also been formed or deposited.	no recognized alteration related to ore, although ore and country rocks are altered locally along post-ore dykes and faults.

[1] After Finch (1967).

detrital minerals. We must conclude that the assemblage of heavy detrital minerals either included ore minerals or in some way generated conditions highly favourable to precipitation of dissolved uranium, thus developing a concentration gradient that effected a replenishment of the supply of uranium. There is evidence that uranium was absorbed by altered titanium minerals but it seems unlikely that this was a major primary ore-forming process and, in any case, there is little or no correlation between uranium and titanium in the highest grade, uraninite-rich, ores. Anthigenic pyrite was likely formed through reactions involving iron originally present in the heavy detrital mineral suite and hydrogen sulphide that pervaded all of the strata, having been generated biogenically principally in the most pelitic sediments. There is no reason to presume that this phenomenon would have engendered conditions remarkably favourable to the deposition of uranium in the conglomerates as opposed to other rocks.

A variety of special conditions and processes could doubtless be postulated to support the idea that the conglomeratic deposits could have been of epigenetic origin despite the great differences between them and known epigenetic deposits. Such exercises would perhaps be justified if there were no evidence for a placer origin, but this is not the case as evidence within this report indicates.

Credibility of the Placer Hypothesis

Evidence for the placer origin of the Huronian uranium deposits may be summarized as follows: The deposits occur in a geological environment that is consistent with a belief that they are placers. They contain a large variety of heavy minerals that are found commonly or at least rarely (e.g., uraninite) in placers. The source terrain was likely to have contained all of these heavy minerals and most (uraninite is a notable exception) have been identified in the more deeply eroded rocks now exposed in the source area. Apart from abundant pyrite, few of these minerals are commonly concentrated in epigenetic mineral deposits, particularly not in epigenetic deposits in unmetamorphosed or little metamorphosed strata. The minerals, including uraninite and some of the pyrite, resemble detrital grains, not intergrowths or impregnations of epigenetic minerals. Variations in proportions and grain sizes of heavy minerals (again including uraninite) indicate that they were hydraulically sorted. While it may not be beyond one's powers of imagination to conceive of mechanisms whereby the deposits could have been formed epigenetically and modified so as to resemble placers, there is no evidence that this was the case.

Objections to the placer hypothesis can only be made on the basis of credibility not on grounds that it is scientifically unsound.

The fact that uraninite has not been found in Archean rocks near Elliot Lake is not a serious objection to the placer hypothesis. Great areas of Archean rocks sourceward from the deposits are covered. The exposed rocks have not been exhaustively sampled and in any case represent a deeper level of erosion than that which provided the source of Matinenda sediments. Finally, it can be pointed out that the mother lodes of numerous gold, diamond and other placers remain undiscovered.

The abundance of pyrite compared to detrital iron oxides is explained in part by the evident formation of authigenic pyrite. The abundance of uranium-rich minerals in the ores is explained in part by evident, not simply hypothesized, hydraulic differentiation of heavy minerals. In addition, the source terrains doubtless contained abundant pyrite and above average amounts of radioactive minerals and it would not be unreasonable to postulate that they may have contained abnormal concentrations of uranium-rich minerals. Many students, however, would consider that these mechanisms are inadequate to explain the abundance of pyrite and particularly that of uraninite in most ores. One may suspect that oxidation and dissolution of pyrite and uraninite under modern conditions of weathering and stream transport would prohibit the formation of rich detrital concentrations of these minerals no matter how abundant they might have been in source terrains. Such concentrations have not been found in modern placers or in sedimentary rocks younger than the Aphebian host rocks of the Huronian and Witwatersrand deposits. If this objection is valid, then one may conclude that some aspects of weathering more than 2×10^9 years ago were different from those that have prevailed in relatively recent times. Evidence that pre-Huronian rocks were weathered and Huronian sediments deposited under non-oxidizing conditions has been presented in this report.

EXPLORATION POSSIBILITIES

General

The main known sources of low-cost uranium are conglomeratic deposits in continental strata more than 2×10^9 years old and 'sandstone-type' deposits in post-Devonian continental sedimentary rocks. Most exploration for such deposits has been carried out in regions that are known to contain deposits but increasing attention is being directed to the problem of recognizing units that may be favourable for prospecting despite their lack of known enrichments of uranium. Certain criteria can be outlined in the form of a 'key' that may be used to select strata warranting intensive prospecting for uranium deposits of the conglomeratic type or to eliminate unfavourable strata. The most favoured target rocks should be Aphebian or older in age (preferably 2×10^9 years old) because important deposits of the Huronian-Witwatersrand type have not been found in younger rocks and because there is reason to believe that they are a special type of placer deposit that could not have been formed in more recent geological times when the earth's atmosphere had changed from a non-oxidizing to an oxidizing one. Some of the features outlined in the criteria below may be restricted to ancient rocks deposited in a reducing environment. Regardless of age, however, sedimentary sequences may be considered favourable if they meet the following conditions:

(1) they include thick continental sandstone formations evidently derived from a weathered granitic source;

(2) these sandstones and associated shaly beds lack hematite or red coloration due to hematite or ferric oxide in their matrices;

(3) the sandstones include extensive units of very coarse grained crossbedded, drab or greenish coloured, argillaceous arkose or subarkose;

(4) the coarse arkosic rocks contain quartz or chert pebbles, however sparsely distributed, but few or no pebbles of other sorts;

(5) concentrations of assemblages of detrital heavy minerals, such as rutile, monazite and zircon, are present and result in radioactivity at least equal to that of common granites;

(6) disseminated pyrite is present;

(7) thorium to uranium ratios in the most radioactive strata are not excessively higher than those found in most granitic rocks (about 4);

(8) the nearest older igneous and metamorphic terrains do not contain abnormally low contents of uranium;

(9) uranium concentrations of some type are found within the region.

The occurrence of beds of non-radioactive quartz-pebble conglomerate in a succession probably should not, by itself, be considered a particularly favourable or unfavourable feature. Radioactive hematitic quartz-pebble conglomerates suggest an oxidizing regime rather than a favourable reducing regime; on the other hand, they indicate the existence of an environment that was perhaps otherwise favourable for the formation of conglomeratic uranium deposits. Hematitic conglomerates occur in the Cobalt Group, the uppermost group of the Huronian succession whereas pyritic conglomeratic uranium ores occur nearby at Elliot Lake in the anoxic lowermost group of the succession. This suggests that older strata should be sought and examined in any area where hematitic conglomerates have been found (e.g. Mistassini-Otish Mountain region, Roscoe, 1967).

The chances of finding all of the favourable indications outlined above in many places in the Canadian Shield cannot be great, particularly if these chances are restricted to areas where little-metamorphosed remnants of the oldest Proterozoic cover rocks have been preserved from erosion. It is encouraging, however, that some of these features have been found in at least two places outside of the Huronian belt – near Padlei in the Northwest Territories (Heywood and Roscoe, 1967) and the Papaskwasati Formation north of Lake Mistassini in central Quebec (Roscoe, 1967).

It is possible that more strata of the Huronian type have become incorporated in various metamorphic terrains in the Shield than are preserved as remnants of cratonic cover rocks. The original concentrations of uranium, thorium and other elements in most such metasedimentary rocks would probably have become modified nearly or completely beyond recognition but might have been the source of uranium in some of the pegmatitic and other deposits that appear to be particularly abundant in many gneissic, migmatitic terrains in the shield.

Huronian Belt

Exploration possibilities in the Huronian belt are circumscribed by the extent and depth of stratigraphic units likely to contain radioactive conglomerates. The Matinenda Formation contains all of the ore deposits and important prospects found to date. In the western part of the belt there are extensive layers of radioactive pyritic conglomerate interbedded with volcanic flows near the base of the Thessalon Formation at about the same stratigraphic level within the Elliot Lake Group as the Matinenda Formation. The Livingstone Creek Formation beneath the Thessalon Formation is virtually unexplored but radioactive conglomerates are likely to be found at its base in places. Stobie, or equivalent, volcanics in the eastern part of the belt may contain some interbedded layers of radioactive conglomerate. The thickest, most radioactive, pyritic conglomerates in the Mississagi Formation are in coarse-grained, sourceward facies beyond the northern limit of the Elliot Lake Group. The Mississagi Formation is believed to lie directly on Archean rocks throughout an extensive area northeast of Sudbury. Farther northeast near Timagami radioactive pyritic quartz-pebble conglomerate beds occur in feldspathic quartzite beneath the Gowganda Formation. This unit is probably correlative with the Mississagi Formation but there is a possibility that it is correlative with the Serpent Formation or that more than one favourable unit is present. An interesting feature of the Sudbury-Timagami area is the possibility that significant amounts of gold as well as low uranium contents may be found in some of the conglomerate beds there. Monazite-bearing hematitic conglomerates in the lower part of the Lorrain Formation, where this unit rests on Archean rocks about 20 miles north of Elliot Lake, must be distinguished from the uraniferous, pyritic variety as there is little possibility that they might become economically valuable or that they mark a horizon worth exploring for uranium.

Estimated extents and depths (or core distances) of various favourable strata mentioned above are shown in Figure 12. Depths are known from drillhole data in a few limited areas as near Elliot Lake but in most parts of

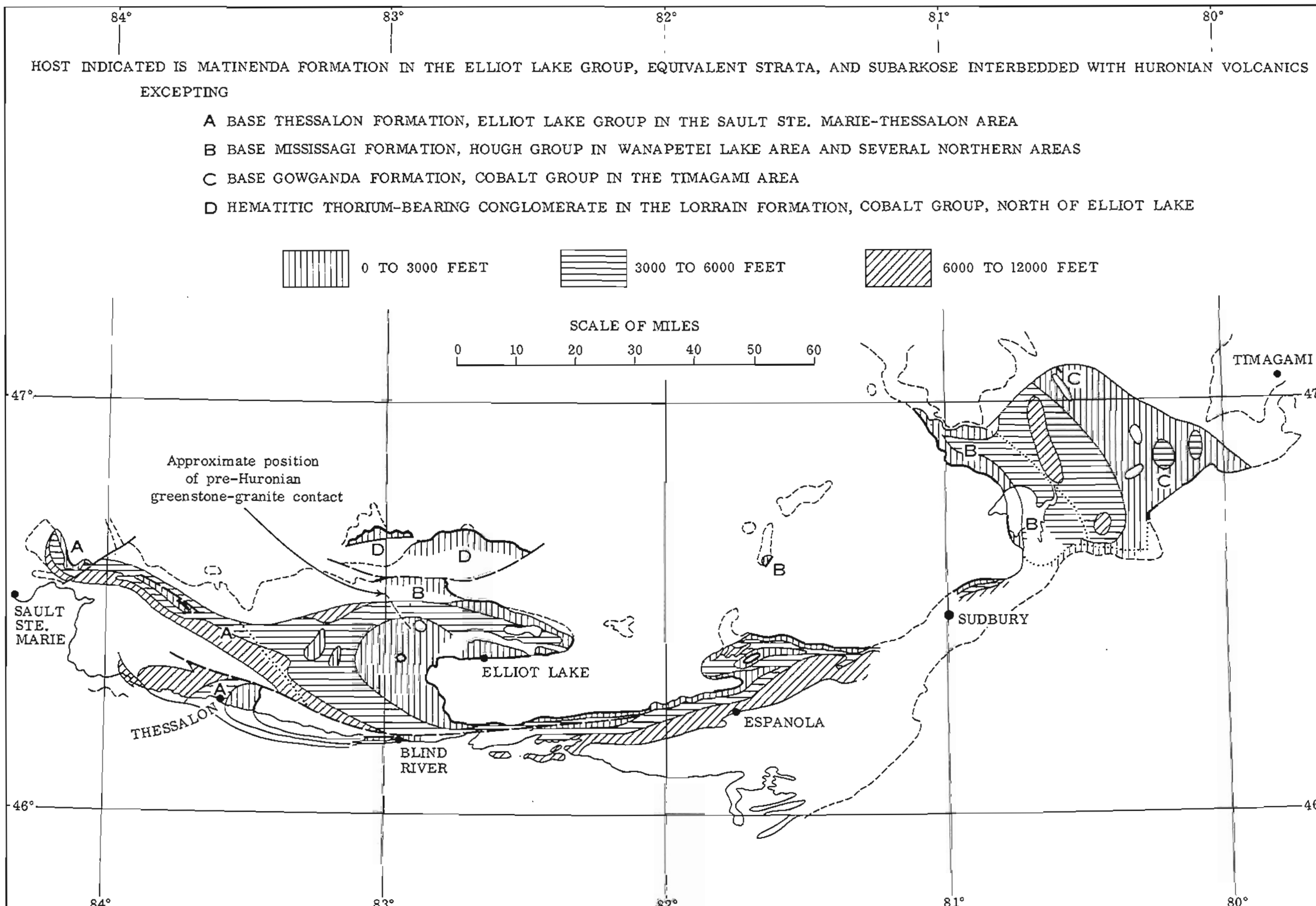


Figure 12. Approximate depth or core distance to strata likely to contain radioactive quartz pebble conglomerate.

the region they can only be estimated very approximately by totalling the interpolated or extrapolated, varying thicknesses of overlying units, making some allowances for diabase sills. Our main concern here must be the Matinenda Formation, the only proven ore host. Areas with more speculative possibilities in other stratigraphic units are indicated by letters, A (base of the Thessalon Formation), B (base of the Mississagi Formation), C (base of the Gowganda Formation) and D (base of the Lorrain Formation), in Figure 12.

It is estimated that about 900 square miles of Matinenda Formation may be explorable by drillholes less than 6,000 or 7,000 feet deep. Relatively closely-spaced holes to depths of as much as 4,000 feet near Elliot Lake and shallower holes elsewhere along many miles of the basal contact of the formation have defined ore zones and economically uninteresting zones totalling perhaps about 100 square miles. An additional total of 100 to 200 square miles in the Quirke Syncline, the Matinenda Lake area and elsewhere may be considered partially explored by widely separated holes and found unlikely to contain extensive deposits. About 250 square miles of Matinenda Formation may underlie the area north of Espanola and a narrow strip between Pronto Mine and Espanola at depths of less than 6,000 feet. Exploration in these structurally complex areas is much more difficult, costlier and slower than in gently-dipping strata. Work on the Agnew Lake Uranium Mines property in central Hyman Township suggest that there are possibilities of finding deposits totalling tens of millions of tons in these parts of the region although the reefs may be thinner and lower grade than those in the Elliot Lake area.

The main unexplored areas are west and northwest of Elliot Lake but an unexplored area, nearly 10 square miles in extent, 11 miles east of Elliot Lake is of special interest as the basement rocks are greenstones, there is a basement high immediately to the northwest, and very low grade uraniferous conglomerates occur downstream to the southeast at Whiskey Lake. The extent of the main block of unexplored ground west of Elliot Lake depends upon the positions of the eastern limit of Thessalon volcanics and the northern limit of the Matinenda Formation. With positions of these features as arbitrarily shown in Figure 12, the area would be about 400 square miles in extent. Of this, about 50 square miles in the south halves of Townships 156, 162 and 168 west of Quirke Lake are of special interest. Basement rocks beneath this block include the southwestern flank of the Whiskey Lake greenstone belt so that a 'mirror image' duplication of features present beneath the Quirke Lake ore zone, which overlies the northeastern flank of the greenstone belt, should be sought here. Some holes recently drilled north of Matinenda Lake in the southern fringe of this block have intersected volcanic rocks only short distances beneath the Ramsay Lake Formation. This could mean that the Matinenda Formation wedges out farther south and thins much more abruptly than expected or it might indicate the presence of a local basement high such as the one found southeast of the Quirke Lake ore zone and one to two miles south of the northern limit of the formation. Granite has been intersected, reportedly, beneath the volcanic rocks so there is a disconcerting possibility that these volcanics represent a tongue or outlier of the Huronian Thessalon Formation rather than basement rocks that are correlative with the Archean greenstone belt. If this were so, favourable valley sites for deposition of Matinenda quartz-pebble gravels might instead have been filled by volcanic flows. The main contact zone between Matinenda strata and Thessalon-Livingstone Creek strata to the west may have been a favourable area for gravel deposition as the volcanic accumulations likely formed positive areas during deposition of the Matinenda Formation. As envisaged in Figure 12 this zone (along the dotted line that separates area A from the main area of Matinenda rocks northeast of Thessalon) may be some 20 miles long and its extension could be sought offshore in Lake Huron on the south flank of the Thessalon Anticline near or just west of the French Islands and Mississagi Bay.

Elsewhere in the 400 square mile unexplored area described above there are possibilities of finding small deposits like the Pronto in declevities atop granitic basement rocks where grittly zones in the Matinenda Formation 'head' south and east of positive areas. Such deposits might be long and narrow, controlled by fractures in basement rocks. Some of the fractures that cut Huronian rocks may have been inherited from the older pre-Huronian fracture pattern and may thus prove to be useful guides to exploration.

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APPENDIX TABLE A

Analyses of Selected Rocks, Elliot Lake Area.

	Sample No.	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	FeO %	MgO %	CaO %	Na_2O %	K_2O	S %	C %	TiO_2 %	ZrO_2 ppm	ThO_2 ppm	U_3O_8 ppm	Co ppm	Ni ppm
Granitic rocks and paleosol beneath the Matinenda Fm. at Quirke Lake																	
pink biotite-hornblende granite	21-2	76.0	13.4	0.36	1.22	0.22	0.49	3.3	4.9	tr	0.05	0.09	67	29	30	< 20	< 30
altered granite	21-4C	78.1	11.8	2.6	1.45	0.11	0.18	3.9	2.6	tr	0.08	0.05	130	42	30	< 20	< 30
granite saprolite	21-4A	74.5	14.7	0.55	2.00	0.46	0.45	2.8	4.1	tr	0.07	0.06	120	42	20	< 20	< 30
pink biotite granite	715	78.4	12.5	0.59	1.22	0.23	0.46	2.5	4.9	0.27	0.06	0.06	86	54	30	< 20	41
altered granite, 10 feet above 715	713	76.2	12.9	0.69	1.19	0.36	0.62	2.2	5.6	tr	0.10	0.04	68	46	18	< 20	35
paleosol, 10 feet above 713	711	77.2	13.2	0.18	1.04	0.27	0.19	3.1	4.9	tr	0.06	0.08	58	38	18	< 20	36
paleosol, 10 feet above 711	709	77.0	12.9	0.22	0.90	0.19	0.27	3.1	5.0	0.09	0.07	0.04	52	23	13	< 20	50
top of paleosol, 10 feet above 709	707	77.0	14.8	0.61	0.68	0.19	0.11	0.30	5.0	0.22	0.04	0.06	100	35	13	< 20	50
Residual argillite overlying meta-	39	45.6	33.1	0.42	1.36	0.33	0.02	0.72	11.0	tr	0.04	1.7	81			< 20	< 30
volcanics beneath Matinenda Fm.	A16	42.5	28.9	3.1	1.83	1.0	1.4	0.14	9.4	tr	0.11	4.3	31			< 20	50
green argillite, McKim Fm.	576	57.3	23.7	1.6	1.3	0.76	0.24	0.28	8.5	0.15	0.06	0.56	140	14	14	< 20	38
grey argillite, McKim Fm.	573	56.3	21.0	1.3	4.5	2.7	0.26	1.2	6.4	0.12	0.29	0.93	160	9	8	25	45
black argillite, Pecors Fm.	1048	60.2	16.6	1.2	7.33	1.6	2.7	1.4	4.8	0.34	0.59	0.71	170	51	31	27	45
Matinenda Fm., Subarkose																	
Ryan Mbr., basal grit	263	89.0	6.0	0.25	0.84	0.11	0.05	0.14	1.9	0.13	0.05	0.07	72	14	8	< 20	54
Ryan Mbr., grit above ore	207	85.0	6.8	0.13	0.84	0.10	0.02	0.16	4.0	0.05	0.06	0.03	110	17	6	< 20	88
Manfred Mbr., basal grit, 4 feet above 707	705	85.3	8.3	0.22	0.72	0.16	0.03	0.20	2.6	0.12	0.04	0.14	180	24	18	< 20	< 30
Conglomeratic Greywacke																	
Ramsay Lake Fm.	157	71.4	10.0	0.34	6.26	2.3	1.6	2.1	1.3	0.16	0.33	0.45	160	10	3	< 20	45
Bruce Fm.	627	75.2	11.4	0.76	2.18	1.1	0.03	0.46	5.0	0.39	0.10	0.70	160	11	6	< 20	80

Analyses by analytical laboratories, Geological Survey of Canada.

APPENDIX TABLE B

Partial analyses of radioactive conglomerates and conglomeratic quartzites.

Location[1]	Strat.[2]	Sample No.	U_3O_8 %	ThO_2 %	Fe %	Ti %	Zr %	Cr %	V %	La %	Y %	Pb %	Sn ppm	Au oz	Ag oz	Co %	Ni %	Cu %	Mo %	Ba %	Other %
LN 19, 2399	1	292	0.12	0.015	8.5	0.25	.010	.002			.01	.02	<5		.03		<.01	.01	.002	.1	
LN 16, 2275	1	412	.19	.034	8.1	.33	.015	.006	.02		.01	.025	<5		.007		<.01	.02	.010	.08	
LN 16, 2271	1	411	.06	.11	8.6	.41	.020	.001	-	.01	.01	.2	<5	.01	.015	-	<.01	.02	.011	.05	
Stanleigh ore*	2	443	.11	.018	6.1	.11	.008	.003	.003		.011	.048			<.06	.006	.005	>.015	.003		
SL 12, 3450	2	88	.17	.026	6.5	.41	.028	.005	<.01	-	.01	.07	<5		.008	-	.01	<.01	.014	.1	
SL 12, 3445	2	87	.48	.077	8.1	.47	.024	.003	<.01	.05	.04	.09	11		.007	.02	.01	<.01	.006	.1	
M 15, 3276	2	215	.24	.037	9.1	.17	.010	.001		-	.01	>.07	<5		.027	-	<.01	<.01	.005	.08	
Lacnor ore*	2	493	.28	.044	4.8	.17	.001	.006	.006		.015	.107			<.06	.006	.008	<.015	.004		
Nr 928, 997	2	453	.36	.068	13.0	.13	.026	.001	-	.01	.01	.1	<5		.013	-	.01	.04	.003	.05	Be .001
Nr 923, 598	2	459	.42	.052	5.5	.08	.012	.001	-	.01	.02	.2	<5		.01	.01	<.01	.1	.002	.05	
Nordic ore*	2	1171	.19	.038	4.8	.11	.010	.005	<.002		.015	.056			<.06	.001	.001	.006			
Nordic ore*	2	281	.073	.025	2.1	.28	.017	.001								.001	.001	.005			
Nordic ore*	2	282	.16	.052	7.9	.36	.070	.008								.024	.014	.019			
M 2A, 2473	2	538	.074	.087	6.0	.56	.015	.006	-	.02	.01	.022	5.2		.015				.006	.08	
LN 19, 2372	2	276	.17	.16	9.5	.35	.012	.001													
M 2A, 2438	3	533	.067	.093	3.7	.41	.010	.005		.01	.01	.016	<5	.002	.004	-	<.01	.02	.005	.05	
LN 16, 2198	3	401	.067	.11	7.6	.55	.038	.004	<.01	.2	.02	.013	<5		.017	.03	.02		.011	.1	
Nr 923, 533	3	457	.18	.10	6.0	.24	.012	.001	-	.05	.02	.023	<5		.10	.01	<.01	.02	.001	.08	
Stinson Lake*	3	210	.030	.039	4.3	.21	.023	.004	.007		.013	.006			1.0	.006	.007	<.001	.004		
Pecors Lake*	3	200	.038	.039	8.7	.19	.012	.004	.005		.013	.011			<.06	.008	.007	<.001	.001		
SL 12, 3380	4	79	.080	.10	9.8	.46	.022	.006		.2	.01	.017	<5	.015	.012	.03	.02	.01	.006	.1	
M 5, 3066	4	253	.064	.11	5.8	.33	.010	.001		.1	.01	.022	<5		.011	.02	<.01	.01	.001	.1	
M 2A, 2402	4	529	.058	.10	4.6	.44	.034	.002		.05	<.01	.021	<5		.027	-	<.01	.02	.009	.08	
SM 6, 3030*	5	169	.043	.029	9.8	.12	.015	.005	.004		.010	.010			.12	.010	.007	<.001	.009		

Pecors Lake	5	26	.16	.23	11.5	.23	.059	.005	<.002		.026	.086			<.06	.019	.013	>.015	.012		
Q 86*	6	499	.58	.072	5.1	.10	.013	.001		.01	.02	.2	9.3		.10	-	<.01	.05	.001	.05	Zn .01
D 27, 1459	6	646	.080	.30	7.6	.95	.031	.007		-	<.01	.021	<5	.005	.01	-	.01	.1	.001	.05	
D 27, 1452	6	642	1.73	.20	5.0	.27	.025	.006		-	.05	.3	6.1	.032	.03	-	-	.2	.001	.08	
Denison, 1 shaft*	6	1174	1.15	.24	4.4	.18	.019	.005	<.002		<.063	>.40			.24	.023	.007	.010	<.002		
D 19, 2246	6	697	.31	.045	3.9	.05	.010	.006		-	.01	.08	<5		.026	-	-	.08	.001	.08	
D 23, 2388	6	847	.11	.12	8.2	.14	.010	.003		.4	.02	.06	13		.10	.02	.02	.05	.005	.02	
D 23, 2387	6	846	.11	.29	8.6	.73	.027	.009		.2	.01	.06	14		.12	-	.02	.03	.010	.01	As .01
D 23, 2386	6	845	.11	.12	8.2	.14	.010	.003		.2	.02	.06	5		.05	.03	.02	.04	.006	.08	
D 29, 1905	6	623	.038	.20	8.1	.95	.022	.008		.2	.01	.020	6.7		.005	-	.01	.02	.001	.05	Be .003
P 25, 1132	6	427	.43	.072	13.2	.32	.020	.005		.02	.02	.2	12		.07	.03	<.01	.05	.002	.1	
Panel ore*	6	131	.15	.11	10.7	.17	.023	.006	<.002		.028	.094			.15	.021	.011	.005	<.002		
P 9, 1542	6	703	.021	.10	5.4	.63	.022	.009		.2	.01	.006	12		.014	-	<.01	.08	.002	.2	
P 9, 1526	6	701	.052	.11	8.0	.30	.018	.003		.2	.03	.006	5.3		.018	-	<.01	.1	.001	.2	
P 17, 1622	6	435	.053	.17	4.5	1.13	.060	.008		.05	.01	.004	11		.013	-	-	<.01	.001	.1	
Spanish American*	6	497	.13	.072	3.7	.15	.018	.003	<.002		.013	.046			<.06	.010	.004	.011	.003		
Stanrock*	6	441	.047	.046	10.7	.20	.020	.007													
SA 6, 3090	6	980	.31	.16	9.2	.75	.037	.011		.2	.03	.05	14		.09	-	<.01	.02	.002	.08	
SA 6, 3087	6	979	.59	.15	6.5	.23	.025	.005		.1	.02	.2	15		.18	-	.01	.1	.002	.02	
SA 5, 3233	6	973	.045	.11	14.4	.58	.019	.010		.2	.01	.012	12		.10	.06	.03	.05	.001	.02	
SA 9, 3101	6	991	.12	.20	4.9	.84	.035	.005		.2	.05	<.03	15		.11	.03	.01	.05	.002		
SR 8, 2854	6	1134	.49	.15	18.9	.40	.031	.008		.2	.02	.02	14		.21	.02	.01	.05	.002	.08	
SR 5, 3256	6	1126	.20	.20	9.9	.56	.048	.009		.2	.01	.08	11		.11	-	-	.01	.001	.04	
CM 3, 2337	6	1120	.39	.057	4.4	.14	.016	.003		-	.02	.08	9		.06	-	-	.02	.002		
CM 6, 2245	6	1116	.37	.072	11.7	.62	.031	.001		.1	.03	.2	12		.20	.06	.02	.1	.002	.1	
Can Met*	6	400	.093	.12	4.5	.32	.039	.005	.003		.022	.016			<.06	.009	.005	>.015	.003		
Can Met 6, 2010	6	1112	.14	.30	6.0	.92	.045	.001		.2	.08	<.03	12		.21	.01	<.01	.02	.001	.08	
Can Met 8, 2092	6	998	.051	.12	5.6	1.31	.058	.007		.2	.03	.027	16		.042	.04	.01	.08	.002	.1	

APPENDIX TABLE B (cont'd.)

Location[1]	Strat.[2]	Sample No.	U_3O_8 %	ThO_2 %	Fe %	Ti %	Zr %	Cr %	V %	La %	Y %	Pb %	Sn ppm	Au oz	Ag oz	Co %	Ni %	Cu %	Mo %	Ba %	Other %
SC 18-3, 2021	6	1136	.053	.089	8.0	.41	.031	.009		.1	.01	.008	11		.022	.02	.01	.02	.002	.1	
SC 18-6D, 1728	6	1142	.013	.064	8.2	.32	.018	.009		.1	.01	.005	13		.026	.05	.01	.02	.002	.1	
SC 18-6D, 1723	6	1141	.15	.11	10.6	.44	.020	.011		.2	.05	.018	12		.042	.04	<.01	<.01	.001	.1	
NC 2, 3713	6	36	.023	.090	5.4	.41	.020	.002		.1	.01	.008	<5		.011	-	-	<.01	<.001	.1	
Conecho*	6	45	.045	.040	4.7	.33	.042	.007	.003		.024	.032			<.06	.009	.006	.006	.003		
CE 18, 572	6	146	.055	.15	4.4	.95	.053	.001		.2	.01	.007	13	.002	.033	-	<.01	<.01	.007	.2	
Quirke Mine*	7	1177	.15	.049	4.7	.12	.015	.004	<.002		.015	.078			<.06	.017	.009	.007	.002		
Q 258*	7	479	.56	.25	7.6	.85	.020	.006								.012	.006	.006			
Q 258*	7	478	.035	.019	2.1	.22	.011	.003								.006	.003	.004			
Q 231	7	468	.08	.12	4.2	.33	.014	.004	-	.01	.01	.007	5.4		.008		-	<.01	.003	.03	
D 27, 1201	7	673	.11	.13	4.1	.37	.013	.001		.1	.02	>.03	<5		.028	-	.02	.08	.001	.08	
Whiskey Lake*	8	43	.006	.008	20.0	.21	.048	.006	.004		.015	.024			<.06	.025	.013	>.015	.011		
SR 4, 2866	9	142	.016	.16	6.9	.58	.024	.003		.01	<.01	.021	<5	-	.006	-	-	.01	.003	.1	
Mount Lake*	10	348	.001	.012	3.7	.26	.035	.006	.011		<.002	<.002			<.06	<.001	<.003	<.003	<.002		

* Analyses from Pienaar 1958, Table XXX, p. 275 and Tables XIII and XIV, p. 126 and 128.
Gold analyses are fire assays by Mines Branch, Department of Energy, Mines and Resources, other analyses by analytical laboratories of the Geological Survey Branch.

Explanatory notes

1 Location by Mine or geographic locality and by drillhole and core footage LN 19 drillhole on Lacnor property, SL – Stanleigh, M – Milliken Lake, Nr – Algom Nordic, SM – Silvermaque older drilling, Q – Algom Quirke, D – Denison, P – Panel, SA – Spanish American, SR – Stanrock, CM – Can Met, SC – Can Met easterly extension, CE – Conecho (east of Panel), NC – Nasco (Poppy Lake area, south of Quirke Lake)

2 Stratigraphic positions:

1. basal reefs, Ryan Member, Matinenda Formation
2. main ore reefs, Ryan Member
3. Pardee or upper ore reef, Ryan Member
4. higher conglomerate beds in Ryan Member
5. Stinson Member, Matinenda Formation
6. Denison reef zone, Manfred Member, Matinenda Formation
7. Quirke Reef zone, Manfred Member
8. indeterminate position, Manfred Member
9. Mississagi Formation
10. Lorrain Formation, Hematitic conglomerate

APPENDIX TABLE C. Gold contents of some ores, conglomerates and associated radioactive rocks.

	Sample No.	U_3O_8 %	ThO_2 %	Au oz/ton	Ag oz/ton
Matinenda Formation, Ryan Member					
basal conglomerate, Stanleigh Hole 12	95	0.005	0.004	n.d.	
main ore zone, Stanleigh Mine		.071	.03	.003	< 0.01
Stanleigh Hole 3	939	.043	.007	.01	
Milliken Mine		.095	.04	.005	.06
Lacnor Mine		.071	.03	.005	.01
east margin, Nordic Hole 603	46	.14	.022	.002	
west margin, Milliken Hole 2A	533	.07	.09	.002	
Nordic Mine		.16	.02	.002	.02
upper reef, Stanleigh Hole 12	79	.08	.10	.015	
Milliken Hole 2A	529	.05	.10	.005	
higher beds, Silvermaque Hole 2	18	.06	.02	.002	
Kamis Hole 2	62	.012	.027	.002	
Matinenda Formation, Stinson Member					
Stanleigh Hole 12	74	.002	.003	.002	
pyritic seam, Silvermaque Hole 6	168			.05	.90
Matinenda Formation, Manfred Member					
Denison Hole 27	646	.08	.30	.005	
	642	1.73	.20	.032	
Denison Mine		.23	.07	.003	.09
Denison Hole 19	691	.15	.03	.01	
Denison Hole 23	872	.12	.10	.002	
	863-4	.11	.017	.015	
	845	.15	.11	.005	
	843	.27	.19	.015	
Panel Hole 25	421	.08	.04	.02	
Panel Mine		.11	.06	.002	.05
Spanish American Hole 6	977	.18	.04	.015	
	976	.07	.08	.002	
Spanish American Hole 9	994	.63	.18	.03	
Spanish American Hole 5	965	.09	.18	.002	
Spanish American Ore		.11	.05	.002	.02
Stanrock Mine		.071	.03	.003	tr
Stanrock Hole 5	1125	.38	.14	.005	
Can Met Hole 3	1121	.19	.07	.01	
Can Met Hole 8	1103-5	.18	.07	.005	
Can Met Hole 18-3	1137	.10	.07	.01	
Conecho Hole 18	146	.15	.06	.002	
uranite seam, Quirke Mine	58RF8			.002	
Matinenda Formation, general					
conglomerate Baldwin Twp.	10-1B	high		<.005	
Hyman Twp.	20-1	low		<.005	
Porter Twp.	49-4	high		<.005	
Mississagi Formation					
conglomerate Stanleigh Hole 12	72	.008	.007	.01	
Stanrock Hole 4	142	.016	.16	n.d.	
Nasco Hole 1	2-1			<.005	
grit Denison Hole 19	683			<.005	
conglomerate Thessalon area	40-2			<.005	
Wanapetei Lake	7			.015	
Milnet	10-3			<.005	
conglomerate Turner Twp.	6			<.005	
grit Turner Twp.	5			.008	
grit Pardo Twp.	11-1			<.005	
Lorrain Formation					
hematitic conglomerate Twp. 1C			high	<.005	
conglomerate, Browing Twp.			low	n.d.	

Gold and silver analyses by fire assay, Mines Branch, Ottawa; assays reported as trace are listed as 0.002 oz. per ton in this table.

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