Report on

Selected
Precambrian Environments
in
the Province of Ontario

for

Ontario Parks, Ministry of Natural Resources

by
C.E. Blackburn, P.Geo.
Blackburn Geological Services
Victoria, B.C.

2010

PREFACE - SUMMARY OF FORMAT

In order to facilitate comparison and some degree of compatibility with the *Earth Science Framework* document of 1981, and maintain a firm scientific basis for this new document, the following hierarchy of chapters and sections is used in what follows.

1) First ordering of the format is by Precambrian **eons**, divisible into **Archean** and **Proterozoic** by chapters.

2) Second ordering is by **provinces or orogens**. That of the Archean Eon is **Superior Province**. In agreement with the generally accepted scheme in Ontario, those of the Proterozoic Eon are: **Trans-Hudson Orogen**; **Southern Province**; and **Grenville Province** (not discussed in the present document).

3) Third ordering is by **eras**. In Ontario, those of the Archean Eon are: **Neo to Mesoarchean**; and **Neoarchean**. In Ontario, those of the Proterozoic Eon are: **Paleoproterozoic**; and **Neoproterozoic** (not discussed in the present document).

4) Fourth ordering is by **environments**, the key designation. These devolve into **greenstone belt**, **sedimentary basin**, and **batholithic**. Thus, environments are grouped according to their geochronologically defined age range (era), structural location (province or orogen), and broader age grouping (eon).

5) Fifth ordering, but only for greenstone belts, is by **assemblages**. These devolve into **platform**, **mafic plain**, **volcanic arc**, and **successor basin**.

In the following hierarchy, the various environments that have arisen from revision of the *Earth Science Framework* document to date are bolded:

- Archean
  - Superior
    - **Neo- Mesoarchean**
      - **greenstone belt environment**
        - platform (Steep Rock type)
        - mafic plain (Wapageisi type)
        - volcanic arc (Keewatin type)
        - successor basin (Timiskaming type)
      - **batholithic environment**
    - **Neoarchean**
      - **sedimentary basin environment**

- Proterozoic
  - Trans-Hudson
    - **Paleoproterozoic**
      - sedimentary basin:
      - **Sutton Hills platform environment**
  - Southern
    - **Paleoproterozoic**
      - sedimentary basins:
      - 1) **Huronian crustal rifting and continental margin environment**
      - 2) **Animikie continental foredeep environment**

PRECAMBRIAN ENVIRONMENTS

Table of Contents

Tables

Figures

PRECAMBRIAN ENVIRONMENTS

A. INTRODUCTION

Ontario lies in the heart of Laurentia, the North American craton[1], assembled into the "United Plates of America" (P.F.Hoffman 1988) in the early part of the Proterozoic eon (Table 1). The craton includes (Figure 1) the Precambrian shields of Canada and Greenland, and the covered platform and basins of the North American interior.

The Ontario Geological Survey's seminal "Geology of Ontario" project presented for the first time in one compendium (OGS 1991a, 1992), an interpretation of the development of the **Canadian Shield** based for the most part on plate tectonic models.

Given ongoing lack of consensus on models, whether plate tectonic based or not, description of Precambrian environments is presented here with as little reference as possible to them: instead, the broad lithologic parameters presented in the Geology of Ontario volumes (OGS 1991a, 1992) and geological maps (OGS 1991b,c,d,e) and explanatory notes (OGS 1991f), here collectively referred to as GOO, will be utilized.

---

[1] Stable part of the continental crust, no longer affected by mountain building activity.

Table 1. PRECAMBRIAN TIME SCALE AND ONTARIO REPRESENTATION

EON (My)	**ERA (My) – terminology used in this manual (adapted from OGS 1991a, Figure 1.4)**	**ERA (My) – alternate terminology (adapted from Okulitch 1999)**	**ONTARIO REPRESENTATION – PROVINCES**	**ONTARIO REPRESENTATION – OROGENS (My)**
PROTEROZOIC 2500 - 570	NEOPROTEROZOIC 900 - 570	HADRYNIAN 1000 - 544		
	MESOPROTEROZOIC 1600 - 900	HELIKIAN 1750 - 1000	GRENVILLE PROVINCE	MIDCONTINENT RIFT 1100 GRENVILLE OROGEN 1600 - 1000
	PALEOPROTEROZOIC 2500 - 1600	APHEBIAN 2500 - 1750	SOUTHERN PROVINCE	TRANS-HUDSON OROGEN 1900 – 1800 PENOKEAN OROGEN 1900 - 1700
ARCHEAN 4000 - 2500	NEOARCHEAN 2900 - 2500	LATE ARCHEAN 3000 - 2500	SUPERIOR PROVINCE	KENORAN OROGENY 2710 - 2670
	MESOARCHEAN 3400 - 2900	MIDDLE ARCHEAN 3400 – 3000	SUPERIOR PROVINCE	
	PALEOARCHEAN 4000 - 3400	EARLY ARCHEAN 4000 - 3400		

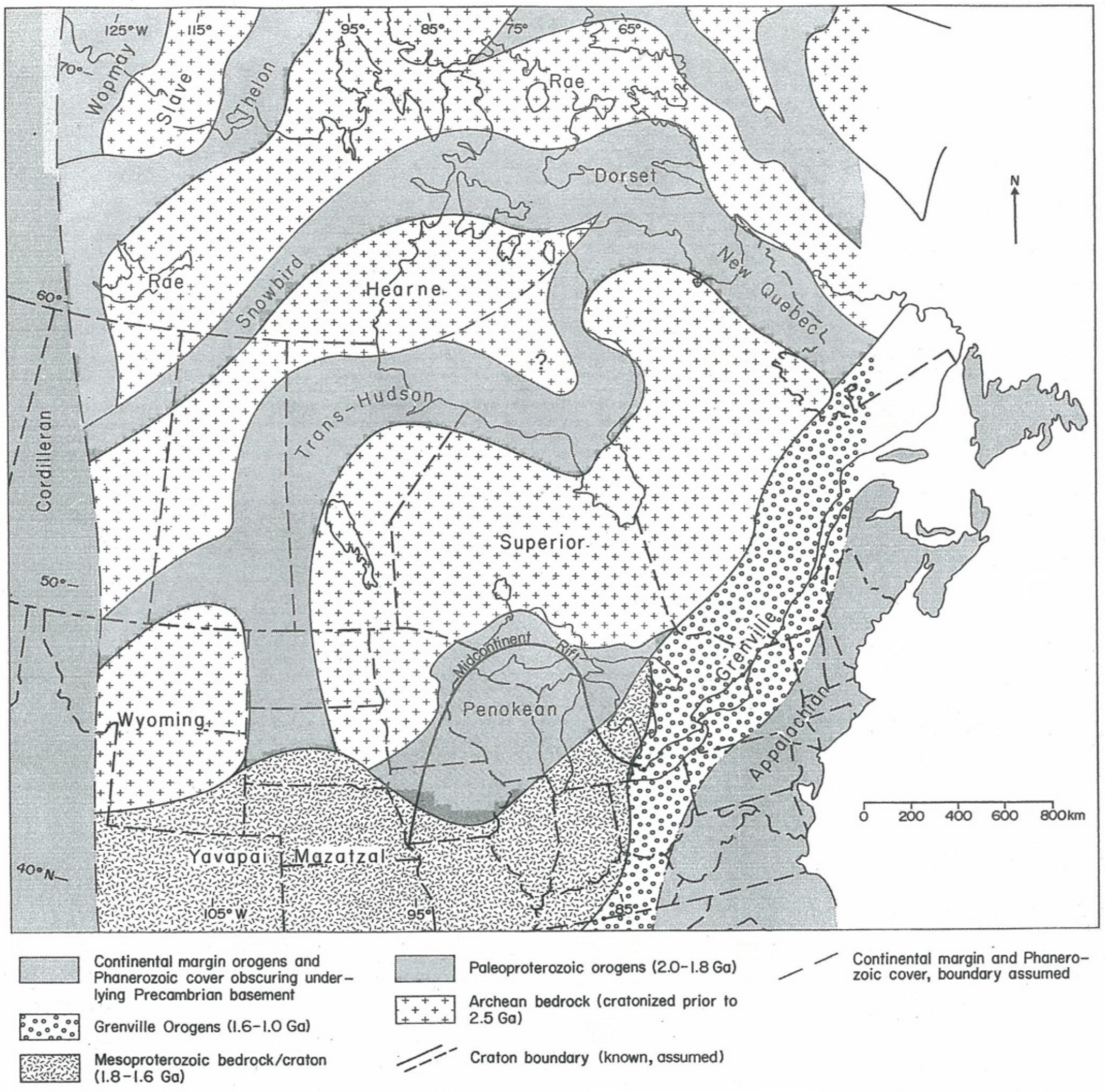

Figure 1. The Laurentian craton and flanking continental margin orogens (*from* OGS 1991a, Figure 15).

B. ARCHEAN

In the Archean Superior Province, development of greenstone belts[2] and sedimentary basins had historically been explained as being autochthonous[3]. The new GOO compendium sought to free greenstone belts and sedimentary basins from that autochthonous constraint, by presenting their development from an allochthonous[4] viewpoint. Although similar tectonic models had been presented well over a decade earlier (e.g. Langford and Morin 1976), these had largely been speculative and presented from a very limited data base. Such contrasting models have sometimes been referred to (e.g. Blackburn 1980; Williams et al 1992) as “fixist” for the former and “mobilist” for the latter. The new approach presented accretion of crustal blocks by lateral movement (Williams et al 1992) with superimposed rifting or strike-slip fault-related processes, followed or accompanied by erosion and deposition of sediments in large basins.

However, further work in the intervening years, particularly in the Archean-age Abitibi greenstone belt, has led many workers to revert to an autochthonous model for that and other parts of the Canadian Shield in Ontario and Quebec (e.g. Ayer et al 2002; Thurston 2002). But, other workers continue to espouse an allochthonous model for the Abitibi greenstone belt (e.g. S.L. Jackson et al 1994; Daigneault et al 2004), and by implication elsewhere in the Superior Province.

Models of Archean greenstone belt development are crucial for mineral exploration (e.g. Thurston et al 2008), so that debates on applicable tectonic models will continue as new data is acquired.

---

[2] General term for all the rocks within a predominantly volcanic sequence, but including sedimentary and igneous intrusive rocks. The belts commonly have a curvilinear form.

[3] Formed in the same relative position to each other as seen at present.

[4] Moved from their original site of formation.

B.1 SUPERIOR PROVINCE

Superior Province (Figure 1) constitutes the major portion of the Canadian Shield in Ontario. Earlier workers noticed a natural subdivision of the Superior Province into belts or subprovinces (e.g. Stockwell 1964) dominated by characteristic lithologies and structures. The “Geology of Ontario” project more firmly established their defining characteristics and terminology (OGS 1991f; Figure 2). However, the number of such subprovinces, their naming and their boundaries continue to be modified by subsequent work, in particular in the northern portion of Ontario.

The general concept of subprovinces remains valid, but names assigned to them, and positioning of their boundaries, are likely to continue to be changed. They are therefore not useful as a framework for categorizing Archean environments. Furthermore, various large-scale fault-bounded areas with distinct geologic histories, termed terranes, and their amalgamations into superterranes have been proposed, that may either be identical to, enclosed within, or transect subprovinces (e.g. Stott 1997, Stott et al 2007). Such terranes imply reference to particular tectonic models, and again are not useful in categorizing Archean environments.

The Archean eon (Table 1) was extraordinarily endowed with metal concentration processes, such that various environments within Ontario’s portion of Superior Province are characterized by distinctive suites of metals.

Ontario Archean geology, from geochronologic evidence accumulated up to the present, spans a range within Mesoarchean to Neoarchean time, i.e. within the age range 3400 My to 2500 My (My = million years). No Paleoarchean rocks (i.e. older than 3400 My: Table 1) have been identified in Ontario.

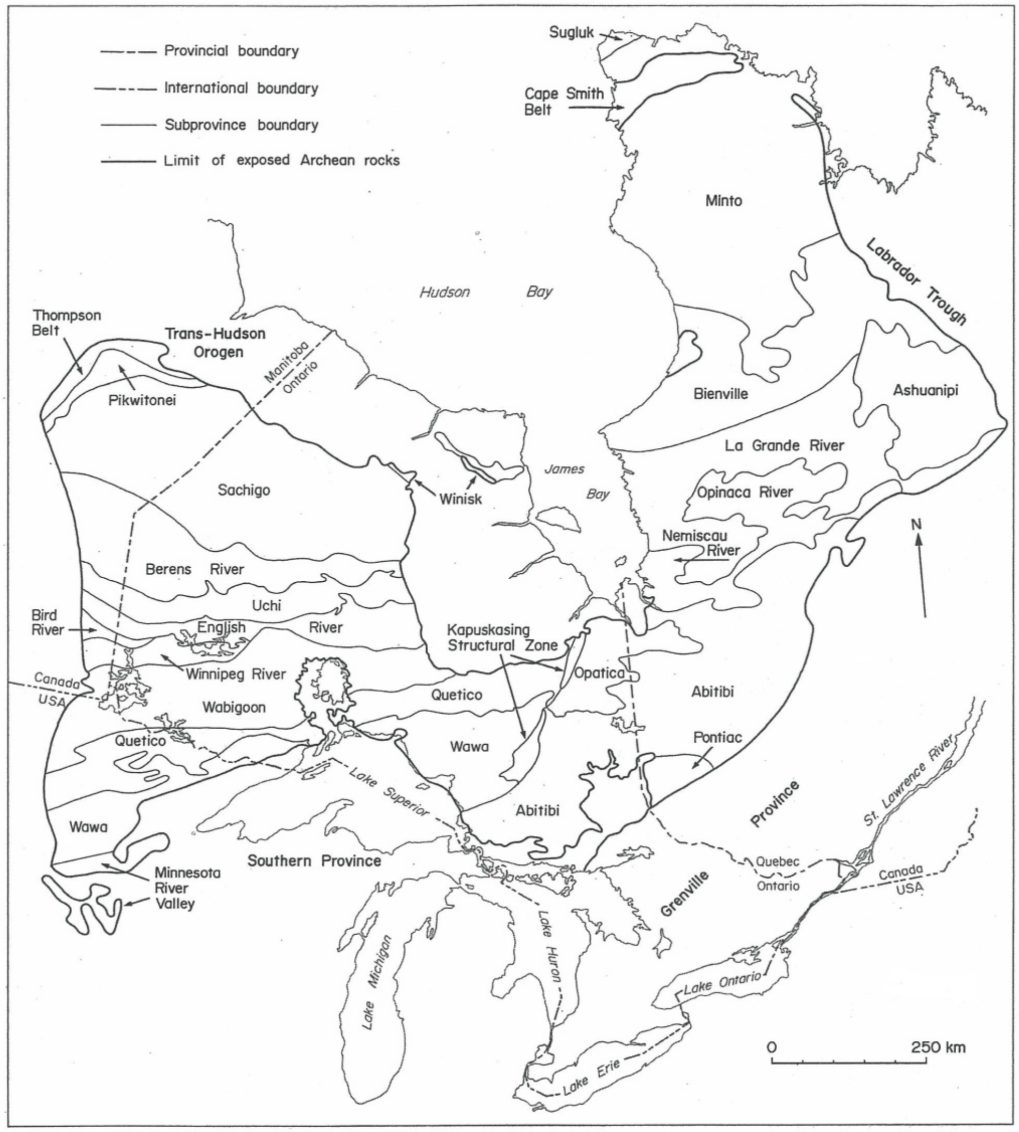

Figure 2. Subdivision of the Superior Province into subprovinces (*from* OGS 1991a, Figure 4.2).

Archean environments, the key designation, are here identified in relation to their age ranges, in the following format:

1. Neo- to Mesoarchean greenstone belt environment
2. Neo- to Mesoarchean batholithic environment
3. Neoarchean sedimentary basins environment

Three types of subprovinces have been recognized in Ontario:

(a) granite-greenstone subprovinces
(b) plutonic subprovinces
(c) sedimentary subprovinces

Each subprovince type (a) through (c) possesses features of various environments (1) through (3). Greenstone belt environments (1) fall within (a) granite-greenstone subprovinces; batholithic environments (2) fall within both (a) granite-greenstone and (b) plutonic subprovinces; and large sedimentary basins (3) fall within (c) sedimentary subprovinces.

1. Neo- to Mesoarchean greenstone belt environment

Granite-greenstone subprovinces, such as Sachigo, Berens River, Uchi, Bird River, Wabigoon, Wawa and Abitibi, consist of greenstone belts surrounded and cut into by granitic rocks (Figure 3). The sinuous to bifurcating map pattern of greenstone belts is a product of: a collage of the four assemblage types[5] described below; intrusion of granitic batholiths; and multiple deformation events within them.

Geochronologic evidence suggests that greenstone belts developed over a protracted period of time that spans from about 3200 to 2650 My ago. However,

---

[5] The term “assemblage” as used here is not to be confused with “tectonic assemblage” as defined on p.1256 in Chapter 25, Part 1 of the GOO volume (Williams et al 1992) and upon which much of the discussion in that part of the chapter is based. “Assemblage” as used here is purely descriptive of a sequence of rock types that imply a depositional environment, but without tectonic implications.

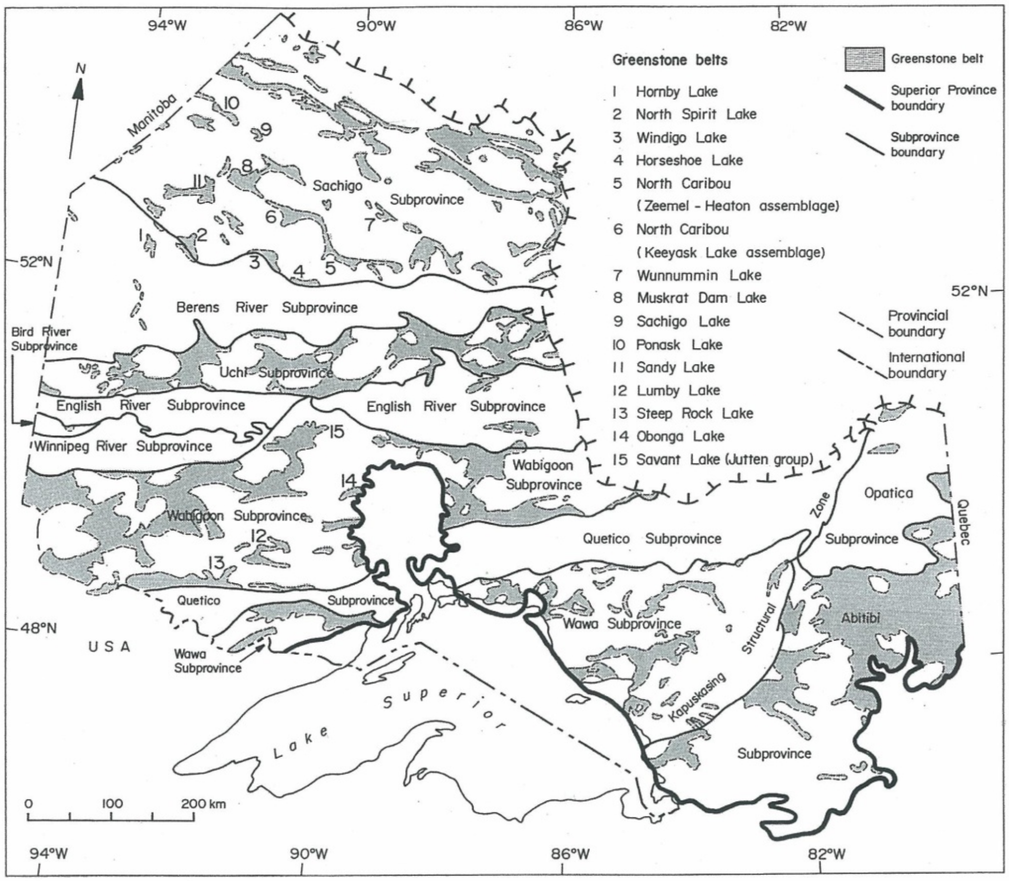

Figure 3. Greenstone belts of the Superior Province of Ontario, and location of platform assemblages (*from* OGS 1992, Figure 25.1).

this range may be extended as research progresses. As geochronologic evidence was accumulated, it was recognized that, as a general observation, oldest ages are recorded in the northwest of the province, leading to the suggestion (Langford and Morin 1976) of progressive accretion of volcanic island arcs[6] around a nucleus in far northwest Ontario. Stott (1997) cites abundant evidence that the Superior Province is the product of a Neoarchean orogenic[7] episode, the **Kenoran Orogeny**, between about 2710-2670 My ago (Table 1). Furthermore, the timing of the orogenic stage varies diachronously across the Superior Province: it occurred prior to 2710 My in the north, between 2710 and 2690 My in the centre, and between 2710 and 2680 My in the south (Corfu and Davis 1992). Geochronologic evidence to date supports the possibility of more than one ancient (Mesoarchean) nucleic granitic basement, within Sachigo and Wabigoon subprovinces respectively. Their extent, however, is unknown.

1.1 Platform assemblages (Steep Rock type)

These assemblages consist of thin clastic, chemical and biochemical rock sequences formed on shallow-water platforms. They were deposited on older substrates of lithologically variable crust, which they unconformably overlie. The assemblages are typically represented by quartz-rich sandstones and carbonate-rich sediments, indicating epicontinental[8], tectonically inactive conditions. In Ontario, at least 15 localities have been suggested where these conditions pertain, mostly in the far north (Figure 3), and none east of Lake Nipigon. Of these, three localities are well documented. The best documented is at Steep

---

[6] Series of volcanoes that form a string of islands that parallel an adjacent continent at the edge of an ocean.

[7] Mountain building, especially where a belt of the Earth's crust is compressed by lateral forces to form a chain of mountains.

[8] Deposited in a shallow sea extending into the interior of a continent, or shallow seas on a continental shelf.

Rock Lake in the Wabigoon Subprovince, where the type name originates (Wilks and Nisbett 1988; and locality #13 in Figure 3), and where the substrate is granitoid[9]. In the Sachigo Subprovince, a number of localities have been recorded where the substrate is supracrustal[10]. Such is the case at the west end of Eyapamikama Lake in the North Caribou greenstone belt (Thurston and Chivers 1990; and locality #6 in Figure 3). Again, in the North Spirit Lake greenstone belt, platformal Nemakwis sedimentary rocks (Wood et al 1986; and locality #2 in Figure 3) lie on a supracrustal substrate. Another platformal assemblage may be the Nekence in the Muskrat Dam Lake greenstone belt (locality #8 in Figure 3). Where dated, the assemblages are found to be of late Mesoarchean to early Neoarchean age (~3000 My).

Rock types include but may not be confined to quartz arenites, quartz conglomerates, iron formation, marble, and stromatolitic carbonate, typically belonging to GOO unit 1.

1.2 Mafic plain assemblages (Wapageisi type)

Along with volcanic arc assemblages, mafic plain assemblages constitute the major components of greenstone belts. The assemblages are thick and extensive, and commonly constitute the lowermost volcanic sequence in a greenstone belt, for example at Wapageisi Lake in the Manitou Lakes-Stormy lakes greenstone belt (Blackburn 1982, Blackburn et al 1991), from where the type name is here taken. A further example is the lower unit of the Blake River assemblage in the Abitibi greenstone belt (e.g. Thurston et al 2008). Mafic plain assemblages consist dominantly of mafic to lesser amounts of ultramafic flow rocks, with minor layers of deep-water sedimentary rocks such as graphitic and or sulphide-bearing argillite. As with arc volcanics, submarine eruption is

---

[9] General term applied to intrusive igneous rocks with visibly distinct crystallinity that are quartz-bearing: includes granite, granodiorite, tonalite, quartz monzonite and quartz diorite.

[10] Formed above the crust, i.e. of either volcanic or sedimentary origin.

exemplified by characteristic pillow lavas. Volcanogenic and geochemical evidence suggests that these rocks are ancient analogues of modern oceanic volcanism. The economic importance of these assemblages is also evident in that they host copper-nickel base metal deposits, and associated platinum-palladium precious metal deposits.

Rock types include but may not be confined to mafic to ultramafic volcanic flow rocks (basalts, komatiites), and minor clastic (siltstones, wacke sandstones) and chemical (iron formation, chert) sediments, typically belonging to GOO units 4 and 5, and subvolcanic mafic to ultramafic intrusive rocks (gabbro, anorthosite, pyroxenites, peridotite) of GOO unit 10.

1.3 Volcanic arc assemblages (Keewatin type)

Volcanic arc assemblages consist of mafic to felsic volcanic rocks deposited in situations akin to those of modern volcanic island arcs. The type name comes from the former Town of Keewatin in the Lake of the Woods area, where early studies were made (see references in Ayer et al 1991). Mafic varieties are dominantly flows, while felsic volcanics are commonly pyroclastic. Mafic volcanics therefore typically show submarine characteristics such as pillow lavas, whereas felsic volcanics may be primary pyroclastic tuffs and agglomerates, the products of emergent edifices, or water-reworked varieties such as debris flows. These assemblages are of great economic importance as they host the majority of copper-lead-zinc volcanic-related base metal deposits, along with gold-silver precious metal deposits.

Rock types include but may not be confined to mafic to intermediate volcanic flow rocks (basalts, andesites), felsic to intermediate pyroclastic tuffs and breccias and flow rocks (rhyolites, rhyodacites, dacites, andesites), and minor clastic (siltstones, wacke sandstones) and chemical (iron formation, chert) sediments, typically of GOO units 2, 3, 5 and 6.

1.4 Successor basin assemblages (Timiskaming type)

Late, intra-continental, structurally controlled successor basins are characterized by a sedimentary association of alluvial-fluvial deposits that are in apparent fault or overlying, but markedly unconformable, contact with volcanic arc and mafic plain assemblages. A further characteristic is presence of alkalic[11] volcanic rocks, in marked contrast to the calc-alkalic, tholeiitic and komatiitic sequences of the volcanic arc and mafic plain assemblages. This volcanic suite and accompanying conglomerates and turbiditic[12] sandstones have long been known (e.g. Cooke and Moorhouse 1969) in the Abitibi Subprovince from the Kirkland Lake area in Timiskaming District, from where the type name is derived. There is no evidence of submarine eruption of lavas with their typical structures such as pillowed flows. The basins are considered to have opened either by crustal rifting or by wrench faulting[13], late in the tectonic-amalgamation, shield-forming history of the Superior Province. Similar to the volcanic arc assemblages, they also host gold-silver precious metal deposits.

Rock types include but may not be confined to coarse (conglomerates) to medium (sandstones) clastic sedimentary rocks, with accompanying alkalic mafic to felsic flow and pyroclastic rocks (syenites, trachytes, trachyandesites, trachybasalts) of GOO unit 9.

2. Neo- to Mesoarchean batholithic environment

It is generally recognized that only one plutonic subprovince is present in Ontario, namely Winnipeg River Subprovince (Figure 2). Justification for the setting apart

---

[11] Relatively higher in sodium content compared with the more calcium to magnesium rich intermediate (calc-alkalic), mafic (tholeiitic) and ultramafic (komatiitic) suites.

[12] Deposited from sediment-laden currents that flow down submarine slopes as a result of slumping of unconsolidated sediment, commonly triggered by earthquake activity.

[13] Faulting in which the net slip is parallel to the strike of the fault.

of plutonic subprovinces from granite greenstone subprovinces lies in relative absence of such contained greenstone belts, within a predominantly granitoid assemblage: Winnipeg River Subprovince contains only small such slivers, such as at Dalles and at Ross Lake (Beakhouse 1991, p. 280). Berens River Subprovince may also be characterized as such, given paucity of contained greenstone belts (Figure 3).

The granitoid plutons and batholiths contained within the granite-greenstone subprovinces characteristically intrude earlier volcanic sequences. Only rarely have they been recognized to form basement to supracrustal rocks, and where this occurs those supracrustals are predominantly platform assemblages, as discussed above. Geochronologic determinations to date show that they run the gamut from early in the Mesoarchean to late in the Neoarchean era. No Paleoarchean ages have been recorded.

Rock types include but may not be confined to massive to foliated to gneissic felsic (granite, granodiorite, tonalite, syenite) through intermediate (diorite, syenodiorite, monzonite) through undersaturated (nepheline syenite) plutonic rocks. These varieties have been grouped into various suites as the following GOO units:

Unit 11 – gneissic tonalite suite
Unit 12 – foliated tonalite suite
Unit 14 – diorite-monzonite-granodiorite suite
Unit 15 − massive granodiorite to granite
Unit 16 – diorite-nepheline syenite suite

3. Neoarchean sedimentary basin environment

At least two long, linear sedimentary basins that have been characterized as subprovinces are present in Ontario: English River Subprovince (Breaks 1991) and Quetico Subprovince (Williams 1991). The lesser-studied Opatica Subprovince in northeast Ontario (Figure 2) is possibly a third. Geochronologic evidence to date suggests that sedimentary rocks of these subprovinces span an age range of deposition within Neoarchean time, i.e. between 2900 My and 2500 My ago. In addition to sedimentary rocks ranging in metamorphism from low-grade (greenschist) to high-grade (granulite), they contain granitoid plutons derived from melting of the parent sedimentary sequences. It is inferred from both mineral content and age range of sedimentary materials, some of which is of Mesoarchean age, that its source was dominantly from precursor granitic and greenstone belt rocks.

Environments of deposition within the sedimentary subprovinces range from proximal, in which coarse clastic conglomeratic facies prevail, to distal, characterized by sandstones to finer-grained clastic sediments. The latter are far more voluminous, and where preserved constitute the bulk of the subprovinces. Conglomeratic facies commonly lie close to the subprovince boundaries, for example at Separation Lake at the south boundary of the English River Subprovince (Blackburn and Young 2000; and references in Breaks 1991) and in the Beardmore-Geraldton area, at the north boundary of the Quetico Subprovince (Devaney and Williams 1989; Williams 1991). Much less voluminous amounts of chemical sediments are locally present. High grade metamorphism has led to partial melting of the sediments, resulting in voluminous amounts of migmatite, and under extreme melting conditions to generation of magma emplaced dominantly as granitoid batholiths.

Rock types include but may not be confined to wacke, arkose, argillite, conglomerate, arenites and their metamorphic equivalents (slate, paragneiss, migmatites), and iron formation and chert, all typically belonging to GOO unit 7. Associated granitoid plutons are commonly muscovite-cordierite and muscovite-biotite granodiorites and tonalites, typically of GOO unit 13, and granodiorite to granite of GOO unit 15. Migmatites and gneisses of uncertain protolith (GOO unit 8) were most probably derived by high-grade metamorphism of rocks of this sedimentary basin environment, and are therefore grouped within it.

4. Archean biodiversity

Biodiversity in the Archean was restricted to primitive life forms. Stromatolites have been noted at a number of localities in the Archean of northwestern Ontario, most notably at Steep Rock Lake (Wilks and Nisbett 1988), Red Lake (H.J. Hofmann et al 1985), Woman Lake in the Birch-Uchi greenstone belt (H.J. Hofmann et al 1985), Eyapamikama Lake in the North Cariboo greenstone belt (ref. in Thurston et al 1991), and possibly in the Lumby Lake greenstone belt (M.C. Jackson 1985).

Some of these occurrences can be directly correlated with platformal assemblages, most notably at Steep Rock Lake, the type locality for these assemblages, and at Eyapamikama Lake. However, the association is less clear at others, where the fossil occurrences are confined to very restricted localities within dominantly volcanic assemblages of probable volcanic arc (Keewatin) type. Such are those in the Ball volcanic assemblage in the Red Lake greenstone belt (Stott and Corfu 1991, p. 163) and the Woman volcanic assemblage in the Birch-Uchi greenstone belt (Stott and Corfu 1991, p. 166).

C. PROTEROZOIC

In contrast to the Archean, application of the plate tectonic model is widely accepted for the following Proterozoic eon, just as it is for all of subsequent geologic time.

Proterozoic rocks in Ontario are part of an anastomosing network of orogenic belts that criss-cross the Laurentian craton. For the most part, they lie between probably unrelated Archean cratons. This network is represented in northern Ontario by the **Trans-Hudson Orogen** and in central Ontario by the **Penokean Orogen** (Figure 1). Further to the southeast, in southern Ontario, lies the **Grenville Orogen** (Figure 1).

Each of the three orogens differs fundamentally from one another. The Trans-Hudson Orogen is a zone of collision between Superior and Hearne Provinces: it involves both reworked Archean crust and juvenile Proterozoic crust that includes both magmatic rocks and sediments. The Penokean Orogen involves rocks of the Southern Province, which represents zones of lateral accretion of juvenile Proterozoic crust onto Superior Province. The Grenville Orogen is referred to as the Grenville Province, and is in effect an orogenic belt that involves rocks of both Archean and Proterozoic age (Easton 1992).

C.1 TRANS-HUDSON OROGEN

1. Paleoproterozoic sedimentary basin

The following account is summarized from Sutcliffe and Bennett (1992). The 1.9 to 1.8 billion-year-old **Trans-Hudson Orogen** (Table 1) separates the Superior and Hearne Provinces (Figure 1). Following cratonisation[14] of the Superior

---

[14] The process by which continental crust becomes stabilized, and is no longer affected by orogenic (mountain building, mostly compressional) activity.

Province during the Kenoran Orogeny, a Paleoproterozoic sedimentary basin lay to its present north. In Ontario, rocks of the basin are only found in the Sutton Inlier (SI in Figure 4; *see also* OGS 1991f), exposed in the Sutton Hills (or Ridges) in the lowlands marginal to Hudson Bay.

In Ontario, the Hudson Bay segment of the Trans-Hudson Orogen (Figure 4) is comprised from southeast to northwest of:

- the Nastopoka homocline;
- the Belcher fold belt;
- and the Winisk trough.

East of Hudson Bay, in northern Quebec, in the Nastopoka homocline[15], basal shelf sediments (arkose and carbonate rocks) are overlain by foredeep[16] sediments (quartz arenites and succeeding iron formation, shale and turbiditic sandstone). In addition, mafic volcanic rocks are interbedded with these sedimentary sequences. In the Belcher Islands fold belt to the west, only the upper part of this marine sequence is exposed. Unfolded sedimentary rocks outcropping in the Sutton Hills of northern Ontario have in turn been correlated with the uppermost of three sedimentary cycles in the Belcher Islands: folded equivalents of the Belcher Islands rocks are interpreted on geophysical evidence to lie northeast of the Sutton Hills, buried beneath the Phanerozoic rocks of the Hudson Bay basin.

The succeeding Winisk trough, the rocks of which do not outcrop in Ontario, is interpreted on geophysical evidence by extension from sequences in Manitoba. The Winisk trough is an episutural[17] sedimentary basin formed during collision

---

[15] A large scale structure in sedimentary rocks in which the beds all dip in the same or similar direction; in this case to the west.

[16] A basin adjacent to a craton which is filled with a thick accumulation of sediment derived from an orogenic belt during its uplift.

[17] Lying above a suture zone.

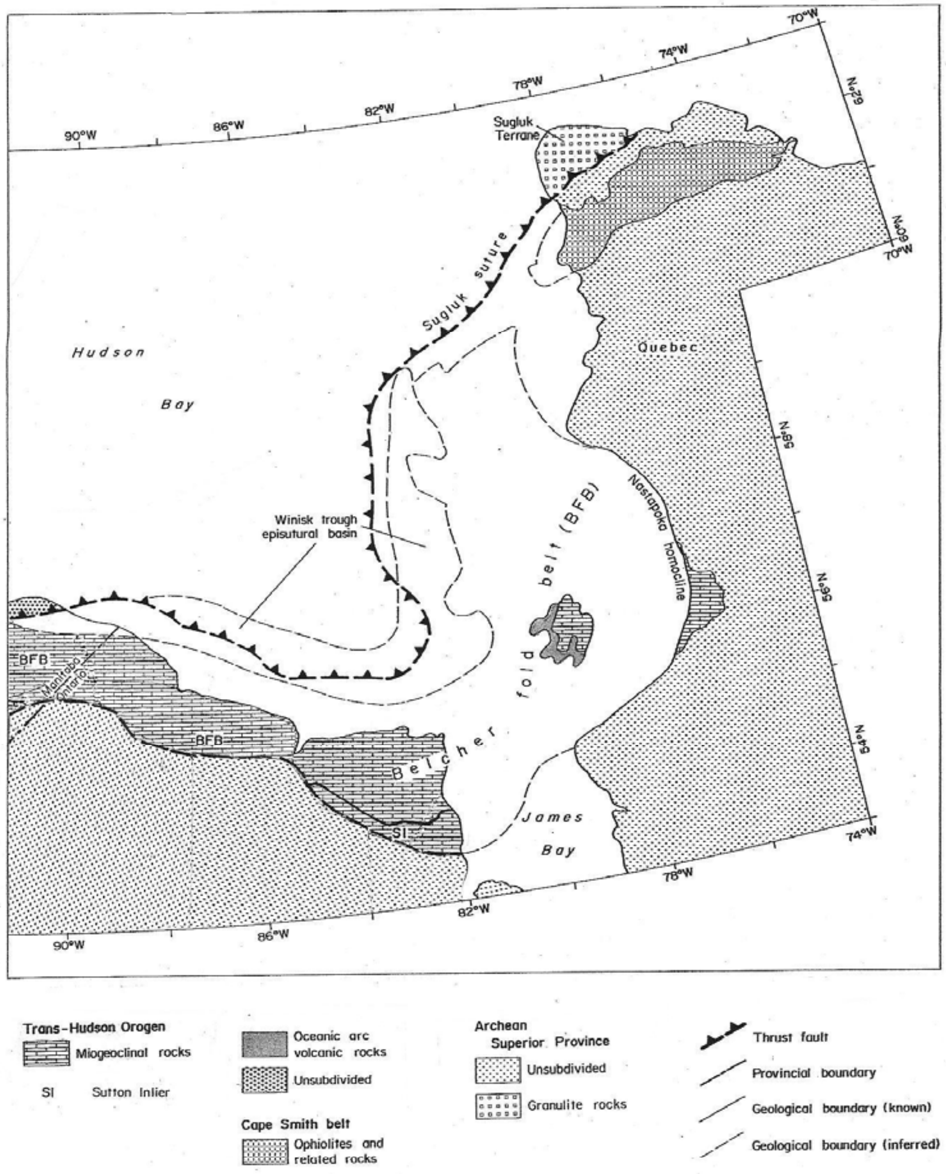

Figure 4. The Trans-Hudson Orogen in northwestern Ontario (*modified from* OGS 1992, Figure 25.12).

and suturing[18] along the Sugluk thrust of Archean rocks of the Hearne Province that are inferred to occupy a foreland[19] beneath central Hudson Bay (*see* Figure 1) with the ensialic[20] sedimentary domain of the Nastopoka homocline (Figure 4).

In summary, the above account indicates that collision of Superior Province with Hearne Province involved sediments deposited in a Proterozoic sedimentary basin, that were overthrust to the north toward an Archean foreland (Hearne Province).

In Ontario, the sole outcrops of rocks of the Trans-Hudson Orogen are exposed in the Sutton Hills, an inlier within the Hudson Bay cover. In contrast to those of the Nastopoka homocline, no volcanic rocks are interlayered with the sedimentary rocks. Gabbroic sills and dikes are emplaced into the sedimentary sequence, where they have caused limited contact metamorphism. These gabbros may correlate (G. Stott, Ontario Geological Survey, personal communication 2009) with diabase dikes from near Fort Albany on the west coast of James Bay, dated at 1871 My (Hamilton and Stott 2008). This date may then provide a youngest age for deposition of the sedimentary rocks of the Sutton Hills inlier. No maximum age is directly available for the sedimentary rocks of the Sutton Hills inlier, but diagenetic apatite from the basal sandstone in the Nastapoka homocline on the east side of Hudson Bay has yielded an age of 2025 My (Chandler 1988; Chandler and Parrish 1989), thus ensuring that the rocks of the inlier lie well within Paleoproterozoic age range.

1.1 Sutton Hills platform environment

Sedimentary rocks of the Sutton Hills inlier were deposited on a passive continental margin represented by Archean massive to gneissic granitic rocks of

---

[18] The process of uniting of two large crustal blocks.

[19] The stable craton behind a foredeep (see footnote 16 for a definition of foredeep).

[20] Deposited on continental crust.

the Winisk Subprovince (Figures 2 and 4). The contact is not exposed but interpreted to be an unconformity (Sutcliffe and Bennett 1992). The most recent and detailed mapping (Bostock 1971) documented (Figure 5) a basal 75m thick unit (Nowashe Formation) consisting of stromatolite-bearing dolostone with minor siliceous calcareous argillite, limestone and dolomitic limestone, which is overlain at least in part unconformably by a 120m thick succession (Sutton Ridges Formation) of basal chert breccia conglomerate succeeded upward by greywacke and interbedded silicate- and carbonate-facies iron formation and chert.

Rock types, including but not limited to dolostone, chert breccias, argillite, wacke, conglomerate, and iron formation, all belong to GOO unit 22b. Gabbroic sills that intrude these sedimentary rocks belong to GOO unit 23a.

1.2 Biodiversity in the Sutton Inlier

The stromatolite-bearing dolomitic rocks of the Nowashe Formation are quoted by Sanford et al (1968) after Hawley (1926) to occur in sections up to 60 feet thick, containing equally thick pockets of chert breccia and conglomerate. These are disconformably to unconformably overlain by sedimentary rocks of the Sutton Ridges Formation (Figure 5).

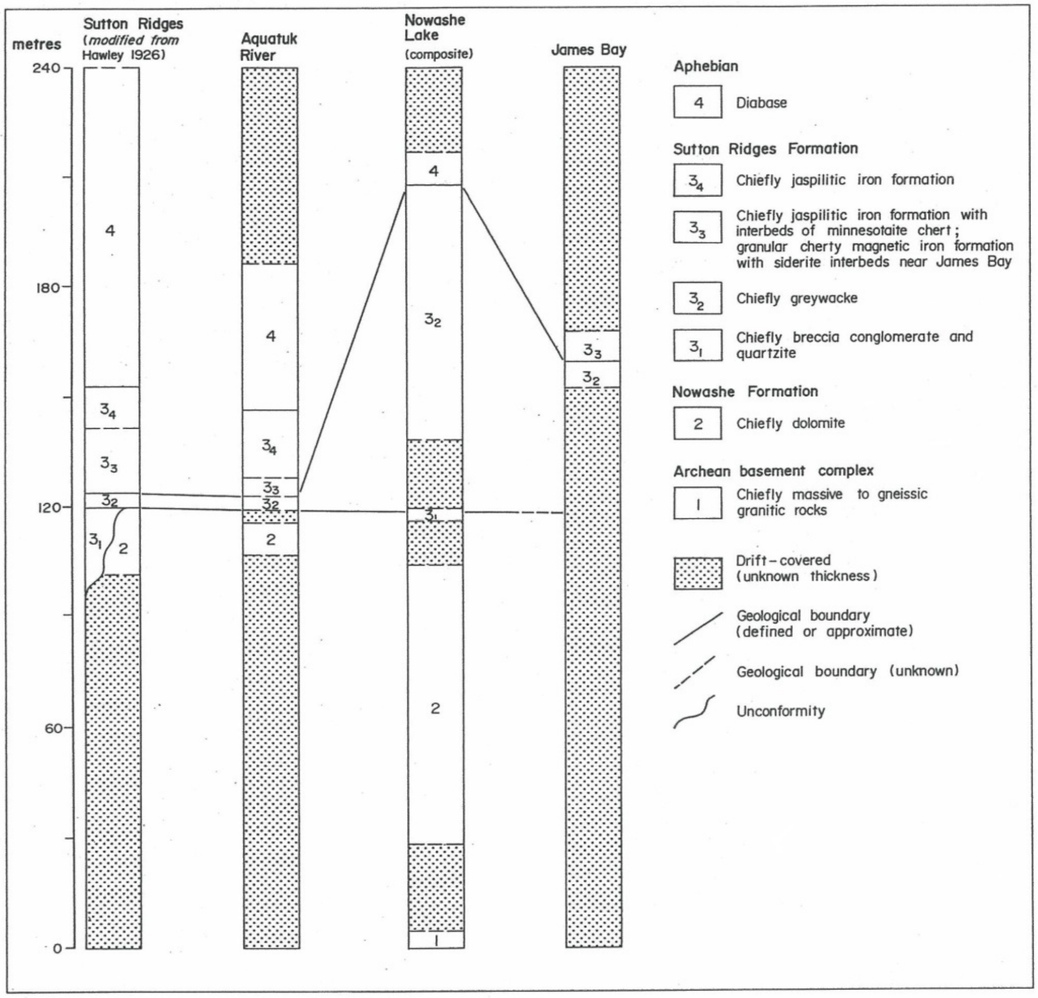

Figure 5. Stratigraphic sections of Paleoproterozoic rocks of the Sutton Hills area (*from* OGS 1992, Figure 25.13)

C.2 SOUTHERN PROVINCE

The following introductory account is freely adapted from Thurston (1991), and with additional information obtained more recently.

At the southern margin of the Superior Province, north of Lake Huron (Figure 6), the Southern Province consists of Paleoproterozoic, 2.4 to 2.2 billion-year-old siliceous continental margin sedimentary rocks of the Huronian Supergroup (Cobalt Embayment and Penokean Fold Belt: Figure 6 and OGS 1991f). South of Lake Superior, the edge of the Superior Province is overlain by the Marquette Range Supergroup, a 2.2 to 1.7 billion-year-old strongly deformed, rifted, passive margin to ocean basin sequence that is confined to those states of the USA that adjoin Ontario. This is in turn overlain by the Animikie Group, a foredeep[21] sequence that extends northeastward from the USA north of Duluth into Ontario west of Thunder Bay (Figure 6). The Huronian Supergroup is affected by a poorly documented, less than 2.3 billion-year-old deformation and the approximately 1.8 billion-year-old **Penokean Orogeny[22]** (Table 1).

The 1.85 billion-year-old Sudbury Igneous Complex and associated Whitewater Group of sedimentary rocks lie along the northern margin of the Penokean Fold Belt, to the northeast of Lake Huron (Figure 6). After years of debate, sufficient evidence has now accumulated to confirm that the Complex originated by meteorite impact of catastrophic proportions, and not by more conventional igneous intrusion. The most recent and compelling evidence lies in the discovery and positive identification, firstly in drill holes in northwest Ontario and northeast Minnesota (Addison et al 2005), and then in outcrop in Michigan (Pufahl et al 2007, Cannon et al 2010) and northeast Minnesota (Jirsa 2010), of distal ejecta from the impact as layers within Paleoproterozoic sedimentary rocks dated at the same age as the Complex, at ~18.5 By.

---

[21] See footnote 16 for a definition of foredeep.

[22] See footnote 7 for a definition of orogeny.

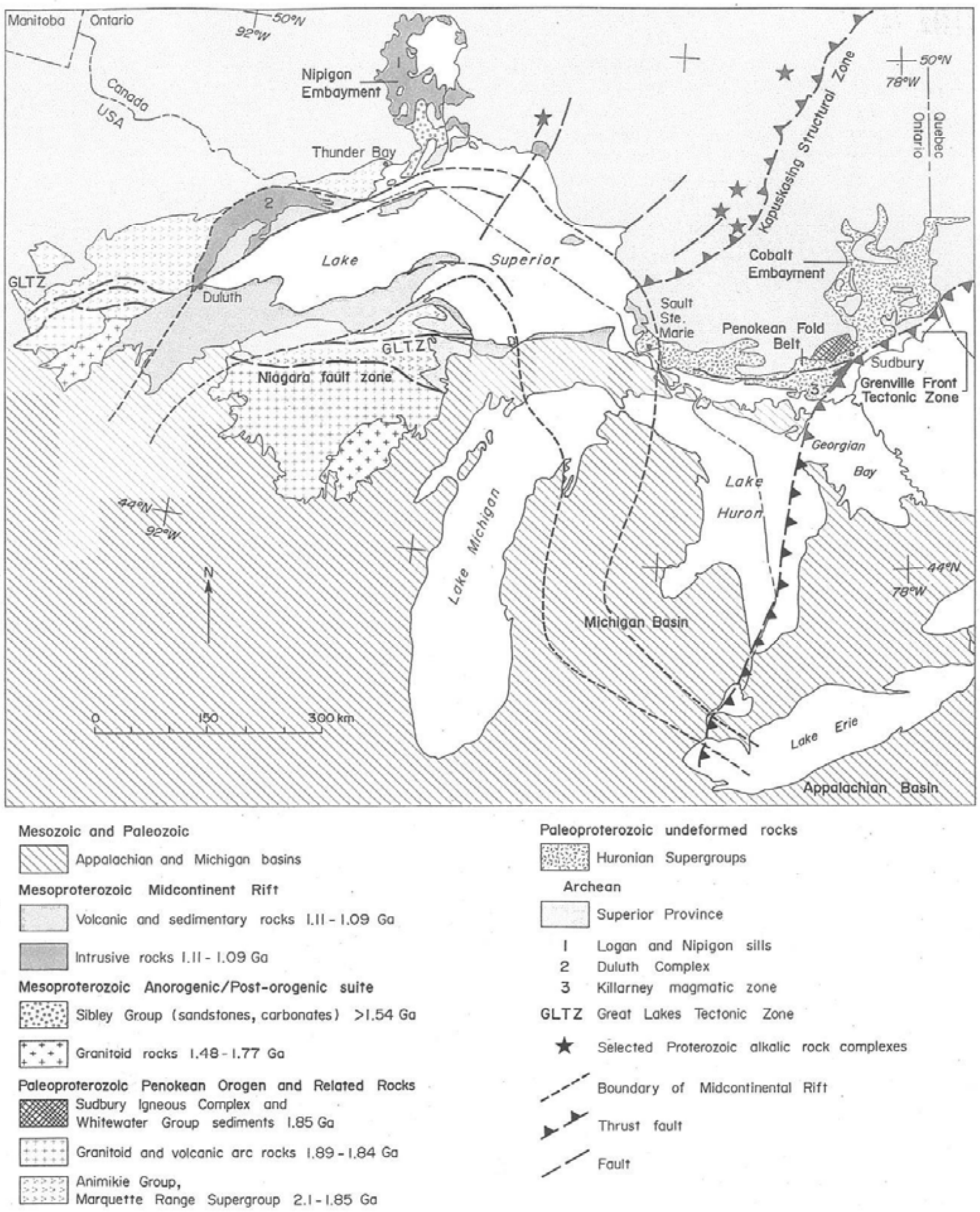

Figure 6. Major Proterozoic geologic elements in the Lake Superior region (*modified from* OGS 1991a, Figure 16.2).

In the Mesoproterozoic era, rifting resulted in an arcuate structure over 2000 km long, the Midcontinental Rift (Figure 6). In the Lake Superior region the rift is filled with an up to 30 km thickness of basalts and sedimentary rocks of the Keweenawan Supergroup, which includes the Sibley Group sedimentary assemblage and the Osler Group volcanic rocks. Alkalic intrusive complexes were also emplaced along the older north- to northeast-trending Kapuskasing Structural Zone[23] (Figure 6).

2. Paleoproterozoic sedimentary basins

In Ontario, progressive accretion of sedimentary rocks onto the Archean Superior Province craton is represented in Ontario firstly by older (2.4 to 2.2 By) (By = billion years) Huronian Supergroup sedimentary rocks, and secondly by younger (~1.8 By) Animikie Group sedimentary and mafic volcanic rocks.

Although there is broad agreement that both of these sequences were deposited along a continental margin, controversy ranges over the applicable tectonic regime. For example, P.F. Hoffman (e.g.1988) has suggested an accretionary sequence formed during impingement of a volcanic island arc or arcs against the Superior craton to the north, while others (e.g. Bennett et al 1991; LaBerge 1994; Ojakangas et al 2001; Young et al 2001) have suggested initial rifting of a precursor Archean mega-craton, followed by ocean closure. Young et al invoked a “Wilson cycle” of ocean opening followed by closure, as envisaged by J.T. Wilson in a seminal paper (Wilson 1960) for the eastern seaboard of North America in the Paleozoic era. More recently, Schulz and Cannon (2007) have endorsed ocean closure that involved accretion of Archean crust to the present south of a volcanic island arc or arcs environment, but without suggesting initial rifting of an Archean mega-craton.

---

[23] A zone of uplift that transects the predominant east to west structural trend of the Superior Province and has exposed rocks of the midcrust.

2.1 Huronian crustal rifting and continental margin environment

The Huronian Supergroup consists of four groups, named in ascending stratigraphic order (Figure 7) the Elliot Lake, Hough Lake, Quirke Lake and Cobalt groups. These groups and their constituent formations were presented with intent toward formalization in 1969 by Robertson et al (1969). Stratigraphic thicknesses of these units varies considerably from place to place across the region north of Lake Huron (Figure 8).

Type sections proposed by Robertson et al (1969) for the various formations of the supergroup are given in Table 2: it should be noted that no further work has been done since the Federal-Provincial Committee on Huronian Stratigraphy issued this progress report, and that considerable progress and inevitable change to this initial stratigraphic column has been made since then. One of these is the addition of the Livingstone Creek formation at the base of the sequence in the west only (Figures 7 and 8), near Sault Ste. Marie: it is comprised of arkosic and wacke sandstones, and polymictic conglomerate.

At the base of the Huronian, the Elliot Lake Group contains economic paleoplacer uranium deposits hosted in quartz-pebble conglomerates of the Matinenda Formation. It is also the only group that contains volcanic rocks (e.g. Thessalon Formation; Figure 8) and turbiditic sandstone. It does not display the threefold paleoenvironmental subdivision characteristic of the three overlying groups. These latter groups form three sedimentary cycles of a) paraconglomerate[24], overlain by b) either mudstone, siltstone or carbonate all of off shore marine origin, and capped by c) coarse, cross-bedded arenites of nearshore marine origin. The paraconglomerates of all three cycles have been widely regarded (see discussion *in* Young et al 2001) as having been deposited

---

[24] Conglomerate in which the pebbles are supported by a finer-grained matrix, and do not touch each other (also called matrix-supported).

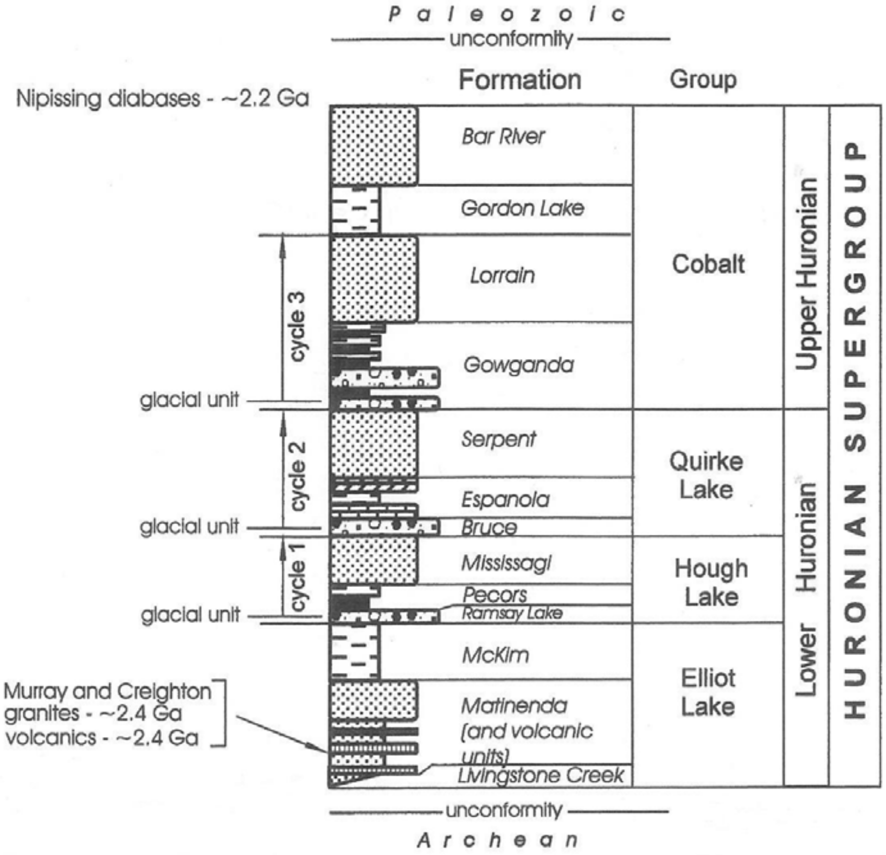

Figure 7. Generalized stratigraphic section of the Huronian Supergroup (*modified from* Young et al 2001, Figure 2).

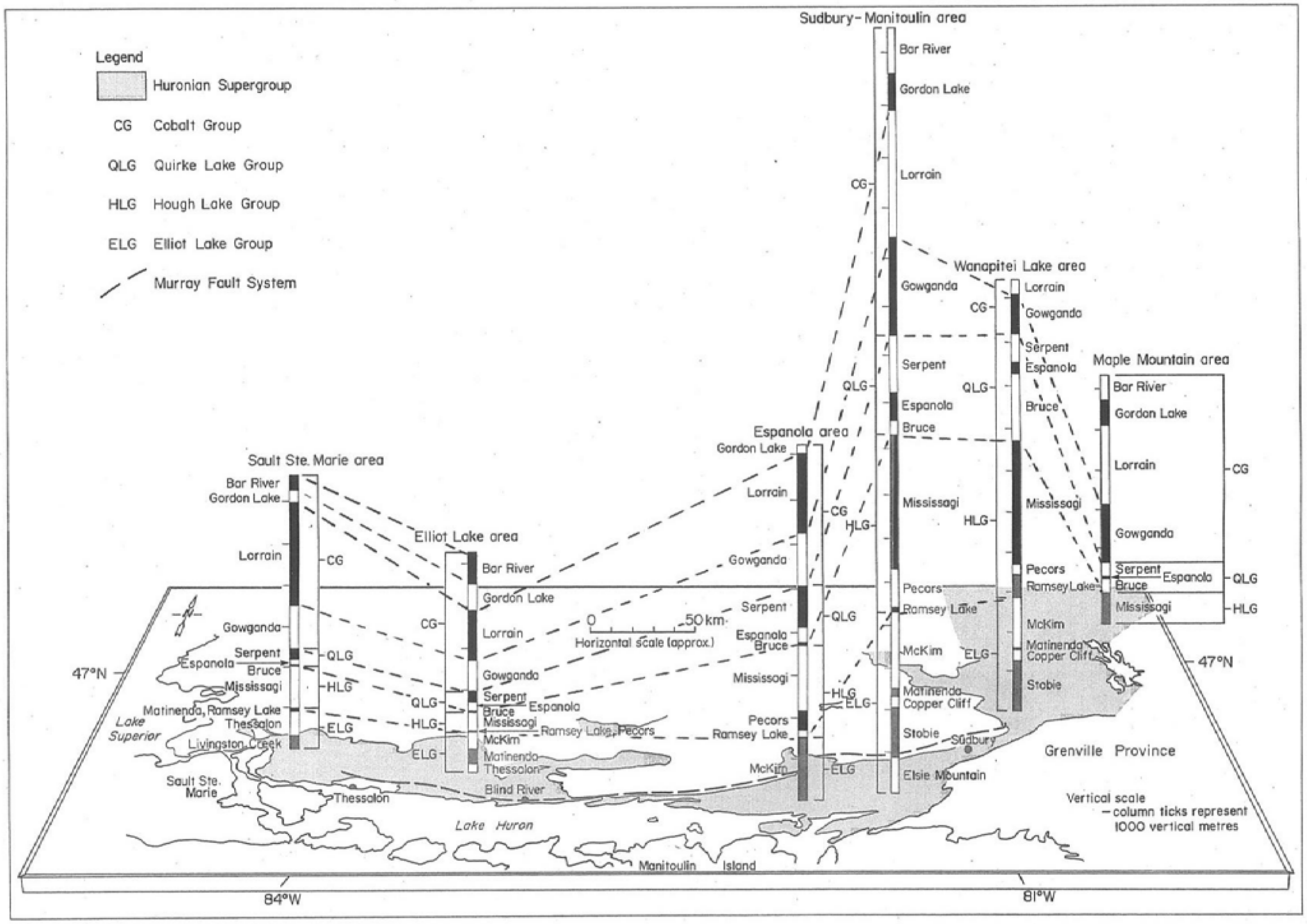

Figure 8. Variation of stratigraphic thickness of units in the Huronian Supergroup (*modified from* OGS 1991a, Figure 14.2).

Table 2.

LIST OF PROPOSED PRINCIPAL REFERENCE SECTIONS AND REFERENCE SECTIONS FOR SEDIMENTARY FORMATIONS OF THE HURONIAN SUPERGROUP

(Taken verbatim from Robertson et al, 1969, Appendix, p. 17; see also discussion in section 2.1 of the present text: for contained references, see source document)

Bar River Formation: (Top not defined)

Principle Reference Section	Diamond Lake, Collins 1925, Bruce Mines Sheet
Reference Sections	1. East End of Baie Fine - George Lake 2. Flack Lake – Flack Lake Fault

Gordon Lake Formation:

Principle Reference Section	Gordon Lake – Diamond Lake, Collins 1925, Bruce Mines Sheet
Reference Sections	1. East End of Baie Fine 2. Cobre Lake – Flack Lake

Lorrain Formation:

Type Area	(Top not exposed) Lorrain Township, Cobalt silver area, R. Thomson 1964
Reference Sections	1. Bruce Mines – Desbarats, Collins 1925, Bruce Mines Sheet 2. Whitefish Falls 3. Mount Lake

Gowganda Formation:

In order to retain Gowganda Formation as the name, the Coleman and Firstbrook Formations should be relegated to members. These members are to be defined from drill core stored in Henwood Township (R. Thomson 1966, Map 2126).

Principle Reference Section	Drill core, Henwood Township (R. Thomson 1966)
Reference Sections	1. North of Bruce Mines 2. Highway 108 – Dunlop Lake 3. Whitefish Falls or Lake Penage

Discussion of the nature of the lower boundary of the Gowganda Formation is required in any presentation of Huronian stratigraphy.

Serpent Formation:

Principle Reference Section	Denison Mines or Stanrock Mine, Quirke Lake
Reference Sections	1. Aberdeen Township near Ophir 2. Whitefish Falls

Table 2 contd.

Espanola Formation:

Principle Reference Section	Espanola
Reference Sections	1. Bruce Mines
	2. Quirke Lake (north of Denison Mine)

The status of members within the Espanola Formation will require discussion in any presentation of Huronian stratigraphy.

Bruce Formation:

Principle Reference Section	Bruce Mines or Echo Lake
Reference Sections	1. Quirke Lake (Denison Mine)
	2. Whitefish Falls or Lake Penage

Mississagi Formation:

Principle Reference Section	Blind River
Reference Sections	1. Quirke Lake (north of Denison Mine)
	2. Lake Penage
	3. Bruce Mines area?

Pecors Formation:

Principle Reference Section	Pecors Lake (poorly exposed; drill core will be used)
Reference Sections	1. Quirke Lake
	2. McCharles Lake, Denison – Graham Townships
	3. Highway 69 South, Sudbury

Ramsay Lake Formation:

Principle Reference Section	McCharles Lake, Graham Township
Reference Sections	1. Quirke Lake
	2. Highway 69 South, Sudbury

McKim Formation:

Principle Reference Section	Aer Mine, Denison Township
Reference Sections	1. North half Merritt Township
	2. Victoria Township
	3. Nordic Mine (core?)

Matinenda Formation:

Principle Reference Section	Mack Township
Reference Sections	1. Pronto Mine, Long Lake
	2. Agnew Lake area

by repeated continental glaciation, as supported by presence of dropstones[25] in interbedded and overlying mudstones and siltstones.

Elliot Lake Group rocks are notable also for having been deposited under anoxygenic conditions, indicative of an atmosphere lacking in free oxygen. There is evidence to suggest that this reductive environment continued during deposition of succeeding Hough Lake and Quirke Lake groups, but that by the time of deposition of Cobalt Group rocks, Earth's atmosphere had become oxygenic: presence of red rocks, containing iron in the oxidized state, is widespread in the Gowganda and succeeding Lorraine and Gordon Lake formations.

Paleosols underlie the Matinenda Formation where they lie on Archean basement at the western end of the Huronian basin, in the Elliot Lake and Sault Ste. Marie areas (Figure 8). This suggests that in fact free oxygen was present in the Huronian atmosphere, but estimated (Grandstaff 1980) to be at less than 1% of present atmospheric levels.

As noted above, paleoenvironmental interpretation of the three polymictic paraconglomerate formations at the base of each sedimentary cycle is strongly indicative of continental glaciation in the hinterland to the present north of the sedimentary basin. Numerous interpretations have been presented for each or all of the Ramsay Lake, Bruce and Gowganda formations (see references in Bennett et al 1991), but almost all of them are compatible with either a glacial, glacial marine, or glaciolacustrine origin. The overlying formations of each cycle can be taken as having been deposited under similarly cool climatic conditions (presence of occasional pebble-sized dropstones[26] in succeeding deep water fine grained mudstones and siltstones supports glacial ice rafting). The 3-fold cyclical

---

[25] Clasts released by melting from the base of a floating ice sheet or glacier, subsequently to settle in muddy sediment.

[26] See footnote 25 for a definition of dropstone.

nature of sedimentation in the Huronian Supergroup above the Elliot Lake Group remains controversial, but may be indicative of repeated continental glaciation depressing the crust, followed by crustal rebound during warmer times, and further subsequent glaciation on a continental scale, leading to repetition of the same cyclical character. However, tectonic conditions could similarly have played a major part in determining the cyclicity.

The maximum age of the Huronian Supergroup is given by the age of the rhyolitic Copper Cliff Formation, lying within the Elliot Lake Group near its base, at 2450 My. Date of orogeny affecting the Huronian Supergroup has proven to be controversial. Open folding indicative of onset of orogeny prior to deposition of the Cobalt Group in the Cobalt Embayment is noted prior to intrusion of Nipissing diabase dated at about 2.2 By. However, the main Penokean phase (in the Penokean Fold Belt: Figure 6) has been variably estimated (Bennett et al 1991, p. 553) within the range 1.9 to 1.7 By.

Bennett et al (1991) noted that although numerous investigations have classified the group-level contacts as conformable,[27] others have recorded disconformable[28] relationships at some or all of these group-level contacts. Angular unconformity[29] at the base of the Cobalt Group is particularly evident in the Cobalt Embayment, where essentially flat-lying Gowganda Formation conglomerates lie upon various formations of the older Quirke Lake Group, that are open-folded. In the main Penokean Fold Belt to the southwest, Cobalt Group rocks are folded along with the older Elliot Lake, Hough Lake and Quirke Lake groups around a much tighter regional fold couple (Quirke Lake syncline and

---

[27] No tectonism (tilting, folding, uplift etc.) or erosion in the interval between deposition of the lower and upper sequences, resulting in parallel bedding.

[28] No tilting or folding in the interval between deposition of the lower and upper sequences, but erosion of the lower sequence, all resulting in parallel bedding.

[29] Tectonism and erosion in the interval between deposition of the lower and upper sequences, but erosion of the lower sequence, all resulting in non-parallel bedding.

Chiblow anticline), but the contact of Cobalt Group with older groups is notably also still disconformable or unconformable.

The pronounced difference in fold style, and hence tectonic significance, between the Cobalt Embayment and the Penokean Fold Belt is clearly displayed in the GOO east-central sheet (OGS 1991d) by the colour contrast of map unit 19 (Cobalt Group) against map unit 18a (combined Quirke Lake, Hough Lake and Elliot Lake groups). By implication, the effect of the Penokean Orogeny was considerably more profound in the Penokean Fold Belt than in the Cobalt Embayment.

Bennett et al (1991), in an attempt to resolve all of the above characteristics of the Huronian Supergroup, have suggested a tectonic regime in which:

1) **initial rifting** of Archean crust led to deposition of locally derived erosional material (Livingston Creek Formation) followed by volcanism (Thessalon and other volcanic formations);

2) succeeding **late breakup** with deposition in a restricted basin of mostly fluviatile[30] arenites (Matinenda Formation) followed by deeper water laminated mudstones and turbiditic sandstone (Mc Kim Formation) as new ocean crust was formed to the south;

3) deposition on a **passive margin** of three sedimentary cycles, each consisting of basal conglomerate (Ramsey Lake, Bruce, and Gowganda formations respectively), followed by mudstone-siltstone±limestone (Pecors, Espanola, and Gordon Lake formations respectively) and ending with arenites (Mississagi, Serpent, and Lorrain/Bar River respectively);

---

[30] Sediments deposited in a river.

4) **convergent tectonics,** as a volcanic island arc or arcs advanced toward the Superior continent, culminating in the Penokean Orogeny. The major locus of the orogeny was well south of Ontario, and exemplified further to the west by the so-called “Wisconsin magmatic terranes” south of Lake Superior (granitoid and volcanic arc rocks south of the Niagara Fault Zone in Figure 6).

The extent of the basin in which sedimentary rocks were deposited during time of deposition of the Huronian Supergroup remains largely unknown: at certain times it may have been much larger than that now suggested by the areal extent of the Huronian rocks in Ontario. For example, over the years numerous workers in Canada and the USA (e.g. Young 1970; Schneider et al 2002) have presented evidence to correlate uppermost Cobalt Group rocks, commencing with the glaciogenic Gowganda Formation, with certain similar sequences of the Marquette Range Supergroup to the west, in Michigan and Wisconsin. Similarly, the extent of the Huronian to the east is largely unknown, being terminated against, and probably involved in, the later Grenville Orogen (Figure 1). To the south, extent of Huronian and other correlative sedimentary sequences is unknown, since they are hidden beneath Paleozoic platformal cover rocks of the Michigan Basin.

Rock types of the Huronian Supergroup include but may not be confined to conglomerate, wacke, arkose, quartz arenites and argillite, as referred to in GOO unit 19, and the same rock types plus additional limestone and dolostone in GOO unit 18a. Volcanic rocks within the Elliot Lake Group, variably assigned to five formations (Figure 8: Elsie Mountain, Salmay Lake, Stobie, Copper Cliff and Thesalon formations) include but may not be confined to basaltic through rhyolitic flows, and pyroclastic rocks, all grouped together as GOO unit 18b.

2.2 Huronian biodiversity

To date, no unequivocally identified fossils have been discovered in Huronian rocks. Accounts of biological-like structures have been reported intermittently since at least the earliest 20th century: Bain (1927); Frarey and McLaren (1963); T.A. Jackson (1967); H.J. Hofmann (1967); Young (1967). However, Young (1969) recanted on the organic origin of worm-like (or vermiform) structures that he earlier reported on, while H.J. Hofmann (1971) suggested that all of the earlier findings were inconclusive and that real fossils were yet to be found. Later, he and others (Hofmann et al 1980) reported on possible stromatolites in the Espanola Formation at Quirke Lake and other structures of possible microbial origin in the Gordon Lake Formation, near Gordon Lake at Plummer, which may represent the first examples of life forms in the Huronian. No further suspected fossil sites or remains have been reported since the latter work.

2.3 Animikie continental foredeep environment

The following section is freely adapted and expanded from Sutcliffe (1991), with additional references as quoted.

In Ontario, Animikie Group sedimentary rocks form a homoclinal, gently dipping sequence southwest of Thunder Bay, separated from their much larger area of exposure in the adjoining USA by the mafic to ultramafic Duluth Complex (Figure 6). The entire sedimentary basin, termed the Animikie Basin (the Ontario portion is shown on OGS 1991f) occupies parts of Ontario, Minnesota, Wisconsin and Michigan. The basin has been divided into two segments by the younger, sinuous, Midcontinent Rift (Figure 6). The southern segment, occupied by the Marquette Range Supergroup and entirely in Wisconsin and Michigan, is much thicker and more diverse than the Animikie Group in Ontario and its equivalent in Minnesota, southwest of the Duluth Complex. In addition, the southern segment was deformed during the Penokean Orogeny, along with the Huronian Supergroup, but the Animikie in Ontario was largely spared this event.

The Animikie Group in Ontario is subdivided into the Gunflint Formation and the overlying Rove Formation (Figure 9). Because of the potential for discovery of large, economic-grade iron deposits, geologists working for the Ontario government studied the Gunflint Formation in detail in the 1950s (Goodwin 1956, 1960; Moorhouse 1960). Moorhouse, working in the central east portions, commented on the great variety of sedimentary rock types, of clastic, biogenic and chemical origin, and their rapid vertical and lateral changes. Goodwin, however, working in a much smaller area at the west end of the belt, defined a stratigraphic section, which he suggested demonstrated two cycles.

Subsequent study by Shegelski (1982, 1990) has tended to confirm the view of Moorhouse that vertical and lateral changes preclude a simple stratigraphic interpretation. Shegelski introduced a classification scheme for the chemical sedimentary rocks of the Gunflint Formation parallel to that used for limestones to describe chert and carbonate rocks alike: there is a complete gradation in composition between end members, and identical textures exist in both[31]. Although various members are discontinuous laterally, lateral correlation of some members can be attempted (Figure 9). Shegelski interpreted the sedimentary environment of the Gunflint to be intertidal to supratidal, along a shelf, and the grainstone-micrite members to represent barrier island complexes which migrated parallel to the shoreline. Stromatolites would have formed as mounds constructed on the Archean basement (Figure 10).

To the south, in the adjoining state of Minnesota, to the north and west of the city of Duluth (Figure 6) the Gunflint Formation hosts some of the most prolific iron deposits in the world, variously known as the Gunflint Iron Formation and the

---

[31] In Figures 9 and 10, “grainstone” refers to grain-supported limestone with no mud matrix, and “micrite” refers to limestone consisting of lithified lime mud.

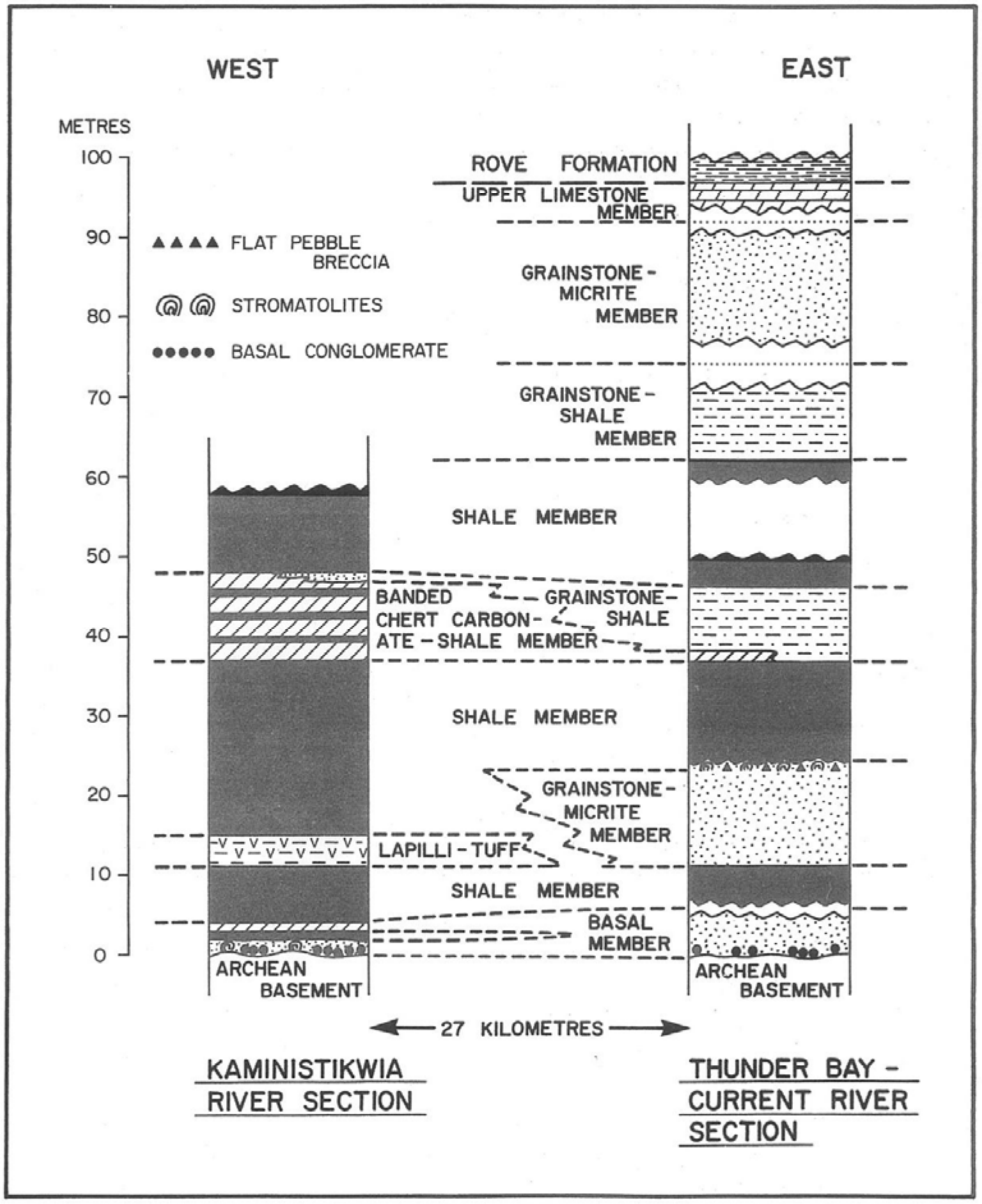

Figure 9. Generalized stratigraphic sections and lateral correlation of the Gunflint Formation (*from* Shegelski 1982).

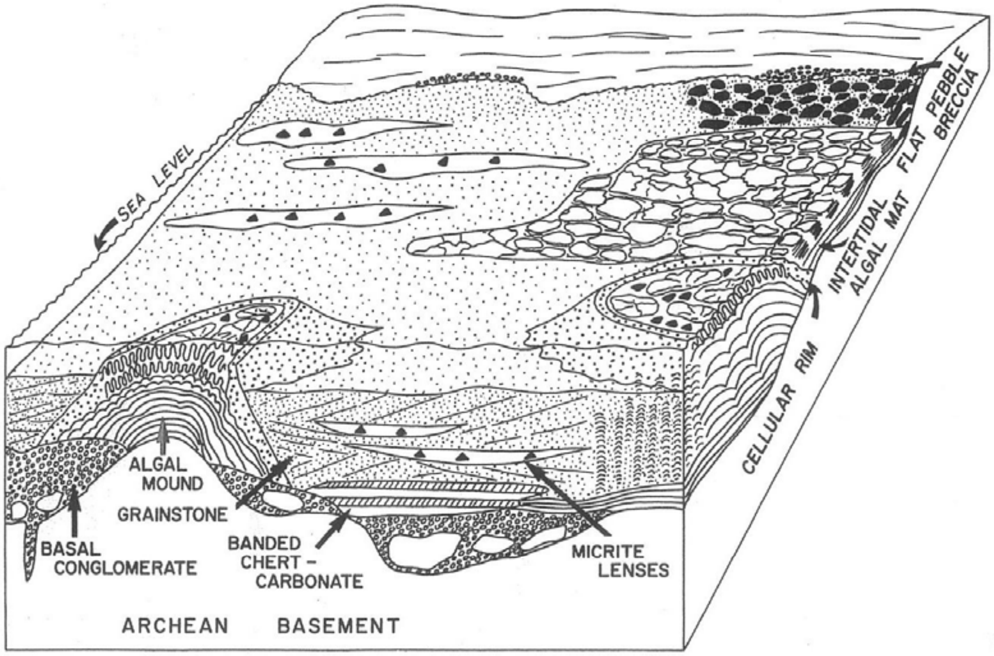

Figure 10. Sedimentary facies reconstruction of chemical-sedimentary rocks of the Gunflint Formation (*from* Shegelski 1982).

Biwabick Iron Formation. These are the equivalents of the similarly chemically-precipitated chert, jasper and ferruginous carbonate in Ontario. No economically viable iron formation has been discovered in the Ontario portion.

The Rove Formation, in stark lithological contrast to the Gunflint, consists of a lower part of black, locally pyritic shales which grades upward into shales interbedded with arkosic wacke deposited by turbidity currents. Drill-indicated thickness of the Rove Formation grades from its thinnest in the north, in Ontario, where it is about 500 m thick, to about 1000 m in Minnesota. The Great Lakes Tectonic Zone to the south of Lake Superior (GLTZ *in* Figure 6), has been considered to mark the northern extent of Penokean Orogeny (*see references in* Sutcliffe 1991). The Niagara Fault Zone (Figure 6) is interpreted as the zone of collision by LaBerge (1994), while others (e.g. Ojakangas et al 2001) make the granitoid and volcanic arc rocks south of the fault zone ("Wisconsin magmatic terranes") the major collision zone. More recently however, it has been suggested that the effect of Penokean Orogeny extended as far north as the Thunder Bay area, as represented by flat-lying thrust faults and associated folding in the Gunflint Formation (Hill and Smyk 2005).

P.F. Hoffman (1988 *and references therein*) considered the Animikie to have been deposited in a foredeep[32] related to ocean closure during the Penokean Orogeny. Others (e.g. Ojakangas et al 2001) have presented evidence of turbiditic sandstone in the Rove Formation to have been derived from both the Superior continent to the north and island arc volcanic rocks to the south.

Rock types of the Animikie Group include but may not be confined to wacke, shale, iron formation (including magnetite, chert, and jasper), limestone, and minor volcanic rocks, as referred to in GOO unit 22a.

---

[32] See footnote 16 for a definition of foredeep.

2.4 Animikie biodiversity

The Gunflint Formation of the Animikie Group contains the first extensive record of Precambrian fossils to be found within the Canadian Shield. Starting at the end of the 19th century, numerous workers have studied and commented on them, notably Moorhouse and Beales (1962), H.J. Hoffman (1969), and Awramik and Barghoorn (1977). In 1953, Stanley Tyler examined the Gunflint Formation and noted the red-coloured stromatolites. He sampled a jet-black chert layer, which when examined under the microscope, revealed some life-like micrometer-size forms. The paleobotanist E.S. Barghoorn subsequently examined them and deemed them to be unicellular organisms (Barghoorn and Tyler 1965).

By analogy with present-day stromatolites, those in the fossil record have generally been thought to have formed as a result of biogenic action, by trapping and binding of sediment by cyanobacteria-dominated microbial ecosystems, to form algal “mats”. However, in addition to biogenic processes, some stromatolites in the Gunflint Formation and correlative Biwabick Iron Formation have been thought to be of non-biogenic origin, such as siliceous sinter[33]. This inferred hot spring deposition in such a broad distribution and stratigraphic setting is highly unlikely: Planavsky and Shapiro (2005) have suggested that all stromatolites in fact formed under a biogenic influence in a shallow marine, tidal environment (cf. Figure 10).

In contrast, the Rove Formation is devoid of fossils, despite being carbon-rich which would suggest that life was flourishing at this time. The discovery (Addison et al 2005) at the top of the Gunflint Formation, immediately below black shales of the Rove Formation, of distal ejecta from the Sudbury impact event that generated the Sudbury Igneous Complex, has strengthened the argument that the impact would have had a profound effect on life on Earth, perhaps causing

---

[33] A silica-rich precipitate found around the mouth of a hot spring whose waters carry large amounts of dissolved minerals which precipitate when the water cools suddenly on exposure to the atmosphere.

mass extinctions (cf. the mass extinction of the dinosaurs at the close of the Cretaceous, attributed to the Chicxlub meteorite impact in Mexico).

D. ACKNOWLEDGEMENTS

Preparation of this document was greatly facilitated by consultation with the following workers:

J.A. Ayer, Ontario Geological Survey, Sudbury
G.P. Beakhouse, Ontario Geological Survey, Sudbury
G. Bennett, Ontario Geological Survey, Sault St. Marie (retired)
T. Boerboom, Minnesota Geological Survey, St. Paul, Minnesota
F.W. Chandler, Geological Survey of Canada, Ottawa (retired)
W.R. Church, University of Western Ontario, London
E. Frey, Consulting Geologist, Vancouver
J.M. Franklin, Consulting Geologist, Ottawa
M. Jirsa, Minnesota Geological Survey, St. Paul, Minnesota
D.G.F. Long, Laurentian University, Sudbury
M.C. Smyk, Ontario Geological Survey, Thunder Bay
K.J. Schulz, United States Geological Survey, Reston, Virginia
J. Scott, Ontario Geological Survey, Thunder Bay
G.M. Stott, Ontario Geological Survey, Sudbury
P.C. Thurston, Laurentian University, Sudbury
J. Wood, Geological Survey of Canada, Ottawa (retired)
G.M. Young, University of Western Ontario, London

E. REFERENCES

Addison, W.D., Brumpton, G.R. Vallini, D.A. McNaughton, N.J., Davis, D.W., Kissin, S.A., Fralick, P.W., and Hammond, A.L. 2005. Discovery of distal ejecta form the 1850 Ma Sudbury impact event; Geology, v. 33, p. 193-196.

Awramik, S.M. and Barghoorn, E.S. 1977. The Gunflint microbiota; Precambrian Research, v. 5, p. 121-142.

Ayer, J.A, Johns, G.W. and Blackburn, C.E. 1991. Archean volcanology and sedimentology of Lake of the Woods - the classic Keewatin greenstone belt; Geological Association of Canada, Mineralogical Association of Canada, Society of Economic Geologists, Joint Annual Meeting, Toronto '91, Field Trip B2: Guidebook, 59 p.

Ayer, J.A., Amelin, Y., Corfu, F., Kamo, S., Ketchum, J.F., Kwok, K., and Trowell, N.F. 2002. Evolution of the Abitibi greenstone belt based on U-Pb geochronology: autochthonous volcanic construction followed by plutonism, regional deformation and sedimentation; Precambrian Research, v.115, p. 63-95.

Bain, G.W. 1927. Huronian stromatoporid-like masses; Pan American Geologist, v. 47, p. 281-284.

Barghoorn, E.S. and Tyler, S.A. 1965. Microorganisms from the Gunflint chert; Science, v. 147, p. 563-577.

Beakhouse, G.P. 1991. Winnipeg River Subprovince; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p. 279-301.

Bennett, G., Dressler, B.O. and Robertson, J.A. 1991. The Huronian Supergroup and associated intrusive rocks; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p. 549-591.

Blackburn, C.E. 1980. Towards a mobilist tectonic model for part of the Archean of northwest Ontario; Geoscience Canada, v. 7, p. 64-72.

Blackburn, C.E. 1982. Geology of the Manitou lakes area, District of Kenora (stratigraphy and petrochemistry); Ontario Geological Survey, Report 223, 61 p. Accompanied by Map 2476, scale 1:50 000.

Blackburn, C.E. and Young, J.B. 2000. Precambrian geology of the Separation Lake area, northwestern Ontario; Ontario Geological Survey, Open File Report 6001, 94 p. Accompanied by Maps 2673 and 2674, scale 1:20 000.

Blackburn, C.E., Johns, G.W., Ayer, J. and Davis, D.W. 1991. Wabigoon Subprovince; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p. 303-381.

Bostock, H.H. 1971. Geological notes on Aquatuk River map-area, Ontario, with emphasis on the Precambrian rocks; Geological Survey of Canada, Paper 70-42, 57p.

Breaks, F.W. 1991. English River Subprovince; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p. 239-277.

Cannon, W.F., Schulz, K.J., Wright Horton Jr., J. and King, D. 2010. The Sudbury impact layer in the Paleoproterozoic iron ranges of northern Michigan, USA; Geological Society of America Bulletin, v. 122, p. 50-75.

Chandler, F.W. 1988. The Early Proterozoic Richmond Gulf Graben, east coast of Hudson Bay, Quebec: Geological Survey of Canada, Bulletin 362, 76p.

Chandler, F.W. and Parrish, R.R. 1989. Age of the Richmond Gulf Group and implications for rifting in the Trans-Hudson Orogen; Precambrian Research, v.44, p. 277-288.

Cooke, D.L. and Moorhouse, W.W. 1969. Timiskaming volcanism in the Kirkland Lake area, Ontario, Canada; Canadian Journal of Earth Sciences, v.6, p.117-132.

Corfu, F. and Davis, D.W. 1992. A U-Pb geochronological framework for the western Superior Province, Ontario; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p. 1335-1346.

Daigneault, R., Mueller, W.U., and Chown, E. 2004. Abitibi greenstone belt plate tectonics: a history of diachronic arc development, accretion and collision; *in* The Precambrian earth: tempos and events; Elsevier, Amsterdam, Developments in Precambrian Geology 12, p. 88-103.

Devaney, J.R. and Williams, H.R. 1989. Evolution of an Archean subprovince boundary: a sedimentological and structural study of part of the Wabigoon-Quetico boundary in northern Ontario; Canadian Journal of Earth Sciences, v.26, p.1013-1026.

Easton, R.M. 1992. The Grenville Province and the Proterozoic history of central and southern Ontario; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p. 715-904.

Frarey, M.J. and McLaren, D.J. 1963. Possible metazoans from the Early Proterozoic of the Canadian Shield; Nature, 200, (4905), p. 461-462.

Goodwin, A.M. 1956. Facies relations in the Gunflint iron formation; Economic Geology, v. 51, p. 565-595.

Goodwin, A.M. 1960. Gunflint iron formation of the Whitefish Lake area; Ontario Geological Survey, v. 69, pt. 7, p. 41-63.

Grandstaff, D.E. 1980. Origin of uraniferous conglomerates at Elliot Lake, Canada, and Witwatersrand, South Africa: implications for oxygen in the Precambrian atmosphere; Precambrian Research, v. 13, p. 1-26.

Hamilton, M.A. and Stott, G.M. 2008. The significance of new U/Pb baddelyite ages from two Paleoproterozic diabase dikes in northern Ontario; *in* Summary of Field Work and Other Activities 2008, Ontario Geological Survey, Open File Report 6226, p. 17-1 to 17-10.

Hawley, J.E. 1926. Geology and economic possibilities of Sutton Lake area, District of Patricia; Ontario Geological Survey, Annual Report, v.34, pt.2.

Hill, M.L. and Smyk, M.C. 2005. Penokean fold-and-thrust deformation of the Paleoproterozoic Gunflint Formation near Thunder Bay, Ontario; 51st ILSG Annual Meeting, Part 1,Proceedings and Abstracts, p. 26.

Hoffman, H.J. 1967. Precambrian fossils (?) near Elliot Lake, Ontario; Science, 156, (3774), p. 500-504.

Hoffman, H.J. 1969. Stromatolites from the Proterozoic Animikie and Sibley Groups; Geological Survey of Canada, Paper 68-69, 77 p.

Hoffman, H.J. 1971. Precambrian fossils, pseudofossils and problematica in Canada; Geological Survey of Canada, Bulletin 189, 146 p.

Hoffman, H.J., Pearson, D.A.B. and Wilson, B.H. 1980. Stromatolites and fenstral fabric in Early Proterozoic Huronian Supergroup, Ontario; Canadian Journal of Earth Sciences, v. 17, p. 1351-1357.

Hofmann, H.J., Thurston, P.C. and Wallace, H. 1985. Archean stromatolites from the Uchi greenstone belt, northwestern Ontario; *in* Evolution of Archean Supracrustal Sequences, Geological Association of Canada, Special Paper 28, p. 125-132.

Hoffman, P.F. 1988. United plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia; Annual Review of Earth and Planetary Sciences, v.16, p.543-603.

Jackson, M.C. 1985. Geology of the Lumby Lake area, western part, districts of Kenora and Rainy River; Ontario Geological Survey, Open File Report 5534, 178p.

Jackson, S.L., Fyon, J.A., and Corfu, F. 1994. Review of Archean supracrustal assemblages of the southern Abitibi greenstone belt in Ontario, Canada: products of micro-plate interactions within a large-scale plate-tectonic setting; Precambrian Research, v.65, p. 183-205.

Jackson, T.A. 1967. Fossil actinomycetes in Middle Precambrian glacial varves; Science, 155, (3765), p. 1003-1005.

Jirsa, M.A. 2010. Stratigraphy of Sudbury “impactite” near Gunflint Lake, N.E. Minnesota; 56th ILSG Annual Meeting, Part 1,Programs and Abstracts, p. 31.

Langford, F.F. and Morin, J.A. 1976. The development of the Superior Province of northwestern Ontario by merging island arcs; American Journal of Science, Vol. 276, p.1023-1034.

LaBerge, G.L. 1994. Geology of the Lake Superior Region; Geoscience Press, 313 p.

Moorhouse, W.W. 1960. Gunflint iron range in the vicinity of Port Arthur; Ontario Geological Survey, Annual Report, v. 69, pt. 7, p. 1-40.

Moorhouse, W.W. and Beales, F.W. 1962. Fossils from the Animikie, Port Arthur, Ontario; Royal Society of Canada, Transactions, Section 3, v. 3, p. 97-110.

OGS 1991a. Geology of Ontario; Ontario Geological Survey, Special Volume 4, Part 1, 709 p.

OGS 1991b. Bedrock Geology of Ontario, northern sheet; Ontario Geological Survey, Map 2541, scale 1:1 000 000.

OGS 1991c. Bedrock Geology of Ontario, west-central sheet; Ontario Geological Survey, Map 2542, scale 1:1 000 000.

OGS 1991d. Bedrock Geology of Ontario, east-central sheet; Ontario Geological Survey, Map 2543, scale 1:1 000 000.

OGS 1991e. Bedrock Geology of Ontario, southern sheet; Ontario Geological Survey, Map 2544, scale 1:1 000 000.

OGS 1991f. Bedrock Geology of Ontario, explanatory notes, legend and map; Ontario Geological Survey, Map 2545, scale 1:5 000 000.

OGS 1992. Geology of Ontario; Ontario Geological Survey, Special Volume 4, Part 2, 816 p.

Ojakangas, R.W., Morey, G.B. and Southwick, D.L. 2001. Paleoproterozoic basin development and sedimentation in the Lake Superior region, North America; Sedimentary Geology, v. 141-142, p. 319-341.

Okulitch, A.V. 1999. Geological time chart, 1999 (National Earth Science Series, Geological Atlas); Geological Survey of Canada, Open File 3040.

Planavsky, N. and Shapiro, R. 2005. Formation of “abiogenic” Animikie basin stromatolites; Geological Society of America, North-Central Section 39th Annual Meeting, Abstracts with Programs, v. 37, No. 5, p. 23.

Pufahl, P.K., Hiatt, E.E. Stanley, C.R., Morrow, J.R., Nelson, G.J. and Edwards, C.T. 2007. Physical and chemical evidence of the 1850 Ma Sudbury impact event in the Baraga Group, Michigan; Geology, v.35, p. 827-830.

Robertson, J.A., Frarey, M.J. and Card, K.D. 1969. The Federal-Provincial Committee on Huronian Stratigraphy progress report; Ontario Geological Survey, Miscellaneous Paper 31, 26p.

Sanford, B.V., Norris, A.W. and Bostock, H.H. 1968. Geology of the Hudson Bay Lowlands (Operation Winisk); Geological Survey of Canada, Paper 67-60, p. 1-45.

Shegelski, R.J. 1982. The Gunflint Formation in the Thunder Bay area; *in* Proterozoic geology of the northern Lake Superior area; Geological Association of Canada – Mineralogical Association of Canada, Joint Annual Meeting, Field Trip Guidebook 4, p. 14-31.

Shegelski, R.J. 1990. The Gunflint Formation in the Thunder Bay area; *in* Mineral deposits in the western Superior Province, Ontario (Field Trip 9), 8th IAGOD Symposium; Geological Survey of Canada, Open File 2164, p. 110-122.

Schneider, D.A., Bickford, M.E., Cannon, W.F., Schulz, K.J. and Hamilton, M.A. 2002. Age of volcanic rocks and syndepositional iron formations, Marquette Range Supergroup: implications for the tectonic setting of Paleoproterozoic iron formations of the Lake Superior region; Canadian Journal of Earth Sciences, v. 39, p. 999-1012.

Schulz, K.J. and Cannon, W.F. 2007. The Penokean orogeny in the Lake Superior region; Precambrian Research, v.157, p.4-25.

Stockwell, C.H. 1964. Fourth report on structural provinces, orogenies, and time classification of rocks of the Canadian Precambrian shield: *in* Age Determinations and Geological Studies, Part 2, Geological Studies; Geological Survey of Canada, Paper 64-17, Part 2, p. 1-21.

Stott, G.M. 1997. The Superior Province, Canada: Chapter 5.2 *in* Greenstone Belts, Clarendon Press – Oxford, p. 480-507.

Stott, G.M. and Corfu, F. 1991. Uchi Subprovince; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p. 145-236.

Stott, G.M., Corkery, T., Leclair, A., Boily, M., and Percival, J. 2007. A revised terrane map for the Superior Province as interpreted from aeromagnetic data [abs.]: Institute on Lake Superior Geology, 53 Annual Meeting, v.53, pt.1, p.74-75.

Sutcliffe, R.H. 1991. Proterozoic geology of the Lake Superior area; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p. 627-658.

Sutcliffe, R.H. and Bennett, G. 1992. Proterozoic geology of the Great Lakes region: a deformed craton margin and the Midcontinent Rift; p.1294-1299 *in* Tectonic Evolution of Ontario: Summary and Synthesis; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p. 1255-1332.

Thurston, P.C. 1991. Proterozoic geology of Ontario: Introduction; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p. 543-546.

Thurston, P.C. 2002. Autochthonous development of Superior Province greenstone belts?; Precambrian Research, v.115, p. 11-36.

Thurston, P.C. and Chivers, K.M. 1990. Secular variation in greenstone sequence development emphasizing Superior Province, Canada; Precambrian Research, v.46, p.21-58.

Thurston, P.C., Ayer, J.A., Goutier, J., and Hamilton, M.A. 2008. Depositional gaps in Abitibi greenstone belt stratigraphy: a key to exploration for syngenetic mineralization; Economic Geology, v.103, p. 000-000.

Thurston, P.C., Osmani, I.A. and Stone, D. 1991. Northwestern Superior Province; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p. 81-142.

Wilks, M.E. and Nisbett, E.G. 1988. Stratigraphy of the Steep Rock Group, northwestern Ontario: a major Archean unconformity and Archean stromatolites; Canadian Journal of Earth Sciences, v.25, p. 370-391.

Williams, H.R. 1991. Quetico Subprovince; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p. 383-403.

Williams, H.R., Stott, G.M. and Thurston, P.C. 1992. Part 2: Revolution in the Superior Province; p. 1256-1294 *in* Tectonic Evolution of Ontario: Summary and Synthesis; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p. 1255-1332.

Wilson, J.T. 1966. Did the Atlantic close and then reopen?; Nature, v.211, p. 676-681.

Wood, J., Thurston, P.C., Corfu, F. and Davis, D.W. 1986. Ancient quartzites and carbonates in northwestern Ontario – evidence for early (Archean) stability?; *in* Program with Abstracts, Geological Association of Canada, Annual Meeting, v.11, p. 146.

Young, G.M. 1967. Possible organic structures in Early Proterozoic (Huronian) rocks of Ontario; Canadian Journal of Earth Sciences, v.4, p. 565-568.

Young, G.M. 1969. Inorganic origin of corrugated vermiform structures in the Huronian Gordon Lake Formation near Flack Lake, Ontario; Canadian Journal of Earth Sciences, v.6, p. 795-799.

Young, G.M. 1970. An extensive early Proterozoic glaciation in North America?; Palaeogeography, Palaeoclimatology, Palaeoecology, v. 7, 85-01.

Young, G.M., Long, D.G.F., Fedo, C.M. and Nesbitt, H.W. 2001. Paleoproterozoic Huronian basin: product of a Wilson cycle punctuated by glaciations and a meteorite impact; Sedimentary Geology, v. 141-142. P. 233-253.