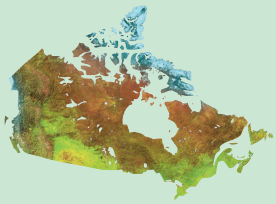
Natural Resources Canada | Ressources naturelles Canada



Geological Survey of Canada
Bulletin 597

Stratigraphic and structural framework of the Potsdam Group in eastern Ontario, western Quebec, and northern New York State

B.V. Sanford and R.W.C. Arnott

2010

Canada

The CD-ROM accompanying this publication contains the full report, including any oversized figures and/or A-series maps, in Portable Document Format (PDF). Oversized items may be purchased separately as paper plots from any Geological Survey of Canada Bookstore location:

Geological Survey of Canada Bookstore (Ottawa)
615 Booth Street
Ottawa, Ontario
K1A 0E9
Tel.: (613) 995-4342
Tel.: (888) 252-4301 (toll-free)
Fax: (613) 943-0646
E-mail: gscbookstore@nrcan.gc.ca
Web: http://gsc.nrcan.gc.ca/bookstore/index_e.php

Geological Survey of Canada Bookstore (Vancouver)
101-605 Robson Street
Vancouver, B.C.
V6B 5J3
Tel.: (604) 666-0271
Fax: (604) 666-1337
E-mail: gscvan@gsc.nrcan.gc.ca
Web: http://gsc.nrcan.gc.ca/org/vancouver/bookstore/index_e.php

Geological Survey of Canada Bookstore (Atlantic)
1 Challenger Drive
P.O. Box 1006
Dartmouth, Nova Scotia
B2Y 4A2
Tel.: (902) 426-4386
Fax: (902) 426-4848
E-mail: Jennifer.Bates@nrcan-rncan.gc.ca
Web: http://gsca.nrcan.gc.ca/pubprod/pubprod_e.php

Geological Survey of Canada Bookstore (Québec)
490, rue de la Couronne
Québec, Quebec
G1K 9A9
Tel.: (418) 654-2677
Fax: (418) 654-2660
E-mail: cgcq_librairie@rncan.gc.ca
Web: http://www.gscq.nrcan.gc.ca/bibliotheque/

Le CD-ROM qui accompagne cette publication renferme le rapport au complet, y compris les figures surdimensionnées ou les cartes de série A, en format PDF. Pour acheter des copies papier des éléments surdimensionnés, adressez-vous à la Librairie de la Commission géologique du Canada :

Librairie de la Commission géologique du Canada (Ottawa)
615, rue Booth
Ottawa (Ontario)
K1A 0E9
Tél. : (613) 995-4342
Tél. : (888) 252-4301 (sans frais)
Télécopieur : (613) 943-0646
Courriel : librairiecgc@nrcan.gc.ca
Web : http://cgc.rncan.gc.ca/librairie/index_f.php

Librairie de la Commission géologique du Canada (Vancouver)
101-605 Robson Street
Vancouver (C.-B.)
V6B 5J3
Tél. : (604) 666-0271
Télécopieur : (604) 666-1337
Courriel : gscvan@gsc.nrcan.gc.ca
Web : http://cgc.rncan.gc.ca/org/vancouver/bookstore/index_f.php

Librairie de la Commission géologique du Canada (Atlantique)
1 Challenger Drive
P.O. Box 1006
Dartmouth (Nouvelle-Écosse)
B2Y 4A2
Tél. : (902) 426-4386
Télécopieur : (902) 426-4848
Courriel : Jennifer.Bates@nrcan-rncan.gc.ca
Web : http://gsca.nrcan.gc.ca/pubprod/pubprod_f.php

Librairie de la Commission géologique du Canada (Québec)
490, rue de la Couronne
Québec (Québec) G1K 9A9
Tél. : (418) 654-2677
Télécopieur : (418) 654-2660
Courriel : cgcq_librairie@rncan.gc.ca
Web : http://www.cgcq.rncan.gc.ca/bibliotheque/

Geological Survey of Canada
Bulletin 597

Stratigraphic and structural framework of the Potsdam Group in eastern Ontario, western Quebec, and northern New York State

B.V. Sanford and R.W.C. Arnott

2010

ISSN 0068-7626
Catalogue No. M42-597E-MRC
ISBN 978-0-660-19922-1

Available in Canada from the Geological Survey of Canada Bookstore
(see inside front cover for details)

A copy of this publication is also available for reference in depository libraries across Canada through access to the Depository Services Program's Web site at http://dsp-psd.pwgsc.gc.ca

A free digital download of this publication is available from GeoPub: http://geopub.nrcan.gc.ca/index_e.php

Recommended citation
Sanford, B.V. and Arnott, R.W.C., 2010: Stratigraphic and structural framework of the Potsdam Group in eastern Ontario, western Quebec, and northern New York State; Geological Survey of Canada, Bulletin 597, 83 p.

Cover illustration
Centre Block of Canada's Parliament Buildings constructed from sandstone of the Nepean Formation (Potsdam Group). Photograph by B.V. Sanford. 2008-047

Critical reviewers
Robert Rainbird
Jeffrey Chiarenzelli
Allan Donaldson
André Desrochers

Authors
B.V. Sanford
Geological Survey of Canada (retired)
17 Meadowglade Gardens
Ottawa, Ontario
K2G 5J4

R.W.C. Arnott
warnott@uottawa.ca
Department of Earth Sciences
University of Ottawa
140 Louis Pasteur Private
Ottawa, Ontario
K1N 6N5

CONTENTS

Figures

Tables

Appendices

Stratigraphic and structural framework of the Potsdam Group in eastern Ontario, western Quebec, and northern New York State

Abstract

The presence of a regional unconformity within the Potsdam Group is an important key to unlocking the geological history of this succession throughout its area of distribution in the Ottawa Embayment and Quebec Basin.

The beds below the unconformity (Abbey Dawn and Covey Hill or Ausable formations) are largely of continental origin and up to 600 m thick; they comprise a complex assortment of red and grey quartzite-cobble, quartz-pebble, quartz arenite, and feldspathic arenite deposits of assumed Neoproterozoic to Middle Cambrian age. The Covey Hill and Ausable formations have been further divided into four units of wide distribution beginning with the marine and marginal marine Jericho Member, which is confined to the Quebec Basin bordering the Oka-Beauharnois Arch on the east, and succeeded and overlapped to the west by the mostly eolian and fluvial Hannawa Falls, Chippewa Bay, and Edwardsville members. During and immediately following deposition of these members, the beds were locally faulted, folded, and subjected to a long period of subaerial erosion.

Above the regional unconformity are the white and grey Nepean and partly equivalent Cairnside and Keeseville formations (up to 110 m thick) composed of upper Middle and Upper Cambrian to Lower Ordovician quartz arenite and quartz-pebble conglomerate containing minor evaporite deposits. They were deposited on the floor and margins of a seaway that entered the Ottawa Embayment from the east.

Post-Nepean, Cairnside, and Keeseville deformation (faulting and folding) of Potsdam and younger Ordovician strata was widespread throughout the Ottawa Embayment and Quebec Basin, likely triggered by Taconian and Acadian orogenesis and by the much later rifting and breakup of the continents beginning in the Middle to Late Triassic.

Résumé

La présence d'une discordance régionale dans le Groupe de Potsdam est un élément important pour comprendre l'histoire géologique de cette succession dans toute sa zone de distribution dans le rentrant d'Ottawa et le bassin de Québec.

Les couches sous la discordance (formations d'Abbey Dawn et de Covey Hill ou d'Ausable) ont une origine en grande partie continentale et leur épaisseur peut atteindre 600 m; elles consistent en un assortiment complexe de dépôts de galets de quartzite, de cailloux de quartz, de quartzarénite et de feldsparénite de couleur rouge et grise datant probablement du Néoprotérozoïque au Cambrien moyen. Les formations de Covey Hill et d'Ausable ont été subdivisées en quatre unités largement réparties, qui débutent par le Membre de Jericho, d'origine marine et margino-marine et confiné au bassin de Québec, jouxtant l'arche d'Oka-Beauharnois à l'est, et qui est suivi et chevauché à l'ouest par les membres de Hannawa Falls, de Chippewa Bay et d'Edwardsville, d'origine surtout éolienne et fluviale. Pendant et juste après le dépôt de ces membres, les couches ont été localement faillées, plissées et soumises à une longue période d'érosion subaérienne.

Au-dessus de la discordance régionale se trouvent la Formation de Nepean, blanche et grise, et les formations en partie équivalentes de Cairnside et de Keeseville (jusqu'à 110 m d'épaisseur), composées de quartzarénite et de conglomérat à cailloux de quartz contenant des dépôts mineurs d'évaporite qui s'échelonnent du sommet du Cambrien moyen et du Cambrien supérieur à l'Ordovicien inférieur. Elles ont été déposées sur le fond et les marges d'un bras de mer qui a pénétré dans le rentrant d'Ottawa depuis l'est.

La déformation (formation de failles et de plis) du Groupe de Potsdam et des strates ordoviciennes plus récentes qui a suivi le dépôt des formations de Nepean, de Cairnside et de Keeseville, a été généralisée dans tout le rentrant d'Ottawa et le bassin de Québec; elle a probablement été déclenchée par les orogenèses taconique et acadienne, et beaucoup plus tard, par le rifting et la rupture des continents à compter du Trias moyen à tardif.

SUMMARY

Sandstone and conglomerate deposits of probable Neoproterozoic to Early Ordovician age at the base of the Paleozoic succession are widely distributed across the St. Lawrence Platform in eastern Canada and adjacent areas of the United States. The beds extend from western Newfoundland Island and southeastern Labrador to the east, to Michigan and adjacent states to the west, a distance of 1700 km. The rock units that make up the succession in each of the Eastern, Central, and Western divisions of the platform have certain lithological and structural characteristics in common. However, the units are known by different stratigraphic terminology in each of the divisions, and regional correlation and depositional history of the succession have long been uncertain.

The basal sandstone and conglomerate deposits are particularly well developed in the Central Division of the St. Lawrence Platform (Ottawa Embayment and Quebec Basin), where the present studies were focused. They were first described and named 'Potsdam Sandstone' in northern New York State by Ebenezer Emmons in 1838. A refined definition of the Potsdam was later adopted by William Logan, founder and first director of the Geological Survey of Canada, for rocks of similar composition and age that were then in early stages of investigation in immediately adjacent areas of eastern Ontario and western Quebec.

Throughout subsequent years, the Potsdam Sandstone has been examined in a fair level of detail, but the areas of study were greatly restricted in terms of geographic coverage, largely due to political jurisdictional constraints.

In western Quebec, substantial progress was made in piercing together the stratigraphic framework with the recognition of two principal rock units within the newly defined Potsdam Group. These were named Covey Hill and Cairnside formations in that order of succession, both assumed to be Late Cambrian.

In Ontario, basal sandstone and conglomerate deposits were named 'Nepean Formation' and dated Early Ordovician on the basis of their assumed gradational contact with known Early Ordovician carbonate rocks. More recently, beds similar to the Covey Hill of Quebec were noted at the base of the Paleozoic succession at several locations and were identified by that name. The term 'Potsdam Group' was introduced to eastern Ontario to embrace the newly defined Covey Hill and Nepean formations where the two formations were found to the juxtaposed.

In New York State where the Potsdam Sandstone was first identified and defined, the succession has essentially been undivided and to this day is referred to in the geological literature as 'Potsdam Formation' throughout

SOMMAIRE

Les dépôts de grès et de conglomérats à la base de la succession du Paléozoïque, qui datent probablement du Néoprotérozoïque à l'Ordovicien précoce, sont largement répartis dans toute la Plate-forme du Saint-Laurent dans l'est du Canada et dans les régions adjacentes des États-Unis. Les couches s'étendent de l'ouest de l'île de Terre-Neuve et du sud-est du Labrador, à l'est, jusqu'au Michigan et aux États adjacents, à l'ouest, soit sur une distance de 1700 km. Les unités lithologiques qui composent la succession dans chacune des divisions orientale, centrale et occidentale de la plate-forme présentent certaines caractéristiques lithologiques et structurales communes. Toutefois, ces unités sont connues selon une terminologie stratigraphique différente dans chacune de ces divisions, et pendant longtemps, la corrélation régionale et l'évolution sédimentaire de la succession ont été entachées d'incertitude.

Les conglomérats et grès de base sont particulièrement bien développés dans la division centrale de la Plate-forme du Saint-Laurent (rentrant d'Ottawa et bassin de Québec), où ont été axées les études présentes. Ils ont été décrits pour la première fois dans le nord de l'État de New York en 1838 par Ebenezer Emmons, qui les a nommés « Grès de Potsdam ». William Logan, fondateur et premier directeur de la Commission géologique du Canada, a plus tard adopté la définition du Grès de Potsdam et l'a adaptée aux roches de composition et d'âge similaires qui faisaient alors l'objet des premiers travaux de recherche dans les zones immédiatement adjacentes de l'est de l'Ontario et de l'ouest du Québec.

Au cours des années subséquentes, le Grès de Potsdam a été étudié de façon assez détaillée, mais les zones d'étude étaient très restreintes du point de vue géographique, essentiellement en raison de contraintes d'ordre politique et juridictionnel.

Dans l'ouest du Québec, des progrès importants ont été réalisés dans l'établissement du cadre stratigraphique avec la reconnaissance des deux unités lithologiques principales dans le Groupe de Potsdam nouvellement défini. Ces unités ont été appelées formations de Covey Hill et de Cairnside, dans cet ordre de succession, et l'on présumait qu'elles dataient toutes deux du Cambrien tardif.

En Ontario, les conglomérats et grès de base ont été désignés « Formation de Nepean » et datés de l'Ordovicien précoce, d'après leur contact graduel présumé avec des roches carbonatées que l'on savait dater de l'Ordovicien précoce. Plus récemment, on a constaté en plusieurs endroits à la base de la succession paléozoïque, la présence de couches similaires à celles de la Formation de Covey Hill au Québec; ces couches ont été identifiées sous ce nom. L'expression « Groupe de Potsdam » a été introduite dans l'est de l'Ontario pour englober les formations de Covey Hill et de Nepean nouvellement définies, là où l'on a trouvé les deux formations juxtaposées.

Dans l'État de New York où l'on a identifié et défini pour la première fois le Grès de Potsdam, la succession n'est pratiquement pas subdivisée, et encore aujourd'hui on la désigne dans

its area of distribution. One important exception is the two-fold subdivision of the formation into Ausable and Keeseville members and the use of these terms for map units in the Plattsburgh–Rouses Point area of New York State. The resurrection and redefinition of the Ausable and Keeseville members was an important contribution to the geological history of the Potsdam Formation in that extreme northeastern region of the state. Prior to the present investigation, the Ausable and Keeseville members, as map units, were apparently never extended systematically west of the Plattsburgh–Rouses Point area along the northern margins of the Adirondack Mountains, or in the Thousand Islands region of the state.

Despite the voluminous literature relating to the Potsdam Sandstone, there has long been a need for gathering consistent information to reconstruct the succession of depositional and tectonic events on a broad regional scale throughout eastern Ontario, western Quebec, and northern New York State. Such information has important ramifications also in establishing more reliable correlation of geological events that took place along the entire length of the St. Lawrence Platform during the Neoproterozoic, Cambrian, and Early Ordovician.

During this investigation in the Ottawa Embayment and western part of the Quebec Basin, a number of new observations and interpretations pertaining to the Potsdam Group were recorded. The most significant of these findings in their order of importance are summarized as follows:

1. *The recognition and documentation of a regional unconformity within the Potsdam Group that can be used on a wide regional scale in Ontario and New York State as a stratigraphic marker to separate the Covey Hill and equivalent Ausable formations from the succeeding Nepean and equivalent Keeseville formations*. Following the discovery of the unconformity on Rideau Ferry Road in Ontario, 19 additional locations were found in Ontario and New York State where the units are separated by an unconformity and at 4 of these, by an angular unconformity. It was also noted that at each of these locations the rocks beneath the unconformity are largely of continental origin, and those above are marine and marginal marine. During the long hiatus that prevailed between the two units, the Covey Hill and equivalent Ausable formations were subjected to intense deformation and erosion on a regional scale. This was especially so along the axis of the Frontenac Arch on the Ontario side of the St. Lawrence River where these strata have been mostly eroded and stratigraphically overlapped by the Nepean Formation.

2. *The identification of several new rock units on the basis of lithology, colour, and environment of deposition, and the redefinition of some of the previously named units contained within the Potsdam Group*. This includes the recognition of a quartzite-cobble and -boulder conglomerate of probable

la documentation géologique sous le nom de « Formation de Potsdam » dans toute son aire de distribution. Une exception importante est la subdivision de la formation en deux membres, ceux d'Ausable et de Keeseville, et l'utilisation de ces termes pour les unités cartographiques dans la région de Plattsburgh-Rouses Point, dans l'État de New York. L'utilisation et la redéfinition des membres d'Ausable et de Keeseville représentent une contribution importante à l'histoire géologique de la Formation de Potsdam dans cette région sise à l'extrême nord-est de l'État. Avant les recherches actuelles, les membres d'Ausable et de Keeseville en tant qu'unités cartographiques n'avaient vraisemblablement jamais été étendus systématiquement à l'ouest de la région de Plattsburgh-Rouses Point le long de la marge nord des Adirondacks, ou dans la région des Mille-Îles de cet État.

Malgré la volumineuse documentation sur le Grès de Potsdam, la collecte d'information cohérente s'imposait depuis longtemps pour reconstituer la succession des événements sédimentaires et tectoniques à une échelle régionale étendue dans l'est de l'Ontario, l'ouest du Québec et le nord de l'État de New York. Cette information a d'importantes ramifications, car elle permet de corréler avec plus de fiabilité les événements géologiques qui ont eu lieu sur toute la longueur de la Plate-forme du Saint-Laurent pendant le Néoprotérozoïque, le Cambrien et l'Ordovicien précoce.

Au cours de cette étude du rentrant d'Ottawa et de la partie ouest du bassin de Québec, plusieurs observations et interprétations nouvelles relatives au Groupe de Potsdam ont été consignées. Voici un résumé des ces résultats, par ordre d'importance

1. *La reconnaissance et la documentation d'une discordance régionale à l'intérieur du Groupe de Potsdam, laquelle peut être utilisée à une échelle régionale étendue en Ontario et dans l'État de New York comme repère stratigraphique séparant la Formation de Covey Hill et son équivalent, la Formation d'Ausable, de la Formation de Nepean ultérieure et de son équivalent, la Formation de Keeseville*. Après la découverte de la discordance sur la route Rideau Ferry en Ontario, 19 emplacements additionnels ont été trouvés en Ontario et dans l'État de New York où les unités sont séparées par une discordance et, dans quatre de ces endroits, par une discordance angulaire. On a également constaté à chacun de ces endroits que les roches sous la discordance sont essentiellement d'origine continentale, alors que celles au-dessus sont d'origine marine et margino-marine. Pendant la longue lacune sédimentaire entre les deux unités, la Formation de Covey Hill et l'équivalente Formation d'Ausable ont subi une déformation et une érosion intenses à une échelle régionale. Cela a particulièrement été le cas le long de l'axe de l'arche de Frontenac du côté ontarien du fleuve Saint-Laurent, où ces strates ont été en grande partie érodées et stratigraphiquement chevauchées par la Formation de Nepean.

2. *L'identification de plusieurs nouvelles unités lithologiques d'après leur lithologie, leur couleur et leur milieu de dépôt, et la redéfinition de certaines unités antérieurement nommées et présentes dans le Groupe de Potsdam*. Ceci comprend la reconnaissance d'un conglomérat à galets et à blocs de

Neoproterozoic age that occurs locally at the base of the Potsdam in Ontario and is herein named the 'Abbey Dawn Formation'. Identified also within the newly defined Lower to Midle Cambrian strata of the Covey Hill and equivalent Ausable formations are, in ascending stratigraphic order, the Jericho, Hannawa Falls, Chippewa Bay, and Edwardsville members.

These newly identified units, abruptly bounded in most instances by unconformable contacts, have wide lateral continuity that provides a high level of confidence with regard to their local and regional correlation at surface and in subsurface throughout the Ottawa Embayment and Quebec Basin. The detailed definition of the above members has in turn necessitated the redefinition of the previously named Covey Hill and Nepean formations in Ontario and the Ausable and Keeseville members in New York State. For the sake of consistency, it is herein proposed that the latter members in New York State be raised to formation status, and the Potsdam Formation in the same region be raised to Potsdam Group to conform with the status of equivalent units in eastern Ontario and western Quebec.

3. *The recognition of lateral and vertical facies changes within the Covey Hill and equivalent Ausable formations, which point to a variety of depositional conditions mainly of continental origin*. These were largely controlled by long periods of arid climatic conditions and an intervening period of high humidity, coupled with intense tectonic activity. The Covey Hill and equivalent Ausable formations were presumably deposited as a redbed sequence. The Jericho, Hannawa Falls, and Edwardsville members retained much of their red and pink colouration as a result of arid conditions during deposition and subsequent diagenetic alteration. The Chippewa Bay Member, on the other hand, was intensely leached during early burial. This difference in early diagenetic processes was likely related to more humid environmental conditions, plus increased subsurface fluid flow. Throughout the western part of the Ottawa Embayment, strata of the Covey Hill and equivalent Ausable formations are dominated by eolian deposits. Intercalated with these strata, especially in the Rideau Lakes area, are local patches of quartzite-pebble and -boulder conglomerate that were transported by major fluvial systems that flowed eastward off the Frontenac Arch. To the east, and bordering the Oka-Beauharnois Arch, thick sequences of quartz-feldspar-pebble conglomerate and feldspathic arenite represent deposits of major fluvial systems that transported a mixture of sand and gravel into the Ottawa Embayment and Quebec Basin.

quartzite datant probablement du Néoprotérozoïque, que l'on trouve par endroits à la base du Groupe de Potsdam en Ontario et qui est nommé « Formation d'Abbey Dawn » dans le présent bulletin. On a également identifié, dans les strates nouvellement définies de la Formation de Covey Hill et de l'équivalente Formation d'Ausable, qui remontent au Cambrien inférieur à moyen, les membres suivants, en ordre stratigraphique ascendant : Jericho, Hannawa Falls, Chippewa Bay et Edwardsville.

Ces unités nouvellement identifiées, abruptement limitées dans la plupart des cas par des contacts discordants, présentent une grande continuité latérale qui permet d'avoir un niveau de confiance élevé à l'égard de leur corrélation locale et régionale en surface et en subsurface dans tout le rentrant d'Ottawa et tout le bassin de Québec. La définition détaillée des membres susmentionnés a, à son tour, nécessité la redéfinition des formations auparavant nommées Covey Hill et Nepean en Ontario et des membres auparavant nommés Ausable et Keeseville dans l'État de New York. Afin d'assurer l'uniformité, il est proposé dans le présent bulletin d'accorder le rang de formation aux deux membres susmentionnés dans l'État de New York, et d'accorder le rang de groupe à la Formation de Potsdam dans la même région, afin de les harmoniser avec les rangs des unités équivalentes dans l'est de l'Ontario et l'ouest du Québec.

3. *La reconnaissance de changements latéraux et verticaux des faciès dans la Formation de Covey Hill et l'équivalente Formation d'Ausable laisse supposer diverses conditions de dépôt d'origine surtout continentale*. Ces changements sont attribuables en grande partie à de longues périodes de conditions climatiques arides et à une période intermédiaire d'humidité élevée, couplées à une intense activité tectonique. La Formation de Covey Hill et l'équivalente Formation d'Ausable ont probablement été déposées sous forme d'une séquence de couches rouges. Les membres de Jericho, de Hannawa Falls et d'Edwardsville ont conservé la majeure partie de leur coloration rouge et rose à la suite des conditions arides qui régnaient pendant le dépôt et la diagenèse subséquente. Par contre, le Membre de Chippewa Bay a fait l'objet d'un intense lessivage au cours de son enfouissement précoce. Cette différence dans les processus diagénétiques précoces était probablement associée aux conditions plus humides et à un écoulement accru de fluides en subsurface. Dans toute la partie occidentale du rentrant d'Ottawa, les strates de la Formation de Covey Hill et de l'équivalente Formation d'Ausable sont dominées par des dépôts éoliens. On trouve intercalés dans ces strates, en particulier dans la région des lacs Rideau, des amas locaux de conglomérats à galets et à blocs de quartzite qui ont été transportés par les grands réseaux fluviaux qui s'écoulaient vers l'est, depuis l'arche de Frontenac. Vers l'est, et jouxtant l'arche d'Oka-Beauharnois, les séquences épaisses de conglomérats à galets de quartz-feldspath et de feldsparénite représentent des dépôts des grands réseaux fluviaux qui ont transporté un mélange de sable et de gravier dans le rentrant d'Ottawa et le bassin de Québec.

4. *The recognition of the Nepean Formation and its equivalents at surface and in subsurface throughout the Ottawa Embayment as a highly saline basin of deposition*. Upon entering the Ottawa Embayment from the east, the Late Cambrian to Early Ordovician seaway, bounded on four sides by Precambrian highland areas, became highly saline probably at a very early stage, and progressively more so throughout the depositional period of the Nepean Formation and its counterparts. This is suggested by the paucity of normal marine faunas within the confines of the embayment and by the presence of gypsum interbeds in distal segments of the basin, along with the presence of stromatolites of local biostromal proportions and the brecciation of Nepean beds that may be due to the dissolution of evaporite deposits and the collapse of the overlying strata. West of the Frontenac Arch and east of the Oka-Beauharnois Arch, marine organisms appear to be more abundant and diverse, suggesting more open marine conditions in these regions during deposition of the Nepean Formation and its counterparts.

5. *The identification of water-expulsion cones and vertical columnar structures, and their very differing characteristics in terms of origin and development*. Water-expulsion structures noted during this study are cone-shaped features, narrow at their base where pore fluids entered from the adjacent stratified deposits, and wide at the top where the channels through the soft sediment branched outward and upward. As fluid pressure and accordingly the velocity of the escaping fluids decreased, fluidized sediment collapsed and infilled the previously excavated void. Such features are uncommon in the Potsdam Group, and only one of any significance was observed, it having intersected the Hannawa Falls Member of the Covey Hill Formation at Jones Falls, Ontario. Columnar structures, on the other hand, consist of parallel-walled vertical columns 0.5 to 1.0 m or more in diameter that are concentrically banded throughout. Most of these are herein interpreted to have formed by a simple drilling process on the floor of a stream bed where a fast-flowing current set in motion the rotating tools (quartzite cobbles) that bored a vertical cylinder up to 6 m deep. When the rotating current could no longer sustain the drilling process, the cylinder was filled with sand in a similar rotating manner, forming concentric parallel layering.

   The columns are well developed in cross-section on the William Hughes property on the shore of the Cataraqui River (Rideau Canal). In the Norman Sloan quarry on the opposite bank of the river, quartzite cobbles and pebbles, which potentially were the tools that performed the drilling, overlie the strata that host the columns on the Hughes property. In addition, a plan

4. *La reconnaissance du fait que la Formation de Nepean et ses équivalents en surface et en subsurface dans tout le rentrant d'Ottawa constituent un bassin de dépôt hautement salin*. À l'entrée du rentrant d'Ottawa, le bras de mer du Cambrien tardif-Ordovicien précoce en provenance de l'est, qui était limité des quatre côtés par des hautes terres du Précambrien, est probablement devenu très salin à un stade très précoce, et encore plus pendant toute la période de dépôt de la Formation de Nepean et de ses équivalents. Cette hypothèse s'appuie sur la rareté de faunes marines normales à l'intérieur des limites du rentrant, sur la présence d'intercalations de gypse dans les segments distaux du bassin, sur la présence de stromatolites localement de proportions biostromales et sur la bréchification des couches de la Formation de Nepean qui peut être le résultat de la dissolution d'évaporites et de l'effondrement des strates sus-jacentes. À l'ouest de l'arche de Frontenac et à l'est de l'arche d'Oka-Beauharnois, les organismes marins semblent avoir été plus abondants et plus diversifiés, ce qui permet de supposer des conditions marines plus ouvertes dans ces régions pendant le dépôt de la Formation de Nepean et de ses contreparties.

5. *L'identification de cônes d'expulsion d'eau et de structures verticales en colonnes, et leurs caractéristiques très différentes en termes d'origine et de formation*. Les structures d'expulsion d'eau observées au cours de cette étude sont coniques : étroites à leur base où les fluides interstitiels ont pénétré depuis des dépôts stratifiés adjacents, et larges au sommet où les chenaux traversant les sédiments meubles se sont ramifiés vers l'extérieur et vers le haut. À mesure que la pression des fluides, et par conséquent la vitesse d'échappement des fluides, a diminué, les sédiments fluidisés se sont effondrés et ont comblé les vides antérieurement excavés. Ces structures sont plutôt rares dans le Groupe de Potsdam, et une seule structure d'importance a été observée qui recoupait le Membre de Hannawa Falls de la Formation de Covey Hill, à Jones Falls (Ontario). Par ailleurs, les structures columnaires consistent en colonnes verticales de 0,5 à 1,0 m ou plus de diamètre, aux parois parallèles et à rubanement concentrique. Selon l'interprétation que nous en faisons, la plupart d'entre elles ont été formées par un processus de forage simple dans le lit de cours d'eau, où un courant rapide a mis en mouvement les outils de rotation, en l'occurrence des galets de quartzite, qui ont creusé un cylindre vertical jusqu'à une profondeur de 6 m. Lorsque le courant giratoire ne pouvait plus soutenir le processus de forage, le cylindre s'est rempli de sable selon un mécanisme giratoire similaire, ce qui a formé des couches parallèles concentriques.

   Les colonnes sont bien développées dans une coupe transversale dans la propriété de William Hughes, sur la berge de la rivière Cataraqui (canal Rideau). Dans la carrière de Norman Sloan, sur la berge opposée de la rivière, des galets et des cailloux de quartzite qui ont probablement été les outils de forage susmentionnés, recouvrent les strates dans lesquelles se trouvent les colonnes de la propriété de Hughes. En outre, une

view of a column is exposed and shows the concentric layering of sand as it may have appeared during the final stages of infilling of the cylinder.

Similar but much smaller columns were found elsewhere bordering the Frontenac Arch, in the Chippewa Bay Member of the Covey Hill Formation, in eastern Ontario. Vertical cylinders were also observed at two other locations, in Covey Hill strata at Charleston Lake Provincial Park, and near Jones Falls, both in Ontario. These cylinders, unlike those described above, lack a sediment fill and most probably were formed during Quaternary deglaciation.

6. *The gross petrographic comparison of rock units as a possible tool for reconstructing depositional environments and establishing local and regional correlation*. Although lithological differences and the presence of an unconformity are usually sufficient criteria for distinguishing the Covey Hill and Nepean formations and their equivalents in various localities, it may be difficult in the field to differentiate between the two stratal units in areas where the Nepean or equivalent Keeseville formations rest directly on the lithologically similar Chippewa Bay Member of the Covey Hill or equivalent Ausable formations. Invariably, the Covey Hill and equivalent Ausable formations contain red iron-oxide dust rims around the framework sand grains that are overgrown by quartz precipitated during burial diagenesis. Even in the highly leached strata of the Chippewa Bay Member, framework grains contain microscopic remnants of red iron-oxide rims that are in sharp contrast to those of the overlying Nepean Formation or its Keeseville equivalent, where hematite rims are absent.

7. *The identification and documentation of structural deformation (folds and faults) and its possible relationship to regional tectonics centred well beyond the margins of the study area, during and subsequent to deposition of the Potsdam Group*. Deformation in the form of folding and faulting of the Covey Hill and equivalent Ausable formations was in progress at numerous localities in eastern Ontario, western Quebec, and northern New York State throughout much of the Middle Cambrian, The deformation, largely triggered by uplift of the Frontenac, Laurentian, and Oka-Beauharnois arches, was locally intensive, and for the most part occured prior to the deposition of the Nepean, Cairnside, and Keeseville formations.

   Post-Nepean and equivalent Keeseville and Cairnside deformation, resulting in both folding and faulting, was also widespread throughout the study area, although its timing is uncertain. Deformation was most likely due in part to widespread epeirogeny in the Canadian craton related to early Middle Ordovician to Late Devonian Taconian and Acadian orogenesis, and

vue en plan d'une colonne est exposée et montre les couches concentriques de sable, telles qu'elles se sont probablement formées pendant l'étape finale de remplissage du cylindre.

Des colonnes similaires, mais beaucoup plus petites, ont été trouvées le long de l'arche de Frontenac, dans le Membre de Chippewa Bay de la Formation de Covey Hill, dans l'est de l'Ontario. On a observé également des cylindres verticaux dans des strates de la Formation de Covey Hill en deux autres endroits en Ontario, dans le parc provincial du lac Charleston et près de Jones Falls. Ces cylindres, à la différence de ceux qui sont décrits ci-dessus, n'ont pas de remplissage de sédiments et ont fort probablement été formés pendant la déglaciation du Quaternaire.

6. *La comparaison pétrographique brute des unités lithologiques, comme outil possible pour la reconstitution des milieux de dépôt et l'établissement de corrélations locales et régionales*. Bien que les différences lithologiques et la présence d'une discordance soient habituellement des critères suffisants pour distinguer les formations de Covey Hill et de Nepean et leurs équivalents dans diverses localités, il peut s'avérer difficile sur le terrain de différencier deux unités de strates dans des régions où la Formation de Nepean, ou l'équivalente Formation de Keeseville, repose directement sur le membre lithologiquement similaire de Chippewa Bay de la Formation de Covey Hill ou de l'équivalente Formation d'Ausable. La Formation de Covey Hill et l'équivalente Formation d'Ausable contiennent invariablement des lisérés de poussières d'oxyde de fer autour des grains de sable de charpente qui ont subi un accroissement secondaire de quartz précipité pendant la diagenèse d'enfouissement. Même dans les strates fortement lessivées du Membre de Chippewa Bay, les grains de charpente contiennent des vestiges microscopiques des lisérés d'oxyde de fer qui contrastent nettement avec ceux de la formation sus-jacente de Nepean ou de l'équivalente Formation de Keeseville, où les lisérés d'hématite sont absents.

7. *L'identification et la documentation de la déformation structurale (plis et failles) et sa relation éventuelle avec le cadre tectonique régional centré bien au-delà des marges de la région à l'étude, pendant et après le dépôt du Groupe de Potsdam*. La déformation qui a engendré des plis et des failles dans la Formation de Covey Hill et l'équivalente Formation d'Ausable se poursuivait à de nombreux endroits dans l'est de l'Ontario, l'ouest du Québec et le nord de l'État de New York durant une grande partie du Cambrien moyen. Elle avait été largement déclenchée par le soulèvement de l'arche de Frontenac, de l'arche laurentienne et de l'arche d'Oka-Beauharnois et a eu lieu en grande partie avant l'accumulation des formations de Nepean, de Cairnside et de Keeseville.

   La déformation qui a suivi l'accumulation de la Formation de Nepean et des formations équivalentes de Keeseville et de Cairnside et qui a engendré des plis et des failles, était également généralisée dans toute la région à l'étude, bien que l'on ne connaisse pas sa chronologie exacte. La déformation était fort probablement due en partie à l'épirogenèse généralisée dans le craton canadien associée aux orogenèses taconique

perhaps also to rifting and continental separation that began during the Middle to Late Triassic and continued into the Jurassic and Cretaceous.

8. *The development of a rationale for establishing the age and regional correlation of formations contained within the Potsdam Group, with possible equivalent sequences at opposite extremities of the St. Lawrence Platform*. The age of the Abbey Dawn conglomerate units is uncertain, but is more than likely Neoproterozoic, their deposition having been triggered by epeirogeny that prevailed along the Laurentian Arch resulting from rifting and breakup of the continents during the Late Proterozoic to Early Cambrian. The beds are thus likely equivalent to the basal part of the Labrador Group in western Newfoundland Island. The much younger Covey Hill and Ausable formations are for the most part unfossiliferous except for the lower beds (Jericho Member) in New York State, which contain upper Lower to lower Middle Cambrian trilobite faunas. The Covey Hill and Ausable formations are thus coeval with the upper and lower parts of the Labrador and Port au Port groups respectively, and possibly also roughly equate with the Jacobsville and Middle Run formations in the Michigan and Appalachian basins respectively. The much younger strata of the Potsdam Group (Nepean, Cairnside, and Keeseville formations) are of marine to marginal marine origin and unconformably overlie the Covey Hill or Ausable formations except in the Frontenac Arch area of Ontario, where they overlap Covey Hill or Ausable strata to lie directly on Precambrian rocks. Keeseville strata exposed in the Ausable Chasm, New York, have been dated late Middle to Late Cambrian on the basis of their trilobite fauna, and to the west are known to become progressively younger closer to the Frontenac Arch in the Thousand Islands region of New York and Ontario. Conodont dating of the upper beds of the Nepean Formation in the Ottawa region has yielded Tremadocian to Arenigian ages, thus confirming an Early Ordovician age. Coeval marine carbonate deposits at the eastern extremity of the St. Lawrence Platform in western Newfoundland Island are the Upper Cambrian to Lower Ordovician Petit Jardin, Berry Head, and Watts Bight formations. Beds equivalent to the Nepean, Cairnside, and Keeseville formations in the Michigan Basin are the Upper Cambrian to Lower Ordovician sandstone and carbonate rocks of the Mount Simon, Galesville, Franconia, Trempealeau, and Oneota formations.

et acadienne du début de l'Ordovicien moyen au Dévonien tardif, et probablement également au rifting et à la séparation des continents qui a débuté entre le Trias moyen et tardif et qui s'est poursuivie pendant le Jurassique et le Crétacé.

8. *L'établissement d'une approche rationnelle pour dater et corréler régionalement les formations présentes dans le Groupe de Potsdam, avec des séquences équivalentes possibles aux extrémités opposées de la Plate-forme du Saint-Laurent.* L'âge des conglomérats de la Formation d'Abbey Dawn est incertain, mais ils remontent fort probablement au Néoprotérozoïque, leur accumulation ayant été déclenchée par l'épirogenèse survenue le long de l'arche laurentienne à la suite du rifting et du morcellement des continents au cours du Protérozoïque tardif et jusqu'au Cambrien précoce. Les couches seraient donc vraisemblablement équivalentes à la base du Groupe de Labrador dans l'ouest de l'île de Terre-Neuve. Les formations beaucoup plus récentes de Covey Hill et d'Ausable sont largement dépourvues de fossiles, exception faite des couches inférieures (Membre de Jericho) dans l'État de New York qui recèlent des faunes de trilobites s'échelonnant du sommet du Cambrien inférieur à la base du Cambrien moyen. Les formations de Covey Hill et d'Ausable sont donc contemporaines des parties supérieures et inférieures des groupes de Labrador et de Port au Port, respectivement, et pourraient aussi être plus ou moins équivalentes aux formations de Jacobsville et de Middle Run dans les bassins du Michigan et des Appalaches, respectivement. Les strates beaucoup plus récentes du Groupe de Potsdam (formations de Nepean, de Cairnside et de Keeseville) ont une origine marine à margino-marine et reposent en discordance sur les formations de Covey Hill ou d'Ausable, sauf dans la région de l'arche de Frontenac en Ontario, où elles chevauchent les strates des formations de Covey Hill ou d'Ausable pour reposer directement sur les roches du Précambrien. Les strates de la Formation de Keeseville exposées dans l'abîme d'Ausable (New York) ont été datées de la fin du Cambrien moyen et du Cambrien tardif d'après leur faune de trilobites; on sait que les couches à l'ouest rajeunissent progressivement plus l'on se rapproche de l'arche de Frontenac dans la région des Mille-Îles de l'État de New York et de l'Ontario. La datation par les conodontes des couches supérieures de la Formation de Nepean dans la région d'Ottawa a donné des âges remontant au Trémadocien et à l'Arénigien, ce qui confirme donc l'âge de l'Ordovicien précoce. Les dépôts contemporains de roches carbonatées d'origine marine à l'extrémité est de la Plate-forme du Saint-Laurent, dans l'ouest de l'île de Terre-Neuve, constituent les formations de Petit Jardin, de Berry Head et de Watts Bight du Cambrien supérieur à l'Ordovicien inférieur. Des couches équivalentes aux formations de Nepean, de Cairnside et de Keeseville dans le bassin du Michigan sont les roches carbonatées et les grès (Cambrien supérieur-Ordovicien inférieur) des formations de Mount Simon, de Galesville, de Franconia, de Trempealeau et d'Oneota.

INTRODUCTION

The Potsdam Group, the object of this study, and its counterparts in adjacent regions of the St. Lawrence Platform, are among the oldest unmetamorphosed sedimentary sequences in eastern North America. They are composed largely of sandstone and conglomerate that form the basal stratigraphic units that were deposited along the southeastern margin of the Canadian Shield in eastern Canada and adjacent areas of the United States during the latest Precambrian to Early Ordovician.

These sequences, in varied levels of preservation, occur the length of the St. Lawrence Platform, from western Newfoundland and Labrador on the east, to Ohio, Michigan, and Wisconsin on the west, a distance of 1700 km. Throughout this broad area, the rocks are locally well exposed along the inner margins of the St. Lawrence Platform, and in subsurface have been identified in boreholes and from seismic data where they overlie Precambrian basement rocks and are obscured beneath younger Paleozoic cover.

In the Central Division of the St. Lawrence Platform (Quebec Basin and Ottawa Embayment), the Potsdam Group has been studied in some detail, but little attempt has been made at establishing a consistent stratigraphic framework that links the three principal outcrop belts in New York State, eastern Ontario, and western Quebec. In New York State, for example, where the Potsdam was first identified by Emmons (1838), the succession to this day is simply referred to as 'Potsdam Formation' throughout most of the state. Early attempts were made to subdivide the unit in the Lake Champlain region, and these are described in some detail herein under the heading 'Early investigations'. The most recent work in this regard was by Fisher (1968) and Landing et al. (2007, 2009), who divided the Potsdam Formation into two units — the Ausable and Keeseville members as geological map units. These terms were adopted from previous investigations by Alling (1919) and Emmons (1841), respectively. There is some uncertainty, however, as to whether or not the Ausable and Keeseville members defined by those authors are the exact correlatives of the Covey Hill and Cairnside formations, as is currently in use in the adjacent area of Quebec. Also, the two map units were never systematically extended westward beyond the limits of the Plattsburgh–Rouses Point area bordering the northern margin of the Adirondack Mountains.

Similar classification uncertainties have long prevailed in adjacent areas of Ontario and largely relate to the original naming and definition of the Nepean Formation by Wilson (1937, 1946). In defining the term, Wilson was apparently unaware of the presence of much older rocks (Covey Hill and equivalent Ausable formations) beneath the Nepean Formation elsewhere immediately south and east of Ottawa, in Ontario, Quebec, and adjacent areas of New York State. Thus, her definition of the Nepean Formation at the type section comprised a succession quite different from the rocks she mapped as Nepean elsewhere in eastern Ontario and western Quebec.

This was in part corrected by Williams and Wolf (1984a, b), who recognized beds older than the Nepean Formation in the Ottawa Embayment that were shown on their geological maps as isolated exposures, the authors presumably unaware of their stratigraphic continuity along the eastern margin of the Frontenac Arch from the vicinity of Perth to the St. Lawrence River and beyond. To these beds, Williams and Wolf (1984a, b) applied the name 'Covey Hill Formation', a term borrowed from earlier studies in Quebec by Clark (1966, 1972). The same authors also used the term 'Potsdam Group', previously defined by Clark (1966, 1972) to embrace the Covey Hill beds and the much younger Nepean Formation where the two are juxtaposed.

In Quebec, the term 'Potsdam Sandstone' was used for many years by Logan (1863) and others to identify the thick sandstone unit lying at the base of the Paleozoic succession. Much later, Clark (1966, 1972) and Globensky (1987) established a very useful classification for their newly defined Potsdam Group, by erecting a two-fold subdivision of units, i.e. Covey Hill and Cairnside in that ascending order. So far as is known, however, their classification was never tied into the New York section immediately across the border, or into Ontario for that matter, and thus no precise correlations were ever established beyond the jurisdictional boundaries of the province of Quebec.

The published and unpublished database relating to the stratigraphic, sedimentological, and petrographic framework of the Potsdam Group is voluminous for all three regions of the present study area, and represents a most valuable resource. In perusing the literature, however, it is evident that most of if not all the maps, papers, and reports published to date are greatly restricted in terms of geographic coverage. This may in many instances be due to constraints placed upon the various authors by state and provincial boundaries that define the political jurisdiction of New York State and the provinces of Quebec and Ontario.

On the basis of the above considerations, the authors have long been cognizant of the need to examine the Potsdam Group in a level of detail sufficient to map and establish an accurate regional correlation of rock units, determine facies changes, and establish a structural framework for the Ottawa Embayment and Quebec Basin. Such information is important also to establish a more reliable correlation with laterally equivalent stratigraphic sequences that occur elsewhere in the eastern and western extremities of the St. Lawrence Platform.

The first author became involved in such a project in recent years, beginning with the chance finding of an angular unconformity within the Potsdam Group in a roadcut on Rideau Ferry Road (Fig. 1), approximately 8 km southeast of Perth, Ontario. Here, the sandstone beds beneath the unconformity were observed to be faulted and tilted at

Figure 1. Potsdam Group in a roadcut on Rideau Ferry Road, Ontario, at station O-16. **a)** Faulted and tilted Covey Hill strata unconformably overlain by flat-lying Nepean Formation. The arrow points to the contact. Photograph by B.V. Sanford. 2008-048a **b)** Angular unconformity (at arrowhead) between the Covey Hill Formation and the Nepean Formation, immediately west of the section in a). Photograph by B.V. Sanford. 2008-048b

a steep angle and overlain by flat-lying sandstone containing a basal quartz-pebble conglomerate. The brittle character of the faulting and the intense level of erosion of the lower unit clearly suggest that the hiatus between the two units must have been substantial. After several visits to the site, one could only conclude that a contact of major historical significance between the Covey Hill and Nepean formations had been found, and exposed to good advantage, at this very accessible locality in eastern Ontario.

Realizing the practical stratigraphic and structural significance of this discovery provided the incentive to look farther afield to determine whether or not similar contact relationships could be found within the Potsdam Group elsewhere around the margins of the Quebec Basin and Ottawa Embayment. Unconformable contacts at the same stratigraphic horizon were indeed found at many locations in Ontario and adjacent areas of New York State during further investigations in both these regions. At the same time, a number of additional findings were added to the geological database pertaining to the classification and petrogenesis of the Potsdam Group generally, chief among which are

- the identification of several rock units within the Potsdam Group, some of which had not been previously recognized. For the most part, these have wide stratigraphic continuity that provides an element of consistency to regional correlation and thus improves the quality of surface and subsurface geological mapping throughout the study area;
- the recognition of lateral and vertical facies changes that point to a variety of depositional and climatic conditions (e.g. deposition initially of eolian, fluvial, and possible lacustrine deposits of terrestrial and locally marine origin followed, after a long hiatus, by a sequence of marine deposits);
- the identification of water-expulsion cones and vertical columnar structures and their very different characteristics in terms of origin and development;
- the gross petrographic comparison of rock units as a possible tool for reconstructing depositional environments and establishing regional correlation; and
- the identification and documentation of structural deformation (folds and faults) and its relationship to regional tectonics possibly triggered by events centred well beyond the margins of the present study area.

ACKNOWLEDGMENTS

The authors wish to express sincere appreciation to Joe Wallach for his assistance in the field and laboratory, particularly for logistical support and locating rock exposures throughout the study area, for the many stimulating discussions related to stratigraphy and structure of the Potsdam Group, and for the loan of selected field photos and the production of photomicrographs used in this bulletin. In addition, much useful information in the form of descriptive logs of deep boreholes completed in the Quebec Lowlands segment of the study area was made available through the courtesy of Pascal Perron of Quebec's Ministère des Ressources naturelles et de la Faune. Many thanks are also extended to Robert Rainbird, Allan Donaldson, Jeffrey Chiarenzelli, and André Desrochers for their very thorough and helpful reviews of an earlier manuscript. Many thanks also to Alan Grant and Philip Moir of the Atlantic Division of the Geological Survey of Canada for facilitating the publication of this work.

REGIONAL GEOLOGICAL SETTING

The St. Lawrence Platform, as originally defined by Poole et al. (1970) and Sanford (1993a), comprises the following three major divisions separated by south-trending basement arch systems: a Western Division embracing the Michigan and Appalachian basins, a Central Division com-

prising the Quebec Basin and its western extension, the Ottawa Embayment, and an Eastern Division containing the Anticosti Basin.

The Central Division, the object of this study (Fig. 2), is in turn divisible into two tectonic features, the Quebec Basin bounded on the west, north, and east by the Oka-Beauharnois, Laurentian, and Saguenay arches respectively, and on the south by the Appalachian Orogen, and the Ottawa Embayment, an appendage of the Quebec Basin bounded on all four sides by Precambrian highs, namely the Frontenac, Laurentian, and Oka-Beauharnois arches to the west, north, and east respectively, and the Adirondack Dome to the south. Results of the present study suggest that most of if not all the arch systems listed above were structurally positive and active to varying degrees during deposition of the Potsdam Group. This was especially so during its initial (Covey Hill and equivalent Ausable formations) depositional phase. The Appalachian Orogen and Quebec Basin as shown in Figure 2 were non-existent as tectonic features in the Neoproterozoic to Early Ordovician, that area being the inner segment of a continental shelf lying marginal to a spreading seafloor at the time of Potsdam deposition (Williams et al., 1995; Knight et al., 1995; Salad Hersi et al., 2002).

The thick wedge of sandstone and conglomerate that constitutes the Potsdam Group was obviously derived directly from Precambrian terranes, partly from basement rocks upon which it lies, and from adjacent areas of the Adirondack Dome and Canadian Shield, the detritus transported into the region by fluvial processes. The two principal Precambrian provenance areas for the Potsdam Group, as shown in Figure 2, are the Eastern Granulite and Central Metasedimentary subprovinces of the Grenville Province (Baer et al., 1977). The Central Granulite terrane is an igneous and metamorphic belt containing a preponderance of granite and granite-like basement rocks, bordering and underlying a large region of the Quebec Basin and the eastern segment of the Ottawa Embayment. The lower beds of the Potsdam Group in this particular region of the platform thus reflect a provenance consistent with those rocks containing an abundance of quartz and feldspar. The basement rocks of the Central Metasedimentary Belt, on the other hand, contain a variety of metamorphosed sedimentary rocks, chiefly quartzite, which provided the bulk of the detritus for the conglomeratic strata in the Potsdam Group throughout the western part of the Ottawa Embayment, especially in eastern Ontario.

The Potsdam Group, being the oldest of the Paleozoic sedimentary sequences in the Central Division of the St. Lawrence Platform, forms the bedrock surface around the margins of the Quebec Basin and Ottawa Embayment, bordering the Precambrian highland areas (*see* Fig. 3 [on CD-ROM]). The beds outcrop at surface at numerous localities along the eastern edge of the Frontenac Arch in Ontario, from the vicinity of Ottawa and Gatineau to the St. Lawrence River and beyond into New York State, from where they extend eastward along the northern margins of the Adirondack Mountains to the vicinity of Lake Champlain. From the northeast extremity of the Adirondacks, the beds form an almost continuous outcrop belt trending north, paralleling the axis of the Oka-Beauharnois Arch. Potsdam strata are locally present at surface along the northern margin of the Ottawa Embayment and Quebec Basin, but for the most part are obscured beneath downfaulted Paleozoic strata bordering the Laurentian Arch. Remnants of Potsdam strata occur sporadically along the axis of the Frontenac Arch north of the St. Lawrence River in eastern Ontario. They also occur as outliers immediately southwest of the arch in the south-central region of the province. South of the St. Lawrence River in New York State, the beds form an almost continuous cover across the southeastern extremity of the Frontenac Arch between the Ottawa Embayment and the Western Division of the St. Lawrence Platform (Appalachian Basin) to the west. From their exposed edges around the margins of the Ottawa Embayment, Potsdam strata dip basinward into subsurface beneath younger Ordovician rocks where they lie on Precambrian basement at an elevation of 1 km below sea level near Russell, Ontario (Sanford, 1993b). In the Quebec Basin, Potsdam strata dip generally southward, also beneath Ordovician rocks, where their contact with the Precambrian basement lies at an elevation in excess of 3 km below sea level near the Appalachian Structural Front (Sanford, 1993b).

The Potsdam Group and succeeding Ordovician strata contained within the Quebec Basin and Ottawa Embayment are readily divisible into six stratigraphic sequences, each bounded by regional unconformities. Sequences I and II and the lower part of sequence III are represented by the Potsdam Group. Sequence I, of assumed Neoproterozoic age, is herein newly defined and named 'Abbey Dawn Formation'; it consists of quartz-cobble conglomerate locally exposed along the eastern and western margins of the Frontenac Arch in eastern Ontario. Sequence II, the Covey Hill and largely equivalent Ausable formations of late Early and Middle Cambrian age, is composed mainly of quartz arenite, feldspathic arenite, and quartzite-cobble and quartz-pebble conglomerate of wide distribution throughout eastern Ontario, western Quebec, and northern New York State. Sequence III comprises the upper Middle, and Upper Cambrian to lower Lower Ordovician Nepean and equivalent Cairnside and Keeseville formations composed of quartz arenite, which give place to carbonate with interbeds of sandstone of the March and equivalent Theresa formations, followed by dolostone of the Oxford and equivalent Beauharnois and Ogdensburg formations, all Early Ordovician, in that respective order of succession.

The carbonate beds of sequence III, and the carbonate, shale, and minor sandstone of sequences IV, V, and VI are beyond the scope of this study. However, the formations included in these sequences are shown in Figures 3 and 4 (on CD-ROM) to provide the reader with a better understanding of the stratigraphic and structural relationships of the Potsdam Group with the remainder of the Ordovician succession throughout the Central Division of the St. Lawrence Platform.

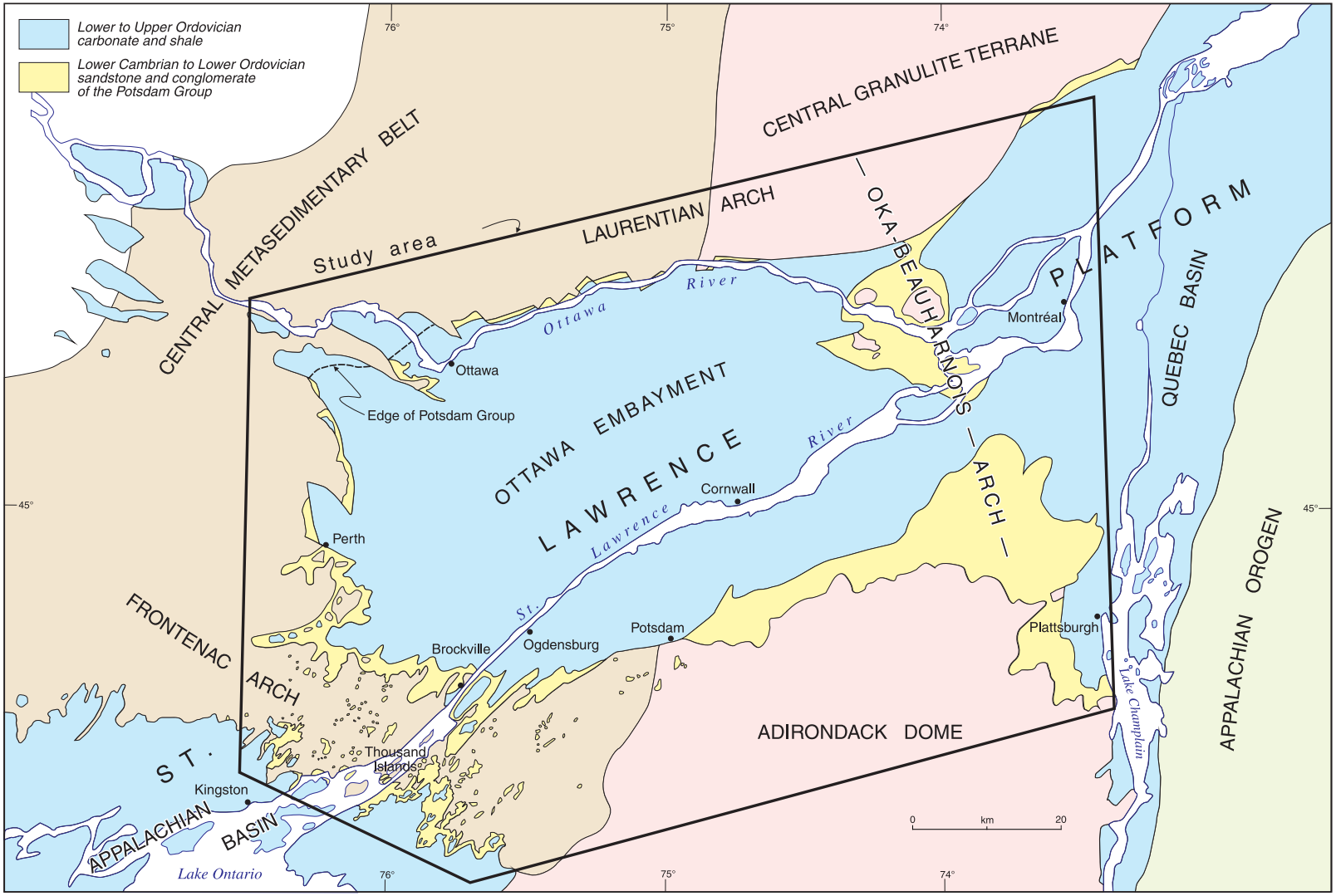


Figure 2. Index map showing the approximate boundaries of the study area and the distribution of immediately adjacent geological provinces and tectonic features.

The above-identified sequences are intersected by numerous faults, not all of which are shown in Figures 3 and 4. Many are most likely very old fracture systems that formed in the Late Proterozoic and were reactivated by the succession of epeirogenic movements associated with plate tectonic events in the Neoproterozoic rifting phase of continental separation (Williams et al., 1995) and during the succeeding Taconian and Acadian orogenies in the early Middle to Late Ordovician and upper Middle and Late Devonian, respectively (Knight et al., 1995).

EARLY INVESTIGATIONS

Geological investigations in eastern North America began on a large scale with the founding of the New York Geological and Natural History Survey in 1836. Its principal objective at the time was to establish a comprehensive stratigraphic framework for the Paleozoic and Mesozoic sequences that would serve as a standard for the state, as well as elsewhere on an international scale. The New York classification was not universally accepted, however, but it did find immediate favour in New York State and in adjacent areas of eastern Canada, where many of the terms are still applicable and in common use today.

'Potsdam Sandstone', a term proposed by Ebenezer Emmons in 1838, was one of the early names erected by the New York Geological and Natural History Survey. Its original definition was confined mainly to a redbed sequence of sandstone at Hannawa Falls in the general vicinity of Potsdam, New York. The redbeds as originally described form merely the basal strata of the Potsdam Group as it is known today. Shortly thereafter, Emmons (1841) recognized a rock stratigraphic sequence higher in the section in the Lake Champlain area of the state, to which he applied the term 'Keeseville Sandstone'.

With the founding of the Geological Survey of Canada in 1842, a program for the systematic mapping of Canada was begun. William Logan, the GSC's founder and first director, leaned very heavily on the stratigraphic classification established earlier by the New York Geological and Natural History Survey. He borrowed the term 'Potsdam Sandstone' for rocks of similar age and lithological composition for inclusion on his early published geological maps of immediately adjacent areas in the southern parts of Ontario and Quebec, and for inclusion in his monumental *Report on the Geology of Canada* (Logan, 1863).

Following the very early investigations described above, a fair interval of time elapsed through the latter half of the nineteenth century and the early twentieth century during which geological investigations within the study area were substantially curtailed, although useful contributions were made from time to time by workers on both sides of the international boundary. This was especially so in New York State, where significant efforts were made by a number of workers to piece together the stratigraphic framework of the Potsdam Sandstone. Some of the more noteworthy of these were the investigations of Cushing (1901, 1908), Van Ingen (1902), Chadwick (1915, 1920), and Alling (1919).

An important step forward in redefining the upper and lower boundaries of the Potsdam Sandstone was made in 1901 by Cushing, who excluded the uppermost interbedded sandstone and dolostone, known as 'Passage Beds', a subunit that was long considered a part of the Potsdam Sandstone by previous workers. In 1908, Cushing proposed the name 'Theresa Formation' for the same beds, and that term subsequently gained wide acceptance in New York State.

In 1902, Van Ingen documented a three-fold subdivision of the Potsdam Sandstone in the Lake Champlain region that included a lower member of unfossiliferous red and brown sandstone with feldspar clasts, a middle member of white and yellow sandstone with *Climactichnites*, and an upper member of interbedded sandstone and dolomite. The lower member is herein assumed to be the equivalent of Emmons' (1838) basal Potsdam Sandstone (redbeds) of the Hannawa Falls area, and possibly including older redbed shale, siltstone, sandstone, and dolostone (Jericho Member of this report) known to be present in the Plattsburgh area. The middle member would have included Emmons' (1841) Keeseville Sandstone, along with a thick and much older succession of grey sandstone and arkosic conglomerate that are now known to lie unconformably below the Keeseville, herein identified as the Chippewa Bay Member of the Ausable Formation. One can readily recognize Van Ingen's upper member in today's terminology as the Theresa Formation.

In 1915, Chadwick established a classification for the Potsdam Sandstone much like that of Emmons (1838, 1841) and Van Ingen (1902), embracing the typical red Potsdam Sandstone and Keeseville Sandstone. Perhaps Chadwick's (1920) most significant contribution was the 'suggestion' of a possible disconformity between the two units, an interpretation that has been confirmed by the present study. However, this disconformity, near the base of the Potsdam Group (between the Hannawa Falls and Chippewa Bay members as defined herein) should not be confused with the major unconformity representing a much longer period of geological time, found by the first author much higher in the section, e.g. between the newly defined Ausable and Keeseville formations and equivalent units in Ontario and Quebec as is described elsewhere in this bulletin (Fig. 5).

Perhaps the most significant achievement since the time of Emmons (1838, 1841) in the construction of a stratigraphic framework for the Potsdam Sandstone was the introduction, by Alling in 1919, of the term 'Ausable Member' for the red and grey feldspathic sandstone and pebble conglomerate exposed along the northern margin of the Adirondack Mountains, although its upper and lower boundaries were not well defined.

During the latter half of the twentieth century, important contributions to the geology of New York State were made by Fisher (1956, 1968, 1977), Fisher et al. (1970), and Rickard

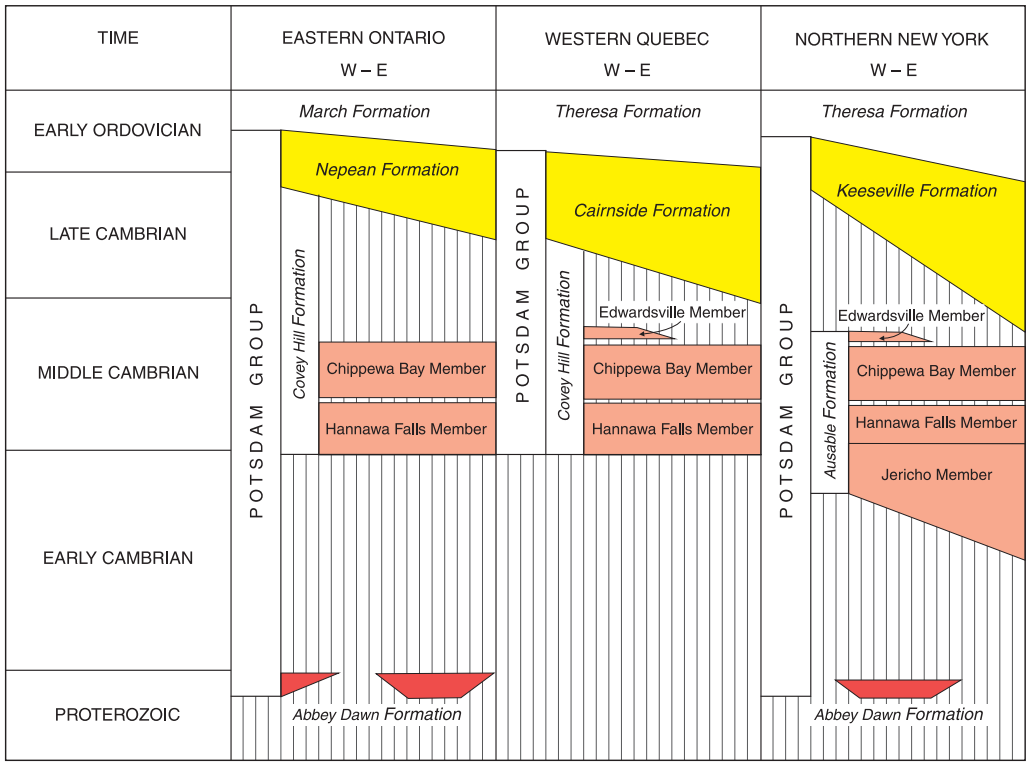


Figure 5. Potsdam Group stratigraphic succession in eastern Ontario, western Quebec, and northern New York State.

(1973). This was particularly so in terms of surface and subsurface mapping and the refining of regional correlations and biostratigraphic dating of Cambrian and Ordovician rock units over a wide region of New York.

Fisher's (1968) stratigraphic studies and mapping of the Plattsburgh–Rouses Point area was a most useful contribution to anyone contemplating field investigations in that region and elsewhere in New York State and on the Canadian side of the international boundary. His division of the Potsdam Formation into the Ausable and Keeseville members in accordance with Alling (1919) and others should have set the stage for applying that or a similar classification on a systematic basis elsewhere in New York State, but for some unknown reason, it did not.

A number of authors have referred to 'upper' and 'lower' Potsdam Formation, on an informal basis, for sections located here and there along the northern margins of the Adirondack Mountains (e.g. Selleck, 1993), although so far as is known, no one has made note of the presence of the unconformity herein defined that occurs within the Potsdam Group at many localities in New York State, although Selleck (1993, p. 221) made reference to "a hiatus of unknown duration" between the upper and lower units of the Potsdam between Ogdensburg and Alexandria Bay. Thus, the most common practice in that region throughout the years, and still today, is to simply apply the term 'Potsdam Formation' to the undivided stratigraphic succession of sandstone and conglomerate that overlies Precambrian basement and is succeeded by interbedded dolostone and sandstone of the Theresa Formation.

Perhaps one of the more important contributions of all to the dating of the Potsdam Group in New York State was recently made by Landing et al. (2007, 2009) with the discovery of diagnostic trilobite faunas and other fossils that have served to establish a precise biostratigraphic framework for the Lower, Middle, and Upper Cambrian succession throughout the northeastern part of the state.

In Canada, major contributions to Paleozoic stratigraphy were made during the early and middle years of the twentieth century by T.H. Clark in Quebec and A.E. Wilson in Ontario. In 1938, Clark began a comprehensive program of geological mapping of the Quebec Lowlands for the Quebec Department of Mines that continued for more than 30 years. The term 'Potsdam Sandstone', as originally applied to the basal sandstone in southern Quebec by William Logan, was continued by Clark (1952); the name was eventually elevated to 'Potsdam Group' (Clark, 1966, 1972) and included two major rock units, the Covey Hill and Chateauguay formations in that stratigraphic order of succession. Clark's Chateauguay Formation was divided into the Cairnside and Ruisseau Norton members, equivalent to the Nepean and March formations in adjacent regions of Ontario. This classification was revised and greatly improved upon by Globensky (1987) who retained the term 'Potsdam Group', but restricted its upper limit to include only the Cairnside, raising the latter to formation status. He dispensed with the term 'Ruisseau Norton Member' and replaced it with the term 'Theresa Formation'. It is of interest to note that this change to the definition of the Potsdam Group was identical to that adopted by Cushing (1901) some 86 years earlier in New York State.

Neither Clark nor Globensky reported a Covey Hill–Cairnside contact anywhere in the field, although Clark provided stratigraphic and structural reasons as to why he believed the two units are bounded by an unconformity.

In Ontario, for a great many years, Wilson (1937, 1946) was the leading authority on matters pertaining to Ordovician stratigraphy in eastern Ontario. Her original definition of the Nepean Formation was long accepted by subsequent workers in the region who failed to recognize the presence of beds (Covey Hill Formation) stratigraphically beneath the Nepean, south and east of the type locality.

During more recent research in the Ottawa–St. Lawrence Lowlands area, Williams and Wolf (1984b, c) of the Ontario Geological Survey noted the local presence of beds of lithological character similar to that of the Covey Hill Formation of western Quebec. On the basis of this finding, Williams et al. (1984a) introduced the term 'Potsdam Group' to embrace the two map units (Covey Hill Formation and a redefined Nepean Formation), a classification presumed by Williams et al. (1984a) to be compatible with that erected earlier in Quebec by Clark (1966, 1972).

Geological mapping of the Paleozoic terrain in the Kingston area of Ontario was carried out by Baker (1916), during which he identified many sandstone outliers directly overlying Precambrian basement that were identified as 'Potsdam series'. Although the sandstone bodies were mapped as a single unit, it is apparent from his excellent descriptions that two very different rock units are present in the region.

Much later, Liberty (1971) examined parts of the same area mapped by Baker, as well as much of the region to the east across the higher structural segments of the Frontenac Arch. He too established the presence of a large number of sandstone outliers, which were identified as a single unit, the Potsdam Formation.

Most of the systematic geological mapping to date in New York State, eastern Ontario, and western Quebec has been carried out by government agencies such as the New York State Geological Survey, the Geological Survey of Canada, the Ontario Geological Survey, and the Quebec Department of Mines (now the Ministère des Ressources naturelles et de la Faune). In addition, many important investigations relating specifically to the Potsdam Sandstone have been carried out by university faculty members, and by graduate and undergraduate students to satisfy partial requirements for doctoral, master's, or bachelor's degrees at the various universities throughout the region. The results of some of these have been published in geological journals, although most were never formally released but can be found for reference purposes in the libraries of the respective universities, and many are contained on microfiche at the library of the GSC in Ottawa.

Worthy of special mention in the above regard are the results of research conducted by Lewis (1963). To the best of the first author's knowledge, this is the only research project to date that is devoted to such a wide regional area. A number of other theses also contain important information relating to the stratigraphy, sedimentology, and petrology of the Potsdam Group for various restricted regions, including Jackson (1955), Sitter (1960), Sahakian (1963), Lewis (1965), Findlay (1968), Forsyth (1968), Roliff (1968), Waterfall (1968), Macey (1970), Selleck (1975), Anderson (2004), and Dobie (2004).

In addition, a large number of special-topic papers, maps, and reports containing a multitude of data relating to the Potsdam Sandstone have been published by government agencies, research institutions, and geological journals, including Logan (1851, 1852), Owen (1852), Goldring (1931), Belyea (1952), Wilson (1956), Sanford and Quillian (1959), Wiesnet (1961), Kirwan (1963), Otvos (1966), Wiesnet and Clark (1966), Greggs and Bond (1972), Bouche et al. (1975), Brand and Rust (1977), Selleck (1975, 1978a, b), Carson (1982), Wolf and Dalrymple (1984), Grier (1993), Sanford (1993a, b), Salad Hersi and Lavoie (2000a, b), Hilowle et al. (2002), Donaldson and Munro (2002), Grady (2002), MacNaughton et al. (2002), and Dix et al. (2004). Getty and Hegadorn (2008, 2009), Hegadorn and Belt (2008), and Larding et al. (2009).

Much useful information pertaining to the Potsdam Group is also to be found in guidebooks that have been prepared for field trips in various parts of the present study area, including Liberty (1967), Clark (1969), Baird (1972), Hofmann (1972), Winder and Sanford (1972), Selleck (1978b, 1993), Williams et al. (1992), Erickson (1993), Erickson and Bjerstedt (1993), Erickson and Fetterman (1993), Donaldson and Chiarenzelli (2004), and Landing et al. (2007).

PRESENT INVESTIGATIONS

Field work for the current project began with reconnaissance surveys of the Potsdam Group along the outcrop belt that borders the Precambrian highlands around the margins of the Ottawa Embayment and in the western part of the Quebec Basin (*see* Fig. 2). The purpose of these initial investigations was to select an area where the Potsdam Group was best exposed, from which to construct a detailed stratigraphic framework that might serve as a standard for the entire study area.

Very early in the investigation it became apparent that the most complete sections were to be found along the northwest margin of the Adirondack Dome in New York State, where the Potsdam beds cross the southeastern extension of the Frontenac Arch. In adjacent Ontario, good sections are exposed along the eastern margin of the Frontenac Arch between Perth and Brockville, and in the Kingston area southwest of the arch, bordering the Appalachian Basin. In New York State, many outcrops can be found along major

highways, such as routes 12, 37, 26, and the many connecting side roads. In Ontario, some of the better sections are in roadcuts on highways 416, 417, 2, 15, and 42, and on secondary roads that connect the many towns and villages throughout this area.

More than 190 sections (Fig. 5, 6 [on CD-ROM]; Appendix A) were examined in the western region of the study area that provided ample information to subdivide the Potsdam Group into two principal stratigraphic units, the Covey Hill and equivalent Ausable formations, and the Nepean and equivalent Keeseville formations. In a few isolated localities on the Ontario side of the St. Lawrence River, a third unit, herein thought to be substantially older than the Covey Hill, was identified and given the name 'Abbey Dawn Formation' (*see* Fig. 5).

An additional finding of substantial importance during the early part of the study was the realization that the Covey Hill and equivalent Ausable formations could be further divided into three subunits, herein named 'Hannawa Falls', 'Chippewa Bay', and 'Edwardsville' members, in that respective stratigraphic order of succession. The type section for each of these is in New York State, all within a few kilometres of the Thousand Islands region of the St. Lawrence River.

The highly generalized composite stratigraphic framework of the Potsdam Group as pieced together in the western part of the study area is shown in Figure 7. Shown in the same diagram is a succession of vertical bars illustrating the approximate stratigraphic range of the key sections examined in the field, many of which are photographically illustrated in this bulletin. In addition to the key sections illustrated in Figure 7, Appendix A provides a complete listing of the outcrop sections examined in the field, their UTM locations, and the principal rock units exposed at any given field station. The numbered field stations are in turn shown on Figure 6. Because of the high density of stratigraphic control encountered in this area of New York State, field mapping was initially detailed at 1:24 000 scale and later reduced to 1:250 000 scale (*see* Fig. 3), compatible with the mapping and compilation carried out elsewhere within the study area.

The Potsdam Group is about 20 times thicker in the eastern sector of the Ottawa Embayment and western part of the Quebec Basin than in the western part of the study area. Outcrops are widely separated and poorly exposed, but nevertheless more than 110 exposures were located. Only a few of these are considered to be important for piecing together the stratigraphic framework of this eastern region (*see* Fig. 8).

In Quebec, sections were examined on Perrot Island and at Saint-Jean Chrysostome, Saint-Pierre (originally known as Cairnside), Havelock, Bridgetown, and Covey Hill where a fair level of stratigraphic control had been reported earlier by Clark (1966) and Globensky (1987). Undoubtedly, the more complete sections observed were located on Perrot Island, Ducharme quarry, and on the hillside that rises steeply in elevation(250 m) above the village of Covey Hill and reaches its summit near the Canada–United States boundary. In the immediately adjacent areas of New York State, stratigraphic data were gleaned primarily from key sections in the Chateaugay River gorge and in roadcuts on routes 87, 22, 9, 11, 190 and the many side roads and stream systems that intersect the region.

In piecing together a stratigraphic framework for the eastern sector of the Ottawa Embayment (*see* Fig. 8), reliance was heavily placed on what had been observed previously during the examination of sections in the Thousand Islands region of New York State and Ontario. Very important in this regard was the recognition of the Covey Hill and equivalent Ausable subunits, i.e. the Hannawa Falls, Chippewa Bay, and Edwardsville members in this eastern region of the study area. Providing an additional level of stratigraphic control in this extreme northeastern sector of the Potsdam outcrop belt is the presence of what may be a thick deltaic marine facies of maroon, brick-red, and pink sandstone and conglomerate, siltstone and shale, with interbeds of dolomitic limestone and dolostone, named 'Jericho Member' by J. L. Wallach Geosciences Inc. and MIR Télédétection Inc. (2004). These beds directly overlie Precambrian basement and are succeeded by the Hannawa Falls Member. Both members are herein included in the Ausable Formation.

Sediment transport studies based mainly on crossbed measurements were carried out at 13 localities in widely separated parts of the study area. The principal purpose of this endeavour was to compare paleoflow directions in the Covey Hill Formation and the much younger Nepean Formation in Ontario, and their equivalents in Quebec and New York State. Measurements were taken at too few localities to establish accurate basin-wide flow patterns, but the retrieval of such information, if done in sufficient detail, would undoubtedly prove useful for any future paleoflow analysis of the Potsdam Group, providing the studies were focused on wind- versus water-transported sediments.

The principal rock units of the Potsdam Group were also sampled at selected localities for the preparation of thin sections that have provided useful petrographic information for reconstructing depositional environments and diagenetic processes. Such information also provides a potential tool for local and regional correlation of rock units.

In addition to field investigations, much time was devoted to the compilation and examination of all published and unpublished data, including readily available borehole subsurface data, diamond-drill cores, well history reports, etc., for the preparation of the geological map (Fig. 3), the Potsdam isopach map (Fig. 6), subsurface stratigraphic sections (Fig. 9 [on CD-ROM]), and cross-sections (Fig. 4).

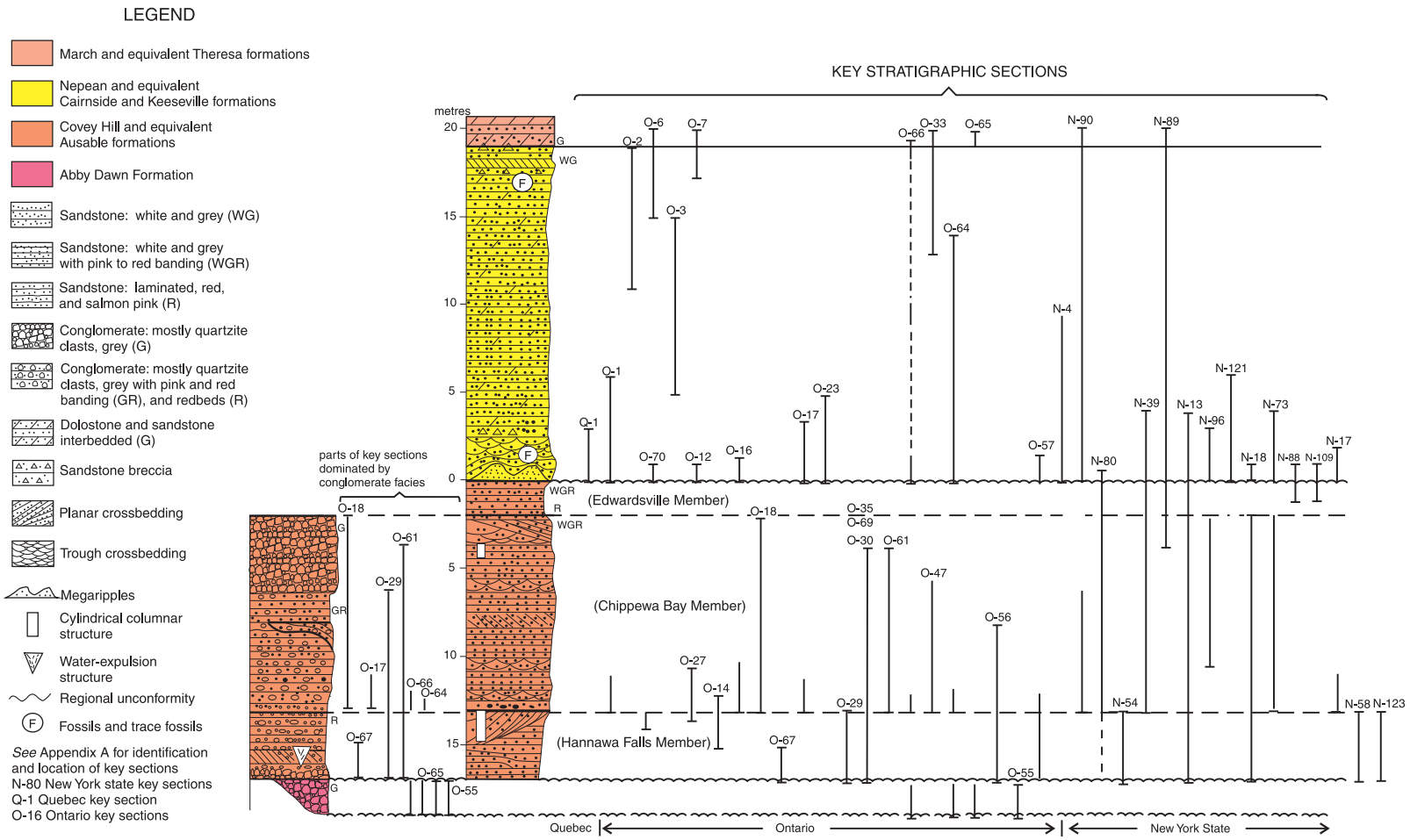


Figure 7. Generalized Potsdam Group succession and vertical stratigraphic range of key sections in the western part of the Ottawa Embayment and adjacent Frontenac Arch.

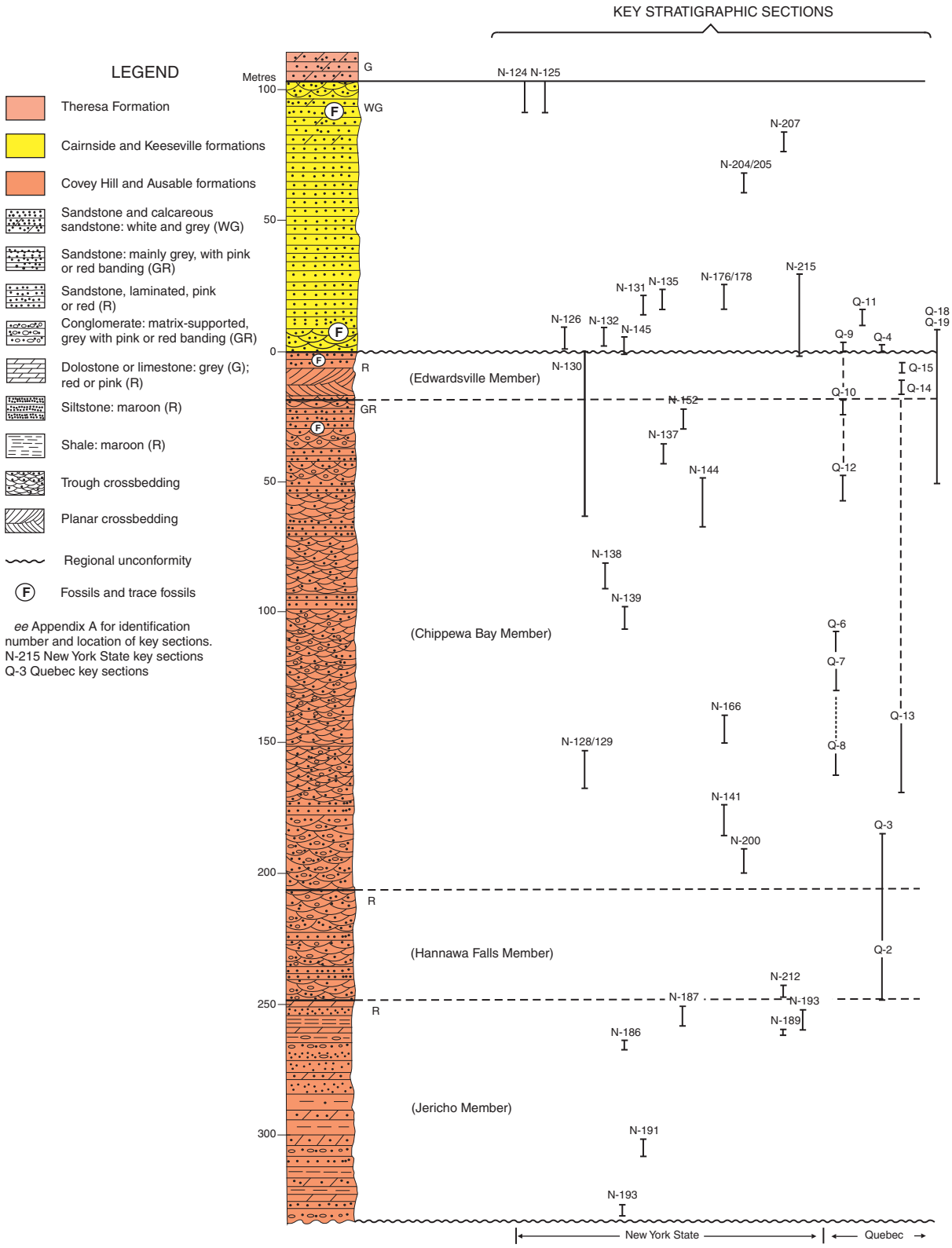


Figure 8. Generalized Potsdam Group stratigraphic succession and vertical stratigraphic range of key sections in the eastern part of the Ottawa Embayment and the adjacent margin of the Quebec Basin.

STRATIGRAPHIC FRAMEWORK

POTSDAM GROUP

Definition and thickness

The Potsdam Group as defined herein comprises a thick succession of sandstone and conglomerate that directly overlie Precambrian basement rocks throughout the Quebec Basin and Ottawa Embayment (*see* Fig. 2, 3). They are succeeded by interbedded dolostone and sandstone of the Theresa Formation in New York State and Quebec, and by the equivalent March Formation in eastern Ontario.

The basal contact of the Potsdam Group with Precambrian basement rocks was found at 10 locations, all within the western part of the study area (*see* Table 1).

In addition to the above, there are many localities in Ontario and New York State where the Potsdam Group–Precambrian basement contact is obscured by only a few centimetres of Quaternary sediments.

The Potsdam contact with the succeeding Theresa Formation in New York State and Quebec, and with the equivalent March Formation in eastern Ontario, is mostly conformable but everywhere abrupt. Some of the best exposures of this contact are on a side road immediately west of Almonte, Ontario, at station O-9, along Highway 416, Ottawa, Ontario, at station O-6, along Hawthorne Road, Ottawa, at station O-7, along Highway 15 near Elgin, Ontario, at station O-24, along Highway 42, near Philipsville, Ontario, at station O-33, and along Route 12, near Blind Bay, New York, where the contact is exposed at two locations in close proximity to one another, at stations N-89 and N-90 (*see* Fig. 6).

For the purpose of this report, the status of the term 'Potsdam Formation', as it is presently known in New York State, is raised to 'Potsdam Group', to be consistent with the definition of its equivalents in adjacent areas of Ontario and Quebec (*see* Fig. 5).

Table 1. Contact between the Potsdam Group and the Precambrian basement in eastern Ontario and northern New York State

Locality *	Station	Beds overlying Precambrian basement
Lac Beauchamp Park, Que.	Q-1	Cairnside
Highway 15, Elgin, Ont.	O-23	Covey Hill
Abbey Dawn Road, Ont.	O-55	Abbey Dawn
Highway 2, Gananoque, Ont.	O-51	Nepean
Highway 401, Butternut Bay, Ont.	O-65	Abbey Dawn
Highway 15, Jones Falls, Ont.	O-27	Covey Hill/Nepean
Lyndhurst, Ont.	O-43	Covey Hill
Route 12, Goose Bay, N.Y.	N-54	Ausable
Route 12, Alexandria Bay, N.Y.	N-13	Ausable
Theresa, N.Y.	N-18	Ausable

*Precise UTM locations are given in Appendix A.

The terms 'Ausable Member' and 'Keeseville Member' of the Potsdam Group, long ago introduced to the literature by Emmons (1841) and Alling (1919), and more recently Fisher (1968) for the Plattsburgh–Rouses Point area of northeastern New York State, are retained but redefined as formations. During the present investigation, the above terminology was applied to similar rock units where these are exposed along the northern margins of the Adirondack Mountains, from Lake Champlain to the Thousand Islands region of New York State (*see* Fig. 2, 3). In the process, the stratigraphic boundaries of the Ausable and Keeseville formations have been standardized to be consistent with the Covey Hill and Cairnside formations in Quebec, and the equivalent Covey Hill and Nepean formations in eastern Ontario (*see* Fig. 5).

To further fulfill the requirements of the present study, the Potsdam Group is enlarged to encompass a relatively thin unit of quartzite-cobble and -boulder conglomerate, herein newly defined and named 'Abbey Dawn Formation'. These beds form a basal unit of the Potsdam Group and thus everywhere unconformably overlie Precambrian crystalline rocks where they were recognized at four isolated localities in eastern Ontario. They are unconformably overlain by rocks with ages ranging from Middle Cambrian to late Middle Ordovician.

The Potsdam Group where mapped at surface and in subsurface (*see* Fig. 3, 4, 6) is a wedge-shaped body of sandstone and conglomerate whose thickness varies from 20 m along the eastern margin of the Frontenac Arch, to about 700 m at the eastern extremity of the Ottawa Embayment. It borders the Oka-Beauharnois Arch to the east, where it exceeds 500 m in thickness, and thins to 360 m or less in the deeper segments of the Quebec Basin (*see* Fig. 6).

The isopach map of the Potsdam Group shown in Figure 6 and those of the Covey Hill and Nepean formations and their equivalents can only be considered approximate in terms of accuracy. This is due mainly to the relatively few deep boreholes that have been completed to date throughout the region. The procedure otherwise taken in the construction of the isopach maps was essentially as follows: 1) obtain rough estimates of the thicknesses of the Potsdam Group and the formations along the basin margins by examining the some 300 sections at the locations shown in Figure 6; 2) obtain thicknesses of the same units from the 14 boreholes that in one place or another penetrated the Potsdam Group in subsurface (*see* Fig. 9); and 3) construct five regional intersecting sections across the basin (Fig. 4) calibrated by the surface and subsurface information obtained during steps 1 and 2. The cross-sections ultimately provide the point-by-point data sets along the lines of sections that were used to construct the isopach diagrams.

The detailed classification of the Potsdam Group in the three principal geographic regions of the study area is shown in Figure 5. The unconformable contact between the Covey Hill and Nepean formations and their equivalents represents a profound break in deposition that was found during the

present study at 21 specific locations in the field. Eight of these are in Ontario, mostly along the eastern margin of the Frontenac Arch, 12, in immediately adjacent areas of New York State and one in Quebec originally reported by Salad Hersi and Lavoie (2000b). Most contacts are abrupt, although structurally concordant, but several are marked by a profound angular unconformity between the two units (*see* Table 2).

At many locations, particularly on the Ontario side of the St. Lawrence River along the axis of and bordering the Frontenac Arch, much of if not all the upper Covey Hill Formation was removed by erosion prior to deposition of the Nepean Formation. This is further confirmation that the hiatus between the two formations was of long duration, as implied in Figure 5

Inconsistency in the use of stratigraphic nomenclature and definition of rock units in New York State, Ontario, and Quebec as applied to the Potsdam Group has long been a major detriment to sorting out the stratigraphic framework from one jurisdiction to another, and without such basic information as stratigraphic control, regional sedimentological and structural studies are of limited value. It is partly for this reason, along with the need for a basin analysis of the Ottawa Embayment in general, that the first author embarked on the present investigation.

Table 2. Unconformable contacts between the Nepean (Keeseville Cairnside) and Covey Hill (Ausable) formations in eastern Ontario and northern New York State and Quebec

Location (Ontario) *	Station
Rideau Ferry Road	O-16**
Highway 15 at Otter Lake	O-17
Highway 15 at Elgin	O-23
Rockland	O-1
5 km southeast of Athens	O-66
Jackson Quarry near Sunbury	O-70**
Sloan Quarry, near Sunbury	O-57
Lyn Valley Conservation Area	O-64
Location (New York)*	**Station**
Near Chippewa Bay	N-88
Near Chippewa Bay	N-91
Route 26, near Chippewa Bay	N-17
Theresa	N-18
Route 12, near Alexandria Bay	N-13
Redwood	N-39**
Route 37, near South Hammond	N-73
Route 12, near Duck Cove	N-80**
Blind Bay Road, off Route 12	N-89
Blind Bay Road, at Pleasant Valley Road.	N-90
Black Lake Road, near Hammond	N-96
Black Lake Road, near Edwardsville	N-109
Location (Quebec)*	station
Ducharme Quarry	Q-18

* precise UTM locations are given in Appendix A.
** denotes an angular unconformity

Lacking the benefit of fossil collections from the lower part of the Potsdam Group in New York State and Ontario, Sanford (2007) considered the Covey Hill and Ausable formations to be much older, i.e. Late Proterozoic to Early Cambrian, a classification essentially identical to that reported by Fisher (1968). The interpretation contained in this bulletin has benefited enormously from the findings that these same beds in the Plattsburgh area of New York State range in age from late Early Cambrian to Middle Cambrian, on the basis of the discovery of diagnostic trilobite faunas in these beds as reported by Landing et al. (2007, 2009).

The following section describes the succession of rock units that constitute the Potsdam Group, which includes the Abbey Dawn Formation, the Covey Hill and equivalent Ausable formations and their contained subunits (Jericho, Hannawa Falls, Chippewa Bay, and Edwardsville members), and the Nepean and equivalent Cairnside and Keeseville formations, in that respective order of succession.

The new terms 'Abbey Dawn Formation', 'Jericho Member', 'Hannawa Falls Member', 'Chippewa Bay Member', and 'Edwardsville Member', along with the redefinition of the Potsdam Group and the Ausable and Keeseville formations, were introduced by Sanford (2007) and are formally applied in this bulletin.

ABBEY DAWN FORMATION

Definition

The term 'Abbey Dawn Formation' is herein proposed for conglomerate that forms a basal unit of the Potsdam Group and is exposed locally on opposite margins of the Frontenac Arch, at four principal localities in eastern Ontario. On the west side of the arch the beds are exposed at a single station (Fig. 10a, b) herein defined as the type locality. At this location, they lie directly on highly deformed Precambrian quartzite of the Grenville Province (Central Metasedimentary Belt), and are unconformably succeeded by late Middle Ordovician limestone.

On the eastern margin of the Frontenac Arch, similar if not identical conglomerate facies outcrop at three locations, either resting on or in close proximity to Precambrian quartzite and granite. Because the Abbey Dawn Formation was deposited at differing levels of elevation on a highly irregular basement surface bordering the Frontenac Arch, it is succeeded regionally by Paleozoic rocks of differing stratigraphic levels that range in age from probable Middle Cambrian (Covey Hill Formation) through Early Ordovician (March Formation) to late Middle Ordovician (Gull River Formation). Because of the general overall appearance of the Abbey Dawn Formation in terms of lithology, weathering characteristics, and sharp angular unconformity with younger formations as referred to above, its strata are assumed to be substantially older than any of the succeeding Potsdam units of the Covey Hill or Nepean formations.

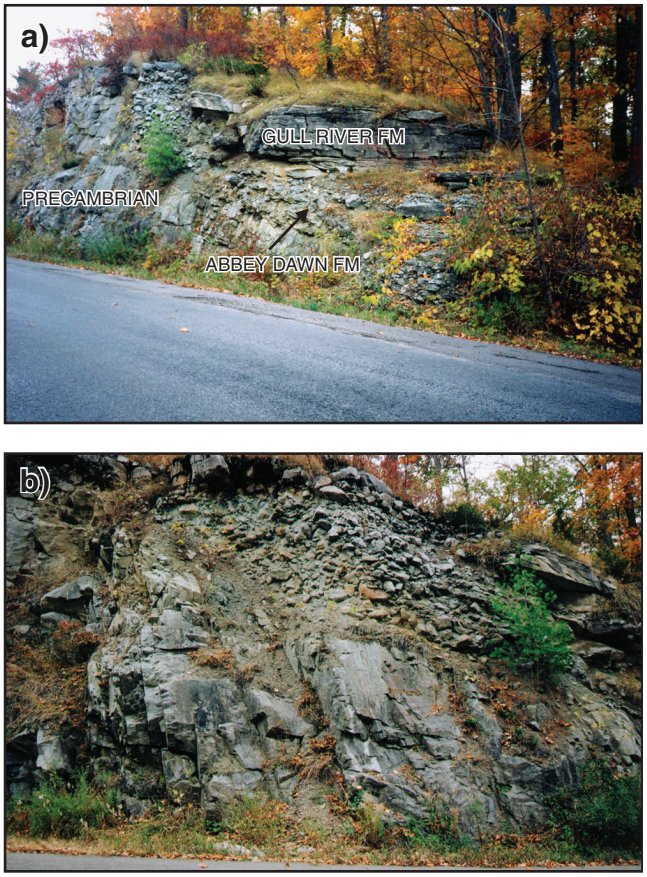


Figure 10. (?) Late Proterozoic Abbey Dawn Formation in a roadcut on Abbey Dawn Road, north of Highway 2, Ontario, at station O-55. **a)** Quartzite-cobble and -boulder conglomerate dipping south off a Precambrian quartzite ridge and unconformably overlapped by late Middle Ordovician Gull River limestone. Photograph courtesy of J.L. Wallach. **b)** Close-up view of quartzite-cobble and -boulder conglomerate shown in a). Photograph courtesy of J.L. Wallach.

The type section of the formation is located approximately 8 km due east of Kingston, Ontario, at station O-55, in a roadcut on Abbey Dawn Road, 0.5 km north of where it intersects Highway 2 (*see* Fig. 3, 6, 10).

Distribution and thickness

The exposed surface distribution of the Abbey Dawn Formation, so far as is known, is limited to the following four isolated geographic localities: the type locality, as defined above (station O-55), where the deposits, up to 2 m thick, blanket the south side of a very steeply sloping Precambrian ridge; the Lyn Valley Conservation Area (station O-64), at the eastern edge of Lyn, 6 km due west of Brockville, Ontario, where 1.8 m of section are exposed (Fig. 11); a roadcut 5 km southeast of Athens, Ontario (station O-66), where 5.3 m of conglomerate are exposed and tilted northward; and a roadcut on both the east and west lanes of Highway 401 (station O-65) near Butternut Bay, Ontario, where the conglomerate is 3.7 m thick (Fig. 12).

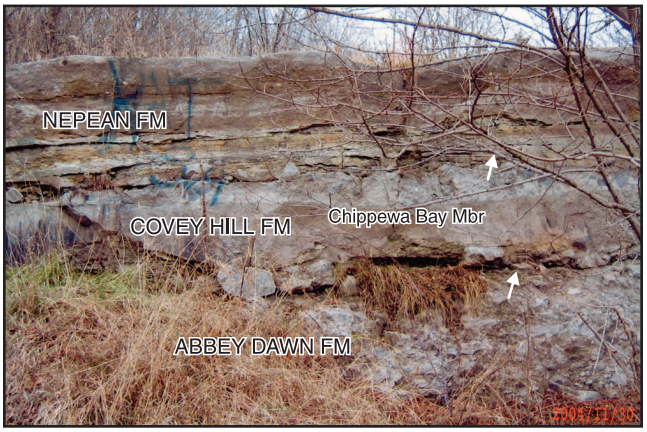


Figure 11. Covey Hill Formation (Chippewa Bay Member) unconformably overlying the Abbey Dawn Formation and unconformably overlain by the Nepean Formation, at the Lyn Valley Conservation Area, Ontario, at station O-64. Contacts are shown by the arrows. Photograph by B.V. Sanford. 2008-049

Undoubtedly, many other occurrences of Abbey Dawn conglomerate are present locally that are obscured beneath either Quaternary deposits or younger Paleozoic rocks in subsurface regions of the Ottawa Embayment and Quebec Basin. Their most likely distribution would be along the margins of the Frontenac, Laurentian, and Oka-Beauharnois arches or Adirondack Dome, where tectonic movements were probably the most intensive during the closing phase of the Proterozoic. In fact, the coarse cobble and boulder conglomerate and breccia that locally occur at the base of the Potsdam Group in the Canton, Hannawa Falls, Allens Falls, and Nicholville areas of New York State, as described and illustrated by Chadwick (1920), Reed (1934), Krynine (1948), and Postel et al. (1959), appear to be similar if not identical to the Abbey Dawn Formation of eastern Ontario, as described herein.

Lithology and stratigraphic relationships

The Abbey Dawn Formation is remarkably similar from place to place with regard to lithological composition, weathering characteristics, and general lack of bedding. For the most part, the formation consists of poorly sorted cobble and boulder conglomerate composed mainly (> 98%) of grey and blue-grey, angular to subrounded quartzite clasts. Few granite clasts were observed at any of the exposures despite the widespread distribution of granite throughout the region and the fact that at two localities (stations O-65 and O-66), the Abbey Dawn directly overlies granite gneiss basement rocks.

Despite the similarities in lithological composition throughout its area of distribution, the Abbey Dawn Formation exhibits substantial differences in clast-size distribution of the framework at any given outcrop, and from one exposure to another. At the type section (station O-55), clasts vary from 2 to 20 cm in diameter. Where the Abbey

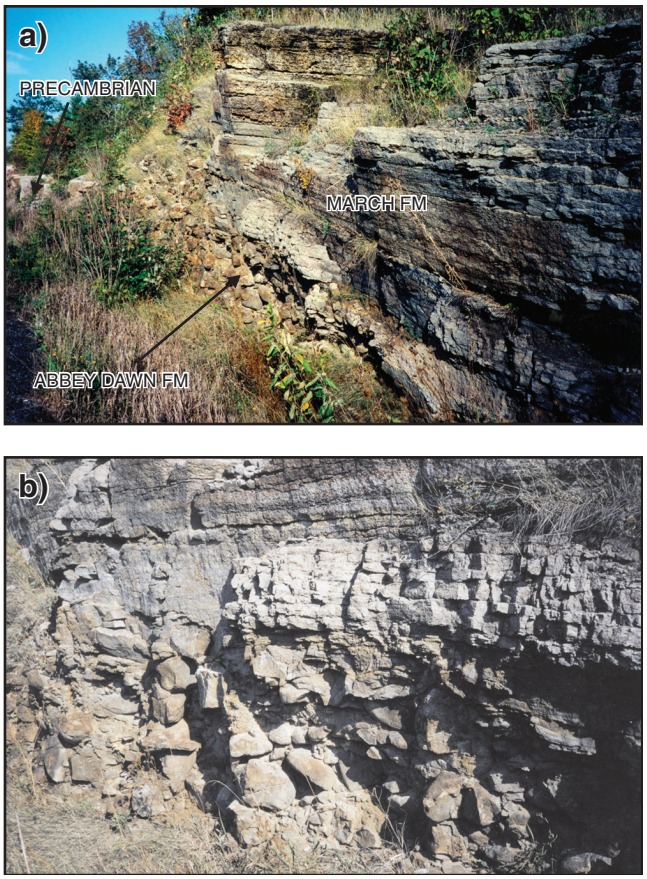


Figure 12. Abbey Dawn Formation in a roadcut on Highway 401, Ontario, at station O-65. **a)** Quartzite-cobble and -boulder conglomerate overlying Precambrian granite gneiss and unconformably succeeded by dolostone and sandstone of the March Formation. Photograph by B.V. Sanford. 2008-050a **b)** Close-up view of cobble and boulder conglomerate. Photograph by B.V. Sanford. 2008-050b

Dawn Formation is exposed on Highway 401 (station O-65), slabs of quartzite up to 60 cm long occur at the base of the formation, their diameter decreasing to 15 cm at the top of the exposure. At the Lyn Valley Conservation Area (station O-64), many of the cobbles and boulders that apparently directly overlie Precambrian quartzite are angular, whereas elsewhere they are substantially more rounded.

The Abbey Dawn Formation everywhere rests on Precambrian rocks of the Central Metasedimentary Belt of the Grenville Province. At the type locality (station O-55), the contact is marked by an angular unconformity (Fig. 10). The basal contact of the formation can also be seen at station O-65 on Highway 401, where strata abruptly and unconformably overlie Precambrian granite gneiss. Elsewhere, near Athens (station O-66) and at the Lyn Valley Conservation Area (station O-64), the basal contact is not exposed, but in both instances the beds undoubtedly unconformably overlie Precambrian granite and quartzite respectively, within a covered interval of a few centimetres.

Rocks stratigraphically succeeding the Abbey Dawn Formation consist of sandstone and minor conglomerate, dolostone, and limestone that range from probable Middle Cambrian to late Middle Ordovician, in all instances likely representing a hiatus of considerable magnitude. At the type section (station O-55), the conglomerate is succeeded by upper Middle Ordovician Gull River limestone, the two being separated by an angular unconformity (*see* Fig. 10). Where the Gull River Formation onlaps and eventually overlaps the truncated edges of the Abbey Dawn Formation, thin stringers of reworked pebble conglomerate derived from the deposits below intertongue with the overlying limestone along the contact interface.

On the eastern margin of the Frontenac Arch 5 km southeast of Athens, Ontario (station O-66), Abbey Dawn conglomerate is unconformably succeeded by a thin veneer of Covey Hill sandstone containing quartzite pebbles and cobbles that were presumably derived, at least in part, from the underlying conglomerate.

At the Lyn Valley Conservation Area (station O-64), the sharply angular conglomerate of the Abbey Dawn Formation is unconformably succeeded by sandstone containing well rounded cobbles and boulders of the Chippewa Bay Member of the Covey Hill Formation (Fig. 11), a sequence largely identical to the stratigraphic succession described above near Athens, Ontario.

On Highway 401 near Butternut Bay (station O-65), the Abbey Dawn conglomerate is overlain by interbedded dolostone and sandstone of the Lower Ordovician March Formation. Here too, the contact is abrupt and unconformable (Fig. 12).

Petrogenesis

During the Neoproterozoic and Early Cambrian, somewhere within the range of 550 to 615 Ma, the eastern margin of the North American continent was undergoing intensive deformation triggered by the rifting and opening of an ancestral Iapetus Ocean (Williams et al., 1995). This process apparently led to widespread rejuvenation of the major arch systems and the corresponding deposition of sandstone and conglomerate throughout the eastern part of the North American continent, including the Central Division (present study area) of the St. Lawrence Platform.

The Frontenac Arch, along with the several other northwest-trending arch systems that separate the basinal areas along the St. Lawrence Platform, would have more than likely been involved in such epeirogeny. The rejuvenation of these features would have been the mechanisms required to produce the conglomerate units of the Abbey Dawn Formation, as well as the enormous volumes of sand and gravel deposits contained in the succeeding Covey Hill and equivalent Ausable formations that accumulated in the Central Division of the St. Lawrence Platform during later intervals of the Early to Middle Cambrian.

The reason for the preponderance of quartzite detritus and the corresponding paucity of granite rock fragments is open to speculation. One possible explanation is that granite clasts were probably abundant during the initial phase of Abbey Dawn deposition and were removed in large part by physical and chemical weathering of the feldspars during transport and diagenesis.

The general lack of sand-sized matrix in the Abbey Dawn conglomerate would suggest that the framework clasts were transported relatively short distances from the provenance areas. The angularity of many of the cobbles, boulders, and blocks would also support such a hypothesis.

The direction of transport can be determined at only two of the four localities. On Abbey Dawn Road, the conglomerate clasts were obviously transported to the south, probably as flow debris, down a steep slope and away from a vertical-dipping, east-trending Precambrian quartzite ridge. On Highway 401 near Butternut Bay, the orientation of the imbrication of some of the larger blocks at the base of the formation indicates an eastward paleocurrent direction of 080º. In both instances, the coarse detritus was probably transported by rapid-flowing fluvial systems that may have been induced by flash flooding during periods of exceptional heavy rainfall.

Age and regional correlation

The precise age of the Abbey Dawn Formation is unknown. One can thus only speculate as to its age by lithological comparison with rocks deposited elsewhere in the St. Lawrence Platform, and by its inferred association with rifting that began along the eastern margin of the North American continent during the final stages of the Proterozoic (Williams et al., 1995).

There would appear to be some similarity in the lithology and depositional processes of the Abbey Dawn Formation as described above, the Double Mer conglomerate of the Lake Melville region of southern Labrador (Stevenson, 1967, 1970; Grant, 1975; Gower, 1986), and the Bateau Formation in the Strait of Belle Isle region of Newfoundland and Labrador (Williams et al., 1995). The late Proterozoic age of the Bateau Formation and overlying volcanic rocks of the Lighthouse Cove Formation is well documented on the basis of their stratigraphic position beneath younger Lower Cambrian sequences. Neoproterozoic mafic dyke swarms and the emplacement of anorogenic plutons in the Lake Melville region and in western Newfoundland Island that range between 550 and 620 Ma and the Long Range dykes provide further documentation as to the likely age of the rifting process (Williams et al., 1995).

In Quebec and Ontario, pluton emplacement and dyke swarms with ages similar to those of the Newfoundland and Labrador occurrences indicate that those regions were under a similar extensional stress regime at the end of the Proterozoic and the beginning of the Paleozoic (Easton, 1992). Thus, the deposition of the Abbey Dawn Formation was quite probably a product of the initial phase of this widespread tectonic event.

COVEY HILL AND EQUIVALENT AUSABLE FORMATIONS

Definition

The Covey Hill Formation in Quebec and Ontario, and its stratigraphic equivalent the Ausable Formation in New York State (herein redefined), comprise red, pink, and grey to locally white sandstone and conglomerate largely of non-marine origin. These deposits accumulated in a variety of dominantly eolian and fluvial environments that, when coupled with alternating arid to humid climatic conditions and intense tectonic movements, produced a complex variety of facies relationships that prevailed throughout a long period of late Early to Middle Cambrian time.

Except for the two known locations in eastern Ontario where the Covey Hill Formation rests on the Abbey Dawn Formation, these same beds and the equivalent Ausable Formation elsewhere rest on metamorphic rocks of the Grenville Province. They are everywhere succeeded by sandstone of the Nepean Formation in Ontario and its counterpart Cairnside and Keeseville formations in adjacent areas of Quebec and New York State respectively.

The preponderance of well exposed stratigraphic sections in the western extremity of the study area is directly attributable to the relatively thin units and erosional conditions that prevailed in the general vicinity of the Frontenac Arch. The relatively thin Covey Hill and succeeding Nepean strata and their equivalents, which once completely blanketed the region, were greatly reduced in areal extent through geological time by erosion along the axis and marginal areas of the arch bordering the Ottawa Embayment to the east, and along the Appalachian Basin to the west. Along the erosional edges of the parent bodies of the Covey Hill Formation and its Ausable equivalent, and the numerous outliers that occur beyond their boundaries throughout this region, the beds have weathered to form low but prominent escarpments in which each of the rock units and their contacts are well exposed on both sides of the international boundary (*see* Fig. 3).

Thus, to establish a standard reference section for these lower strata of the Potsdam Group, the logical place to begin the initial investigation was the Thousand Islands region and immediately adjacent area of New York State, and areas to the north in eastern Ontario, particularly along the eastern margin of the Frontenac Arch. In each of these two regions, criteria were quickly established for separating the Covey Hill and equivalent Ausable formations from the Nepean and equivalent Keeseville formations. In many places this was accomplished by simply searching out the unconformity in

the field between the two principal stratigraphic units, all 21 known sections of which are identified in Table 2 and their localities shown in Figure 6.

The term 'Covey Hill Formation' as herein adopted for Quebec and eastern Ontario is precisely as defined by Clark (1966, 1972) and Globensky (1987). Some uncertainty exists, however, as to the definition of the Ausable Formation in the adjacent area of New York State as originally introduced to the literature by Alling (1919) and later adopted by Fisher (1968). For the purpose of this bulletin, the upper boundary of both the Covey Hill and equivalent Ausable formations is the unconformity discussed above. The base of the two formations is their contact with Precambrian basement, as illustrated in Figure 5, except for the two locations (stations O-64 and O-66) described earlier where the Covey Hill Formation directly overlies the Abbey Dawn Formation.

The three-fold subdivision of the Covey Hill (Ausable) succession in the western part of the study area (*see* Fig. 5, 7), which can be readily identified in the field, provides a greater level of stratigraphic control for purposes of regional correlation and the dating of geological events generally, than would have been possible by the mere identification of the upper and lower boundaries of the formation. The units identified, and herein named in ascending stratigraphic order as the Hannawa Falls, Chippewa Bay, and Edwardsville members, have remarkable regional stratigraphic continuity, not only in the western sector of the study area, but also to the east, where they have been identified in exposures along the northern margins of the Adirondack Mountains and into the adjoining areas of Quebec along the axis of the Oka-Beauharnois Arch (*see* Fig. 3).

In addition to the widespread recognition of the above members in the field around the margins of the Ottawa Embayment and Quebec Basin, identical units can be readily identified in subsurface, as shown in the borehole sections and cross-sections (*see* Fig. 4, 9), particularly the Hannawa Falls and Chippewa Bay members that have the more consistent distribution throughout the study area.

During field investigations, it became evident that a substantial long period of geological time had elapsed between deposition of the Covey Hill (Ausable) and the succeeding Nepean and equivalent Keeseville and Cairnside formations. Thus in many localities, the upper beds of the Covey Hill Formation have been removed by erosion and in some instances, the formation has been completely eroded. This is particularly so along the axis and western margins of the Frontenac Arch in Ontario, where only remnants of the Covey Hill are preserved.

In addition to the erosional removal of the upper beds of the Covey Hill (e.g. Edwardsville and Chippewa Bay members), the lower beds (Hannawa Falls Member) in some areas are absent due to nondeposition. This can be seen in localities underlain by the Precambrian Central Metasedimentary Belt, where the tightly folded rocks form ridges and valleys upon which the Covey Hill (Ausable) sandstone and/or conglomerate were originally deposited. In those areas where the Hannawa Falls Member is missing, its absence is assumed to be due to the presence of significant topographic relief on some of the Precambrian ridges or possible block-faulted structures that were likely emergent during deposition of these lower beds.

The stratigraphic succession of the Covey Hill (Ausable) Formation as established along the western margin of the Ottawa Embayment is duplicated to a large extent along the northeastern margins of the Adirondack Mountains and in adjacent areas of Quebec, although the rock units are many orders of magnitude thicker in the latter regions. Poor exposures and a Quaternary cover have hampered the stratigraphic analysis and determination of unit thicknesses in this part of the study area (*see* Fig. 8).

In addition to the stratigraphic and sedimentological information derived from the recognition of the Hannawa Falls, Chippewa Bay, and Edwardsville members in the eastern region of the study area, important information is obtained from the presence of a highly varied pre-Hannawa Falls redbed sequence of marine origin in the Jericho area of northeastern New York State (*see* Fig. 3). These beds lie directly on Precambrian rocks and are overlain by red and pink beds of the Hannawa Falls Member of the Ausable Formation. Despite its abrupt contact relationship with the overlying Hannawa Falls beds of the Ausable Formation in New York State, and the Covey Hill Formation where identified at the base of the Quonto-International No. 1 St. Vincent de Paul borehole in Quebec (*see* Fig. 9), the Jericho is likely conformable with the overlying Hannawa Falls Member, and is thus included herein as the lower member of those two equivalent formations in this western part of the Quebec Basin.

Distribution and thickness

The Covey Hill (Ausable) Formation is broadly distributed throughout the Ottawa Embayment and Quebec Basin (*see* Fig. 3, 13). In the Thousand Islands and nearby areas of New York State, the Ausable Formation blankets a substantial part of the southern extension of the Frontenac Arch where it has a maximum thickness of about 10 m. From the axis of the arch the beds dip into the subsurface beneath the Keeseville and Theresa formations toward the northeast and southwest into the Ottawa Embayment and Appalachian Basin respectively.

North of the St. Lawrence River in Ontario, Covey Hill strata are largely absent along the axis of the Frontenac Arch, presumably having been removed by erosion prior to deposition of the Nepean Formation. The surface distribution of the Covey Hill Formation along the eastern margin of the arch, however, is fairly consistent in a narrow belt extending from Lyn northwestward to Perth (*see* Fig. 3), from where it dips eastward beneath younger Upper Cambrian and Lower Ordovician rocks into the Ottawa Embayment. Because of

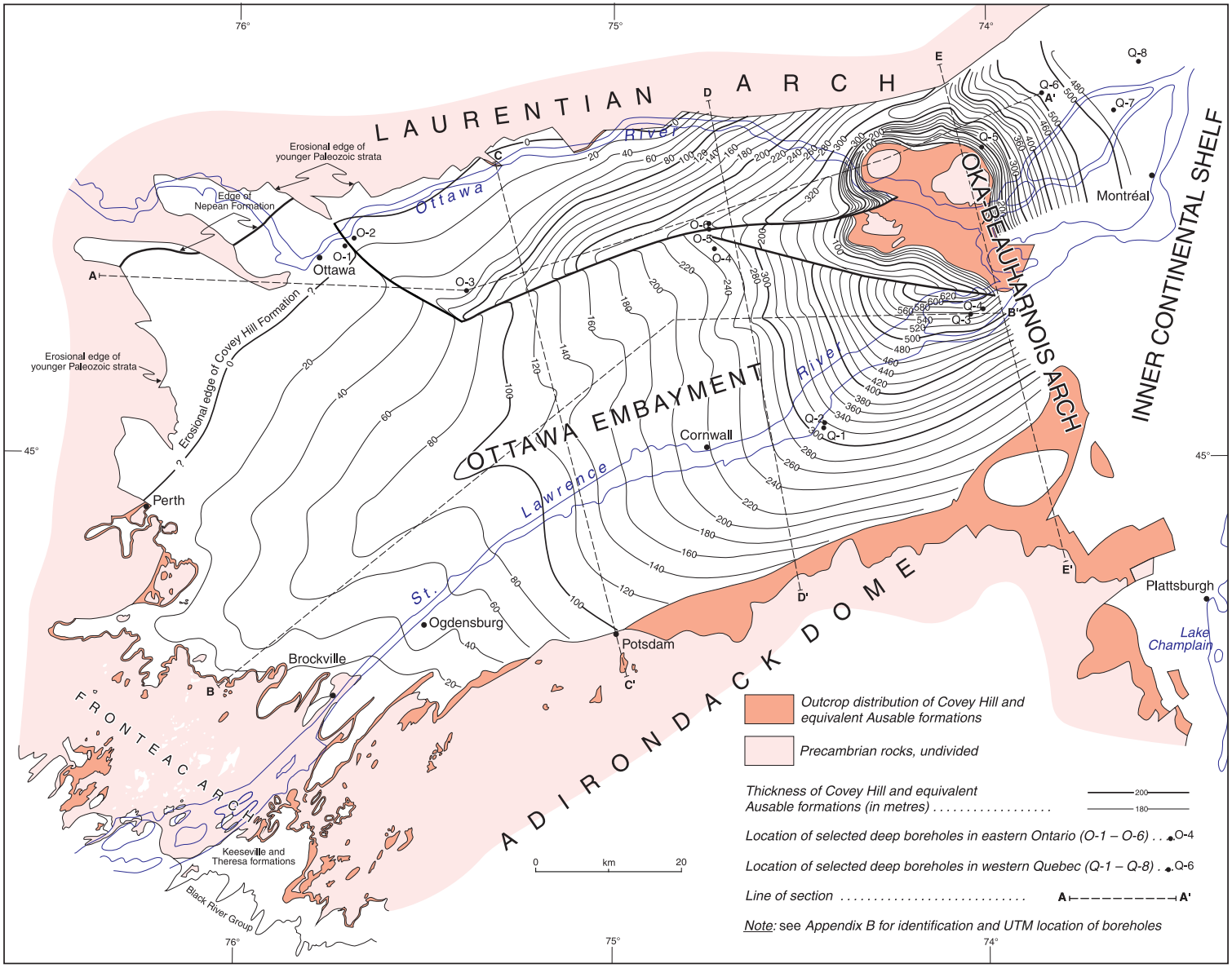


Figure 13. Isopach map showing the distribution and thickness of the Covey Hill and equivalent Ausable formations in eastern Ontario, western Quebec, and northern New York State.

the highly irregular configuration of the Precambrian basement along the eastern margin of the arch, the Covey Hill Formation varies substantially in thickness from a few centimetres to a maximum of about 12 m. Between Perth and an arbitrary point between Gatineau, Quebec, and Rockland, Ontario, the northeast-trending eroded edge of the Covey Hill in subsurface is stratigraphically overlapped to the northwest by the Nepean Formation (*see* Fig. 3, 13).

On the western margin of the Frontenac Arch in central Ontario, about 6 m of Covey Hill strata are preserved in a large outlier and in a few small erosional remnants near Sunbury, approximately 16 km northeast of Kingston. Covey Hill beds are also preserved as a small remnant on the eastern outskirts of Gananoque, in what is perceived as a downfaulted block. These beds lying high on the western flank of the Frontenac Arch, and the larger outliers near Sunbury and at Ellisville, are important occurrences in terms of reconstructing the original distribution of these strata elsewhere to the west along the St. Lawrence Platform.

For more than 150 km along the northern margin of the Ottawa Embayment, extending from the vicinity of Masson, Quebec, to Montréal and beyond, the Covey Hill Formation is largely obscured beneath downfaulted Paleozoic strata bordering the Laurentian Arch, with two possible exceptions, one at Rockland, Ontario (station O-1), where 2 m of Covey Hill strata overlain by the Nepean Formation were tentatively identified (*see* Fig. 3), and another in the Papineauville area, Quebec, where Covey Hill beds are merely assumed to be present in a tilted, block-faulted structure.

Strata of the Ausable Formation extend from the Thousand Islands and adjacent area of New York State along the northern margins of the Adirondack Mountains, either as outliers or in a continuous outcrop belt to near Lake Champlain. There is no way of accurately determining the thickness of the strata along this belt except for information contained in the intersecting cross-sections (*see* Fig. 4) across the Ottawa Embayment transposed onto the Covey Hill isopach map (*see* Fig. 13). This information implies a progressive thickening from 10 m in the Thousand Islands to 250 m or more approaching the Oka-Beauharnois Arch. A similar thickness in the adjacent area of Covey Hill, Quebec, can be assumed from the north-facing block-faulted structure that has been uplifted along the Stockwell Fault, just north of the international boundary, in which Covey Hill strata are exposed sporadically through at least 200 m of vertical relief (*see* Fig. 4, cross section E-E'). The presence of Keeseville or equivalent Cairnside strata at the summit of this structure at an altitude of 200 m above its elevation to the north of the fault, would clearly indicate the time of faulting to be post-Keeseville.

For a short distance north of the Stockwell Fault, Covey Hill strata follow the axis of the Oka-Beauharnois Arch, from where they disappear from surface into the Valleyfield Trough (new name) to lie beneath younger rocks of the Cairnside and succeeding Theresa formations. North of the trough, they again rise to surface in the vicinity of Perrot Island from where they form a halo around the Precambrian inliers of the Oka Hills, Rigaud Mountain, and Saint-André-Est hills, a highland area representing the more prominent northernmost extension of the Oka-Beauharnois Arch. Where the Covey Hill strata are best exposed in this region of the arch (western end of Perrot Island at stations Q-2 and Q-3), the formation by direct measurement is at least 30.5 m thick, with neither its base nor its top exposed.

In the subsurface of the Ottawa Embayment, the Covey Hill and equivalent Ausable formations form a wedge of sandstone and conglomerate varying in thickness from less than 10 m along the Frontenac Arch to 620 m in the deepest part of the Valleyfield Trough, along the northern margin of a downfaulted block bounded by the Sainte-Justine Fault (*see* Fig. 13). Its thickness in the latter region is based on data from the St. Lawrence River No.1 borehole (*see* Fig. 9), which did not reach the base of the Covey Hill Formation, extrapolated into a probable deeper segment of the Ottawa Embayment along the downdropped side of the fault.

Along the northeast margin of the Oka-Beauharnois Arch, the Covey Hill Formation is probably over 500 m thick on the basis of an extrapolation from the Mallet Test No.1 borehole, from where the beds thin eastward toward the deeper part of the Quebec Basin, as noted by their thickness (360 m) in the Quonto-International No. 1 Mascouche borehole (*see* Fig. 9).

Some anomalous thickening of the Covey Hill Formation evidently occurred within a large downfaulted block that occupies the northern part of the Ottawa Embayment (*see* Fig. 13). The beds contained within the structure dip to the south from their northern erosional edge and thicken to over 300 m within the boundaries of the Gloucester and Russell-Rigaud fault systems. These strata appear to have a very different structural style from those located to the west and south. One must assume therefore that this very large graben initially formed very early in the depositional history of the Potsdam Group, an event in all likelihood triggered by late Precambrian to early Early Cambrian rifting.

Lithology and stratigraphic relationships

The Jericho, Hannawa Falls, Chippewa Bay, and Edwardsville members are very important elements in the chronological reconstruction of geological events that took place during deposition of the Covey Hill (Ausable) Formation. The lower two units — Jericho and Hannawa Falls members — are the most readily identifiable, both in the field and in subsurface. Both are redbed sequences, although lithologically distinct because of significant differences inherent to their environments of deposition.

The third successive unit from the base — the Chippewa Bay Member — is typically the youngest unit of the Covey Hill (Ausable) Formation preserved in the field and in subsurface due to the widespread erosion of much of the overlying

Edwardsville Member. The Chippewa Bay Member is more consistently distributed throughout the study area due to its greater thickness and resistance to weathering. However, where the Chippewa Bay Member immediately underlies the Nepean or its equivalent Keeseville and Cairnside formations, it may be difficult to distinguish because of similarities of colour and lithological composition. This similarity is probably why the Potsdam Group of New York State and the Nepean Formation of Ontario have been mapped and described as a single stratigraphic unit for so many years. However, once the subtle differences between the Chippewa Bay Member and the Nepean and equivalent Keeseville formations and the fact that the two are everywhere bounded by an unconformity are recognized, mapping the respective units for the most part can become routine. In the few localities of New York State where the Edwardsville Member is preserved (e.g. station N-80), its unconformable boundary with the overlying Keeseville Formation, where exposed, is readily recognizable in the field.

Jericho Member

The Jericho Member of the Ausable Formation as described herein is a redbed sequence that appears to be confined to the Quebec Basin, its western depositional edge presumably bounded by the Oka-Beauharnois Arch (*see* Fig. 2). Exposures are apparently confined to a single locality in the Jericho area of New York State (*see* Fig. 3), approximately 20 km northwest of Plattsburgh, at stations N-186, N-187, N-188, N-189, N-191, N-193, N-194, and N-219 (*see* Appendix B for precise locations). Because of the very thin intervals of strata exposed (a few centimetres to 2 m) at any given station, it is difficult to piece together the precise stratigraphic order of the individual stratal units that constitute the member. As far as is possible to determine, the succession begins with a layer of deep red, shaly, sandy, and feldspathic dolostone and minor conglomerate, best exposed at station N-193, variously followed by layers of pink, sandy dolostone (station N-194) and greyish-pink dolomitic limestone (station N-191), succeeded by maroon shale and siltstone and interbedded carbonate (station N-187; Fig. 14a, b). The precise thickness of the Jericho Member at the type locality is also difficult to determine in the field, but its thickness of approximately 84 m in subsurface has been firmly established by borehole drilling as illustrated in Landing et al. (2007, Fig. 11, p. 43).

In the Quonto-International No. 1 St. Vincent de Paul borehole completed in an adjacent area of Quebec, 34 m of Jericho strata were penetrated at the base of the Covey Hill Formation, as interpreted from core descriptions. The lower half of the member consists of dark red and brown conglomerate and sandstone and the upper half, of maroon shale and siltstone (*see* Fig. 9). Elongated (soft sediment (?)) clasts of maroon shale typical of the upper strata of the Jericho Member were observed near the base of the Hannawa Falls Member of the Covey Hill Formation at station Q-2, on Perrot Island, indicating that the Jericho Member is likely present in subsurface not too far from that general area of the Quebec Basin.

Brief mention of the redbeds exposed near Jericho was made by Fisher (1968), who suggested their correlation with redbeds exposed approximately 100 km westward at Nicholville (Postel et al., 1959) and at Allens Falls (Krynine, 1948), near Potsdam. To the east of the Oka-Beauharnois Arch, shale and siltstone strata of the Jericho Member, which are interbedded with marine carbonate, are of possible deltaic marine origin, and here are considered to be older than the beds exposed at Nicholville and Allens Falls, the latter of which are more likely equivalent to the Hannawa Falls Member of the Ausable Formation (*see* Fig. 5).

In a recent study of the above-described beds near Plattsburgh, New York, Landing et al. (2007, 2009) proposed the name "Altona Formation", presumably unaware of the term "Jericho Member" previously proposed for the same strata by J.L. Wallach Geosciences Inc. and Mir Tédétection Inc. (2004).

Figure 14. Basal unit of the Ausable Formation (Jericho Member) in the Lake Champlain region, New York State. **a)** Maroon shale and siltstone in a stream cut at station N-187. Photograph by B.V. Sanford. 2008-051 **b**) Thin unit of pink and red sandy dolostone at station N-191, typical of the marine carbonate interbedded with shale/siltstone facies of the Jericho Member. Photograph courtesy of J.L. Wallach.

In contrast to the Jericho Member, the succeeding units of the Ausable and equivalent Covey Hill formations, i.e. the Hannawa Falls, Chippewa Bay, and Edwardsville members of interpreted nonmarine origin, are widely distributed throughout the Quebec Basin and Ottawa Embayment. All three units are exposed locally within the study area, but it is extremely rare to find complete or partial sections bounded at base and top by older and younger rocks, respectively. Exceptions to this occur at Theresa (station N-18) and in an outlier a short distance east of Alexandria Bay (station N-13); both stations are in the general vicinity of the Thousand Islands in New York State and are herein identified as reference sections for the Ausable Formation (Fig. 15a, b). At both locations, the Ausable Formation rests unconformably on Precambrian rocks and is overlain unconformably by the Keeseville Formation. Between the two unconformities at station N-13 are the intervening units of the Hannawa Falls, Chippewa Bay, and Edwardsville members, all very well exposed. At station N-18, only the Hannawa Falls and Chippewa Bay members appear to be represented. Station N-13 near Alexandria Bay is a roadcut on Route 12; it is the more accessible of the two reference sections and the one most recommended for close-up examination of the lithology and contact relationships of the succession of rock units.

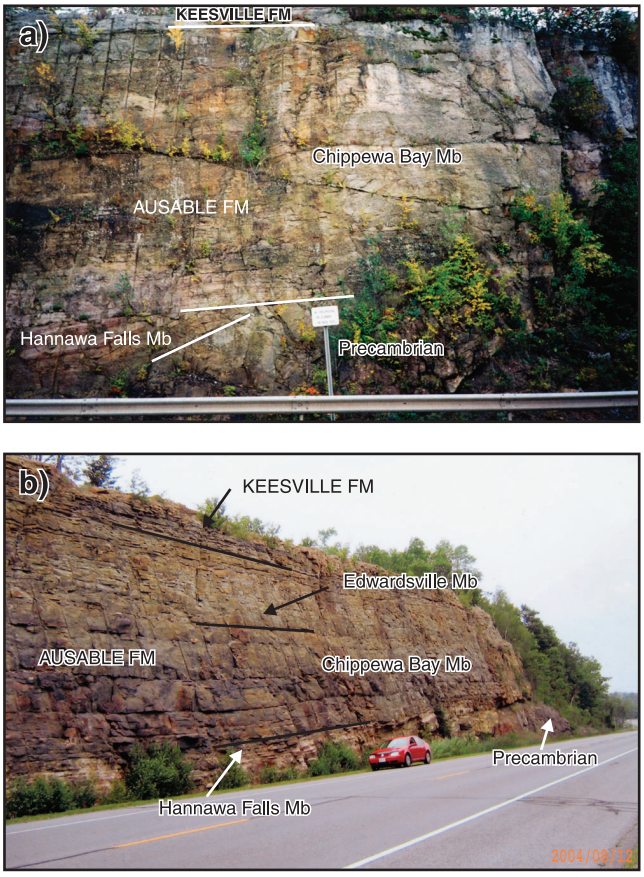


Figure 15. Ausable Formation reference sections in the Thousand Islands region of New York State. In both sections, the formation rests on Precambrian metamorphic rocks and is unconformably succeeded by the Keeseville Formation. **a)** Cliff section in Theresa at station N-18. Note the sharp bounding surface (white line) between the Ausable and Keeseville formations and in members within the Ausable Formation. Photograph by B.V. Sanford. 2008-052 **b)** Roadcut on Route 12 near Alexandria Bay at station N-13 where all three members of the Ausable Formation outcrop. Photograph by B.V. Sanford. 2008-053

Hannawa Falls Member

The type locality for the Hannawa Falls Member is station N-123, close to Potsdam, New York, the original type area for the Potsdam Sandstone named by Emmons (1838). Here, the Hannawa Falls Member of the Ausable Formation, as herein proposed, is a relatively thin veneer (6.4 m thick) of crossbedded, fine- to medium-grained red quartz arenite preserved as a tiny outlier with an areal extent of about 7 km². The inclination of the cross-stratification up to 30º to the southwest suggests that transport from the northeast was more than likely by eolian processes (*see* Fig. 16).

Well sorted, thinly laminated, fine-grained quartz arenite of the Hannawa Falls Member is preserved as outliers at numerous localities in the surrounding Potsdam and Canton areas, and to the southwest along the margin of the Adirondack Mountains to the vicinity of Theresa; most of these are also interpreted to be of eolian origin. At the type section and in adjacent localities in New York State (e.g. stations N-56 and N-58), the steeply dipping strata composed of grainfall and grainflow deposits (e.g. Hunter, 1977) indicate deposition on the leeside of eolian dunes. Elsewhere to the southwest, the Hannawa Falls Member is characterized by thinly laminated, relatively flat-lying quartz arenite with climbing wind-ripple cross-stratification; such deposits are present at the base of the two reference sections at Theresa and near Alexandria Bay, stations N-18 and N-13 respectively (Fig. 15a, b), and in roadcuts along Route 12 at stations N-53, N-54 (Fig. 17), and N-55. Hannawa Falls strata are also present beneath the Chippewa Bay Member at station N-80, but are largely obscured by Quaternary sediments.

Throughout the above-mentioned areas, the Hannawa Falls Member varies from 2 m to 6 m or more in thickness; in some areas it is absent due either to nondeposition over highs on the Precambrian basement surface or to removal by erosion following deposition. In some areas, all members of the Ausable Formation are absent, such as on Wellesley Island and south of the islands along the St. Lawrence River, where the formation is stratigraphically overlapped by the Keeseville Formation that lies directly on Precambrian rocks (*see* Fig. 3).

Two of the more noteworthy characteristics of the Hannawa Falls Member on the New York State side of the St. Lawrence River are the fine-grained character of the quartz arenite and the general lack of gravel detritus, even at the base of the unit such as at station N-54 where the unit lies directly on Precambrian rocks (Fig. 17).

Figure 16. Ausable Formation 6.4 m thick consisting of large-scale cross-stratified eolian deposits at the type locality of the Hannawa Falls Member in New York State, station N-123. This is also the type locality for the Potsdam Sandstone, where it was originally identified and named by Emmons in 1838 (strata are quartz arenite composed of well sorted, well rounded quartz grains). Photograph courtesy of J.L. Wallach.

Figure 17. Ausable Formation (Hannawa Falls Member) resting on Precambrian rocks and consisting of crosslaminated, fine-grained quartz arenite interpreted to be laterally continuous climbing wind-ripple cross-stratification (roadcut on Route 12 near Goose Bay, New York, at station N-54). Photograph by B.V. Sanford. 2008-054

On the Ontario side of the St. Lawrence River the Hannawa Falls Member and indeed all Covey Hill strata are largely absent over the higher structural features of the Frontenac Arch. Thus, in this region, the surface distribution of the formation is confined mainly to a narrow belt along the eastern margin of the arch extending from the vicinity of Brockville to Perth. However, the Hannawa Falls Member was nowhere observed in the field between Brockville and Delta. Whether the beds are absent over this entire distance (35 km) or simply obscured beneath Quaternary sediments is unknown. The first occurrence of the Hannawa Falls Member along this segment of the arch is in a roadcut on Highway 42, at the northern outskirts of Delta, at station O-35. Here, 4.5 m of fine-grained, dark reddish-brown quartz arenite occur,

Figure 18. Covey Hill Formation (Hannawa Falls Member) consisting of dark red, gently folded quartz arenite 4.5 m thick in a roadcut on Highway 42, near the northern town limit of Delta, Ontario, at station O-35. Note the Chippewa Bay Member in the background overlying the Hannawa Falls Member with angular unconformity (contact at black line). Photograph by B.V. Sanford. 2008-055

with their base not exposed (Fig. 18). An angular unconformity separates the gently folded beds from the succeeding Chippewa Bay Member of the Covey Hill Formation.

The next occurrence of Hannawa Falls strata along the highly irregular outcrop belt is at station O-30, 4.5 km southeast of Elgin. The beds exposed here are up to 5 m thick and consist of pink, thinly laminated quartz arenite (Fig. 19a); they lie in a block-faulted structure along a prominent northeast-trending escarpment of Covey Hill sandstone. The lower contact of the Hannawa Falls Member with Precambrian rocks is not exposed, but can be placed within an interval of a few centimetres. Its upper boundary with the Chippewa Bay Member is abrupt and may thus represent a disconformity.

Another excellent section of Covey Hill Formation occurs 11 km south-southeast of station O-30 in the walls of the Ellisville Quarry at an isolated outlier where it is readily divisible into Hannawa Falls and Chippewa Bay members (*see* Fig. 6, 19b, c). The presence of 27 m of Covey Hill Formation at this site (station O-69) is most unusual because of the site's location high on the Frontenac Arch where the Covey Hill Formation is mostly absent as a result of erosion, and outliers are composed of Nepean sandstone for the most part directly overlying Precambrian basement rocks.

The Hannawa Falls Member at this station is 12 m thick and is readily divisible into two tectonostratigraphic units, a lower unit of probable fluvial origin composed of a mixture of brick-red shale, pink sandstone, and quartz-pebble conglomerate containing an abundance of cobble- and boulder-sized marble clasts, all of which are intensely fractured and tightly folded (Fig. 19c), and a dominant upper unit composed of highly fractured, pink, fine- to medium-grained quartz arenite containing a basal quartz-cobble conglomerate that overlies the lower unit with angular discordance. The upper beds of the Hannawa Falls Member are overlain

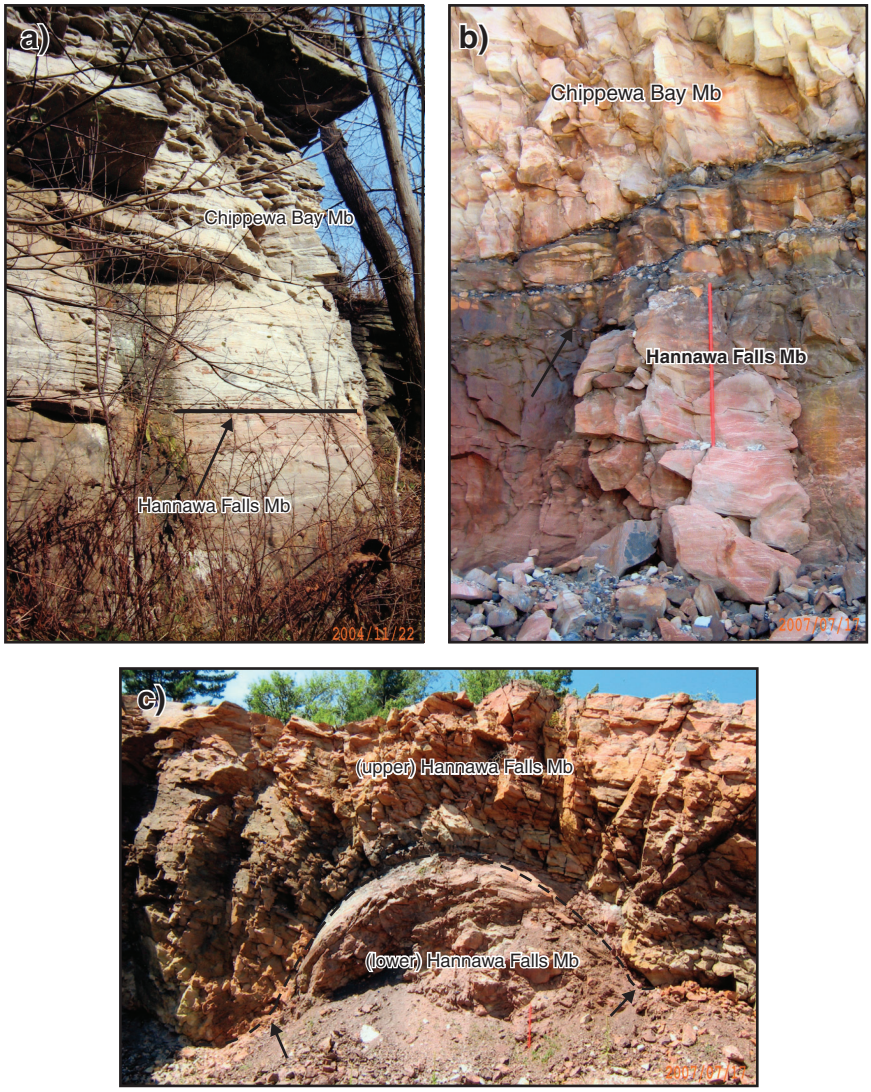


Figure 19. Well developed Covey Hill sections preserved in what appear to be downfaulted structures. **a)** Pink quartz arenite of the Hannawa Falls Member is overlain with possible disconformity by the Chippewa Bay Member (contact at black line) 4.5 km southeast of Elgin, Ontario, at station O-30. Photograph by B.V. Sanford. 2008-056 **b)** Intensely fractured pink quartz arenite of the Hannawa Falls Member unconformably overlain by sandstone (arrow points to contact) containing basal layers of quartz-pebble conglomerate of the Chippewa Bay Member in an isolated outlier about 1 km southeast of Ellisville, Ontario, at station O-69. Note the 1.5 m pole for scale. Photograph by B.V. Sanford. 2008-057 **c)** Pink and red tightly folded lower Hannawa Falls sandstone, shale, and conglomerate unconformably overlain by pink quartz arenite beds (arrow points to contact) of the upper Hannawa Falls Member at station O-69. Note the 1.5 m pole for scale. Photograph by B.V. Sanford. 2008-058

with sharp, unconformable contact by light grey-, white-, and red-banded quartz arenite containing thin basal layers of quartz-pebble conglomerate of the Chippewa Bay Member (Fig. 19b). The upper unit of the Hannawa Falls Member is thinly laminated with dune cross-stratification, and is herein interpreted to be of eolian origin.

Farther west of station O-30 at Jones Falls, good exposures of Hannawa Falls strata can be seen at stations O-28 and O-29. The more complete of the two (station O-28) is over 10 m thick and consists of flat-lying, brick-red quartz arenite that rises vertically to form the east shore of the Rideau Canal. A more accessible section is located at station O-29 on Jones Falls Road, 2.5 km west of Highway 15, where about 6 m of brick-red quartz arenite are exposed in a low escarpment (Fig. 20a). Here, the lowermost maroon, flat-lying, coarse-grained sandstone and shale (about 1.5 m thick) containing well rounded quartzite cobbles are abruptly succeeded by high-angle (30º), cross-stratified sandstone (1 m thick) that indicates sediment transport to the north. Overlying the cross-stratified sandstone is deep red, parallel-laminated sandstone that is continuous to the top of the section. Prominently displayed at the same location and visible in Figure 20a is a water-expulsion structure that apparently formed very early during deposition of the Hannawa Falls Member.

Figure 20. Covey Hill Formation (Hannawa Falls Member) near Jones Falls, Ontario. **a)** Six-metre escarpment section at station O-29. Note the water-expulsion structure intersecting maroon, thinly laminated eolian deposits. Photograph by B.V. Sanford. 2008-059 **b)** A local remnant of Hannawa Falls Member consisting of maroon quartzite-cobble conglomerate, sandstone, and shale is exposed at station O-27, 5.5 km north of Jones Falls Road on Highway 15. It is similar to strata exposed at the base of the section in a). Photograph by B.V. Sanford. 2008-060

Features showing what once were the upward and lateral branching routes of the escaping fluids through the soft sediment layers and the collapse of the sediment back into the cavity are remarkably well preserved at this location.

Approximately 5.5 km north of Jones Falls Road on Highway 15, at station O-27, a unique occurrence of Hannawa Falls Member is preserved as a local remnant (pod) 85 cm thick of maroon sandstone and shale with dispersed quartzite cobbles that overlies Precambrian rocks and is unconformably overlain by the Chippewa Bay Member of the Covey Hill Formation (Fig. 20b). The presence of this tiny remnant and of thin stringers of red sandstone extending along the contact to the south that is identical to the much thicker succession of Hannawa Falls Member located 6 km south at Jones Falls, illustrates clearly the degree of uplift and erosion that occurred in this region of the Frontenac Arch either during or immediately following deposition of the Hannawa Falls Member. Similar evidence for tectonic

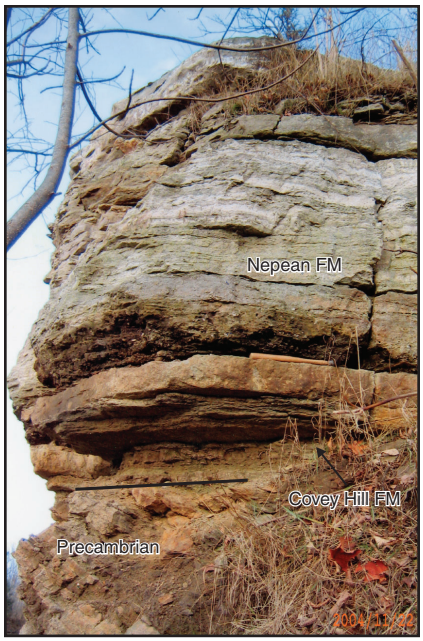


Figure 21. Thin remnant of Covey Hill Formation (Hannawa Falls Member) overlying Precambrian metavolcanic rocks (contact at black line) and unconformably overlain by the Nepean Formation at station O-23 on Highway 15 at Elgin, Ontario. Note the quartz-pebble conglomerate at the base of the Nepean Formation, above the hammer. Photograph by B.V. Sanford. 2008-061

deformation occurs to the north at Elgin, on Highway 15 at station O-23, where only a thin (45 cm) remnant of dark grey shaly sandstone and pink sandstone with dispersed quartz pebbles of the Hannawa Falls Member is preserved between the Precambrian basement and overlying Nepean Formation (Fig. 21). Twenty kilometres to the west, remnants of maroon sandy and shaly quartzite-cobble conglomerate of the Hannawa Falls Member, which are similar to those at the base of the member exposed at and near Jones Falls, occur in the Salem and Fermoy areas near Westport, at stations O-67 and O-68, where the beds are 3 m and 2 m thick, respectively.

A somewhat more spectacular occurrence of the Hannawa Falls Member is contained in a graben structure on Rideau Ferry Road between Perth and Lombardy. At station O-14, near the intersection of Otty Lake Road and Rideau Ferry Road, 2.4 m of finely laminated pink and red quartz arenite with its base not exposed are succeeded by light grey and pinkish-grey sandstone of the Chippewa Bay Member (Fig. 22). The contact between the two members is abrupt and quite possibly disconformable, as it appears to be elsewhere. The Hannawa Falls Member at this locality is a fine- to medium-grained quartz arenite containing large-scale cross-stratified deposits. This occurrence is the most northern exposure of this unit in eastern Ontario. From this general region to the western outskirts of Ottawa, the eroded edge of the Covey Hill Formation, where present in the subsurface, is stratigraphically overlapped to the north by the Nepean Formation (*see* Fig. 6).

Figure 22. Covey Hill Formation in a roadcut on Rideau Ferry Road where it intersects Otty Lake Road, Ontario, at station O-14. Note the sharp (?) disconformable contact (marked by black line) between the salmon-pink, finely laminated beds of the Hannawa Falls Member and overlying, more massive, pinkish-grey sandstone of the Chippewa Bay Member. Photograph by B.V. Sanford. 2008-062

On the western flank of the Frontenac Arch in Ontario, the red quartz arenite of the Hannawa Falls Member of the Covey Hill Formation outcrops in a large outlier near Sunbury, approximately 16 km northeast of Kingston (*see* Fig. 3). Here the unit is approximately 5.5 m thick and is best exposed at station O-57 in the Norman Sloan Quarry on the north bank of the Cataraqui River (Fig. 23a). The strata lie unconformably on Precambrian basement rocks and are overlain disconformably by a thin remnant of yellow and grey Chippewa Bay sandstone containing a thin basal quartzite conglomerate. Within the quarry, steeply dipping (upward to 30º), cross-stratified, red and pink quartz arenite of the Hannawa Falls member was interpreted to be of eolian origin by Wolf and Dalrymple (1984), Cole (1999), and MacNaughton et al. (2002). Midway within the Hannawa Falls Member is a 1 m thick, matrix-supported quartzite-cobble conglomerate that may be the remnant of a fluvial system that temporarily interrupted or co-existed with eolian conditions (McNaughton et al., 2002). The crossbeds indicate paleoflow to the west-southwest (250º) below the conglomerate, but to the south to southeast above the conglomerate. Immediately north of the quarry, steeply dipping eolian deposits grade abruptly laterally to relatively flat-lying strata composed of climbing wind-ripple cross-stratified, dark reddish-brown quartz arenite.

A steeply dipping redbed sequence of the Hannawa Falls Member, with neither the base nor the top exposed, forms a low escarpment along the south bank of the Cataraqui River on the William Hughes property at station O-56. This site is well known as the 'Park of Pillars' and contains vertical columnar structures described by Baker (1916), Hawley and Hart (1934), Winder and Sanford (1972), and others. The beds exposed here are deep red, thinly laminated quartz arenite that dips south, and are thus apparently a continuation of the uppermost eolian bedset exposed on the opposite side of the river in the Sloan Quarry.

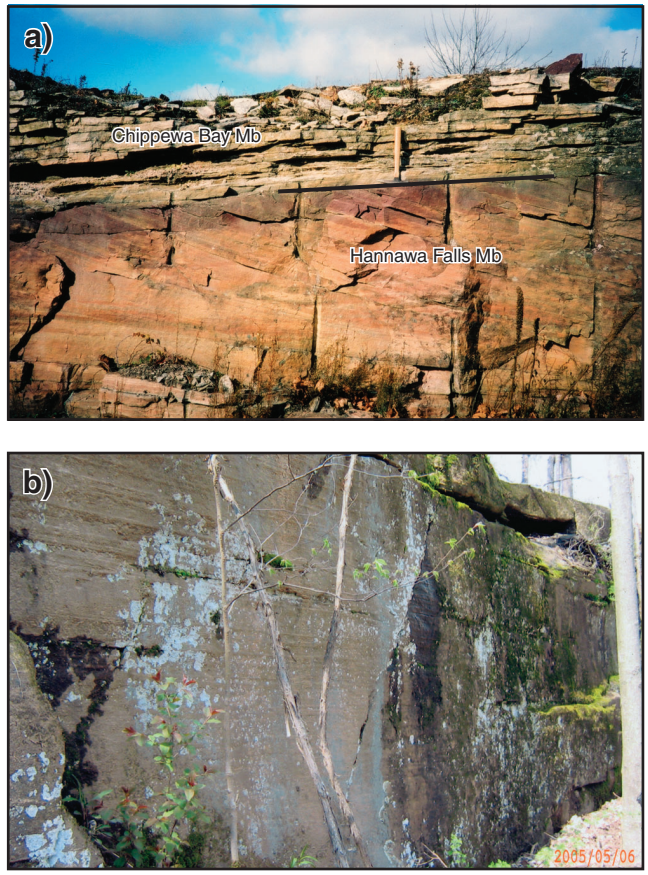


Figure 23. Covey Hill Formation sandstone (Hannawa Falls Member) exposed in a 4.6 m section in a large outlier near Sunbury, Ontario. **a)** South-dipping pink and red sandstone of eolian origin (dunes) in the Sloan Quarry at station O-57. The black line marks the contact between the two members. Photograph by B.V. Sanford. 2008-063 **b)** Flat-lying, dark reddish-brown, thinly laminated sandstone of possible eolian origin (wind-ripple lamination) at station O-59, 2 km west of the section in a). Photograph by B.V. Sanford. 2008-064

Approximately 3 km west of the Cataraqui River, two additional exposures of the Hannawa Falls Member were observed at stations O-58 and O-59; they are 1.5 m and 4.6 m thick. These strata (Fig. 23b) are lithologically similar to the sections described above; they consist of flat-lying, dark reddish-brown, laminated quartz arenite interpreted to have been the product of eolian climbing wind-ripple deposition. Additionally, the occurrence of desiccation polygons on the upper surface of the outcrop at station O-59 suggests that this part of the succession may have accumulated in an interdune area.

From the type locality at Hannawa Falls near Potsdam, New York, the beds are likely continuous, at least in subsurface, to the east along the northern margins of the Adirondack Mountains, although they may be only locally exposed in this general region. Short distances east of Potsdam, at Allens Falls and Nicholville, New York, redbeds lithologically similar to the Hannawa Falls Member have been described by Krynine (1948) and Postel et al. (1959). These strata

Figure 24. Ausable Formation (Hannawa Falls Member) exposed along Interstate 87 near Laphams Mills, New York, at station N-212. The beds here are of fluvial origin, contain quartz-feldspar-pebble conglomerate, and are characterized by a common medium-scale trough cross-stratification. Photograph by B.V. Sanford. 2008-065

occur in re-entrant depressions on the Precambrian surface along the Potsdam Group contact, where they emerge from beneath the Chippewa Bay Member of the Ausable Formation. East of Nicholville, the topographic expression of the northern margin of the Adirondack Mountains progressively rises in elevation, and the Hannawa Falls Member may be stratigraphically overlapped throughout much of if not all this area by the younger and perhaps more areally widespread Chippewa Bay Member. The Hannawa Falls Member was identified with certainty in the Lake Champlain area at only one locality, near Laphams Mills, in an uplifted, block-faulted structure oriented north-northwest that transects Interstate 87, at station N-212 (Fig. 24). Here, 2.1 m of strata composed of red, coarse-grained, feldspathic quartz-pebble conglomerate and feldspathic arenite are exposed.

In the adjacent area of Quebec, the Hannawa Falls Member of the Covey Hill Formation is also apparently restricted in outcrop distribution to a single locality at the western end of Perrot Island. Here, at station Q-2 (Fig. 25), some 20 m of Hannawa Falls strata lie at the base of a prominent northeast-oriented escarpment and are abruptly succeeded higher in the section by slightly more massive grey beds of the Chippewa Bay Member. The fine- to medium-grained strata are red to dark reddish brown and trough cross-stratified. The above beds are described in a fair level of detail by Hofmann (1972).

Figure 25. Covey Hill Formation (Hannawa Falls Member) at station Q-2 at the western end of Perrot Island, Quebec. **a)** Lower beds of the Hannawa Falls Member comprise dark reddish-brown arkosic sandstone. Photograph by B.V. Sanford. 2008-066 **b)** Small-scale cross-lamination at the base of the section in a). Note the maroon shale fragments eroded from the subjacent Jericho Member, which may be present in subsurface at or near this locality. Photograph by B.V. Sanford. 2008-067

The Hannawa Falls Member is not only relatively broadly distributed at surface around the margins of the Ottawa Embayment and Quebec Basin, it is equally consistently present in subsurface throughout the study area (*see* Fig. 4, 9). Also consistent in subsurface is its distinctive salmon-pink to dark reddish-brown colour as it is traced from the vicinity of Ottawa eastward to the Montréal region and beyond. In the western extremity of the Ottawa Embayment, it is largely quartz arenite, which grades eastward to feldspathic arenite with common quartz-feldspar-pebble conglomerate approaching the Oka-Beauharnois Arch. Where boreholes have penetrated basement, or were terminated at depths near basement along the downdropped side of the Gloucester and Russell-Rigaud fault systems, large blocks of Precambrian basement were encountered locally that greatly impeded the drilling process. These are assumed to have been sourced from the upthrown side of the fault systems, from where they had toppled into the graben, either prior to or during the initial depositional phase of the Hannawa Falls Member.

Table 3. Thickness of the Hannawa Falls Member in subsurface

Borehole	Thickness	Borehole	Thickness
GSC Lebreton No. 1	7.6 m	St. Lawrence River No. 1	171.3 + m
GSC Russell No. 1	47.6 m	Mallet Test No.1	152 + m
GSC McCrimmon No.1	33.6 m+	Quonto-International No. 1 St.Vincent de Paul	91.1 m
Imperial Oil Ltd., Laggan No.1	42.7 m+	Quonto-International No. 1 Mascouche	199 m

Precise thicknesses of the Hannawa Falls from west to east in subsurface are difficult to determine, because most boreholes drilled in the Ottawa Embayment terminated within that unit, but some data are available (*see* Table 3). Thicknesses reported in Table 3 were obtained from eight cored boreholes for which good records are available.

The dramatic eastward thickening of the Hannawa Falls Member across the Ottawa Embayment and into the western part of the Quebec Basin is likely attributed in large part to uplift of the intervening Oka-Beauharnois Arch as a likely sediment source area during the late Early and Middle Cambrian.

Chippewa Bay Member

The Chippewa Bay Member of the Ausable and equivalent Covey Hill formations abruptly overlies the Hannawa Falls Member and laterally overlaps that unit at various localities to rest directly on Precambrian basement rocks. This is apparently so on a regional scale, along the northeastern margin of the Adirondack Mountains in New York State and bordering areas of the Oka-Beauharnois Arch, where Precambrian basement rocks are of high relief. Similarly, the Chippewa Bay member would appear to overlap the Hannawa Falls Member at various localities along the eastern margin of the Frontenac Arch, and particularly so in eastern Ontario, bordering the Thousand Islands region of the St. Lawrence River, where tectonic activity was the most intense during the late Precambrian and Middle Cambrian. Similar relations between the two units can also be seen on a more local scale in both Ontario and New York State, where Hannawa Falls strata are absent due to nondeposition over positive structural features on the Precambrian basement. In such cases, the Chippewa Bay Member stratigraphically overlaps the Hannawa Falls Member to lie directly on the Precambrian basement.

The Chippewa Bay Member is succeeded with abrupt contact by the Edwardsville Member, which has very limited distribution in parts of New York State and Quebec. Elsewhere throughout the Ottawa Embayment and western Quebec Basin, the Chippewa Bay Member is overlain unconformably by the Nepean Formation in Ontario and its counterpart Cairnside and Keeseville formations in Quebec and New York State, respectively.

The Chippewa Bay Member is named for the classic section exposed at station N-80 on Route 12, a short distance west of the village of Chippewa Bay, New York, and the indentation of the St. Lawrence River that bears the same name (Fig. 26). The beds, some 6 m thick at this locality, consist of greyish-green and pinkish-grey quartz arenite; they rest on the Hannawa Falls member (the contact is obscured by Quaternary deposits) and are succeeded with sharp, possibly disconformable contact (*see* Fig. 26) by sandstone of the Edwardsville Member. Similar beds can also be seen in both reference sections (stations N-18 [Fig. 15a] and N-13 [Fig. 15b]) where the entire unit and its contact relationships are well exposed. At station N-18, within the townsite of Theresa, New York, approximately 10 m of grey and pinkish-grey quartz arenite of the Chippewa Bay Member rest on the Hannawa Falls Member with sharp angular unconformity. At this location, the upper contact of the Chippewa Bay Member with the Keeseville Formation is uncertain because of the inaccessibility of the uppermost part of the section. Three prominent bounding surfaces are observed within the section, the lower of which coincides with the contact between the Hannawa Falls and Chippewa Bay members and the others occurring within the Chippewa Bay Member. The other prominent boundaries are most likely scour surfaces within the Chippewa Bay Member, although on close inspection evidence is seen of drag folds caused by horizontal dislocation that may have occurred along one or more of these bounding surfaces (J.L. Wallach, pers. comm., 2004).

At the second reference section at station N-13 (Fig. 15b) on Route 12, a short distance east of Alexandria Bay, 6 m of pink and grey quartz arenite of the Chippewa Bay are well exposed, along with their lower and upper contacts with the

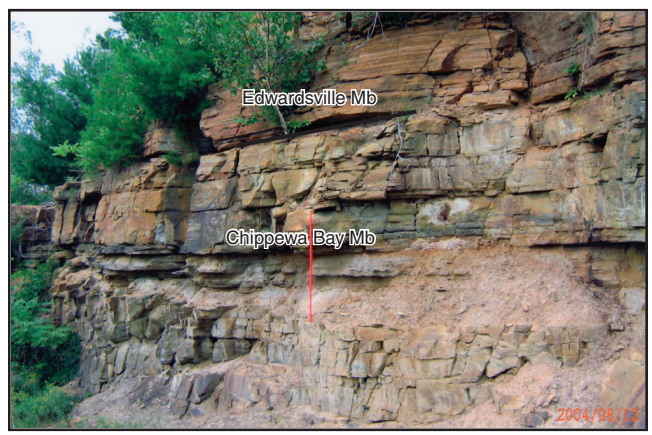


Figure 26. Ausable Formation (Chippewa Bay and Edwardsville members) in a roadcut on Route 12 near Duck Cove, New York, at station N-80. The contact between grey-green sandstone of the Chippewa Bay Member and red, thinly laminated beds of the overlying Edwardsville Member is marked by the black line in the upper part of the photograph. Note the deep weathering of strata 1 m thick above the base of the 1.5 m pole. Photograph by B.V. Sanford. 2008-068

Hannawa Falls and Edwardsville members, respectively. At this roadcut, a prominent discolouration of the weathered surface of the member is evident. This is presumably due to the leaching of iron-oxide minerals from the parent rock by groundwater flow along bedding planes and through the interstices of the rock unit. Close examination of strata at this locality, as well as many of the other Chippewa Bay sections throughout the study area, suggests that the entire unit may have been deposited originally as a redbed sequence and subsequently leached during early diagenesis; this leaching may still be ongoing today.

The Chippewa Bay Member consists of parallel-bedded quartz arenite in much of the western part of the Ottawa Embayment except in a few localities in the Thousand Islands area of New York State (e.g. station N-15), where the strata form lenses of medium-scale, cross-stratified sandstone most probably of fluvial origin (Fig. 27) and, therefore, similar to the stacked sets of cross-stratified sandstone particularly common in northeastern New York State and the adjacent Covey Hill and Perrot Island areas of Quebec.

Chippewa Bay quartz arenite similar to that in the Thousand Islands area of New York State can be traced across the St. Lawrence River into eastern Ontario. One such occurrence is at station O-52 in a tiny outlier in a roadcut on Highway 2, about 1 km east of Gananoque. The beds here (Fig. 28) are preserved in a downfaulted block, and the outlier itself is intersected by a normal fault down to the west. The beds at this station are 5.5 m thick, pinkish grey, and extensively trough cross-stratified. The lower contact with the Precambrian basement is not exposed, but quartzite cobbles in some lower beds indicate that the contact is probably at shallow depth. Outliers in immediately surrounding areas are all Nepean Formation. This would suggest that the Covey Hill Formation (Chippewa Bay Member) once blanketed this segment (western margin) of the arch and was removed for the most part prior to deposition of the Nepean Formation. Another occurrence of the Chippewa Bay Member less than 1 m thick is exposed on the west side of the Frontenac Arch, in the Sloan Quarry, at station O-57 (Fig. 23a). The strata occur in the upper northwest wall of the quarry and consist of yellow, fine- to medium-grained quartz arenite containing a thin quartzite-cobble basal conglomerate with angular consolidated clasts of red sandstone derived from the underlying Hannawa Falls Member eroded at some point in time following its consolidation. Associated with these basal stream-bed deposits is a preponderance of asymmetrical current ripples that are exposed on blocks removed from the quarry face.

On the opposite side of the Frontenac Arch to the northeast, two thin exposures of Chippewa Bay Member outcrop, both less than 1 m thick and composed of grey quartz arenite with quartzite-cobble and -boulder clasts. One exposure is located at the Lyn Valley Conservation Area, on the outskirts of Lyn, at station O-64 (Fig. 11). The other is 11 km west on a county road 5 km southeast of Athens, at station O-66. At both localities, the Hannawa Falls Member is absent and the Chippewa Bay Member unconformably overlies the

Figure 27. Lenses of hummocky, trough cross-stratified sandstone of the Ausable Formation (Chippewa Bay Member) at station N-15, in New York State. Photograph by B.V. Sanford. 2008-069

Figure 28. Outlier of Covey Hill Formation (Chippewa Bay Member) in an isolated remnant (downfaulted block) on Highway 2, 1 km east of Gananoque, Ontario, at station O-52. **a)** Section on the north side of Highway 2 intersected by a normal fault down to the left (white line). Photograph courtesy of J.L. Wallach. **b)** Medium-scale (dune) cross-stratification well displayed on the south side of Highway 2, at the same location as in a). Photograph by B.V. Sanford. 2008-070

Abbey Dawn Formation and is unconformably overlain by the Nepean Formation.

From the general vicinity of Athens northwestward to Otter Lake, on Highway 15, the Chippewa Bay Member is represented by a very complex assortment of quartz-cobble and -boulder conglomerate intercalated with quartz arenite. Throughout much of this region, conglomerate is the dominant facies, although quartz arenite with no conglomerate occurs locally.

Perhaps one of the more spectacular sections of quartzite-cobble and -boulder conglomerate to be seen anywhere in this region is exposed in an outlier on the southwest shore of Charleston Lake (Charleston Lake Provincial Park). At station O-61 (Fig. 29a), upward of 8 m of coarse, clast-supported quartzite-cobble conglomerate containing thin stringers of pinkish-grey, coarse-grained sandstone are present near the entrance to the park. At a nearby location of the same outlier (station O-60; Fig. 29b), the quartz cobbles are interbedded with massive beds and lenses of grey and greyish-green, coarse-grained sandstone. The change from conglomerate (station O-60) to conglomerate and sandstone (station O-61) suggests that gravel-rich sediment was transported southeastward from a northeast-trending fault scarp. Evidence for a possible fault immediately west of the outcrop area appears on satellite images as a major lineament that intersects Charleston Lake at this approximate locality (*see* Fig. 3).

Conglomeratic units somewhat thinner than the above were mapped nearby at two localities bordering Charleston Lake, one on a county road about 0.25 km north of Lyndhurst (station O-43; Fig. 30), where 1.2 m of quartzite conglomerate with minor feldspar clasts unconformably overlie Precambrian coarse crystalline marble, and the other on Slack Road leading south from the village of Charleston Lake to cottages on the lake (station O-46), where about 1 m of clast-supported quartzite conglomerate is overlain by 30 cm of coarse-grained, pinkish-grey, trough cross-stratified sandstone.

One of the better exposures of Chippewa Bay conglomerate and sandstone occurs in an abandoned quarry 5 km west of Highway 15 at Briton Bay (station O-18; Fig. 31a, b). Here, the stratal succession is up to 10 m thick and readily divisible into alternating layers of sandstone and conglomerate. Conglomerate clasts are mainly quartzite pebbles and cobbles, as well as abundant weathered feldspar. The sandstone interbeds weather to a drab olive-green, a characteristic that is common not only to this outcrop, but to a great many other Chippewa Bay exposures throughout the western and eastern parts of the Ottawa Embayment.

Conglomerate strata show a diffuse planar lamination with well developed clast fabric and clast imbrication. These and the sandstone strata were most probably deposited in a bed-load-dominated fluvial environment, quite possibly a sand and gravel braided fluvial stream system. Conglomerate strata were likely deposited as bed-load sheets, whereas the intercalated sandstone indicates infilling of deactivated channels. Sediment consisting of sand and gravel was likely sourced from the Rideau Lakes Fault immediately to the north, which trends northeasterly through the Rideau Lakes region (*see* Fig. 3).

A remnant of the conglomerate facies described above is exposed a short distance north of Briton Bay, at station O-17 in a deep ditch on the west side of Highway 15 at the Twin Pines Camp Grounds (Fig. 32). Here, strata are 2.1 m thick and consist of pinkish-grey, well rounded to subrounded quartzite clasts dispersed in a coarse sandstone matrix. Subtle bedding in the conglomerate dips to the south (to the left in Figure 32), whereas the overlying Nepean Formation

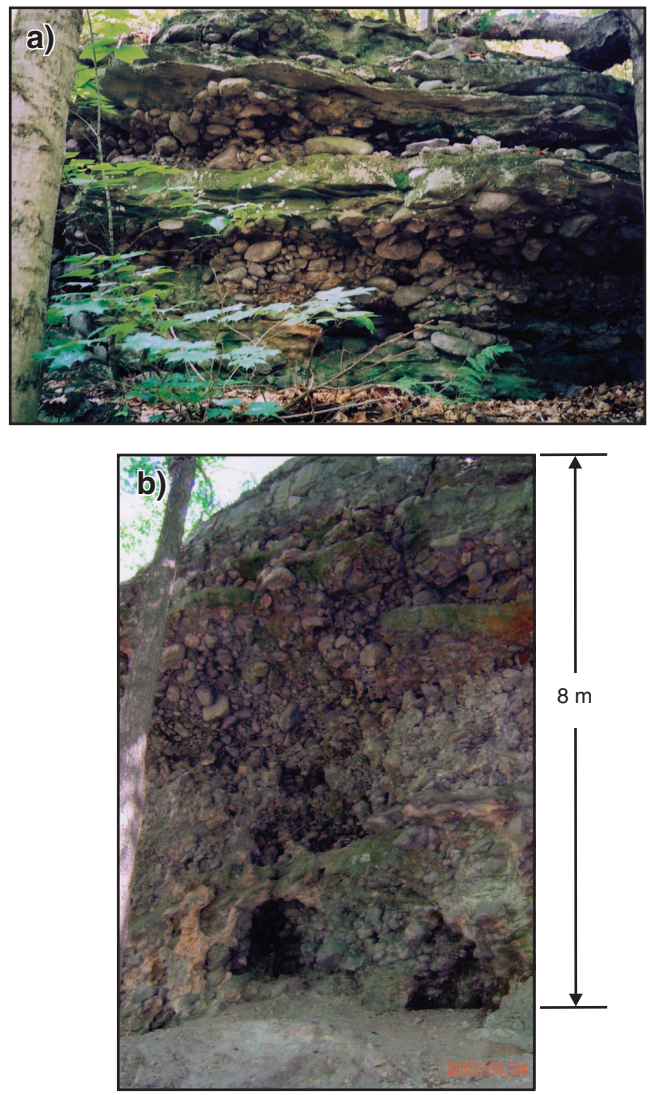


Figure 29. Covey Hill Formation (Chippewa Bay Member) at Charleston Lake Provincial Park, Ontario. **a)** Clast-supported quartzite-cobble conglomerate interbedded with sandstone at station O-60. Photograph by B.V. Sanford. 2008-071 **b)** Clast-supported quartzite-cobble and -boulder conglomerate (approximately 8 m thick) at station O-61. Photograph by B.V. Sanford. 2008-072

Figure 30. Covey Hill Formation (Chippewa Bay Member) quartzite-cobble conglomerate 1.2 m thick near Lyndhurst, Ontario, at station O-43, overlying Precambrian coarse crystalline marble (arrow point to contact). Photograph by B.V. Sanford. 2008-073

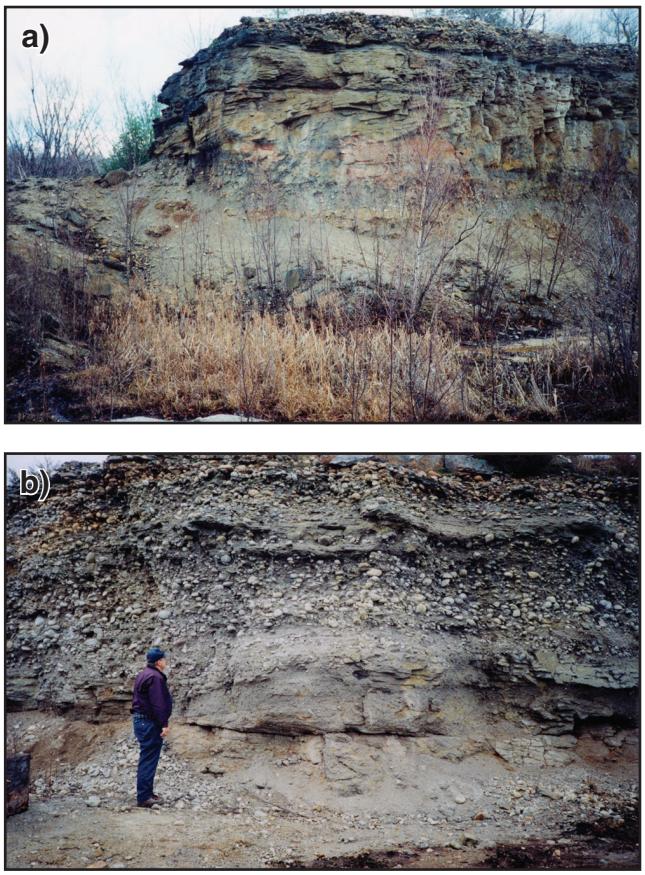


Figure 31. Covey Hill Formation (Chippewa Bay Member) at station O-18, in a quarry at Briton Bay, Ontario. **a)** A 12 m section of grey-green feldspathic sandstone and interbedded quartzite-pebble conglomerate, capped by quartzite-cobble conglomerate. Photograph by B.V. Sanford. 2008-074 **b)** Diffusely planar-stratified cobble conglomerate (bed-load sheets) interstratified with sandstone deposited in abandoned channels. Photograph by B.V. Sanford. 2008-075

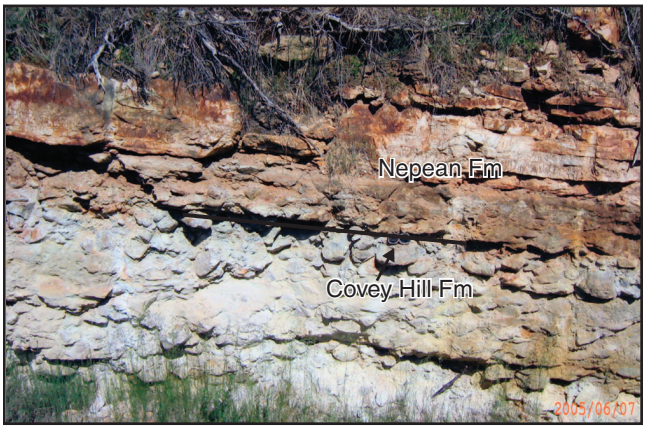


Figure 32. Covey Hill Formation (Chippewa Bay Member) consisting of quartz-cobble and -boulder conglomerate with sandstone matrix, overlain with angular unconformity (contact at black line) by basal conglomerate and sandstone of the Nepean Formation, Highway 15, Ontario, at station O-17. Note the compass for scale immediately below the contact. Photograph by B.V. Sanford. 2008-076

is clearly inclined to the north (to the right in Figure 32), the bounding surface between the two thus constituting an angular unconformity.

Somewhat beyond the periphery of the conglomerate belt are excellent exposures of Chippewa Bay quartz arenite within a few kilometres of Elgin. One of these is at station O-30, in a downfaulted block 4.5 km east-southeast of Elgin (Fig. 19). Here, 5 to 7 m of thinly laminated, pinkish-grey quartz arenite abruptly and possibly disconformably overlie redbeds of the Hannawa Falls Member. Two intervals within the relatively flat-lying fluvial deposits, each at least 1 m thick, consist of steeply dipping, cross-stratified sandstone of probable eolian origin. Near the top of the member is a vertical cylindrical column similar to, albeit much smaller than those occurring on the William Hughes property on the south bank of the Cataraqui River, near Sunbury.

Perhaps the most complete section of Chippewa Bay Member exposed anywhere in eastern Ontario (15 m) or elsewhere within the study area is located near Ellisville at station O-69 (Fig. 19b). The unit contains thin intercalations of granite-pebble conglomerate at its base and consists primarily of grey and yellowish-grey, fine- to medium- and locally coarse-grained quartz arenite with abundant pink and dark red banding throughout; the quartz arenite lies with sharp angular unconformable contact on the Hannawa Falls Member. It is thinly laminated and intensely dune cross-stratified, and is herein interpreted to be of eolian origin.

Four and a half kilometres southwest of Elgin, on a side road leading to Davis Lock on the Rideau Canal, another occurrence of Chippewa Bay Member is contained in a broad syncline at station O-47 (Fig. 33). The unit is 2.7 m thick and consists of pinkish-grey and yellowish-orange, fine- to medium-grained quartz arenite. Because the basal

Figure 33. Covey Hill Formation sandstone (Chippewa Bay Member) near Davis Lock on the Rideau Canal, Ontario, at station O-47. Note the minor folding of the Covey Hill at this locality. Photograph by B.V. Sanford. 2008-077

Figure 34. View to the southeast showing the Ausable Formation (Chippewa Bay Member) in the Chateaugay River gorge, New York, at station N-130. Note the north-dipping beds intersected by north-trending normal faults that are parallel to the flow of the river. Photograph courtesy of J.L. Wallach.

contact is not exposed, it is not known whether these beds overlie Precambrian rocks or a thin layer of the Hannawa Falls Member. A short distance to the east on Highway 15 at Elgin (station O-23, Fig. 21), Chippewa Bay strata are absent between the Hannawa Falls Member of the Covey Hill and overlying Nepean formations, having likely been eroded prior to deposition of the Nepean Formation.

At the northern town limit of Delta, Ontario, at station O-35 (Fig. 18), gently folded redbeds of the Hannawa Falls Member of the Covey Hill Formation are overlain with angular unconformity by flat-lying, medium to dark grey argillaceous sandstone containing quartzite-cobble conglomerate at base and dispersed here and there throughout the unit. These beds were initially thought to be Nepean Formation by Sanford (2007), but on more detailed examination were noted to contain lithological characteristics more similar to the Chippewa Bay Member of the Covey Hill Formation where studied elsewhere in nearby regions of eastern Ontario and in northern New York State.

Thin remnants of Chippewa Bay sandstone occur on the Rideau Ferry Road at stations O-14 and O-16. At station O-14 where the Chippewa Bay Member abruptly overlies the Hannawa Falls Member (Fig. 22), the beds are less than 1 m thick and consist of massive light pinkish-grey quartz arenite, in sharp contrast to the thinly laminated redbeds of the underlying Hannawa Falls Member. At station O-16, near Rideau Ferry, at least 5 m of grey, red-stained, medium-grained quartz arenite of the Chippewa Bay Member are cut by a normal fault, from where the beds dip steeply to the west (Fig. 1a, b). Following deformation, the strata were bevelled by erosion before deposition of the overlying Nepean Formation.

The northernmost exposure of the Covey Hill Formation in the western part of the Ottawa Embayment is located at Rockland, Ontario, near the boat launch to the Ottawa River, at station O-1. Chippewa Bay strata (1.5 m thick) are pinkish-grey and thickly bedded sandstone near the base, becoming more thinly bedded, laminated, and argillaceous upward in section. The contact of the Chippewa Bay Member with the underlying Precambrian marble is not observed, but is likely no more than a few centimetres below the base of the section. The upper contact of the Chippewa Bay Member with the Nepean Formation is placed at the base of a thin-bedded unit of argillaceous sandstone and limestone containing large-scale ripple-like structures of assumed marine origin. Whether the Chippewa Bay Member of the Covey Hill Formation is exposed elsewhere along the Paleozoic–Precambrian contact between Rockland and points eastward is unknown.

Chippewa Bay Member strata were nowhere observed between Black Lake and Malone bordering the Adirondack Mountains in New York State (*see* Fig. 3). The member is very likely present beneath Quaternary deposits, at least from the Potsdam area eastward to the vicinity of Belmont Center where a short distance east of Malone, thin exposures of grey- and red-banded quartz arenite of the Chippewa Bay Member occur at stations N-128 and N-129.

Immediately east of the outcrops at stations N-128 and N-129, in the Chateaugay River gorge where Pulp Mill Road crosses the river at station N-130, an estimated 12 m of Chippewa Bay Member strata are exposed. Near the base of the gorge, strata consist of grey quartz arenite (Fig. 34) and are assumed to belong to the Chippewa Bay Member of the Ausable Formation, overlain near the top of the gorge by the Edwardsville Member.

Farther east approaching the Oka-Beauharnois Arch in New York State, local exposures of the Chippewa Bay Member outcrop, most of which are not more than a few centimetres to 1 or 2 m thick. The most noteworthy are two outcrop sections on Route 190, about 1 km west of Ellenburg Centre at stations N-138 and N-139 (*see* Fig. 6). Station N-139, the more coarse-grained of the two (Fig. 35a), is a 2 m thick section of grey and pink quartz-feldspar conglomerate.

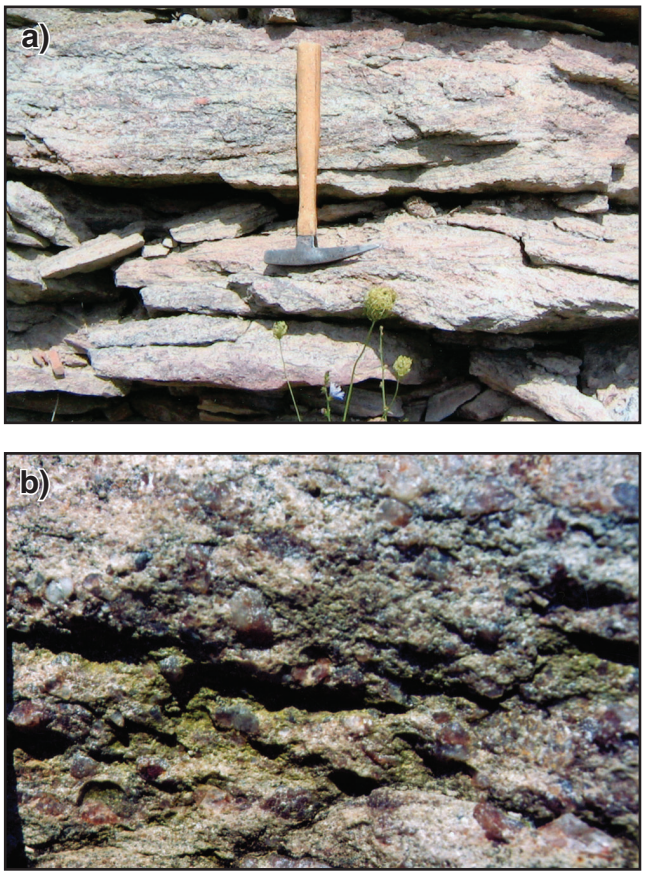


Figure 35. Ausable Formation (Chippewa Bay Member) near Ellenburg, New York, at station N-138. **a)** Medium-scale cross-stratified (dune) pink and grey sandstone with abundant quartz pebbles. Photograph by B.V. Sanford. 2008-078 **b)** Close-up of pink and red quartz-pebble clasts and yellow to white feldspar, the latter mostly decayed to clay minerals (most probably kaolinite). Photograph courtesy of J.L. Wallach.

Sand-sized feldspar grains have been mostly weathered to clay minerals (Fig. 35b). The Chippewa Bay Member at this locality consists of medium-scale trough cross-stratified (dune) strata. Consequently, the beds have a highly irregular appearance that results from the scouring and depositional processes of braided stream systems that transected the area during the Middle Cambrian. In this general area of New York State, sandstone and pebble conglomerate of the Chippewa Bay Member are in sharp contrast to uniformly bedded sandstone equivalents exposed elsewhere along the northern margin of the Adirondack Mountains. A major facies change from eolian to fluvial origin can thus be assumed to have occurred at some point immediately west of station N-139.

The occurrence of conglomerate and feldspar in strata of the Chippewa Bay Member varies substantially throughout this general region of New York State, where sandstone varies from feldspathic arenite to quartz arenite. Also, the red to pink banding that is so characteristic of the Ausable and equivalent Covey Hill formations is commonly observed

Figure 36. Ditch section showing a typical exposure of Covey Hill Formation (Chippewa Bay Member) along the road leading to the summit of the high hill above the village of Covey Hill, Quebec, at station Q-6. Here and elsewhere in this region, the beds are grey-green and locally pink, conglomeratic, and intensely trough cross-stratified. Photograph by B.V. Sanford. 2008-079

in this region of the state, and serves to differentiate these strata from the locally lithologically similar Keeseville Formation.

In the immediately adjacent regions of Quebec, the Chippewa Bay Member of the Covey Hill Formation is exposed at several localities near the village of Covey Hill including the Ducharme Quarry, and in the ditches of the roads that climb the steep incline above the type locality. Undoubtedly the most continuous section anywhere exposed is part way up the incline at station Q-13 (Fig. 36) where 21 m of medium-scale trough cross-stratified, medium-grained sandstone were measured. Strata dip 5º to the north and consist of greenish-grey, coarse-grained sandstone intercalated with quartz-feldspar-pebble conglomerate.

Thirty-seven kilometres north of the above-described section, the Covey Hill Formation (Chippewa Bay Member) rises to surface from beneath the Valleyfield Trough and is exposed near the top of a low escarpment at the western end of Perrot Island. Approximately 9 m of Chippewa Bay strata are exposed at station Q-2 (Fig. 37), in a major roadcut on Don Quichotte Boulevard. Beds comprise mostly grey, medium- to coarse-grained sandstone with characteristic pink and red banding throughout. Interbeds of quartz-feldspar-pebble conglomerate are also common, as is well developed, medium- to large-scale trough cross-stratification (dunes). In outcrop, these latter structures typically weather massive and are dark reddish brown.

Figure 37. Covey Hill Formation (Chippewa Bay Member) on Perrot Island, Quebec, at station Q-3. Beds are grey and pink, medium-scale cross-stratified (dune) sandstone with intervals of quartz-feldspar-pebble conglomerate. Note the pencil for scale. Photograph by B.V. Sanford. 2008-080

With the exception of the Dominion Observatory No. 1 (O-1) and GSC Lebreton No. 1 (O-2) boreholes, the Chippewa Bay Member is interpreted to be present in the diamond-drill-cored boreholes elsewhere in the Ottawa Embayment and Quebec Basin as listed in Table 4 and graphically illustrated in Figure 9. In the western part of the Ottawa Embayment, strata consist of pinkish-grey quartz arenite (GSC Russell No. 1 borehole) that eastward grades into light grey and cream quartz-feldspar conglomerate with sandstone interbeds in the GSC McCrimmon No. 1 borehole. A similar conglomerate facies occurs in both the Imperial Oil Ltd., Laggan No. 1 and St. Lawrence River No. 1 boreholes. On the northeastern margin of the Oka-Beauharnois Arch (Quebec Basin), strata consist of quartz arenite interbedded locally with quartz-feldspar conglomerate (*see* Fig. 4, section A-A').

In most boreholes, beginning with the GSC McCrimmon No. 1, feldspar detrital grains have been extensively weathered to clay minerals, particularly in cores located closer to the Oka-Beauharnois Arch (*see* Fig. 4). The thickness of the Chippewa Bay Member increases from west to east across the Ottawa Embayment and reaches its maximum around the margins of the topographically higher segments of the Oka-Beauharnois Arch (*see* Table 4).

Edwardsville Member

Completing the Ausable succession in New York State is a thin quartz arenite unit, herein named the 'Edwardsville Member', that locally overlies the Chippewa Bay Member with sharp contact. The type section is at station N-109 on Black Lake Road, about 1 km east of Edwardsville, New York. Here, strata comprise light pink quartz arenite slightly less that 1 m thick and unconformably overlain by the Keeseville Formation (Fig. 38). Elsewhere in the Thousand Islands region of New York State the beds have sporadic

Table 4. Thickness of the Chippewa Bay Member in subsurface

Borehole	Thickness	Borehole	Thickness
Dominion Observatory No.1	0.0 m	St. Lawrence River No. 1	324.0 m
GSC Lebreton No.1	0.0 m	Mallet Test No. 1	322.5 m
GSC Russell No. 1	11.6 m	Quonto–International No. 1 St. Vincent de Paul No. 1	338.0 m
GSC McCrimmon No. 1	156.4 m	Quonto–International No. 1 Mascouche	196.0 m
Imperial Oil Ltd., Laggan No. 1	182.3 m		

Figure 38. Ausable Formation (Edwardsville Member) unconformably overlain by the Keeseville Formation, on Black Lake Road near Edwardsville, New York, at station N-109. Note the cross-stratification throughout the Keeseville Formation. Photograph by B.V. Sanford. 2008-081

distribution, having been removed locally and on a regional scale by erosion prior to deposition of the Keeseville Formation. However, they are particularly well developed at station N-80 on Route 12 (Fig. 26), where the Edwardsville Member can be readily divided into two units, a lower, very conspicuous succession of red, thinly laminated strata about 1 m thick, overlain by pink, thinly bedded quartz arenite approximately 2 m thick. A few metres east of station N-80, at the same exposure on Route 12, the upper beds of the Edwardsville member are overlain with slight angular unconformity by fossiliferous sandstone of the Keeseville Formation. An occurrence of Edwardsville Member similar to that described above but somewhat lacking the deep red and pinkish colour is present in the reference section near Alexandria Bay on Route 12, at station N-13 (Fig. 15b), where beds of composition and thickness similar to those at station N-80 are overlain unconformably by the Keeseville Formation. The Edwardsville Member is apparently absent at the other reference section within the town limits of Theresa (station N-18; Fig. 15a), where the Keeseville Formation unconformably overlies the Chippewa Bay Member.

Despite the sporadic occurrence of the Edwardsville Member in the Thousand Islands region of New York State, the unit is apparently nowhere present on the opposite side of

the St. Lawrence River in eastern Ontario. Its absence in the latter area is attributable either to nondeposition or to erosion due to the more intensive tectonic movements that apparently occurred throughout the Ottawa Embayment immediately following deposition of the Covey Hill Formation.

There is no trace of the Edwardsville Member of the Ausable Formation along the northern margins of the Adirondack Mountains between Black Lake and the vicinity of Chateaugay, in northern New York State, perhaps because of its burial beneath Quaternary deposits. In the Chateaugay area, however, it is exposed in the Chateaugay River gorge where Pulp Mill Road crosses the river at station N-130. On the west bank of the river, a short distance downstream from the bridge, the Edwardsville beds are exposed immediately above water level (Fig. 39a), where they consist of medium-scale, cross-stratified, fine-grained sandstone.

Overlying these deposits are 3 m of flat-lying, thinly laminated, pink, fine-grained quartz arenite (Fig. 39b) that is lithologically similar to the Edwardsville Member present to the west in the Thousand Islands region. A few metres west of the above exposure and at a slightly higher topographic level is an outcrop of white, massive-bedded sandstone 1.5 m thick, herein classified as Keeseville Formation. Its lower contact with the Ausable Formation is not exposed. A short distance downstream, the Ausable–Keeseville contact apparently crosses the river, at which point the Keeseville Formation forms the bedrock surface, dipping northward into the Ottawa Embayment (*see* Fig. 3).

Twenty-five kilometres northeast of Chateaugay, New York, and in adjacent areas of Quebec, two thin exposures of Edwardsville Member occur at the very summit of the high hill that rises above the Quebec Lowlands approximately 2 km north of the international boundary, at stations Q-14 and Q-15. The stratigraphically lower of the two (Q-14) is light greenish-grey and red-stained, finely laminated quartz arenite. At the slightly higher elevation (Q-15), the beds (pavement exposure) are deep red and show medium-scale trough crossbedding. These two outcrops and equivalent red sandstone in the Ducharme Quarry are most probably the youngest strata of the Covey Hill Formation found in Quebec during the present study and are interpreted to be equivalent to the beds classified as Edwardsville Member in the Chateaugay River gorge and points to the west in the Thousand Islands region of New York State.

Following deposition of the Ausable and equivalent Covey Hill formations, it is concluded that these units were exposed for an extended period (*see* Fig. 5) during which substantial volumes of sandstone and/or conglomerate were removed by erosion. This was particularly so along the axis and margins of the Frontenac Arch in eastern Ontario, and to a very large extent completely around the outer margins of the Ottawa Embayment and Quebec Basin. In addition to erosion, intense local deformation in the form of faulting and folding of Covey Hill and equivalent Ausable strata left a highly irregular surface upon which the succeeding Nepean and equivalent Cairnside and Keeseville formations were deposited during the Late Cambrian and Early Ordovician.

Figure 39. Ausable Formation (Edwardsville Member) in the upper Chateaugay River gorge, New York, at station N-130. **a)** Pink, thinly laminated, flat-lying strata immediately overlying the strata in b). Photograph by B.V. Sanford. 2008-082 **b)** Medium-scale cross-stratified sandstone. Photograph courtesy of J.L. Wallach.

Where the Ausable Formation forms the bedrock surface around the northern margin of the Adirondack Mountains, the beds locally display unique weathering characteristics, quite unlike the Nepean and equivalent Keeseville formations or any of the other succeeding Ordovician formations. In fact, their very highly irregular surface (mound-like topographic expression), likely the product of structural deformation, closely resembles Precambrian surface terrains in many parts of the Canadian Shield. Some Ausable outcrops would thus have been overlooked during current field investigations had such well rounded dome-shaped exposures not been searched out and examined in closer detail.

Enigmatic large-scale radial structures

Large-scale radial structures occur in outcrop as two end-member forms, i.e. funnel-shaped cones and circular columns with subparallel walls. Both forms crosscut and are

Figure 40. Cylindrical columnar structure formed in eolian sandstone of the Covey Hill Formation (Hannawa Falls Member). **a)** 'Park of Pillars', on the south shore of the Cataraqui River (Rideau Canal), Ontario, at station O-56. Photograph by B.V. Sanford. 2008-083 **b)** Cross-sectional view showing concentric banding within a column. Photograph by B.V. Sanford. 2008-084

oriented approximately perpendicular to bedding. Although rarely observed in the field, an example of an upward-expanding (funnel-shaped) cone is observed on Jones Falls Road, Ontario, 2.5 km west of Highway 15, at station O-29. The funnel-shaped conical features consist of fine- to medium-grained chaotic deposits of deep red quartz arenite that are in sharp contrast to the flat-lying to steeply dipping, finely laminated eolian deposits within which the structure originally formed. Funnel-shaped conical structures are most probably the result of catastrophic fluidization events that caused a major eruption of formation fluids that moved radially upward through the section. As pore pressure dissipated, fluidized sediment collapsed under gravity and filled the funnel-shaped pipe. Similarly shaped structures have been observed in rocks of similar age at or near station N-58 on Stine Road, 3.5 km northeast of Redwood, New York, and were described in some detail by Dietrich (1953).

Perhaps the most enigmatic large-scale radial structures are the circular columns observed in strata of the Covey Hill Formation (Hannawa Falls Member). At station O-56, one such column, which is at least 6 m long and about 1 m in diameter, is exposed both parallel and transverse to its vertically oriented long axis (Fig. 40a). In cross-section, the column is concentrically banded (Fig. 40b). On the opposite side of the Cataraqui River in the Sloan Quarry at station O-57, the top of what may be an unexhumed column is well displayed in plan view (Fig. 41a).

The origin of these structures has been the subject of speculation for a great many years, and the controversy likely will not be settled until such time as one of the columns can be dismantled at its base to determine whether it originated from the bottom or the top. Discussions relating to the description and origin of the columns located on the William Hughes property and elsewhere are contained in Baker (1916), Hawley and Hart (1934), Miser (1935), Dietrich (1953), Gruhman and Peterson (1992), and Donaldson and Chiarenzelli (2004). The origin of these structures, as paraphrased from Winder and Sanford (1972), has been attributed to fossil tree trunks, potholes excavated and later infilled with sand, concretions, collapse or local slumping of sand into cavities in underlying Precambrian marble, and dewatering processes. As proposed by Sanford (2007), a logical explanation for the origin of the columns is that of potholes later infilled with sand, as a fair amount of evidence suggests that they were drilled from the top down by rotating quartzite cobbles caught up in vortices on the

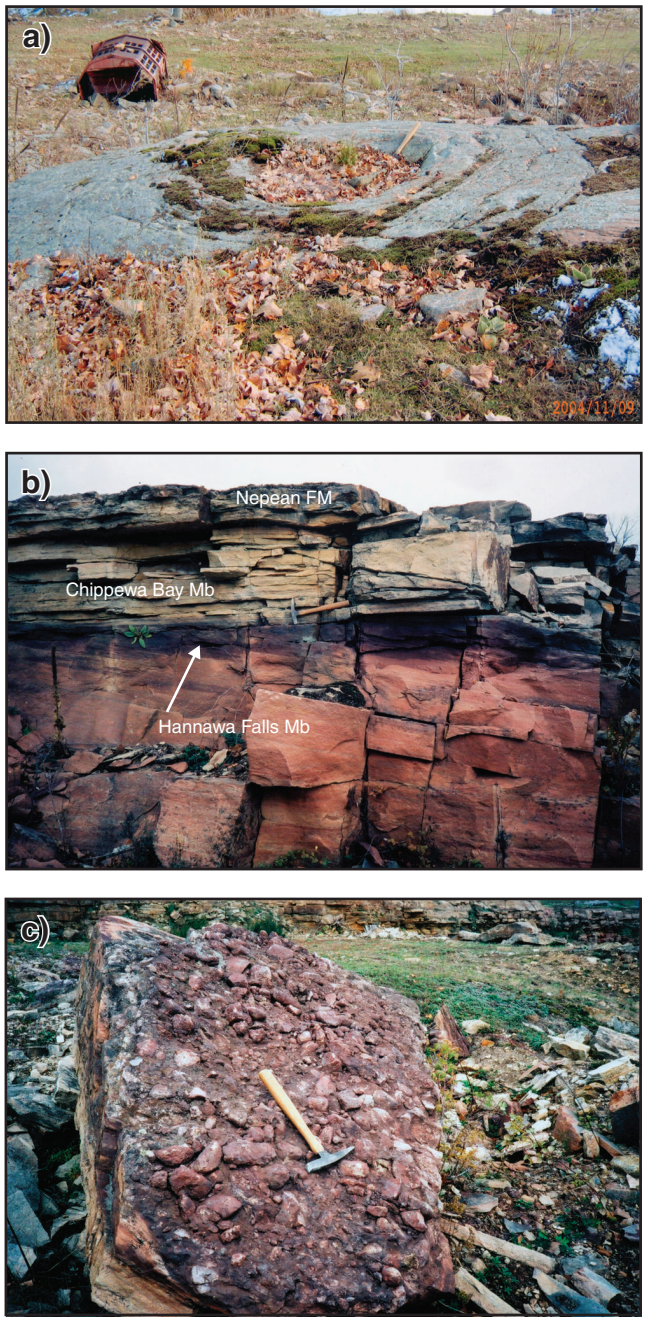


Figure 41. Evidence for the presence of an unexhumed cylindrical column in the Sloan Quarry on the north shore of the Cataraqui River, Ontario, at station O-57. **a)** View of the assumed top and concluding phase of the column (note the concentric banding, marking the final infilling process of the underlying structure). Photograph by B.V. Sanford. 2008-085 **b)** Eolian sandstone of the Hannawa Falls Member, below the hammer, overlain unconformably by stream-bed deposits of the Chippewa Bay Member (arrow points to contact). The hammer head marks the horizon where drilling of the nearby cylinder, shown in a), is believed to have begun. Photograph courtesy of J.L. Wallach. **c)** Overturned block of Chippewa Bay Member showing the basal quartzite-cobble conglomerate, the presumed source of the rotating tools that led to the drilling of the cylinder. Photograph by B.V. Sanford. 2008-086

floor of high-energy stream systems, much like the motion of a diamond bit drilling into bedrock. Supporting evidence includes the following:

- Potholes that formed in Quaternary and more recent times are well documented in the literature, e.g. Kunert and Coniglio (2002). Some are in the process of forming today at the bottom of fast-moving stream systems, cutting perfect cylinders into the bedrock formations; one of the better examples is 'Jacob's Well' in the Ausable Chasm in northeastern New York State. This particular feature is approximately 6 m in depth and 1.6 m in diameter, dimensions that are similar to those of the cylindrical columns on the William Hughes property at station O-56.
- The columns on the Hughes property (station O-56) and in the adjacent Sloan Quarry (station O-57) occur in strata of the Hannawa Falls Member (Covey Hill Formation; Fig. 40a). The unit here is a redbed sequence of eolian deposits that accumulated under arid conditions, and consequently indicates depositional conditions much different from those in the immediately overlying Chippewa Bay Member. The latter strata were deposited in fluvial, eolian, and possible lacustrine settings suggestive of far more humid climatic conditions. Such a change in climate between deposition of the Hannawa Falls and Chippewa Bay members in all probability did not occur abruptly. The evidence here and elsewhere throughout the study area reveals a major hiatus at the top of the Hannawa Falls member that predated initiation of the Chippewa Bay Member, which as a result could have enabled these strata to have become sufficiently consolidated to withstand the drilling process.
- A good example of the 'tools' that may have drilled the cylinders in the Hannawa Falls Member is seen in the overturned block of Chippewa Bay Member (Fig. 41c). These are quartzite pebbles and cobbles that lie at the base of the Chippewa Bay Member, just above the contact of the two members where the drilling began (*see* Fig. 41b).
- Once the current velocity of the stream systems could no longer sustain the drilling process beyond a certain depth (perhaps 5 to 6 m), the cylinder would gradually begin to fill with sand. This would likely have been a mixture of red and yellowish-grey Chippewa Bay detritus, which appears to be what is contained within the columns.
- The introduction of the sand into the cylinder would have been rotational due to the continuing helical motion of the stream-bottom current, as shown by the concentric layering along the inner walls of the cylinder (Fig. 40a) and at the surface expression of the column (Fig. 41a).
- Finally, cylindrical columns at or near station N-58 on Stine Road, near Redwood, New York, are contained in a stratigraphic framework largely identical to that at stations O-56 and O-57 described above, e.g. eolian dunes

abruptly succeeded by fluvial deposits. This would suggest that the two occurrences may have been triggered by a similar, if not identical, geological process.

The columns near Redwood, New York, were described by Dietrich, who attributed their origin to slumping into "cavities [that were] formed in the underlying Precambrian Grenville Series marble, before, during, or after deposition of the sand" (Dietrich, 1953, p. 11).

A similar but much smaller columnar structure was found in the Chippewa Bay Member of the Covey Hill Formation at station O-30, approximately 4.5 km southeast of Elgin, Ontario (Fig. 42a, b). It too presumably formed by current-induced drilling from the top downward, triggered by the onset of fluvial conditions that prevailed briefly between episodes of eolian deposition below and above. Columnar structures were uncovered during quarrying operations in the Ellisville quarry (station O-69) in strata of the Chippewa Bay Member (W. Jackson, pers. comm., 2007).

Figure 42. Miniature cylindrical column in the Covey Hill Formation (Chippewa Bay Member), 4.5 km southeast of Elgin, Ontario, at station O-30. **a**) Plan view of small columnar structure. Photograph by B.V. Sanford. 2008-087 **b)** Partially exposed cross-sectional view of the column. Photograph by B.V. Sanford. 2008-088

Petrogenesis

During the initial phases of Potsdam deposition (latest Proterozoic and Middle Cambrian), the structural configuration of the principal tectonic features bordering and underlying the Ottawa Embayment and immediately adjacent areas is assumed to have had some general similarity to that of today. The Adirondack Dome was probably an upland area, but only mildly active, as evidenced by the preponderance of fine detritus (sandstone versus conglomerate) that was being transported by river systems that flowed northward into the Ottawa Embayment.

The Frontenac Arch, on the other hand, was likely both a prominent physiographic feature and tectonically active during the early stages of deposition of the Covey Hill and equivalent Ausable formations, particularly along the segment of the arch in eastern Ontario immediately north of what is now the St. Lawrence River. Faulting along the eastern margin of the arch is inferred to have been particularly intensive, resulting in the dispersal of sand and gravel eastward into the Ottawa Embayment. Quartzite-cobble conglomerate occurs locally along the uplifted margins of the Precambrian basement, particularly the northeast-trending fault system that transects the Rideau Lakes and the many other faults of dominant northeast orientation that occur in this general region of eastern Ontario. While gravel (conglomerate) was accumulating along the Frontenac Arch, sand-sized detritus was being transported by an ephemeral fluvial system draining eastward into the Ottawa Embayment (*see* Fig. 43), where it was reworked and dispersed by eolian processes.

On the opposite side of the Frontenac Arch, similar processes presumably were underway with sand and gravel being transported into central and southwestern Ontario by fluvial and eolian processes. However, erosion during the long hiatus following early Potsdam deposition has largely removed most of the strata from this region.

The Laurentian Arch, which extends along the southern margin of the Canadian Shield, was also a major tectonic feature during the initial phase of Potsdam deposition. Uplift of the arch, perhaps beginning as early as latest Proterozoic and again in the Early to Middle Cambrian at the latest, in conjunction with ongoing rifting rotated a large rectangular basement block that tilted downward to the south in the northern part of the Ottawa Embayment (*see* Fig. 3). This formed an elongated, east-trending trough that accumulated an anomalous thickness of sand and gravel, as documented from borehole data from this part of the study area (*see* Fig. 9, 13).

Within the study area, the most intensive basement movements occurred along the Oka-Beauharnois Arch, particularly the northernmost segment now known as the Oka Hills, Rigaud Mountain, and Saint-André-Est hills regions of Quebec. Major uplift of this segment of the arch resulted in the dispersal of enormous volumes of sand and gravel by fluvial processes to the west into the Ottawa Embayment, to the south into the Valleyfield Trough, and to the east into

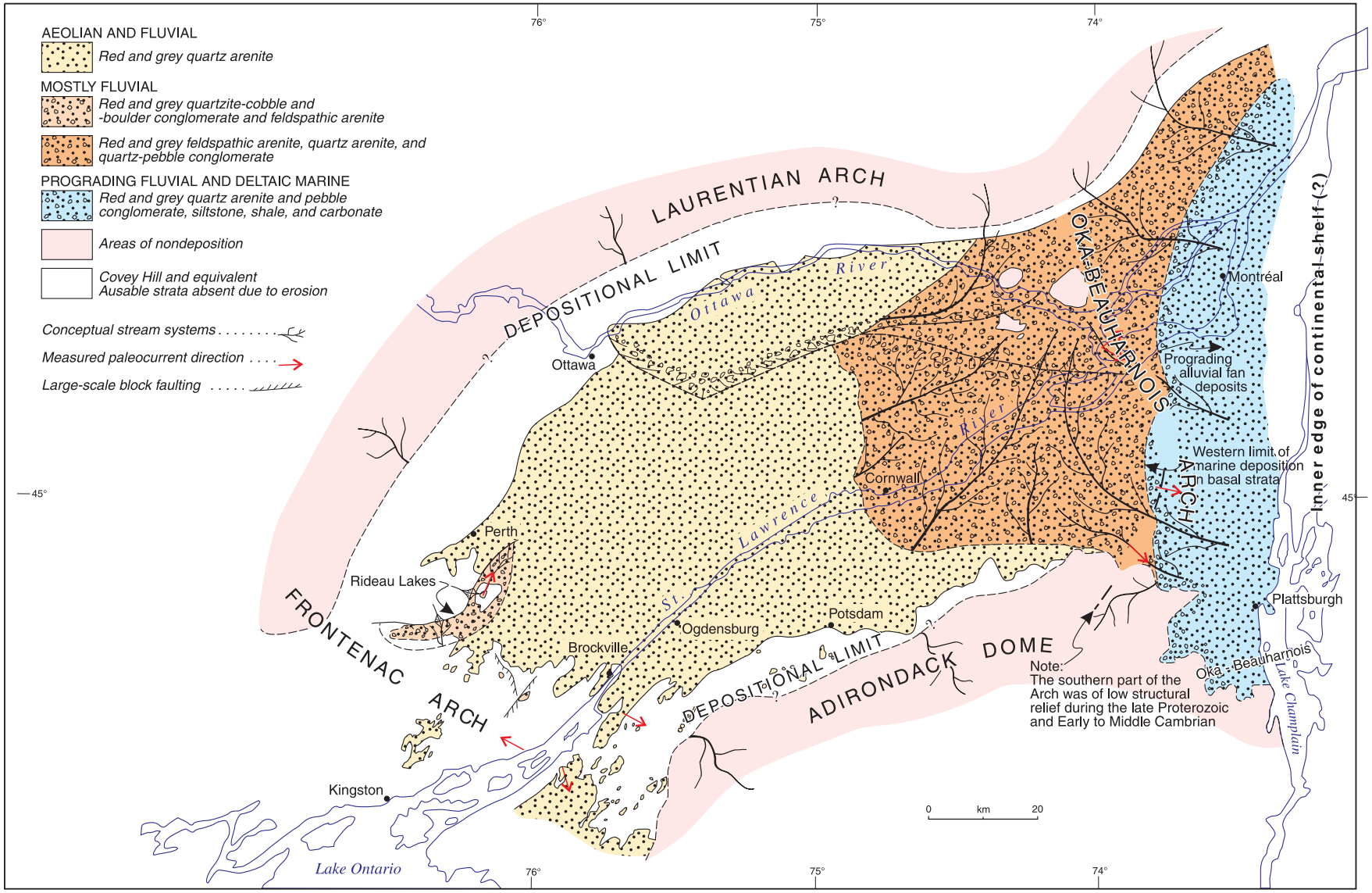


Figure 43. Depositional environments and facies distribution of the Covey Hill and equivalent Ausable formations.

the Quebec Basin (*see* Fig. 4, 9, 43). The high promontory to the south that towers above the Ottawa-Quebec Lowlands near Covey Hill was not present during the Early and Middle Cambrian and is a much younger feature related to uplift of the northeastern region of the Adirondack Mountains. Accordingly, the sediment source for the thick Covey Hill and equivalent Ausable fluvial sequences (250 m or more in the Covey Hill region of Quebec and adjacent New York State, and upward to 600 m in the Valleyfield Trough) was largely the mountainous region of the Oka-Beauharnois Arch to the north, as implied by the isopach map of those formations in Figure 13, rather than the Adirondacks.

At some point in the Middle Cambrian, for reasons that may have been related to the final cessation of continental rifting, Potsdam (Covey Hill and equivalent Ausable) deposition ceased. The ensuing hiatus was apparently long, particularly in the western part of the Ottawa Embayment, and resulted in significant erosion of Covey Hill and equivalent Ausable strata. In some regions, including the Ontario axial segment of the Frontenac Arch and the Waverly extension of the Laurentian Arch that extended into the southwestern part of Ontario, Covey Hill strata were eroded almost entirely (except for a few isolated outliers) prior to deposition of the Nepean Formation.

With the possible exception of the Jericho Member, and some beds higher in the Chippewa Bay in Quebec deposited in a marginal marine environment, each of the members of the Covey Hill and equivalent Ausable formations are interpreted to be of nonmarine origin for the following reasons:

- the absence of marine fossils and trace fossils, except for arthropod trackways that occur locally in eolian deposits near the base of the Hannawa Falls Member. Arthropods survive in marine or freshwater environments and their occurrence in strata in the Sunbury area of Ontario at station O-56 (e.g. McNaughton et al., 2002) suggests that they may have migrated a long distance from the nearest seaway and hence had become adapted to continental conditions;
- the wide occurrence of eolian sedimentary structures, including dune and wind-ripple cross-stratification, in strata of the Hannawa Falls, Chippewa Bay, and Edwardsville members. Subaqueous medium-scale (dune) cross-stratified sandstone and conglomerate of continental origin were deposited adjacent to the Frontenac and Oka-Beauharnois arches;
- the local occurrences of columnar structures inferred to have formed as potholes on the bed of fast-flowing fluvial systems during deposition of Hannawa Falls and Chippewa Bay sediments.

The definition of each of the rock units of the Hannawa Falls, Chippewa Bay, and Edwardsville members of the Covey Hill and equivalent Ausable formations is based to some degree on factors related to lithology and bedding characteristics, but with the principal emphasis on their identification in the field and subsurface on the basis of colour and iron-oxide content. Although the colour of a rock unit is not universally attributable to climatic conditions, the distinctive red staining of the Hannawa Falls and Edwardsville members and the equally distinctive grey and greenish grey of the intervening Chippewa Bay Member were indeed most likely controlled by climatic conditions that prevailed during deposition. Thus, in the regional correlation of these rock units across the Ottawa Embayment and Quebec Basin, some additional benefit is to be had in the knowledge that the sharp climatic boundaries, where these occur, can be used as 'time stratigraphic' indicators.

Redbeds in the Hannawa Falls Member most likely represent periods of aridity (low rainfall and low water table) that during early diagenesis caused iron oxide to be fixed as rims around sandstone and/or conglomerate framework grains. In general, strata of the Hannawa Falls Member contain substantially less conglomerate than the succeeding Chippewa Bay Member, which in turn suggests deposition in lower energy, ephemeral stream systems. Dust rims were succeeded, and hence preserved, by quartz overgrowths and consequently provide a unique tool for local and regional correlation (Fig. 44). The photomicrographs in Figure 44 show the well rounded and well sorted nature of the Hannawa Falls Member at the type section. At this location, strata consist of medium-scale eolian (dune) cross-stratified sandstone that contains higher concentrations of iron oxide than in the more common climbing wind-ripple structures present elsewhere in the Hannawa Falls Member. Nevertheless, a good comparison can be drawn between the two types of deposit as exposed at the type section of the Hannawa Falls Member in New York State (station N-123) and strata exposed 100 km to the north near Jones Falls, Ontario (station O-27; Fig. 45). The similarity of the strata in these two areas in terms of the presence of iron-oxide dust rims, grain size, texture, and the presence of quartz overgrowths, is compelling.

When the above-described Hannawa Falls strata are compared to the same stratigraphic interval at the opposite extremity of the study area near Lake Champlain (station N-212), some significant differences emerge with regard to sphericity, grain size, sorting, and classification of rock type (Fig. 46). In the Lake Champlain area, feldspathic arenite and quartz-pebble conglomerate strata are interpreted to be of fluvial origin, which is in sharp contrast to the eolian quartz arenite at stations N-123 and O-27, described above. Nevertheless, the presence of iron-oxide dust rims succeeded by quartz overgrowths would suggest that the strata at station N-212 were also deposited under arid climatic conditions and thus were in all probability part of the same depositional system.

In contrast to the arid conditions that prevailed during Hannawa Falls deposition, the Chippewa Bay beds are the product of a more humid environment in which the stream systems were capable of transporting much larger volumes of both fine and coarse bed-load detritus into the Ottawa Embayment and Quebec Basin (*see* Fig. 43). The coarse cobble and boulder conglomerate deposited in the Rideau Lakes and Charleston Lake areas of eastern Ontario, described previously, was deposited during this interval. At

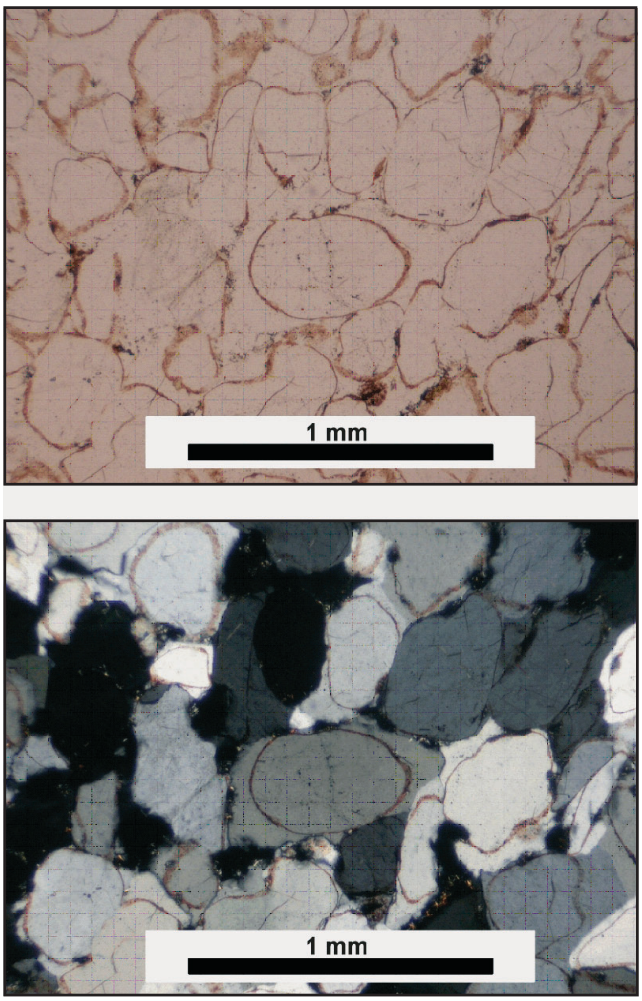


Figure 44. Photomicrographs of the Ausable Formation (Hannawa Falls Member) from the type section at station N-123, in New York State. Note red dust rims preserved by the precipitation of quartz overgrowths. Photomicrographs courtesy of J.L. Wallach.

the same time, the finer constituents presumably derived from a similar source (Frontenac Arch and, to a lesser extent, the Adirondack Dome) were likely carried into the western part of the Ottawa Embayment by fluvial systems and subsequently extensively reworked by eolian processes.

Significant volumes of iron-bearing minerals were undoubtedly transported into the basinal areas by fluvial systems during deposition of the Chippewa Bay Member. The consistent pink and red remnants of iron oxide in these strata interbanded with grey sandstone and conglomerate would suggest that the entire unit may have been deposited originally as a redbed sequence and then selectively leached. The diagnostic red dust rims that surround the individual quartz and feldspar grains (where the latter are present) in the Hannawa Falls Member are much more poorly developed in the Chippewa Bay Member. They were presumably leached during early diagenesis by an active groundwater system associated with the more humid conditions that prevailed at that time.

At a number of locations, however, iron-oxide rims overlain by quartz overgrowths are well developed in strata of the Chippewa Bay Member (Fig. 47). The purpose of thin-section sampling here and elsewhere in this particular stratigraphic interval, in the absence of any other criteria, was to establish local and regional correlation within the Chippewa Bay Member, and to distinguish it from the succeeding Keeseville and equivalent Nepean and Cairnside formations, especially in those few regions where the two formations appear to be lithologically similar. In most places this technique worked well, but nevertheless was not 100% foolproof.

The stratigraphic intervals for which this technique may not be conclusive are those where large volumes of groundwater flushed Covey Hill and equivalent Ausable strata over long periods of time, and hence removed completely the iron-oxide rims. Extensive leaching most likely occurred in the lowermost part of the sequence immediately above its unconformable contact with Precambrian rocks, as seen at station N-54 (Fig. 17), and along its upper boundary where it is overlain by the Nepean or equivalent Cairnside and Keeseville formations. In addition, deeply weathered zones, which are not uncommon in the Covey Hill and equivalent Ausable formations (e.g. station N-80), would have formed local conduits of high permeability and hence enhanced the leaching of the iron-oxide rims.

At a few localities in the eastern part of the study area in northeastern New York State and adjacent areas of Quebec, the use of thin sections would be beneficial in the identification of the Chippewa Bay Member of the Ausable (Covey Hill) Formation whether or not iron-oxide residue is present. Generally, the poorly sorted and arkosic (feldspathic) character of the Chippewa Bay Member can be recognized in a hand specimen in the field. If and when some difficulty in correlation arises, however, a thin section, such as in Figure 48, would clearly identify the arkosic rock unit as Ausable Formation.

The pink to red strata of the Edwardsville Member of the Ausable and equivalent Covey Hill formations, where these beds occur in New York State and Quebec, are lithologically similar to the more broadly distributed Hannawa Falls Member. The thinly laminated Edwardsville strata, also of probable eolian origin, are in sharp contrast to the grey Chippewa Bay strata upon which they rest with abrupt and possibly disconformable contact, such as at station N-80 (Fig. 26). This major change in colour may represent a corresponding change in climatic conditions from a period of high humidity (Chippewa Bay Member) to a period of elevated arid conditions (Edwardsville Member).

Age and regional correlation

The age of the Covey Hill and equivalent Ausable formations has long been uncertain. However, the recent breakthrough in the dating of what is herein referred to as the basal strata of the Ausable Formation (Jericho Member) by

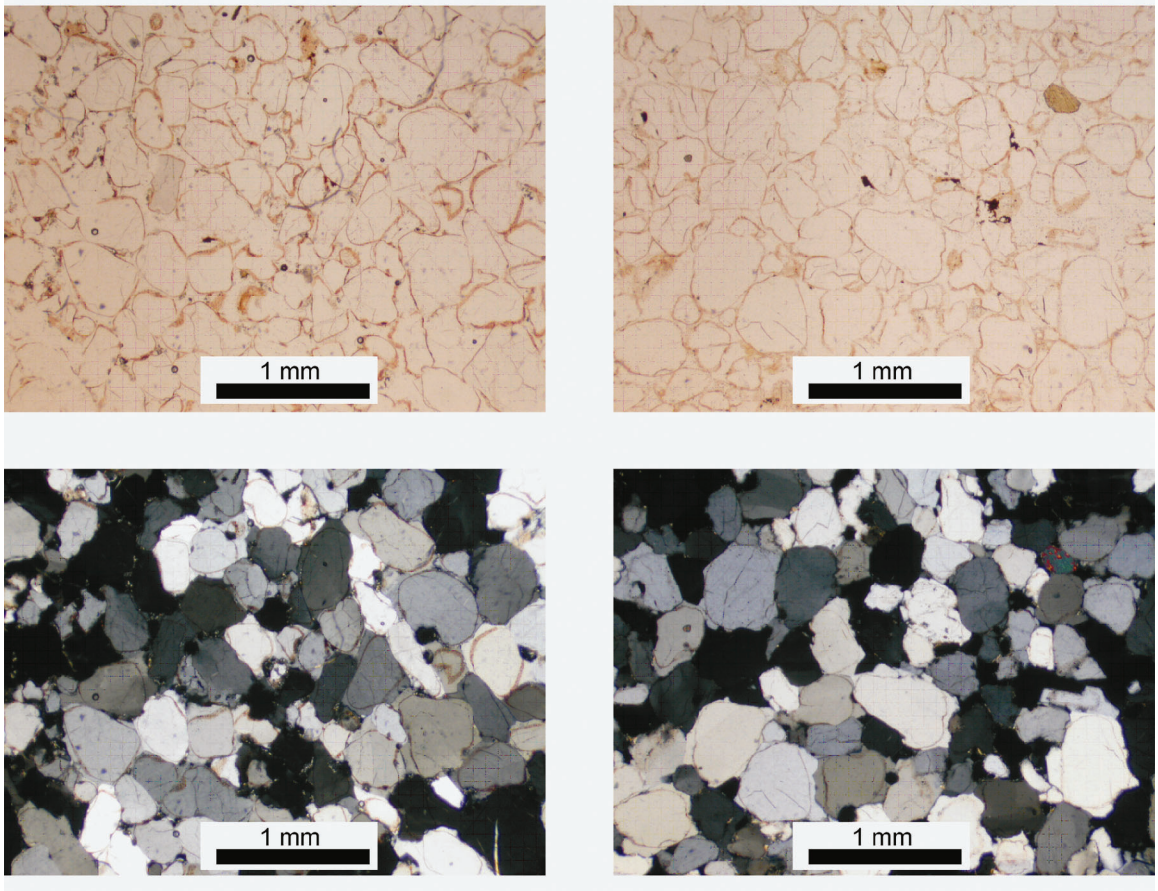


Figure 45. Photomicrographs showing the petrographic similarity of the Hannawa Falls Member in the Ausable and equivalent Covey Hill formations at stations N-123 and O-27, respectively. Note the pervasive iron-oxide dust rims and quartz overgrowths in the samples from both stations. Photomicrographs courtesy of J.L. Wallach.

Landing et al. (2007, 2009) with the discovery of diagnostic trilobite faunas, has established a late Early Cambrian to early middle Middle Cambrian age for these strata. According to E. Landing (pers. comm., 2008), the lowest Altona strata (Jericho in this bulletin) yield a terminal Lower Cambrian *Olenellus* Zone trilobite fauna and the highest strata contain a middle Middle Cambrian trilobite fauna with *Ehmaniella*.

The Covey Hill and equivalent Ausable units stratigraphically higher than the Jericho Member appear to be devoid of marine fossils within the Ottawa Embayment, but one might readily assume on the basis of their stratigraphic position that they too are Middle Cambrian. The presence of fossil trackways of the arthropod *Protichnites* sp. in terrestrial deposits of the Hannawa Falls Member near the base of the Covey Hill Formation at station O-57 has little biostratigraphic significance (Fig. 49) and only indicates that these deposits are not older than Early Cambrian.

The regional tectonics that triggered and accompanied deposition of the Covey Hill and equivalent Ausable formations may in some way be linked to rifting that began in the Neoproterozoic to Early Cambrian at the eastern extremity of the St. Lawrence Platform, as documented and summarized by Williams et al. (1995) and others. The radiometric dates of 564 to 573 Ma shown by Easton (1992) and Williams et al. (1995) for the emplacement of some mafic dykes and anorogenic plutons in southern Quebec and eastern Ontario would imply an extensional stress regime at or near the beginning of the Paleozoic, possibly continuing into the Early to Middle Cambrian throughout the Central and Western divisions of the St. Lawrence Platform.

In addition to the timing of tectonic events as established by radiometric dating along the eastern segment of the St. Lawrence Platform, is the lithological similarity of the Covey Hill and equivalent Ausable formations to rock units (Bradore and Double Mer) that overlie the Precambrian basement in southeastern Labrador and western Newfoundland Island, although they are not precisely correlative (*see* Fig. 50).

The Covey Hill and equivalent Ausable formations also have a number of lithological characteristics in common with the pre-Upper Cambrian Jacobsville and Middle Run formations of Michigan and Ohio, respectively, in the Western Division of the St. Lawrence Platform, which have been dated Grenvillian to Early and Middle Cambrian, with

the most recent emphasis placed on their association with the much older Grenvillian Orogeny (Santos et al., 2002). They consist largely of alluvial redbed lithic arenite and occupy a similar stratigraphic position, unconformably overlying Precambrian metamorphic basement and succeeded by Middle to Upper Cambrian marine quartz arenite (Mount Simon Formation). The Jacobsville Formation, where exposed along the south shore of Lake Superior in the Northern Peninsula of Michigan, was mapped in detail by Hamblin (1958) and interpreted to be Lower to Middle Cambrian. On the basis of its provenance and direction of transport, Hamblin (1958) excluded the Jacobsville from the Precambrian Keweenawan and assigned it a much younger age than had previous workers.

The Middle Run Formation, known only in the subsurface in northwestern Ohio and adjacent states, has been studied in various levels of detail by Shrake et al. (1990), Drahovzal et al. (1992), Potter (1996), Drahovzal (1997), Richard et al. (1997), Dean and Baranoski (2002), and Santos et al. (2002). Most of these authors favour a Precambrian age for the formation, but a precise age has yet to be established. Santos et al. (2002) documented a mainly Grenvillian source for the Middle Run Formation on the basis of the dating of detrital zircon, but this procedure proves only that the formation is likely younger than the Grenville, although how much younger is open to speculation. Richard et al. (1997) suggested an Eocambrian to Early Cambrian age for the Middle Run, which is consistent with the age proposed by Hamblin (1958) for the Jacobsville in the adjoining area of the Michigan Basin, both of which are roughly comparable to the dating of the latest Precambrian and Lower to Middle Cambrian sequences contained within the Central Division of the St. Lawrence Platform (*see* Fig. 50).

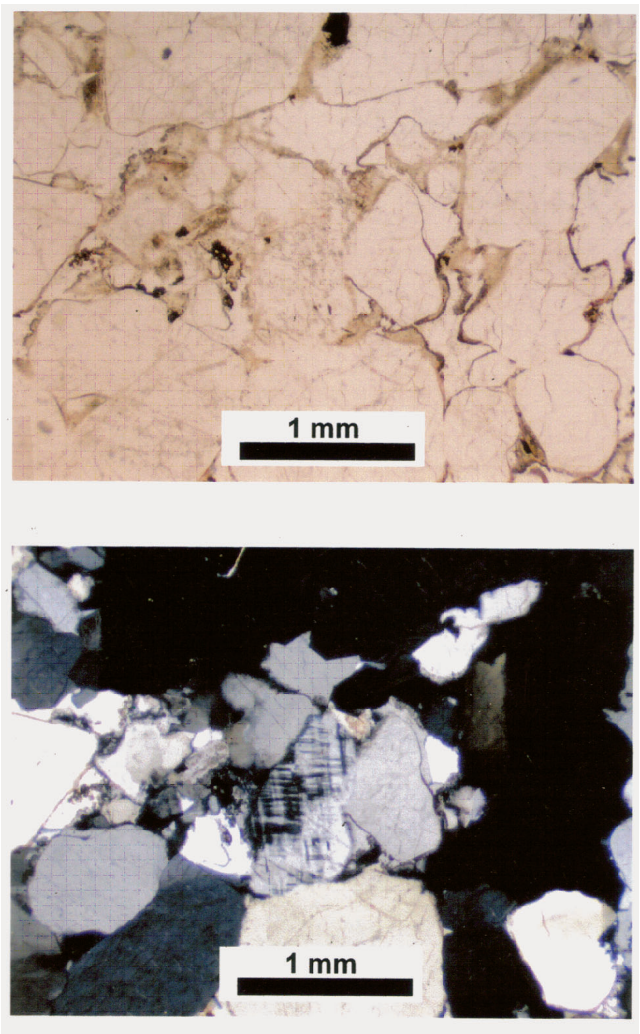


Figure 46. Photomicrographs of the Ausable Formation (Hannawa Falls Member) at station N-212, near Lake Champlain, New York. Note the coarse texture of the framework and the presence of feldspar (microcline) and red dust rims surrounding the sand- and pebble-sized grains. Photomicrographs courtesy of J.L. Wallach.

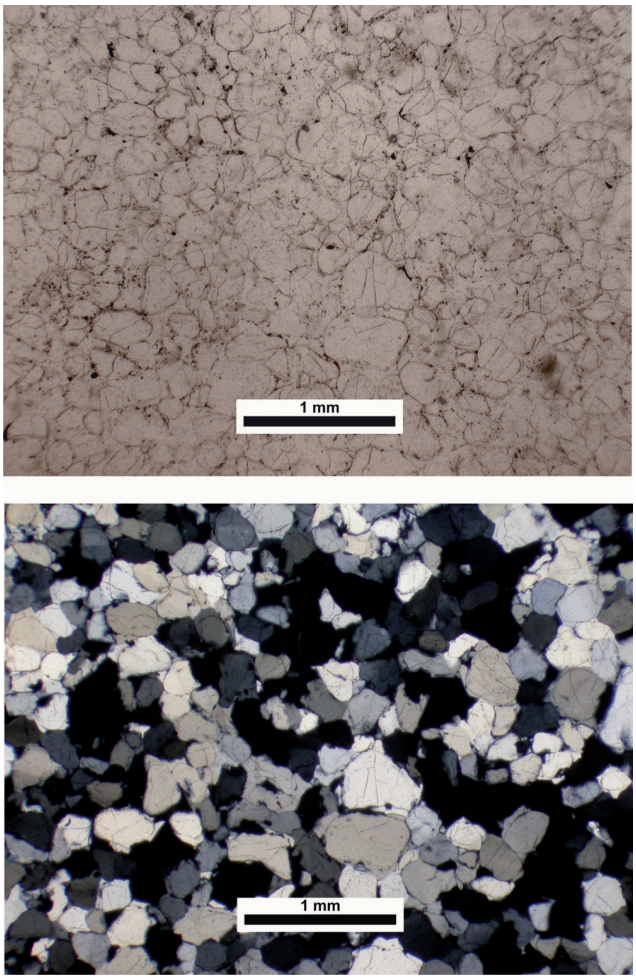


Figure 47. Photomicrographs of the Ausable Formation (Chippewa Bay Member) from the type section at station N-80. Note the traces of red iron-oxide residue dispersed throughout the interstices of the sandstone. Photomicrographs courtesy of J.L. Wallach.

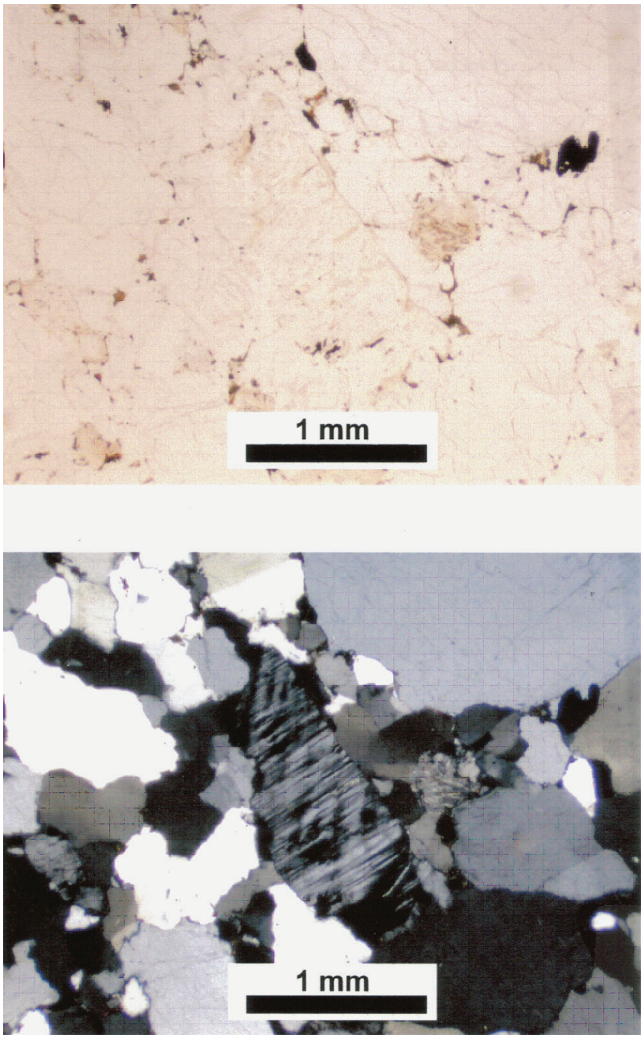


Figure 48. Photomicrographs of the Ausable Formation (Chippewa Bay Member) at station N-152 in New York State. Note the traces of iron-oxide staining, the coarse texture of the framework, and the presence of a large feldspar (microcline) clast similar to that identified in Figure 46 sampled from the Hannawa Falls Member at station N-212. Photomicrographs courtesy of J.L. Wallach.

Midway between the type sections of the Middle Run and Jacobsville formations is the McClure Oil Co., R. and J. Sparks, K. and V. Eckelbarger, R. Whightsil No. 1-8 deep borehole, which was completed in the approximate structural center of the Michigan Basin (Brown et al., 1982). A stratigraphic log of the lowermost sedimentary strata penetrated in this borehole between the approximate depths of 12 060 and 16 306 feet (3676 and 4971 m; D. Michael Bricker, Michigan Geological Survey, pers. comm., 2006) is a red-bed sequence of strata not unlike the Jacobsville of northern Michigan and the Middle Run of northwestern Ohio. This would strongly suggest that the basal redbeds of those two formations may well be a horizontally continuous stratigraphic sequence in subsurface throughout this region of the Michigan and Appalachian basins, as originally speculated by Cohee (1945).

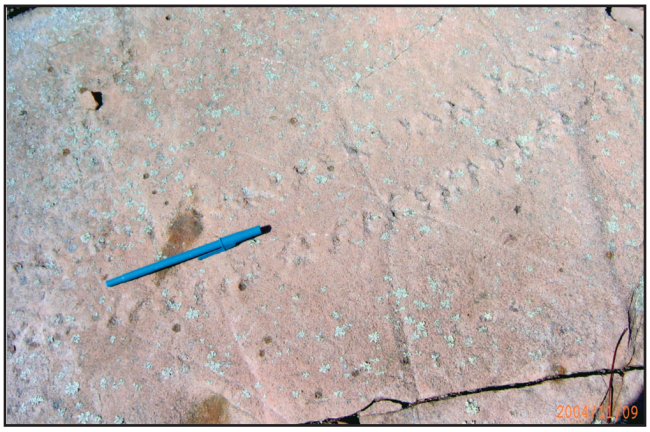


Figure 49. Trace-fossil trackway of the arthropod *Protichnites* sp. in eolian sandstone of the Hannawa Falls Member (Covey Hill Formation), Sloan Quarry, Ontario, at station O-57. Photograph by B.V. Sanford. 2008-089

The original deposition of the Potsdam Group in the Quebec Basin and Ottawa Embayment probably extended well beyond the margins of the Frontenac Arch to the west, through central and southwestern Ontario. Major uplift of the Laurentian Arch and its western extension, the Waverly Arch, resulted in erosion of much of the Covey Hill Formation, and only remnants of that formation were locally preserved (*see* Fig. 51). The tiny remnant of Covey Hill Formation near Gananoque at station O-52, the Ellisville outlier, and the large outlier near Sunbury at stations O-56, O-69, and O-57, are three such remnants. Others were recorded farther to the west by the first author during earlier investigations near Burleigh Falls (Sanford, 1993c, section 29, Fig. 2, p. 255) and near Burnt River at the base of section 18 (location identified in Sanford, 1993c, Fig. 2), and in boreholes drilled by Imperial Oil Enterprises in the Niagara Peninsula, Ontario. Jacobsville sandstone (Covey Hill equivalent) was reported in boreholes drilled along the south shore of Georgian Bay by Roliff (1954), and on Cockburn Island near the western extremity of Manitoulin Island by Cohee (1945).

The presence of scattered Covey Hill outliers as described above throughout central and southwestern Ontario, along with the remarkable lithological similarity to Covey Hill and Ausable strata in the Quebec Basin and Ottawa Embayment and beyond to Michigan and Ohio and their regional correlation with Middle Cambrian rocks in Newfoundland Island and Labrador suggest that all these respective stratigraphic sequences may have been once interconnected, as implied in Figure 50.

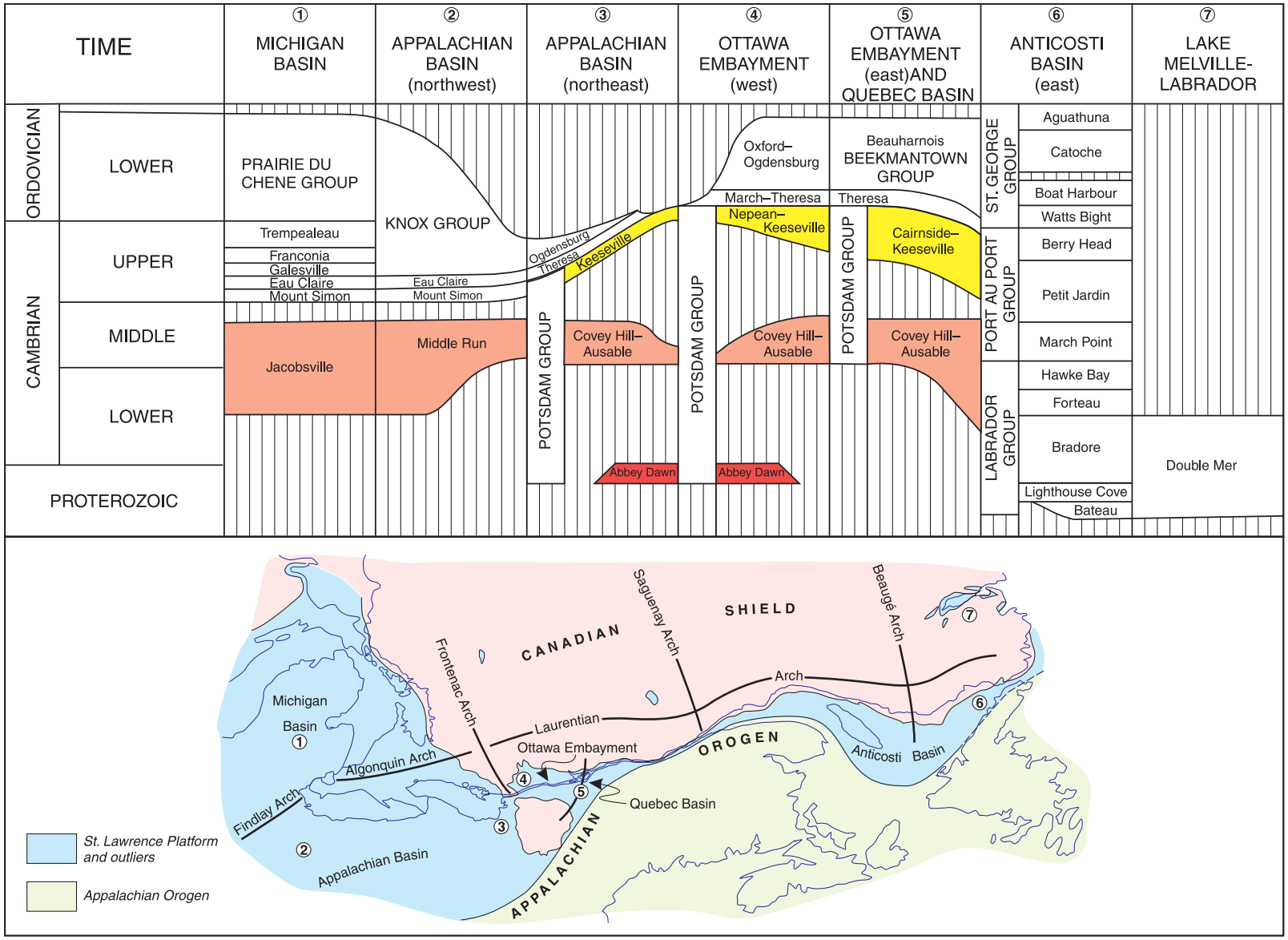


Figure 50. The Potsdam Group in the Ottawa Embayment and Quebec Basin and its possible stratigraphic relationship to Lower Cambrian to Lower Ordovician strata in adjacent regions of the St. Lawrence Platform.

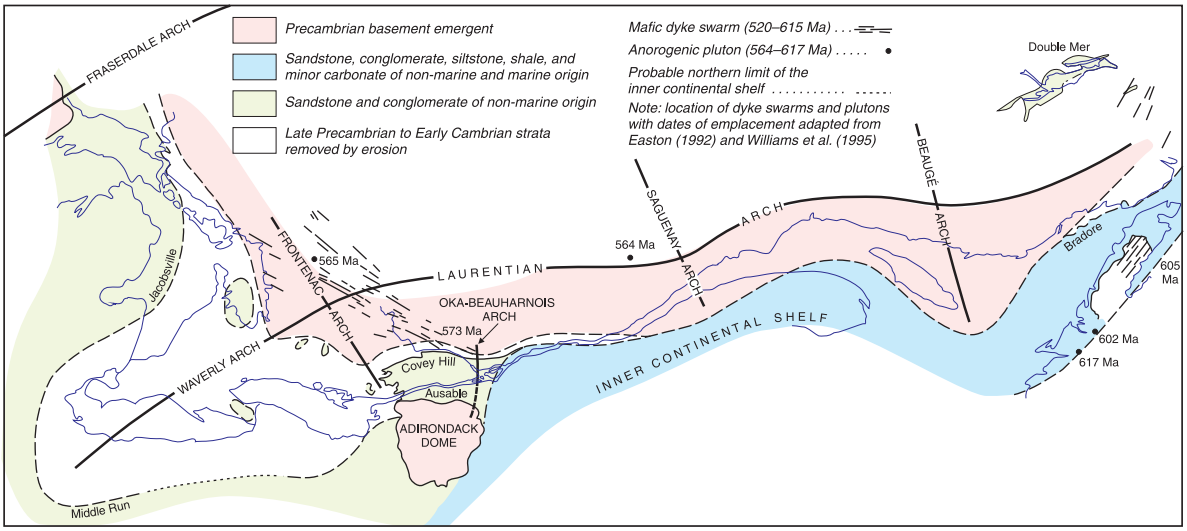


Figure 51. Paleogeography of the Lower to Middle Cambrian depositional sequence (*modified from* Sanford, 1993b).

NEPEAN AND EQUIVALENT CAIRNSIDE AND KEESEVILLE FORMATONS

Definition

The Nepean Formation in Ontario and its approximate equivalents the Cairnside and Keeseville formations in Quebec and New York State, respectively, are composed of white and light grey upper Middle and Upper Cambrian to Lower Ordovician quartz arenite. The beds are mostly of marine origin and form the youngest rock units of the Potsdam Group in the Quebec Basin and Ottawa Embayment. Throughout much of the study area, the beds unconformably overlie substantially older strata of the Potsdam Group, one or another of the Hannawa Falls, Chippewa Bay, or Edwardsville members that constitute the Covey Hill and equivalent Ausable formations. Such stratigraphic relationships are largely continuous across the Frontenac Arch in New York State, as shown in Figure 3; however, the areal distribution of the Keeseville and Ausable formations on the western side of the arch beneath younger rocks of the Theresa Formation is obscure due to the absence of any known deep-borehole data in that region. Quite different conditions prevail north of the St. Lawrence River in Ontario, where the Nepean Formation can be seen to overlap the Covey Hill Formation and overlie Precambrian rocks, only remnants of which are preserved locally across the higher structural segments of the Frontenac Arch.

One such exposure (outlier) among many others, where the Nepean has overlapped the Covey Hill to rest directly on Precambrian rocks, is located near Gananoque, Ontario, at station O-51 (Fig. 52a). Some 40 km east of Gananoque, near Hammond, New York, at station N-96, a section shows the Nepean equivalent — the Keeseville Formation — resting unconformably on the Ausable Formation (Covey Hill equivalent; Fig. 52b); the two units combined are commonly referred to as the 'Potsdam Formation' in this part of the state. In addition to the remarkable lithological similarity of the Nepean and Keeseville formations as seen in Figure 52, such a comparison should also put to rest the long-held misconception that the Nepean Formation, as originally defined by Wilson (1946), in the Ottawa region is stratigraphically equivalent to the 'Potsdam Formation' of New York State.

Throughout the Ottawa Embayment and Quebec Basin, the Nepean Formation is succeeded, usually with abrupt contact, by interbedded dolostone and sandstone of the March Formation in Ontario and by its lithologically similar counterpart, the Theresa Formation, in Quebec and New York State.

In the western part of the study area, key sections have been identified where the Potsdam Group strata are best exposed. These are identified in Figure 7 and their precise locations are recorded in Appendix A. At several localities in Ontario and New York State, either the lower or upper contact of the Nepean or Keeseville Formation with older and younger rocks respectively is exposed. Nowhere in Ontario has the full thickness of the Nepean Formation been observed in outcrop, although at a number of locations it is nearly so. In New York State on the other hand, the Keeseville Formation can be viewed from bottom to top at two closely spaced locations where both its lower contact with the Ausable Formation and its upper boundary with the Theresa Formation are exposed. These locations are near Blind Bay just off Route 12, at stations N-89 and N-90 (Fig. 53a), both of which are herein designated as reference sections.

Throughout the eastern part of the Ottawa Embayment and the western part of the Quebec Basin, the Keeseville and Cairnside formations are mostly poorly exposed, much like the underlying Ausable and equivalent Covey Hill formations. Stratigraphic relationships of the Keeseville and Cairnside strata with older and younger units in this eastern region are also poorly known, as their contacts are

mostly obscured beneath Quaternary surficial deposits. Nevertheless, some success was had in viewing a significant part of the Keeseville and Cairnside composite succession (*see* Fig. 8) to establish the remarkable lithological uniformity of these strata within this part of the study area. With the exception of the Chateaugay River gorge (station N-130) and Ausable Chasm (station N-215), very few exposures of Keeseville and equivalent Cairnside formations would rate being referred to as key sections.

What may be some of the more useful information for establishing a clear-cut definition of the Nepean and equivalent Cairnside and Keeseville formations was gleaned from stratigraphic logs of the cored boreholes completed to date in the western part of the Quebec Basin and Ottawa Embayment. The remarkable uniform lithological characteristics in terms of composition and colour of the formations are such that they are readily recognizable in subsurface and can thus be traced from borehole to borehole, as shown in the detailed logs (Fig. 9) and cross-sections (Fig. 4).

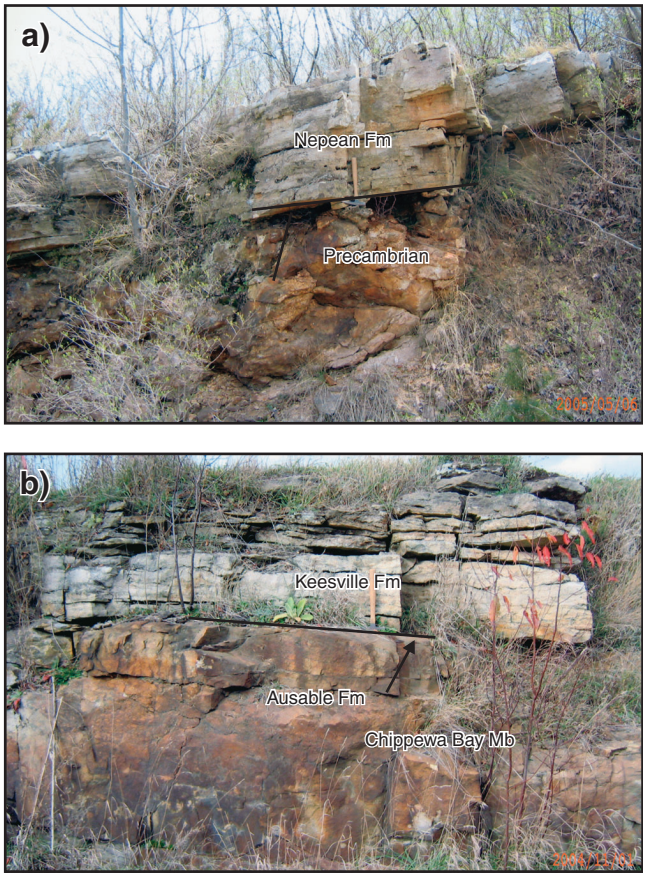


Figure 52. Nepean Sandstone in eastern Ontario and equivalent Keeseville strata in northern New York State, illustrating the lithological similarity of the two units throughout the western part of the Ottawa Embayment. **a)** Nepean Formation overlying Precambrian rocks in a roadcut on Highway 2 near Gananoque, Ontario, at station O-51. Photograph by B.V. Sanford. 2008-090 **b)** Keeseville Formation unconformably overlying the Ausable Formation (Chippewa Bay Member; contact at black line) on Black Lake Road near Hammond, New York, at station N-95. Photograph by B.V. Sanford. 2008-091

Distribution and thickness

The Nepean and its counterparts Cairnside and Keeseville formations are widely distributed in the Quebec Basin and Ottawa Embayment, as shown in Figures 3 and 4. Their outcrop belt essentially parallels that of the underlying Covey Hill and Ausable formations throughout most of this area, except in the northwestern part of the Ottawa Embayment where the Covey Hill and Ausable units were eroded prior to deposition of the Nepean Formation and its counterparts, and where the Nepean and Keeseville formations directly overlie Precambrian rocks. Stratigraphic overlap is particularly evident in the western and northwestern parts of the Ottawa Embayment, particularly west of a northeast-oriented line drawn from near Perth to the Gloucester Fault just south of Ottawa, where the Nepean Formation overlaps the eroded edge of the Covey Hill Formation to overlie directly Precambrian rocks. From this line, the Nepean Formation extends to the northwest where it eventually pinches out near Pakenham (*see* Fig. 3, 54).

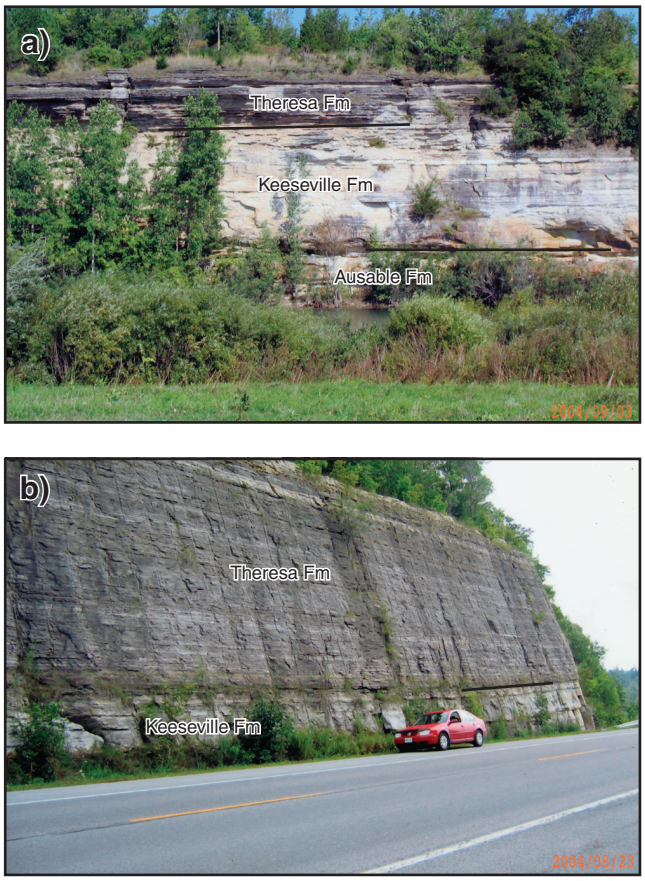


Figure 53. Ausable, Keeseville, and Theresa succession in the Blind Bay area of northern New York State. **a)** View from Pleasant Valley Road near its intersection with Route 12 at station N-89. Here, a complete section (8.8 m) of Keeseville Formation is exposed; it unconformably overlies the Ausable Formation (Chippewa Bay Member) and is conformably overlain by the Theresa Formation (contacts at black lines). Photograph by B.V. Sanford. 2008-092 **b**) Keeseville–Theresa contact (black line) in a nearby roadcut on Route 12, at station N-89. Photograph by B.V. Sanford. 2008-093

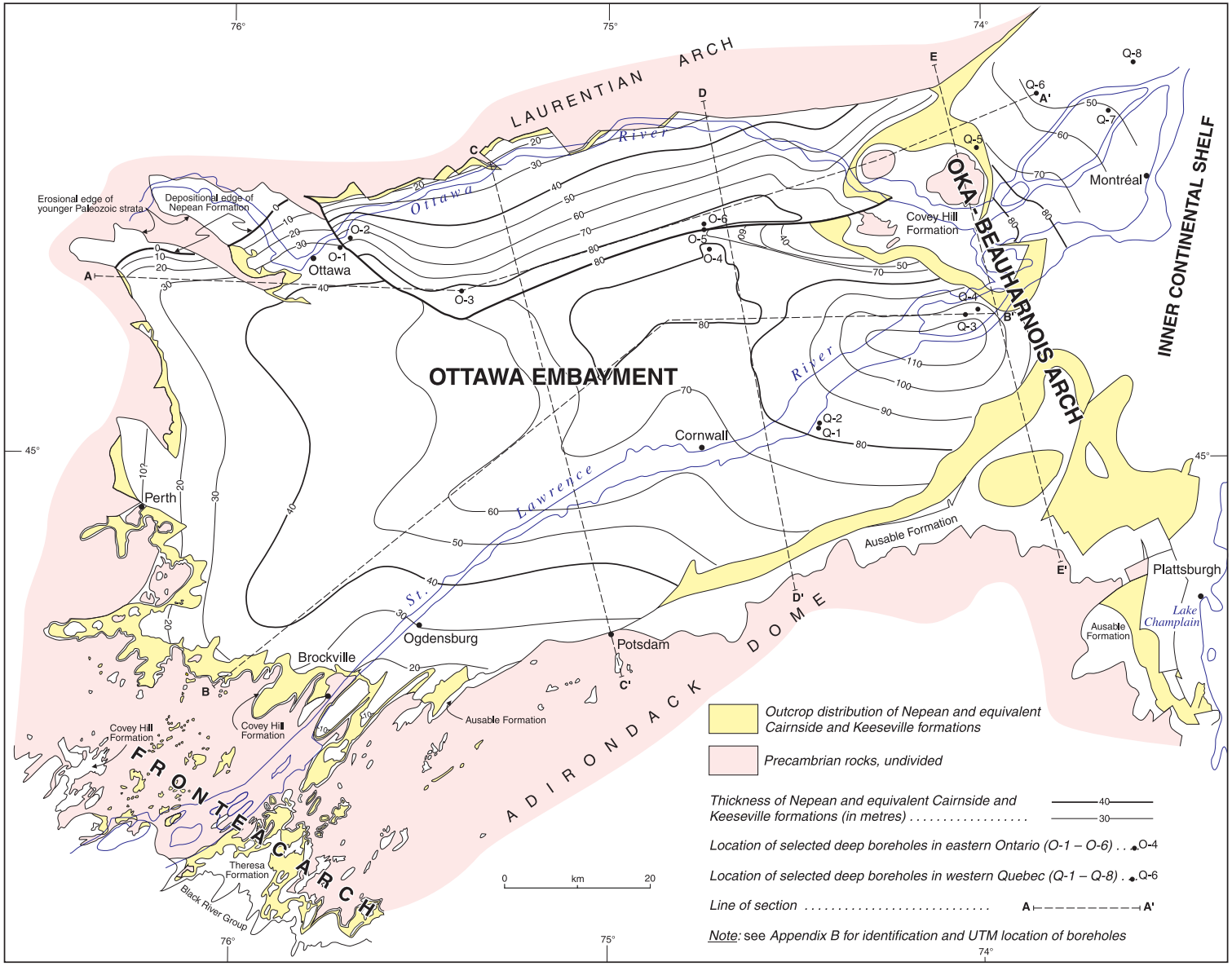


Figure 54. Isopach map showing the distribution and thickness of the Nepean and equivalent Cairnside and Keeseville formations in eastern Ontario, western Quebec, and northern New York State.

Similar conditions occur locally immediately south of the St. Lawrence River in New York State, beginning in the Wellesley Island area and extending for some distance to the southwest, where the Keeseville Formation overlaps the Ausable Formation to lie directly on Precambrian rocks. From the above findings it is evident that the Nepean and Keeseville formations once formed a continuous blanket deposit across the Frontenac Arch and extended into central Ontario, along with successively younger Ordovician formations. Much of the Nepean and younger Ordovician formations have long since been removed by erosion.

In the Thousand Islands region of New York State, a precise thickness of 8.8 m for the Keeseville Formation was obtained where the formation is completely exposed at a single locality on a side road off Route 12 leading to Blind Bay at station N-90, and in a nearby section near the intersection of Route 12 and Pleasant Valley Road at station N-89 (Fig. 53a). Thicknesses may be similar or even less to the southwest, where the Keeseville Formation crosses the higher structural axis of the Frontenac Arch in New York State.

In Ontario, the Nepean Formation forms an almost continuous outcrop belt from Brockville to Pakenham along the eastern margin of the Frontenac Arch. Immediately west of Brockville, the formation is at least 15 m thick at station O-64 at the Lyn Valley Conservation Area. From there it thickens northward along the outcrop belt bordering the Frontenac Arch to 30.5 m at station O-66 near Athens. From Athens north to Ottawa, partially exposed sections are 1 to 5 m thick, the more common thicknesses recorded for the Nepean Formation along the outcrop belt. On the west side of the Gloucester Fault, where it passes through Ottawa in the Dow's Lake area, the Nepean Formation is 30.9 m thick as recorded in the Dominion Observatory No. 1 borehole (*see* Fig. 9).

Sandstone units of the Cairnside and equivalent Nepean formations, contained mostly in a series of tilted fault blocks, have been mapped eastward along the northern margin of the Ottawa Embayment from Gatineau to near Montebello, Quebec (Wilson, 1946; Baird, 1972). East of Montebello, the beds are obscured beneath younger rocks along the downdropped side of the Lachute Fault (*see* Fig. 3).

Along the southwest and south sides of the Ottawa Embayment bordering the Adirondack Mountains, from Black Lake to near Potsdam, New York, the Keeseville Formation is exposed locally, but is mostly obscured beneath downfaulted strata of the Theresa Formation (*see* Fig. 3). It again rises to surface at Brasher Falls, New York, where 2 or 3 m of section are exposed and from where it forms a continuous outcrop belt throughout the remaining distance to the type locality at Keeseville, New York, near the shore of Lake Champlain.

The precise thickness of the Keeseville Formation and the equivalent Cairnside Formation where applicable, is unknown along this stretch of terrain, but from the isopachs of Figure 54, a progressive eastward thickening can be seen to prevail, from 8.8 m at Blind Bay (station N-90) to more than 80 m where the formation approaches the southern extension of the Oka-Beauharnois Arch near Chateaugay, New York.

High above the Quebec Lowlands, mostly contained on the New York State side of the international boundary, is an isolated outlier of Keeseville Formation (*see* Fig. 3, 9, section E-E'). Its presence in this region at an altitude in excess of 200 m above its elevation north of the Stockwell Fault, indicates major uplift of this segment of the Oka-Beauharnois Arch some time after its deposition.

A short distance north of the Stockwell Fault, the Cairnside Formation dips beneath younger rocks of the Theresa Formation along the axis of the Valleyfield Trough. North of the trough the beds again rise to surface to form a halo-like surface expression around the Oka Hills, Rigaud Mountain, and Saint-André-Est hills that collectively form the most northern and prominent part of the Oka-Beauharnois Arch.

Thicknesses of the Keeseville and Cairnside formations along the axis of the Oka-Beauharnois Arch area in New York State and Quebec are unknown because of the relatively thin exposures of those formations in surface outcrops in both areas. On the northeast side of the arch bordering Lake Champlain in New York State, the precise thickness of the Keeseville is also unknown. Fisher (1968) reported a thickness of 455+ ft. (139 m) for the Potsdam sandstone exposed in the Ausable Chasm. It is not completely clear whether Fisher intended the 455+ ft. to include only the Keeseville Formation, or also some of the underlying strata of the Ausable Formation.

In the subsurface regions of the Ottawa Embayment, the Nepean and equivalent formations thicken progressively eastward from a minimum known thickness of 30.9 m in the Ottawa area to a maximum of 110 m in the extreme eastern end of the Ottawa Embayment (*see* Fig. 54). From the isopachs one can conclude that the Ottawa Embayment was likely an enclosed basin bounded by arch systems during deposition of the Nepean and equivalent Cairnside and Keeseville formations. On the east side of the Oka-Beauharnois Arch, the Cairnside thins substantially into the Quebec Basin, as shown in Table 5 and Figure 54.

Table 5. Thickness of the Nepean (Cairnside) Formation in subsurface

Borehole	Thickness	Borehole	Thickness
Dominion Observatory No. 1	30.9 m	St. Lawrence River No. 1	107.3 m
GSC Lebreton No. 1	70.3 m	Gastem - Dundee No. 1	82.6 m
GSC Russell No. 1	84.5 m	Gastem - Dundee No. 2	75.5 m
GSC McCrimmon No. 1	65.8 m	Mallet Test No.1	43 m
Imperial Oil Ltd., Laggan No. 1	85.1 m	Quonto-International St. Vincent de Paul	52 m
Consumers Gas No. 12023	84.3 m	Quonto-International No. 1 Mascouche	49 m

As during the preceding Covey Hill depositional period, anomalous thickening of the Nepean Formation appears to have prevailed within the downfaulted block that occupies the northern part of the Ottawa Embayment. From its northern eroded edge, the Nepean Formation thickens to more than 80 m in the lower structural segment of the half-graben that is bounded on the west by the Gloucester Fault and on the south by the Russell-Rigaud Fault. That this structure was in place at the beginning of the Nepean depositional period can best be demonstrated by comparing the difference in thickness of the formation on opposite sides of those major fault systems. This can be done with some degree of accuracy in the Ottawa area, where the Dominion Observatory No. 1 borehole on the west side of the Gloucester Fault penetrated 30.9 m of Nepean Formation, whereas less than 1 km to the east on the downdropped side of the fault, the thickness recorded in the GSC Lebreton No. 1 borehole is 70.3 m. A similar comparison can be drawn at the eastern end of the Russell-Rigaud Fault near McCrimmon, where a similar discrepancy in the thickness of the Nepean Formation was established by comparing the 65.8 m of Nepean strata in the GSC McCrimmon No. 1 borehole and the 84.3 m encountered in the nearby Consumers Gas No. 12023 borehole, drilled on the downdropped side of the fault.

Table 5 lists the thickness of the Nepean and equivalent Cairnside formations in the succession of boreholes extending across the northern part of the Ottawa Embayment and into the Quebec Basin.

Lithology and stratigraphic relationships

The Nepean and its counterpart Keeseville and Cairnside formations have remarkable lithological similarity throughout the Ottawa Embayment and western part of the Quebec Basin. The beds are mostly white, cream, and light grey and weather medium to dark grey and locally brick-red, the last a surficial discolouration more common to the lower beds of the Nepean Formation in parts of eastern Ontario and adjacent areas of New York State. The beds are composed largely of quartz arenite and commonly contain a basal conglomerate comprising quartz-pebble and/or quartzite-cobble clasts.

Where the complete section of Keeseville Formation is exposed at stations N-89 and N-90 near Blind Bay, New York, it is composed of white and light grey quartz arenite (Fig. 53a, 55a, b) that unconformably overlies the Chippewa Bay Member of the Ausable Formation. The upper contact of the Keeseville with the Theresa is well exposed on Route 12, a few metres west of the section at station N-89 (Fig. 53b). Here the contact is sharp and apparently conformable.

A short distance northwest of station N-89, the other complete section of the Keeseville Formation is exposed at station N-90 on a short side road off Route 12 leading to Blind Bay (Fig. 55a, b). At this location, a quartzite-pebble and -cobble conglomerate at the base of the formation unconformably overlies the Chippewa Bay Member of the Ausable Formation. This 30 cm thick trough crossbedded conglomerate is succeeded with abrupt contact by finely laminated, highly bioturbated quartz arenite (Fig. 55b).

The sharp break in sedimentation processes between the basal conglomerate and the overlying laminated beds could imply that the former were deposited in a fluvial environment before transgression of the Keeseville sea. There are other areas in Ontario, New York State, and Quebec where a thin conglomerate and/or unbioturbated planar- or cross-stratified sandstone unit was deposited before the onset of marine-influenced depositional conditions. The most

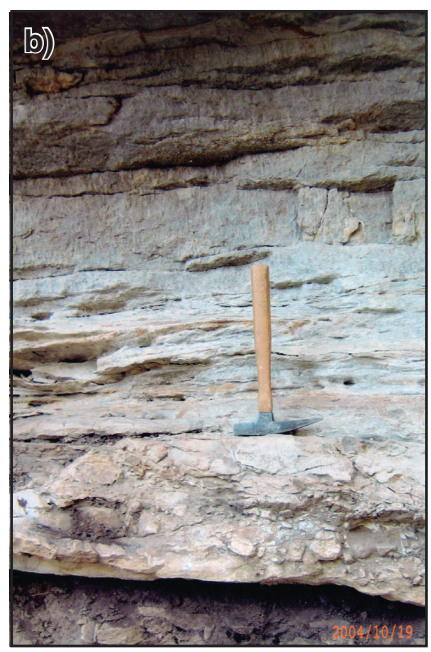


Figure 55. Grey and white, thinly bedded Keeseville Formation resting on the Ausable Formation (Chippewa Bay Member) near Blind Bay, New York, at station N-90. **a)** The white line marks the unconformable contact between the Ausable Formation (Chippewa Bay Member) and the Keeseville Formation identified by the hammer head. Photograph by B.V. Sanford. 2008-094 **b)** Close-up of the Keeseville Formation, showing trough cross-bedded quartzite-cobble conglomerate and breccia at the base of the formation, and intense vertical bioturbation above the hammer handle. Photograph by B.V. Sanford. 2008-095

notable of these in Ontario is on Highway 15, at station O-17 (Fig. 32), and in Quebec in the Lièvre River valley at Masson, at station Q-16 (*see* Fig. 3, 6), and in New York station N-4.

Many good exposures of Keeseville sandstone occur elsewhere throughout the Thousand Islands region of New York State. At 12 of these locations (Table 2), the formation unconformably overlies the Ausable Formation.

A good example of the unconformable relationships that prevail between the Keeseville and Ausable formations in this region of the state can be seen about 1 km west of Redwood, at station N-39 (Fig. 56a, b). Here, the Chippewa Bay Member of the Ausable Formation is assumed to have been deformed prior to deposition of the Keeseville Formation, and the flat-lying Keeseville strata are thus in angular discordance with the beds below the unconformity. Approximately 3 m of Keeseville light grey quartz arenite are exposed at this locality, in sharp contrast to the 20+ m of the underlying Ausable beds that are exposed along the steep incline of the road (Fig. 56a, right). The origin of the pea-sized spherical and elliptical cavities at the base of the Keeseville Formation (Fig. 56b) is not fully understood. They may have originally formed as tiny algal and/or calcite accretionary nodules ((?) pisolites) that were removed by dissolution at a later period of geological time (Pettijohn, 1957, p. 95 and 391).

Throughout most of the study area, the Nepean Formation and its equivalents unconformably overlie the Chippewa Bay Member of the Ausable (Covey Hill) Formation and, at a minimum of two locations in Ontario, the Hannawa Falls Member. At stations N-13, N-109, N-88, and N-80 in the Thousand Islands region of New York State, trace-fossil-rich Keeseville strata lie on stratigraphically higher beds of the Edwardsville Member of the Ausable Formation. One of the better examples is the reference section at station N-13 near Alexandria Bay, where the Keeseville Formation, slightly less than 2 m thick, can be readily distinguished from the Edwardsville Member by its slightly darker weathering colour (Fig. 57a). The contact can also be readily recognized by its irregular character and by the presence locally of thin planar crossbeds at the base of the Keeseville Formation that dip to the east. Normal marine fossils are present in the Keeseville at this locality, although they are poorly preserved and unidentifiable.

A similar unconformable relationship between the Keeseville Formation and the Edwardsville Member of the Ausable Formation was noted in a roadcut on Route 12 near Duck Cove, at station N-80. The excellent section of Ausable strata exposed at this site (Fig. 26) is succeeded by the Keeseville Formation at the eastern end of the roadcut (Fig. 57b). The Ausable strata are tilted slightly to the northeast and thus appear to be in minor angular discordance with the overlying Keeseville strata. The Keeseville is intensely bioturbated here and elsewhere in this part of the study area.

An excellent section of Keeseville Formation occurs farther south of the above-described exposures, where Interstate 81 crosses Wellesley Island, New York, at station N-4 (Fig. 58a, b). Neither the lower nor the upper contact with older and younger rocks is exposed, although the formation at this station is readily assumed to rest directly on granitic rocks of the Grenville Province. The lower 1.8 m are coarse quartzite-cobble conglomerate containing interlayers of light grey kaolinite. These are succeeded by 4 to 5 m of thin, uniformly bedded, white to light grey and yellowish-orange fossiliferous quartz arenite containing a few quartz pebbles and quartzite cobbles in the lower part. A few tens

Figure 56. Ausable–Keeseville contact 1 km west of Redwood, New York, at station N-39. **a)** The sharp boundary between the two formations is marked by an angular unconformity. Photograph by B.V. Sanford. GSC 2008-096 **b**) Close-up of the contact showing vast differences in the physical appearance of the two rock units. Note the pea-sized spherical and elliptical cavities at the base of the Keeseville Formation, possibly of algal and/or calcite accretionary origin. Photograph by B.V. Sanford. 2008-097

of metres north at the same exposure, the beds are intensely trough crossbedded with average paleocurrent direction toward the southwest at 232º.

In Ontario, good exposures of the Nepean Formation were noted along the east side of the Frontenac Arch from Brockville to Ottawa, as well as at isolated locations along the axis of the arch, and locally to the west of the Frontenac Arch. In at least nine of these locations, the Nepean Formation unconformably overlies the Covey Hill Formation (*see* Table 2).

In addition to the above-recorded stations where the Nepean–Covey Hill contact is well displayed, the Nepean Formation can be seen to rest directly on Precambrian rocks at two widely separated exposures, i.e. at station O-51 near Gananoque and at station Q-1 at Lac Beauchamp Park in Gatineau, Quebec. At other locations, the basal contact with Precambrian rocks is obscured by only a few centimetres of Quaternary sediment, notably on the shore of Mississippi Lake at station O-12.

One of the more complete sections of Nepean Formation is exposed in a cliff section at the Lyn Valley Conservation Area, on the eastern outskirts of Lyn, at station O-64. The basal unit of the formation exposed near the park entrance unconformably overlies the Chippewa Bay Member of the Covey Hill Formation and is composed of brown sandy limestone 1 m thick, containing large, well rounded quartzite cobbles at its base (Fig. 11). The remainder of the formation occurs a few metres laterally, where 15 m of white quartz arenite are contained in thick, massive layers (Fig. 59).

In contrast to the clean, white, trace-fossil-rich quartz arenite exposed at Lyn, Nepean strata in a roadcut on Highway 42, near Philipsville, Ontario, at station O-33, were deposited in a lower energy environment in the Ottawa Embayment (Fig. 60). The thin, uniform grey Nepean beds are 4.5 m thick and are here overlain with sharp contact by the March Formation. The slight angle of discordance observed between the Nepean and March formations (Fig. 60, upper right) suggests a minor hiatus in deposition between the two.

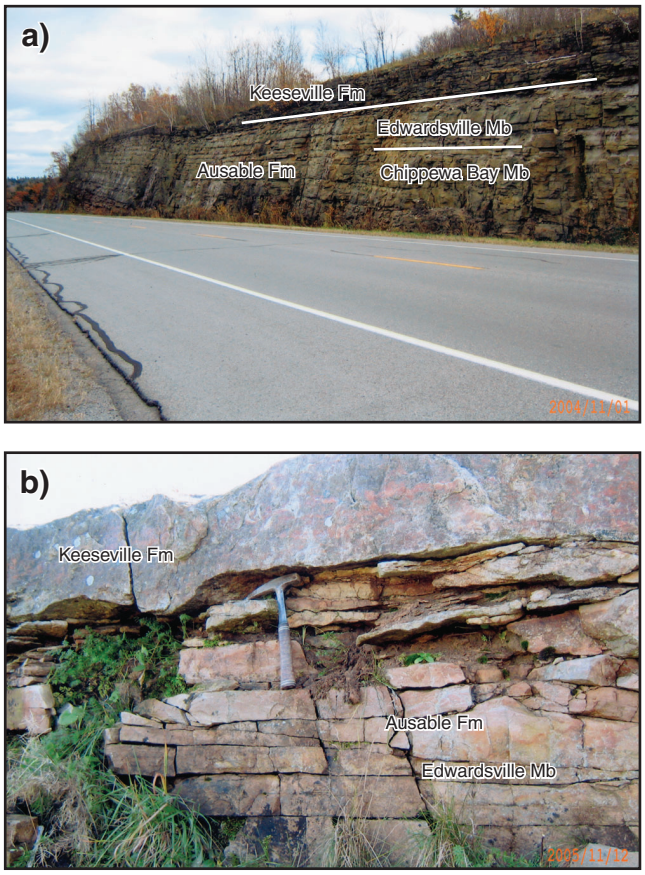


Figure 57. Keeseville Formation unconformably overlying the Ausable Formation on Route 12, New York State. **a)** Darker grey beds at the top of the section are the Keeseville Formation resting on the grey and pink Edwardsville Member of the Ausable Formation at station N-13. The white lines mark the contacts. Photograph by B.V. Sanford. 2008-098 **b**) Grey sandstone of the Keeseville Formation (above hammer) resting with slight angular discordance on thinner beds of the Edwardsville Member of the Ausable Formation at station N-80. Photograph by B.V. Sanford. 2008-099

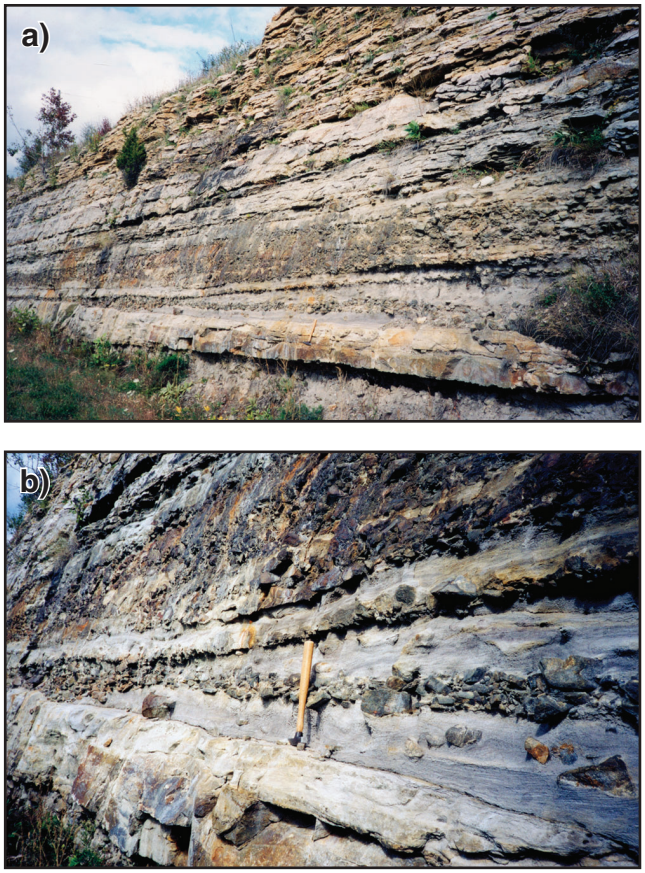


Figure 58. Keeseville Formation at station N-4 in a roadcut on Interstate 81, Wellesley Island, New York. **a)** Nearly complete section of Keeseville sandstone preserved in a block-faulted structure containing thick basal quartzite conglomerate. Photograph by B.V. Sanford. 2008-100 **b)** Close-up of basal quartzite-cobble and -boulder conglomerate. Note the light grey layers composed largely of weathered feldspar (kaolinite). Photograph by B.V. Sanford. 2008-101

Figure 59. Fifteen-metre cliff section of Nepean sandstone exposed at the Lyn Valley Conservation Area, Lyn, Ontario, at station O-64. Photograph by B.V. Sanford. 2008-102

Figure 60. Thin, uniformly bedded Nepean sandstone overlain with sharp contact (at arrowhead) by the March Formation in a roadcut on Highway 42, Ontario, at station O-33. Photograph by B.V. Sanford. 2008-103

Many other good exposures of Nepean Formation are found elsewhere along highways 15 and 42 in Ontario (*see* Appendix A). One would be remiss to omit the well known stratigraphic section on Highway 15 at Elgin (station O-23) in any regional discussion of the Nepean Formation. For many years, it was the only known exposure of the Paleozoic–Precambrian boundary and was thus a popular field trip stop. The oldest Paleozoic beds at this location were long thought to be Nepean Formation resting on steeply dipping Precambrian metavolcanic rocks. What makes the section even of more historical interest is the presence of a thin remnant of Middle Cambrian Covey Hill Formation preserved between the Precambrian and Upper Cambrian to Lower Ordovician Nepean Formation (Fig. 21). Thus, two unconformities are seen at this site, rather than one. Above the base of the Nepean Formation there is a thin shaly and

Figure 61. Nepean Formation at Mississippi Lake, Ontario, at station O-12 Note the nodular limestone beds at the base of the formation. Photograph by B.V. Sanford. 2008-104

sandy quartz-pebble conglomerate 20 cm thick, which is succeeded by pink, greenish-grey to white quartz arenite 2 m thick.

Farther north on Highway 15, the Nepean Formation is exposed at station O-17 (Fig. 32), where it rests with angular unconformity on coarse cobble and boulder conglomerate of the Chippewa Bay Member of the Covey Hill Formation. The basal 0.5 m of the Nepean at this site is composed of well rounded quartz cobbles likely derived from the underlying Covey Hill Formation. Overlying the conglomerate with abrupt contact is white, thinly bedded, bioturbated quartz arenite 3 to 4 m thick that is intensely iron-oxide stained along fractures.

Perhaps the most impressive of any of the Nepean Formation exposures in this general area of Ontario and elsewhere is at station O-16 on Rideau Ferry Road between Perth and Lombardy (*see* Fig. 1). This outcrop is spectacular largely because of the readily apparent angular discordance between the Nepean Formation and the underlying fractured and folded beds of the Covey Hill Formation. The Nepean Formation at station O-16 is a clean white and light grey quartz arenite containing a thin pebble conglomerate where the basal strata of the formation overlie the flatly bevelled erosional surface of the Chippewa Bay Member of the Covey Hill Formation.

From the Perth area, the Nepean outcrop belt extends northward to the Pakenham area, which presumably represents the northwesternmost depositional edge of the formation. Along

much of this outcrop belt, the Nepean Formation can be seen in the ditches of some roads and locally in roadcuts where it reaches up to 2 m in thickness. Where its base is exposed on the shore of Mississippi Lake near Carleton Place at station O-10, the lower 20 cm of the formation are composed of nodular bedded limestone. Overlying these with abrupt contact is bioturbated pinkish-white and grey brecciated sandstone about 1 m thick (Fig. 61). Precambrian quartzite is present immediately below the hammer in Figure 61, and this contact relationship precludes the possibility of any remnants of Covey Hill Formation being present beneath the Nepean Formation in this part of the study area.

From Carleton Place, the Nepean outcrop belt extends northward and is exposed at two localities on a southwest-oriented side road about 1 km west of Almonte, at stations O-8 and O-9. At station O-8, about 2 m of white and light grey quartz arenite are exposed; at station O-9, the Nepean sandstone is overlain by dolostone and sandy dolostone of the March Formation. The contact is abrupt, as it appears to be at most other locations in eastern Ontario and adjacent New York State, where observed during this investigation.

On the west side of Ottawa, in the former cities of Nepean and Kanata, excellent roadcut exposures of the Nepean Formation can be observed along both lanes of highways 417 and 416. The Nepean Formation was originally named by Wilson (1937, 1946) for the sandstone exposed in Nepean Township, "where the large quarries lie from which the stone was taken for the Parliament Building of Canada, and for many other large buildings" (Wilson, 1946, p. 10). One may assume from this that her type section was the Campbell Quarry near Bells Corners. Greggs and Bond, in the belief that "these [Campbell] quarries are now filled in and little outcrop is visible" (Gregg and Bond, 1972, p. 933), set about to establish a 'principal reference section for the Nepean Formation' on the north side of Highway 417, in the approximate vicinity of station O-2 (Fig. 62).

The type section, as so designated on Highway 417, is approximately 7 m thick and composed of white to cream quartz arenite in thin, relatively uniform beds that weather light grey to yellowish orange. Thin yellowish-orange calcitic to dolomitic sandstone interbeds occur sporadically in the middle to upper beds and are more numerous near the top of the section. Greggs and Bond (1972) did not identify any carbonate interbeds at the top of the section as March Formation, having assumed that the March and upwards of 3 m of the uppermost beds of the Nepean Formation were absent because of erosion. New road construction at this site has exposed intensely trough cross-stratified strata near the base of the formation.

In a later study of the same general stratigraphic succession, Brand and Rust (1977) identified a thin layer of sandstone with minor carbonate at the very top of the section as March Formation, as did Williams et al. (1984a) during geological mapping for the Ontario Geological Survey. More recently, Dix et al. (2004) lowered the Nepean–Theresa (March) boundary 1.5 m below that interpreted by Brand and Rust (1977), to coincide with an irregular surface within the sandstone that they interpreted to be an unconformity.

In this study, an examination of the same exposure on Highway 417 failed to identify a stratigraphic horizon within the succession that would be of any value in terms of defining the Nepean–March contact, or that would have any practical application elsewhere beyond the existing limits of this particular outcrop belt. Instead, the more logical alternative may be to classify the entire type section as Nepean Formation, as did Greggs and Bond (1972), and turn one's attention to the Nepean–March contact where it is exposed to far better advantage on Highway 416, at station O-6 (Fig. 63). From these observations, the definition of the Nepean–March boundary at the first appearance of a carbonate interbed, as

Figure 62. Principal reference section for the Nepean Formation, as adopted by Greggs and Bond (1972), on Highway 417, Ontario, at station O-2. The beds are composed of quartz arenite with thin calcareous interbeds, typical of the Nepean and equivalent Keeseville and Cairnside formations throughout the study area. Photograph by B.V. Sanford. 2008-105

Figure 63. Nepean sandstone conformably overlain by dolostone of the March Formation (arrow points to contact) in a roadcut on Highway 416, Ontario, at station O-6. Note the presence of a thin carbonate layer within the Nepean sandstone, approximately 2 m above the base of the section. Photograph by B.V. Sanford. 2008-106

proposed by Wilson (1946) and others, would seem impractical. A simple and more effective method of establishing this boundary throughout the Ottawa Embayment and Quebec Basin, both at surface and in subsurface, is where the Nepean sandstone with minor carbonate interbeds gives place vertically to dominant carbonate with minor sandstone interbeds or lenses (Fig. 53b, 60, 63).

To set the record straight with regard to the Campbell Quarry, it can be said that the workings are still intact, as they were during the professional years of Alice Wilson, thanks to the efforts of the Government of Canada. However, the grounds are not freely accessible to the general public, and therefore Greggs and Bond (1972) needed to establish a new type section for this very important sedimentary succession. The Nepean beds exposed in the long-abandoned Campbell Quarry at station O-3 represent a classic section with much historical significance. Exposed at two levels (benches) are an estimated 11 m of strata consisting of white and light grey, thin to thick, uniformly bedded quartz arenite that weathers grey to faintly pink and yellowish green (Fig. 64). Neither the lower nor the upper contact with the Precambrian basement and March Formation is exposed here, although the base of the lower level of the quarry cannot be too far above the Precambrian surface at this locality. The Campbell Quarry, as currently preserved by Natural Resources Canada, is much the same as it was more than 50 years ago when Alice Wilson used it as a field trip destination to show the source of the stone used in the construction of the Parliament Buildings and other large government buildings in the Ottawa region.

Figure 64. Campbell Quarry, near Bells Corner, Ottawa, Ontario, at station O-3. The photo shows the lower of two benches from which the Nepean sandstone was quarried for the construction of the Canadian Parliament Buildings, the Victoria Memorial Museum, and other large buildings in Ottawa. Photograph by B.V. Sanford. 2008-107

A short distance southwest of the type section as defined by Greggs and Bond (1972), excellent exposures of Nepean Formation are seen at the Terry Fox on-ramp to Highway 417 at station O-4 (Fig. 65) and in the nearby Kanata Centrum shopping centre at station O-5. The strata are thin- to thick-bedded, white and cream quartz arenite. The upper beds exposed at station O-4 contain a stromatolite biostrome, pseudomorphs of gypsum, and desiccation markings suggestive of hypersaline intertidal to supratidal (sabkha) environments of deposition (Hilowle et al., 2000; Anderson, 2004). Eolian deposits near the base of the Nepean Formation have also been identified and described in this area by Dobie (2004). Faulting and soft-sediment deformation structures can be observed locally slightly higher in the section at station O-5.

On the north side of the Ottawa River in Gatineau at station Q-1 at the Lac Beauchamp Park, thick massive beds of the Cairnside (Nepean) Formation form the 3 to 4 m high walls of an abandoned quarry. Cairnside (Nepean) strata unconformably overlie Precambrian rocks (Fig. 66a) and their lowermost part consists of medium-grained sandstone with common dispersed quartzite pebbles and cobbles. The

Figure 65. a) Nepean Formation exposed at the Terry Fox interchange on Highway 417, Ottawa, Ontario, at station O-4. Photograph by B.V. Sanford. GSC 2008-108 **b**) Surface layer of stromatolite biostrome seen in the lower left of a). Photograph by B.V. Sanford. 2008-109

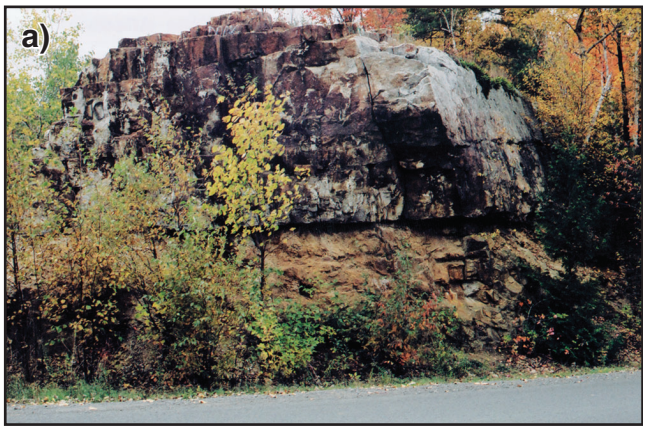


Figure 66. a) Cairnside (Nepean) Formation sandstone (high-energy subaqueous dunes) unconformably overlying Precambrian basement at Lac Beauchamp Park, Gatineau, Quebec, at station Q-1. Photograph courtesy of J.L. Wallach. **b)** Rib-and-furrow structure formed by migrating large-scale subaqueous dunes at the base of the Cairnside Formation on the floor of an abandoned quarry, a few metres south of the location in a) (paleocurrent toward the left). Photograph by B.V. Sanford. 2008-110

sandstone is quartz-rich (quartz arenite), nearly white, and weathered dark grey to black and locally dark reddish brown. Trough crossbedding is ubiquitous throughout the succession and indicates transport toward the southeast, with a subordinate trend toward the northwest. Stylolites, although generally rare in most strata of the Potsdam Group, are common at the Lac Beauchamp Park section, especially along bedding planes throughout the succession. According to Hilowle et al. (2000), the stylolites may in fact be related to biofilms that during deep-burial diagenesis (pressure solution) helped to locate and then concentrate the precipitation of insoluble materials along developing solution seams. Common also at Lac Beauchamp Park are a variety of vertical and commonly very large trace fossils, including *Diplocraterion*, *Skolithos*, and *Rosselia*. Collectively, these lithological characteristics suggest that strata at Lac Beauchamp Park were deposited in a high-energy, marine-influenced, possibly tidally influenced sedimentary environment.

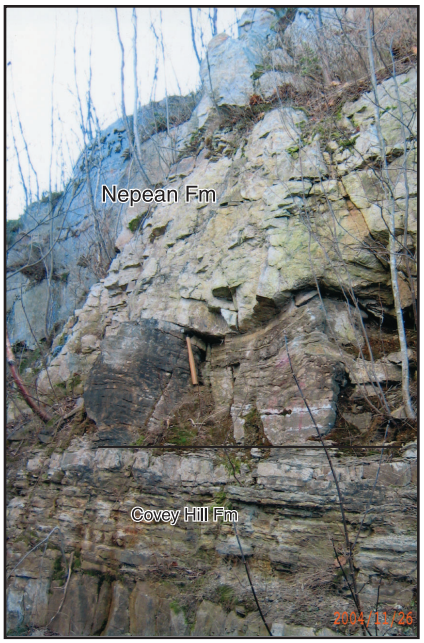


Figure 67. Nepean sandstone unconformably overlying the Covey Hill Formation (Chippewa Bay Member; contact at black line) along the Ottawa River at Rockland, Ontario, at station O-1. Photograph by B.V. Sanford. 2008-111

At Lac Beauchamp Park, the upper contact of the Cairnside (Nepean) Formation with the overlying Theresa (March) Formation is not exposed, but the Theresa Formation outcrops immediately east of the park entrance, on the north side of Maloney Boulevard. This would suggest that the very thin unit of Cairnside Formation exposed in the quarry may be very near its original depositional thickness.

Nepean sandstone, similar to the Cairnside (Nepean) described above, is exposed in a roadcut and quarries on Hawthorne Road in Ottawa, at station O-7. Here, like at Lac Beauchamp Park, locally bioturbated, medium-scale cross-stratified sandstone was deposited under high-energy, marine-influenced conditions, in this case along the upthrown side of the Gloucester Fault, which is assumed to have been structurally high during deposition of the Nepean Formation. Paleocurrent direction was toward the east (087º). The upper boundary of the Nepean Formation, where overlain by the March Formation, is abrupt and placed at the base of a thin unit of brown sandy dolomitic limestone.

In contrast to the exposures in Ottawa and Gatineau where the Nepean Formation lies directly on Precambrian crystalline rocks, an isolated outcrop occurs at Rockland, Ontario, at station O-1, in which the Covey Hill Formation separates Nepean strata and Precambrian rocks (Fig. 67). The lower 10 to 15 cm of the Nepean Formation that overlie the Covey Hill Formation are composed of black, finely crystalline limestone that grades upward to grey, argillaceous sandstone.

Near the crest of the large-scale ripple-like structures are imbricated rip-up soft-sediment sandstone clasts suggestive of paleoflow (from left to right in Figure 67) during an initial stage of Nepean deposition. The lower contact of these beds is abrupt and presumably unconformable with the underlying Covey Hill strata. The upper contact with the white and light grey Nepean quartz arenite that contains high-energy marine dunes and local pea-sized spherical cavities, is also sharp and likely disconformable.

On the southwest side of the Frontenac Arch in the Sloan Quarry near Sunbury, Ontario (station O-57), an erosional remnant of grey, bioturbated quartz arenite of the Nepean Formation unconformably overlies yellow, uniformly bedded sandstone of the Chippewa Bay Member of the Covey Hill Formation (Fig. 68). To date, this is the only place in this part of central Ontario where the above-described stratigraphic relationships are observed in outcrop. Elsewhere in this region, e.g. station O-70, the Nepean Formation rests directly on the Hannawa Falls Member. From a paleogeographic viewpoint, the above-described occurrence is important in that it proves that Covey Hill strata were once widespread throughout south-central and southwestern Ontario in pre-Nepean times, and were removed on a broad regional scale by erosion during the long hiatus that prevailed following deposition.

Along the northern margin of the Adirondack Mountains, between Rensselaer Falls and Potsdam, New York, the Keeseville Formation is apparently obscured beneath downfaulted Theresa strata. From the Potsdam area eastward, the beds form a continuous outcrop belt to the vicinity of Plattsburgh on Lake Champlain. The first occurrence of Keeseville beds is at Brasher Falls (station N-124) where about 2 m or less of sandstone are exposed on the floor and walls of the St. Regis River. From this point eastward to Chateaugay, outcrops are widely separated, occurring on the Salmon River at station N-125 and near Burke at station N-126.

At the Chateaugay River (station N-130) where it is crossed by Pulp Mill Road, a few metres west of the bridge and higher on the river bank a 1.5 m exposure of Keeseville Formation consists of white, massive-bedded quartz arenite. Its basal contact with the Ausable Formation (Edwardsville Member; Fig. 39a, b) present in the upper walls of the gorge is not exposed. However, on the basis of the substantial differences in lithology and colour between the two units, the contact is most probably abrupt and unconformable. A thicker section of Keeseville Formation, which was not examined in this study, is apparently located a short distance downstream where fossils were collected by Fisher (1968). East of Chateaugay, the number of Keeseville exposures increases significantly toward Lake Champlain. Most exposures are not more than 1 or 2 m thick and consist of light grey to white quartz arenite strata (*see* Fig. 69).

Where the Keeseville outcrop belt crosses into Quebec along the southern margin of the Valleyfield Trough (*see* Fig. 3), the beds are known as Cairnside Formation (Globensky, 1987), although the tiny community for which the type section was originally named is now known as Saint-Pierre. At this locality the beds are widely exposed, but nowhere were they observed to be more than 1 to 2 m thick.

At the type section of the Keeseville Formation, a thick succession of uniformly bedded, white and light grey quartz arenite is exposed along the vertical walls of the Ausable Chasm. The beds as viewed from the Route 9 bridge where it crosses the Ausable River (station N-215) are shown in Figure 70. The total thickness of the section exposed is approximately 30 m, although the actual thickness at this locality may be as much as 60 to 90 m on the basis of the thickness recorded in boreholes northeast of the Oka-Beauharnois Arch in adjacent areas of Quebec.

The lithological composition of the Nepean Formation, and the equivalent Cairnside and Keeseville formations where identified in boreholes in the Ottawa Embayment and

Figure 68. Nepean Formation unconformably overlying the Covey Hill Formation (Chippewa Bay Member; above the base of the hammer handle) at the Norman Sloan quarry near Sunbury, Ontario, at station O-57. Photograph by B.V. Sanford. 2008-112

Figure 69. Grey to white ripple cross-stratified quartz arenite of the Keeseville Formation on Route 190 near Ellenburg, New York, at station N-163. Photograph by B.V. Sanford. 2008-113

Figure 70. Keeseville Formation viewed from the bridge where Route 9 crosses the Ausable Chasm, New York, at station N-215. Approximately 30 m of uniformly bedded Keeseville strata are exposed between the viewing platform (upper middle of photo) and the river. Photograph by B.V. Sanford. 2008-114

western part of the Quebec Basin, is essentially identical to that observed in the many exposures examined in the field (*see* Fig. 6). Strata are composed of white, cream, or light grey quartz arenite throughout their area of distribution in subsurface; some contain quartz pebbles at their base and locally higher in the formation. Argillaceous to shaly beds occur locally but make up little of the stratigraphic section. Thin layers of gypsum interbedded with the sandstone occur throughout the upper half of the Nepean Formation in the Imperial Oil Ltd., Laggan No. 1 borehole. The presence of brecciated intervals in the GSC Lebreton No. 1 borehole and some brecciation in the GSC Russell No. 1 borehole may be suggestive of halite deposition and subsequent removal by dissolution at some time during or soon after Nepean deposition. The presence of thin igneous sills of assumed Early Cretaceous age (Monteregian origin) was also reported in the St. Lawrence River No. 1 and Quonto-International No. 1 St. Vincent de Paul boreholes, as shown in Figure 8.

With the exception of the Dominion Observatory No. 1 borehole, where Nepean strata rest directly on Precambrian rocks, Nepean or equivalent Cairnside strata in all other boreholes sharply overlie the Covey Hill Formation. Similarly, the Nepean–Cairnside contact with the overlying March and equivalent Theresa formations is everywhere abrupt and marked by a change to predominantly carbonate and sandy carbonate strata.

Petrogenesis

Marine depositional processes that began at the eastern end of the St. Lawrence Platform (Williams et al., 1995) at the onset of seafloor spreading in the Neoproterozoic and Early Cambrian, progressively spread northward and westward onto the craton and into the southern part of what are now the Quebec, Appalachian, and Michigan basins in the late Middle and Late Cambrian. From the Quebec Basin, the sea is assumed to have entered the Ottawa Embayment initially through the Valleyfield Trough (*see* Fig. 3), which was a much wider geographic feature than it is today. From there it transgressed westward across the much older and partially eroded Covey Hill and Ausable terrains, eventually reaching the eastern margin of the Frontenac Arch in the initial Tremadoc Stage of the Early Ordovician (*see* Fig. 5, 71).

In the western segment of the St. Lawrence Platform, the seaway advanced across the inner continental shelf of what is now the Appalachian Basin where it presumably approached the Frontenac Arch diachronously from the south and west. The two bodies of water probably coalesced across the Frontenac Arch at some point in the early Early Ordovician, forming a continuous seaway over the entire St. Lawrence Platform.

Although the Nepean and equivalent Cairnside and Keeseville formations are traditionally considered part of the Potsdam Group, they have also long been interpreted as a basal transgressive unit of the Beekmantown Group, which grades upward into the March and equivalent Theresa formations and then the Oxford and equivalent Beauharnois and Ogdensburg formations (e.g. Wilson, 1946). On the other hand, the interpretation of a regional unconformity between the Cairnside (Potsdam Group) and Theresa (Beekmantown Group) formations in the Quebec Reentrant by Salad Hersi et al. (2002) suggests that the contact between these two units was not everywhere gradational as had long been assumed.

During the Late Cambrian and Early Ordovician, the Precambrian terranes bordering the Ottawa Embayment and what is now the Quebec Basin were positive physiographic features, similar in some respects to those that prevailed during the Neoproterozoic to Middle Cambrian. However, the intense tectonic activity that accompanied deposition of the older parts of the Potsdam succession was substantially reduced during the later stages of deposition in the Late Cambrian to Early Ordovician. The mechanisms that led to the marine transgression are unknown, but were most likely, or at least in part, a result of the progressive thickening and widening of continental shelves worldwide and the effect of this on the volume of the global ocean basins (e.g. Knight et al., 1995; Williams et al., 1995). This would have resulted in a substantial eustatic rise and consequent submergence of a significant part of the North American craton.

During the Middle and Late Cambrian, the Adirondack Dome was presumably a positive feature and emergent but mildly tectonic, except perhaps for the northeastern region of New York State where substantial thicknesses of sand were apparently transported into the Quebec Basin, in north-northeast and east directions, off the southern extremity of the Oka-Beauharnois Arch (Fisher, 1968). The Frontenac Arch was also a positive structural feature during the Late Cambrian to Early Ordovician as evidenced by the substantial thinning of the Nepean and equivalent

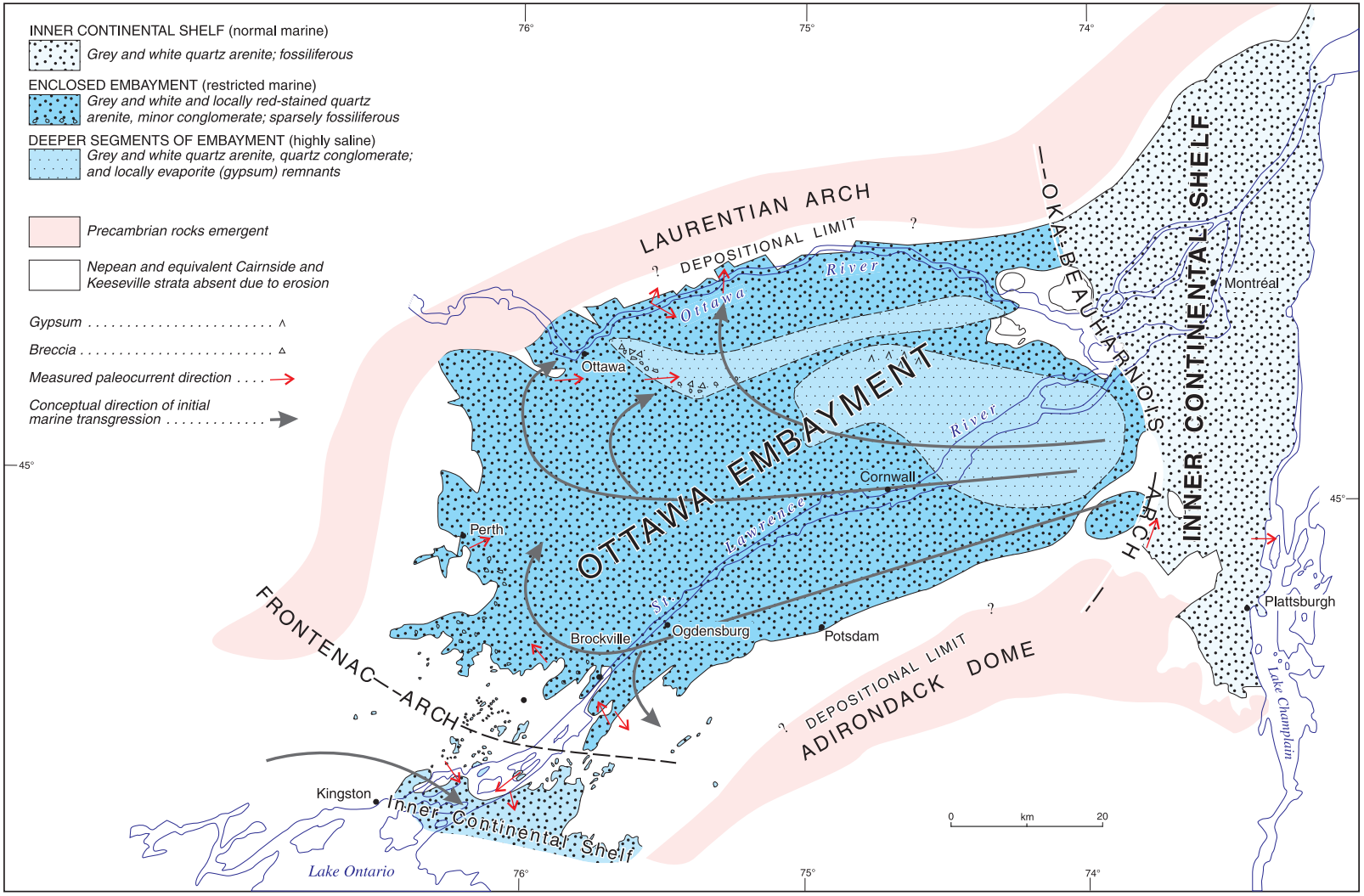


Figure 71. Depositional environments and facies distribution of the Nepean and equivalent Cairnside and Keeseville formations.

Keeseville formations across its higher structural axis that separates the Ottawa Embayment, to the east, from what is now the Appalachian Basin, to the west.

Throughout the western part of the Ottawa Embayment, the Nepean and Keeseville quartz arenite units are mostly coarser grained than the subjacent Covey Hill and Ausable strata, as observed in hand specimens and thin sections. This suggests derivation of the detritus directly from Precambrian areas, rather than a second-cycle origin from eroded Covey Hill and/or Ausable strata. An exception to this may be the conglomerate that occurs at the base of the Nepean Formations at two localities on Highway 15 in Ontario (stations O-17 and O-27; *see* Fig. 20, 32). In both areas, coarse quartzite-cobble conglomerate occurs in the Covey Hill Formation and may well be the second-cycle source of the quartzite conglomerate found locally in the lower part of the Nepean Formation. Sand deposited in the northwestern part of the Ottawa Embayment was presumably derived from the Laurentian Arch bordering the Canadian Shield, although little is known about the Cairnside (Nepean) Formation in the region east of Masson, Quebec, where the beds are largely obscured by residential and commercial development, or otherwise buried beneath downfaulted blocks of younger Ordovician strata.

The principal source of much of the Nepean and equivalent Cairnside and Keeseville detritus deposited in the eastern and central parts of the Ottawa Embayment and adjacent Quebec Basin was presumably the northern segment of the Oka-Beauharnois Arch. The significant thicknesses of sand that accumulated west, south, and east of this major structural feature would suggest that it may have been undergoing tectonic rejuvenation throughout the Late Cambrian and possibly early Early Ordovician. The Cairnside sand derived from this segment of the arch may in part be of second-cycle origin, having possibly been derived from the thick wedge of Covey Hill strata that was deposited around the margins of the Oka Hills, Rigaud Mountain, and Saint-André-Est hills during the Early and Middle Cambrian.

Uranium-lead isotopic analyses by Gaudette et al. (1981) of detrital zircon crystals extracted from the Potsdam Sandstone in the Ausable Chasm in northeastern New York State yielded ages corresponding to the Superior and Grenville provinces of the Canadian Shield. Zircon crystals of Grenvillian age could have been derived from a wide spectrum of locations on the Adirondack Dome and/or immediately adjacent area of the Canadian Shield to the north. Whether or not Archean zircon crystals were derived from pre-Grenvillian rocks preserved in the Adirondack Mountains, as suggested by Gaudette et al. (1981), or were transported southward into the area by river systems that had their headwaters located far to the north in the Superior Province, is currently unknown.

The presence of Precambrian highs on all four sides of the Ottawa Embayment provided sufficient enclosure for the concentration of higher than normal salinities during deposition of the Nepean and equivalent formations. The highly generalized facies map in Figure 71 shows the areas where salinities would have more than likely been significantly higher than normal, and where evaporites could conceivably have been deposited. The Imperial Oil Ltd., Laggan No. 1 borehole (*see* Fig. 9) encountered numerous gypsum interbeds throughout the upper half of the Nepean Formation, indicating hypersaturation of the depositional medium in the eastern, deeper parts of the Ottawa Embayment. Fairly intensive brecciation in the GSC Lebreton No. 1 borehole, and to a lesser extent in the GSC Russell No. 1 borehole, might also suggest the initial presence of minor halite in those areas, with subsequent dissolution and collapse.

The widespread paucity of normal marine fossils, except for local occurrences of trace fossils, represents evidence of elevated salinity throughout the Ottawa Embayment. The occurrence of stromatolites, which can survive and even thrive in hypersaline conditions, is also a good indicator of evaporitic conditions. Stromatolites were observed by the first author during earlier field investigations of evaporite units in the Michigan, Appalachian, and Hudson Bay basins. They occur in great numbers in the Kanata region of Ottawa along Highway 17 at the Terry Fox interchange where they reach biostromal proportions at station O-2 (Fig. 65b), and in various areas of New York State, notably near Chapel Corners where numerous solitary stromatolites were observed at station N-66.

In contrast, on the western margin of the Frontenac Arch in Ontario and New York State, an abundant and diverse assemblage of marine fossils suggests that more normal open marine conditions prevailed in these areas. Similarly, on the east side of the Oka-Beauharnois Arch bordering what was once an open marine continental shelf, extensive fossil collections were made by Van Ingen (1902) and Fisher (1968).

As seen previously (Fig. 44, 45, 46, 47, 48), iron-oxide dust rims overlain by quartz overgrowths are common in the Covey Hill and equivalent Ausable sandstone and are generally absent in strata of the Nepean and equivalent formations. Such a difference was noted at Rideau Ferry Road, Ontario (station O-16), where iron-rim-rich and iron-rim-poor strata, respectively, of the Covey Hill and Nepean formations were observed (Fig. 72). Moreover, these strata are separated by an angular unconformity (*see* Fig. 1). Petrographic characteristics similar to those described above were observed in thin sections from elsewhere in Ontario and New York State, and therefore may represent a reliable technique for differentiating locally and regionally lithologically similar strata of the Covey Hill or Ausable formations from the Nepean Formation and its equivalents.

Age and regional correlation

Fisher (1968, p. 16) dated the Keeseville Member in Clinton County as "late medial Cambrian" on the basis of the presence of the trilobites *Komaspidella seelyi* and

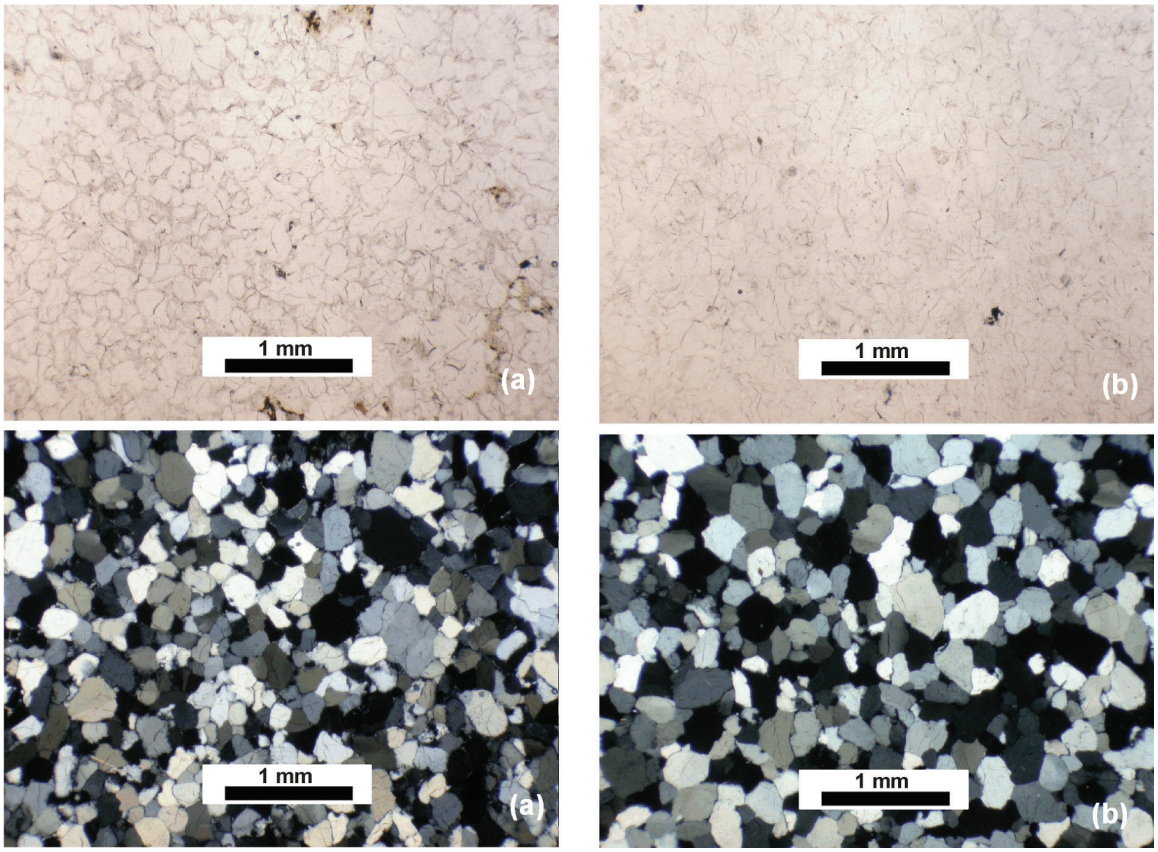


Figure 72. Photomicrographs of Potsdam sandstone from near Rideau Ferry, Ontario, at station O-16. **a)** Fine- to medium-grained sandstone of the Covey Hill Formation (Chippewa Bay Member) from beneath an angular unconformity. Photomicrographs courtesy of J.L. Wallach. **b)** Medium-grained sandstone of the Nepean Formation from above the unconformity. In the photomicrographs taken in plane light, well developed iron-oxide rims are present in Covey Hill strata in a), but are generally absent in Nepean strata in b). Photomicrographs courtesy of J.L. Wallach.

Lonchocephalus minutus that were collected in Ausable Chasm, "about 120 feet from the lowest beds". More recent investigations by Landing et al. (2007) and E. Landing (pers. comm., 2008) have confirmed that the oldest beds of the Keeseville in northeastern New York State are upper Middle Cambrian on the basis of the presence of the trilobite *Crepicephalus*.

Farther west in the Chateaugay River gorge, Fisher (1968, p. 17) dated "the Potsdam (Keeseville Member) later Late Cambrian (Trempealeau), yielding the trilobites *Prosaukia* and *Ptychaspis*". He stated that "in St. Lawrence County (north and west of the Adirondack Mountains) diagnostic trilobites have not been reported, but in view of the progressive northwestward chronologic transgression, the Potsdam [Keeseville] is likely Early Canadian" (Early Ordovician; Fisher, 1968, p. 17).

In adjacent areas of Quebec, Clark (1966, 1972) reported the presence of *Lingulepis acuminata* in the Cairnside Member of the Chateauguay Formation, along with a number of trace fossils including *Climactichnites wilsoni*, *Protichnites* sp., *Arenicolites* sp., *Skolithos* sp., and *Pyrichnites* sp. The Cairnside Formation, as it is now known, has been traditionally dated as Late Cambrian (Clark, 1966, 1972; Globensky, 1987), although none of the fossils described by the above authors appear to be diagnostic of either the Cambrian or the Ordovician.

At the western end of the Ottawa Embayment, Wilson dated the Nepean Formation as Early Ordovician, mainly on the basis of it being a part of what she thought was a continuing depositional sequence, "grading from sandstone [Nepean] into interbedded sandstone and dolomite [March], and then into dolomite [Oxford]" (Wilson, 1946, p. 16). The March and Oxford formations had long been thought to be Early Ordovician on the basis of the presence of *Ophileta compacta*, *Ecciomphalus calciferous*, and other Lower Ordovician fossils. With the exception of trace fossils and stromatolites in eastern Ontario, the only marine fossil indigenous to the Nepean Formation is *Lingulella acuminata*, which according to Wilson (1946, p. 16), "has been cited from New York, Vermont, Wisconsin, Minnesota and Tennessee from both the Cambrian and Lower Ordovician."

In adjacent areas of New York State, fossils appear to be locally abundant, although they were mostly destroyed by abrasion during transport. Elsewhere in New York State and eastern Ontario, stromatolites were noted in fair numbers along with many trace fossils, including *Climactichnite*s sp., possible *Locheia* sp., *Diplocraterion* sp., *Arenicolites* sp., and *Rosselia* sp.

The first major breakthrough in dating the Nepean type section, in the western part of the Ottawa Embayment at station O-2 on Highway 417, was by Brand and Rust (1977) who recovered early Arenigian conodonts from three zones in the upper part of the succession. Two of these zones were in beds near the top of a unit classified as Nepean Formation, and the third was from the very top of the section in what they referred to as 'March Formation'. Beds lower in the section were barren of conodont fauna and were classified as Tremadocian (Lower Ordovician), as originally assumed by Wilson (1946) and Greggs and Bond (1972). Greggs and Bond (1972) considered the entire section to be Nepean Formation of Tremadocian age.

During more recent investigations of the same section, Godfrey Nowlan of the GSC (*in* Dix et al., 2004) recovered conodonts from two intervals that he dated as Tremadocian to Arenigian; the conodonts were from strata identified by Dix et al. (2004) as Theresa (March) Formation. Results from the present study, however, suggest that there is no basis for the identification of March Formation at this location, and thus the entire section is herein classified as Nepean Formation and assumed to be Early Ordovician in accordance with Greggs and Bond (1972) and the more recent dating by Godfrey Nowlan (*in* Dix et al., 2004).

In New York State, where the Keeseville Formation overlies the southern extension of the Frontenac Arch, it thins to 8.8 m or less and appears to be in conformable contact with the overlying Theresa Formation. So far as is known, these upper Keeseville beds have not been dated, but one can reasonably conclude that they too are mostly Early Ordovician (*see* Fig. 50, 73).

The Cairnside and equivalent Keeseville formations in the western part of the Quebec Basin dated late Middle to Late Cambrian by Fisher (1968, 1977) are in all probability equivalents of the carbonate rocks of the Petit Jardin and Berry Head formations (Port au Port Group) in western Newfoundland Island, at the eastern extremity of the St. Lawrence Platform (Knight et al., 1995). They are also presumably correlative of the Upper Cambrian sandstone and carbonate rocks of the Mount Simon, Eau Claire, Galesville, Franconia, and Trempealeau formations, in that respective stratigraphic order of succession in the Michigan Basin.

The slightly younger (Lower Ordovician) Nepean and equivalent Keeseville formations, where these have transgressed through time in those areas approaching and overlying the Frontenac Arch, are likely equivalent to the lower St. George Group (Watts Bight) of western Newfoundland Island (Knight et al., 1955). They are likely also equivalent to the lower Prairie du Chien Group (Oneota Formation) in the Michigan Basin and adjacent area of Wisconsin, at the opposite extremity of the St. Lawrence Platform (Smith et al., 1993).

STRUCTURAL FRAMEWORK OF THE POTSDAM GROUP

The Canadian Shield, composed largely of Precambrian igneous and metamorphic terranes, forms the bedrock surface throughout a wide region of eastern and northern Canada (Wheeler et al., 1996) and is everywhere continuous

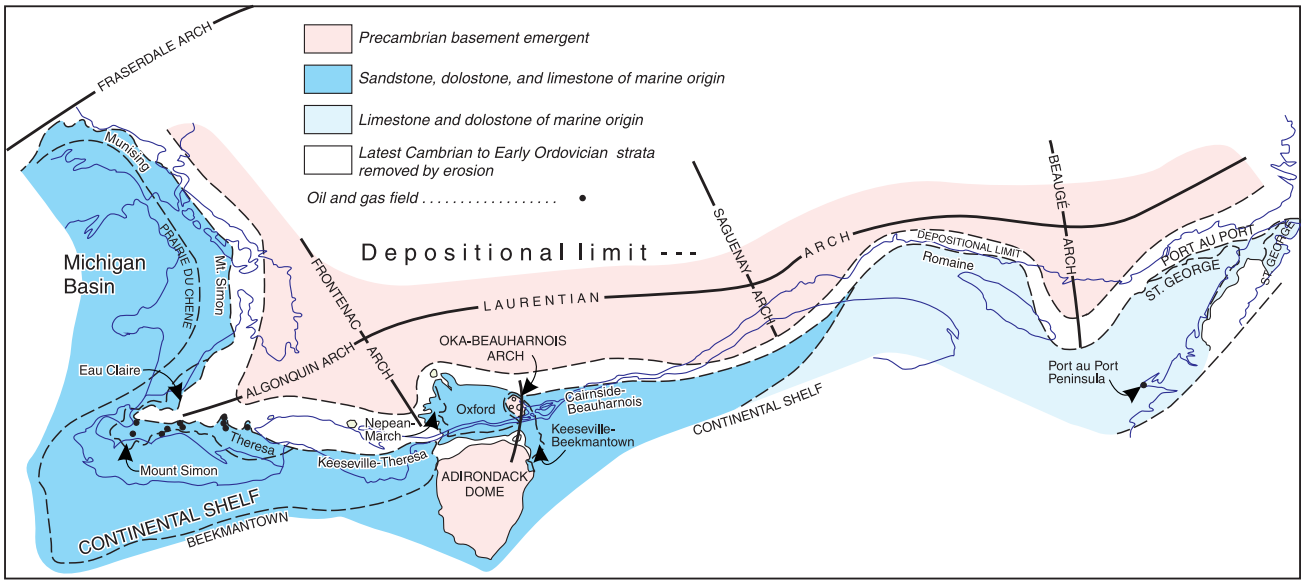


Figure 73. Paleogeography of the upper Middle Cambrian to Lower Ordovician sequence (*modified from* Sanford, 1993b).

in subsurface beneath the Phanerozoic sedimentary terrains of the Arctic, Interior, Hudson, and St. Lawrence platforms. Ingrained in the structural framework of the Canadian Shield and its extensions are a series of northeast- and northwest-trending orthogonal arch systems, which previously were identified and defined by Sanford et al. (1985), Sanford (1987), and Sanford and Grant (1990, 1998). These major tectonic features, some of which extend for several thousand kilometres across the North American continent (Sanford et al., 1985), were described further by Card et al. (1997) who provided new insight into the history of their probable inception and the triggering mechanisms that likely gave rise to episodes of rejuvenation and uplift during the Proterozoic and Phanerozoic. The arch systems as they relate to inception and development of the foreland basins of the St. Lawrence Platform are discussed in Sanford (1993a, 1998).

Although major deformation of the southern margin of the St. Lawrence Platform is known to have accompanied the emplacement of allochthons during Taconian and Acadian orogenesis (Knight et al., 1995; Williams et al., 1995), the more intensive periods of epeirogeny affecting broad regions of the North American craton occurred as a result of the following three specific plate-tectonic-related events, as discussed by Card et al. (1997): the initial rifting and separation of the continents and the opening of the ancestral Iapetus Ocean during the Late Proterozoic and Early Cambrian; an event of uncertain origin ((?) possible continental collision) that abruptly altered the broad transgression of the seaways across the Canadian craton at the close of the Early Silurian and continued through the Late Silurian; and a second period of crustal extension related to continental breakup in the Middle to Late Triassic and Jurassic.

The first of these events in the Late Proterozoic to Early Cambrian and possibly continuing into the Middle Cambrian affected a large area of the southern Canadian Shield, from western Newfoundland Island and southeastern Labrador (Easton, 1992; Williams et al., 1995) to the Great Lakes region of Canada and United States (Sanford 1993a, b). Effects of rifting are recorded in Precambrian basement rocks along the Laurentian Arch where it bordered the St. Lawrence Platform in southern Quebec and southeastern Ontario to the Georgian Bay (Lake Huron) area (*see* Fig. 51), where the Laurentian Arch merged with the Waverly Arch, a precursor to the Algonquin Arch, which curved to the southwest across southwestern Ontario and then extended into northwestern Ohio.

Intersecting the Laurentian Arch at right angles is a series of southeast-trending arches (from east to west the Beaugé, Saguenay, Oka-Beauharnois. and Frontenac arches), all of which were positive tectonic features from the late Precambrian to Middle Cambrian (Sanford, 1993a). In addition, structural rejuvenation of the Grenville structural front that curves sharply to the south near the eastern extremity of Manitoulin Island and passes through eastern Michigan and across western Ohio (Richard et al., 1997), and the broadly distributed Grenville basement rocks exposed in this general region, would most likely have provided a major sediment source for the Jacobsville and Middle Run formations, from late Precambian to Middle Cambrian time.

Most of the deformation that accompanied Neoproterozoic to Early and Middle Cambrian deposition in the Central Division of the St. Lawrence Platform is interpreted to have been a consequence of normal faulting and local thrust faulting. In many places the beds are gently folded, but whether or not such deformation was due to regional stresses *per se*, or was related entirely to fault-block rotation, or a combination of these processes, is not readily known, although the tight folding displayed at the base of the Hannawa Falls Member of the Covey Hill Formation at station O-69, near Ellisville, Ontario (Fig. 19c), would suggest the presence of a regional extensional stress field oriented at about 155º to the southeast possibly resulting from uplift of the Laurentian Arch. Folding and faulting is well displayed throughout the present study area, particularly along the eastern margin of the Frontenac Arch in Ontario and the Frontenac Arch extension in New York State. Here fractures can be readily recognized on satellite images (Sanford et al., 1985). The most common set trends northeast with a second set trending southeast; the least common set trends east and is confined largely to the Ottawa-Bonnechere Graben at the northern part of the Frontenac Arch (Card et al., 1997) and in the Montréal area (*see* Fig. 3).

Major block-faulted structures that involve Covey Hill and equivalent Ausable formations, which clearly predated the Nepean Formation and its Keeseville counterpart, appear to have been related principally to vertical movements along the northeast-trending fracture sets; they are best displayed in outcrop at stations O-14, O-16, O-17, O-27, O-35, and O-52 in Ontario, and at stations N-39, N-80, and N-26 in New York State.

The first and perhaps the most spectacular of such deformation is recorded at station O-16, where the Chippewa Bay Member of the Covey Hill Formation was uplifted along a normal fault oriented at 050º. Uplift caused at least 5 m of displacement and likely much more, as the Covey Hill Formation was substantially bevelled by erosion prior to deposition of the Nepean Formation (*see* Fig. 1). On the upthrown side of the fault, large blocks of quartzite conglomerate represent the basal strata of the formation. Along the downdropped side of the fault, grey and reddish-stained sandstone of the Covey Hill Formation dips steeply to the west, gradually becoming nearly horizontal near the western end of the outcrop. Faulting postdated deposition of the Covey Hill Formation, judging by the brittle nature of the fracturing, but predated deposition of the Nepean Formation, which is flat-lying and overlies the Covey Hill beds with angular unconformity.

Approximately 2.5 km west of the aforementioned structure, remnants of the Hannawa Falls and Chippewa Bay members of the Covey Hill Formation are preserved in a graben at station O-14 (Fig. 22). The outcrop is bounded to the west and east by Precambrian rocks, and the strata between form a well defined syncline with its axis also oriented at 050º. This exposure presumably represents only a part of the original graben, its eastern half apparently having been removed by erosion. At the base of the Covey Hill Formation at its preserved eastern margin is a tightly folded anticlinal structure (Fig. 74). This is assumed to have formed by compression as a result of the horizontal shortening of the Hannawa Falls Member as the beds were squeezed between the two parallel faults as they collapsed into the graben. Folding at station O-14 would appear to predate the faulting and tilting of the younger Chippewa Bay Member of the Covey Hill Formation located a short distance to the east, at station O-16 (*see* Fig. 1). One might further conclude from the above comparison of the two stations that the structural deformation of the Covey Hill Formation may have been an ongoing process in this part of eastern Ontario, at least throughout its depositional phases and for a period of time following its deposition.

Evidence of early Covey Hill folding can also be observed in a roadcut on Highway 42 at the northern town limits of Delta, Ontario, at station O-35, where strata of the Hannawa Falls Member are folded and succeeded with angular unconformity by flat-lying strata of the Chippewa Bay Member. The axis of the fold is 050º, coincident with the axis of folding and fracturing of the Covey Hill at stations O-14 and O-16. This section is similar in some respects to that at station O-69, in that the deformation of the Hannawa Falls beds beneath the angular unconformity in the Ellisville quarry (station O-69) was far more intense.

Pre-Nepean deformation of Covey Hill strata most likely occurred at an isolated locality on Highway 2 near Gananoque, Ontario, at station O-52 (Fig. 28). A tiny remnant of Chippewa Bay strata of the Covey Hill Formation is preserved in a possible downfaulted block in an area where Nepean outliers normally overlie the Precambrian surface. A southeast-trending lineament separating these beds from the nearest Nepean outlier to the east and a normal fault with the same orientation that cuts Covey Hill strata are sufficient evidence to suspect structural movement of these beds prior to deposition of the Nepean Formation in this western part of the Frontenac Arch.

Figure 74. Tightly folded basal strata of the Covey Hill Formation on Rideau Ferry Road at its intersection with Otty Lake Road, Ontario, at station O-14. The arrow defines the axis of the structure. Photograph by B.V. Sanford. 2008-115

In adjacent regions of New York State, there are many areas where Ausable strata have been subjected to faulting and consequent rigid block rotation, resulting in gentle to steep inclination of the strata. At some of these locations, such as at stations N-39 and N-80 (*see* Fig. 56, 57b), deformation clearly predates deposition of the Keeseville Formation. At a number of locations, deformation is believed to have also predated Keeseville deposition, but in the absence of Keeseville strata, the age of faulting is uncertain. Three such structures are shown in Figure 75.

Evidence of pre-Keeseville thrust faulting is observed in at least two localities in New York State, at stations N-40 and N-26 (Fig. 76a, b). Figure 76a shows Chippewa Bay beds of the Ausable Formation cut by what appears to be a low-angle thrust fault oriented at 325º and dipping to the northeast, superimposed on which is a major anticline whose axis is subparallel to the trend of the thrust. A few hundred metres east of this structure, the irregular surface of the Ausable Formation is overlain with angular unconformity by the Keeseville Formation (Fig. 56).

High-angle thrust faults with probable minor displacement occur within the Ausable Formation (Chippewa Bay Member) at station N-26 (Fig. 76b). The lateral and upward movement of strata below the unconformity within the Chippewa Bay Member, and compensating vertical dislocation of strata above the unconformity, have combined to form a prominent monoclinal structure. Here, the thrusts strike 050º and dip 063º to the southeast.

Major deformation, mostly expressed as faulting prior to deposition of the Nepean and equivalent formations, can be assumed to have occurred in many other widely separated parts of the study area, particularly along the northern segment of the Oka-Beauharnois Arch in the Oka Hills, Rigaud Mountain, and Saint-André-Est hills region of Quebec. Exposures of Covey Hill Formation that outcrop on the western part of Perrot Island are succeeded on the eastern end of the island by the Cairnside Formation, which would serve to confirm the presence of a thin (30.5 m) remnant of Covey Hill strata on this more northern segment of the Oka-Beauharnois Arch. The St. Lawrence River No. 1 borehole is located a short distance southwest of Perrot Island; it penetrated 496 m of Covey Hill strata without reaching the Precambrian basement (*see* Fig. 9). A further observation is that the basal dark reddish-brown beds of the Hannawa Falls Member exposed at the western end of Perrot Island are lithologically similar to the basal strata of the Hannawa

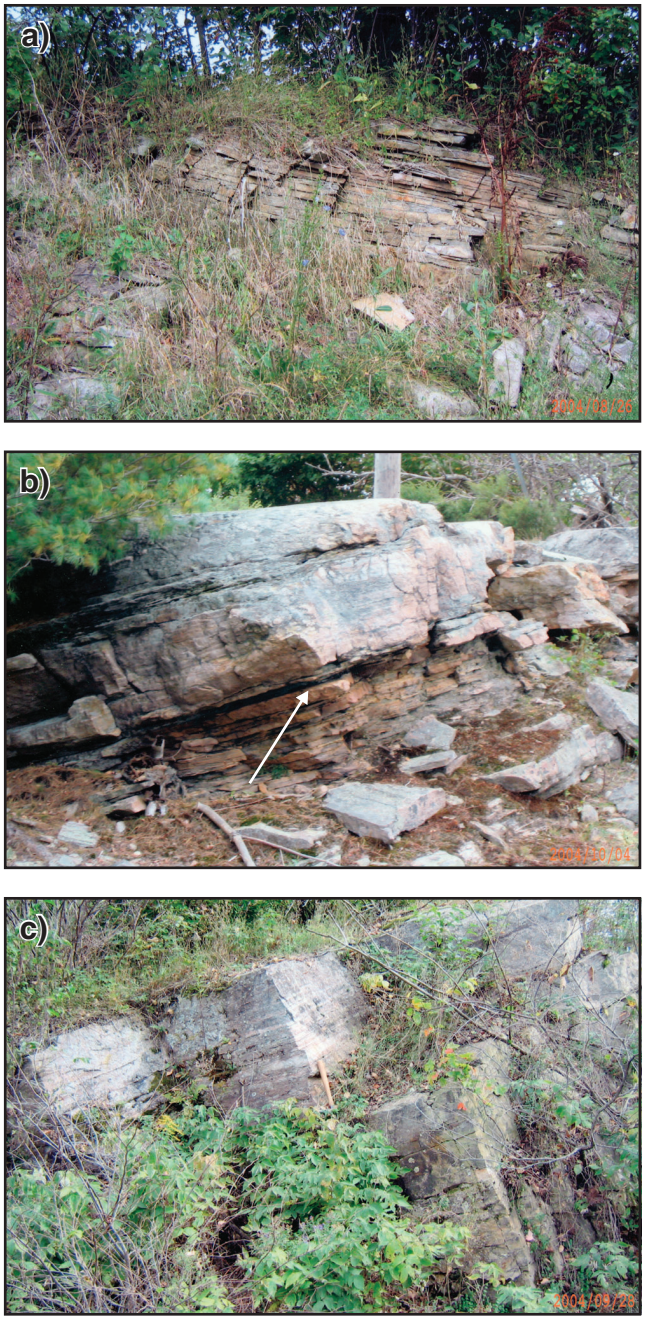


Figure 75. Block faulting and tilting of the Ausable Formation assumed to have occurred prior to deposition of the Keeseville Formation in New York State. **a)** Hannawa Falls Member near Pope Mills at station N-120. Photograph by B.V. Sanford. GSC 2008-116 **b)** Hannawa Falls and Chippewa Bay members (arrow points to contact) near Six Berry Lake at station N-33. Photograph by B.V. Sanford. GSC 2008-117 **c)** An isolated outlier of Hannawa Falls Member, 12 km north of Gouverneur, at station N-122. Photograph by B.V. Sanford. 2008-118

Figure 76. Pre-Keeseville thrust faults within the Ausable Formation. **a**) Possible low-angle thrust fault intersecting the Chippewa Bay Member, 1 km west of Redwood, New York, at station N-40 (direction of transport indicated by arrow). Photograph by B.V. Sanford. 2008-119 **b)** High-angle thrust fault within the Chippewa Bay Member below an unconformity, and compensating vertical normal fault movement in the upper beds; the two combined to form the monoclinal structure to the left of the hammer handle, at station N-26 near Theresa, New York. The arrows point to an unconformity. Photograph by B.V. Sanford. 2008-120

Falls Member that lie in subsurface near the base of the St. Lawrence River No. 1 borehole. This suggests that the east-southeast-trending Sainte-Justine Fault, shown in Figure 3, was probably active during or immediately following Covey Hill deposition, its northern side moving up relative to the deeper Valleyfield Trough to the south. Following uplift of the northern segment of the arch, most of the Covey Hill Formation was presumably eroded prior to deposition of the Cairnside Formation in the Perrot Island region of the Oka-Beauharnois Arch.

In addition to intense and widespread deformation of the Covey Hill and equivalent Ausable formations during and immediately following their deposition, younger units in the Potsdam Group underwent fracturing and folding. At many localities throughout the study area, strata of the Potsdam Group and younger Ordovician formations are intersected

by an array of normal faults (*see* Fig. 3), and many more faults undoubtedly exist, as postulated by Williams and Wolf (1984a, b, c) and Williams et al. (1984a, b, 1985a, b, 1992).

Perhaps one of the best examples of intensive and widespread post-Potsdam uplift occurred south of Montréal along the southern margin of the Valleyfield Trough, which was a much broader feature during Potsdam deposition than it is today (*see* Fig. 3). Uplift along the Stockwell Fault and its southeast and southwest extensions in adjacent areas of New York State is indicated by a thick Covey Hill succession that occurs 200 m or more above its counterpart in the Quebec Lowlands, which at this location is capped by the Cairnside and equivalent Keeseville formations (Fig. 3, 4, section E-E').

Judging by the numerous faults that intersect the entire Paleozoic succession, significant tectonic activity undoubtedly occurred throughout the eastern part of the Ottawa Embayment and the western part of the Quebec Basin following deposition of the Potsdam Group. The age of the faulting has not been established, but there may well have been repeated movements during successive periods ranging from late Early Ordovician, early Middle to Late Ordovician, Early to Late Silurian, Late Middle to Late Devonian, and Triassic, Jurassic to Cretaceous — periods of tectonic activity previously described throughout the St. Lawrence Platform (Sanford, 1993a, b).

Mapping of the faults that intersect the Potsdam Group and younger Ordovician rocks shown in Figure 3 was largely based on topographic lineaments, changes in the structural attitude of the beds, and the presence of juxtaposed rock units of differing lithology and/or ages; only in rare instances, such as at station O-59 (Fig. 77a), are faults actually seen in the field intersecting the rock strata. At this locality, the faults are oriented at 090º and are presumably splays emanating from the nearby Hazeldean Fault (*see* Fig. 3). The yellowish-orange deposits of goethite (Fig. 77b), where observed along the fracture surfaces, were presumably precipitated from iron-rich hydrothermal fluids that moved along the fracture network. Detailed descriptions of Nepean Formation exposures in this area can be found in Dobie (2004) and Anderson (2004).

Folds in the Nepean and counterpart formations and in older units possibly resulting from Taconian and/or Acadian orogenesis can be observed at widely separated parts of the study area, but rarely are they as well developed as in the vicinity of station O-27 (Fig. 78). Here, fold axes trending 066º are perpendicular to Highway 15 and extend a few tens of metres south to where the Covey Hill strata onlap a Precambrian ridge.

Drag folds in Precambrian rocks where they are overlain by the Ausable Formation were observed at two locations in the western part of the Ottawa Embayment on Route 12 in New York State (stations N-13 and N-54). At both locations, the drag fold axes trend north-northeast (030º); asymmetry of the folds indicates tectonic transport of the Ausable Formation toward the west-northwest relative to the underlying basement (Fig. 79).

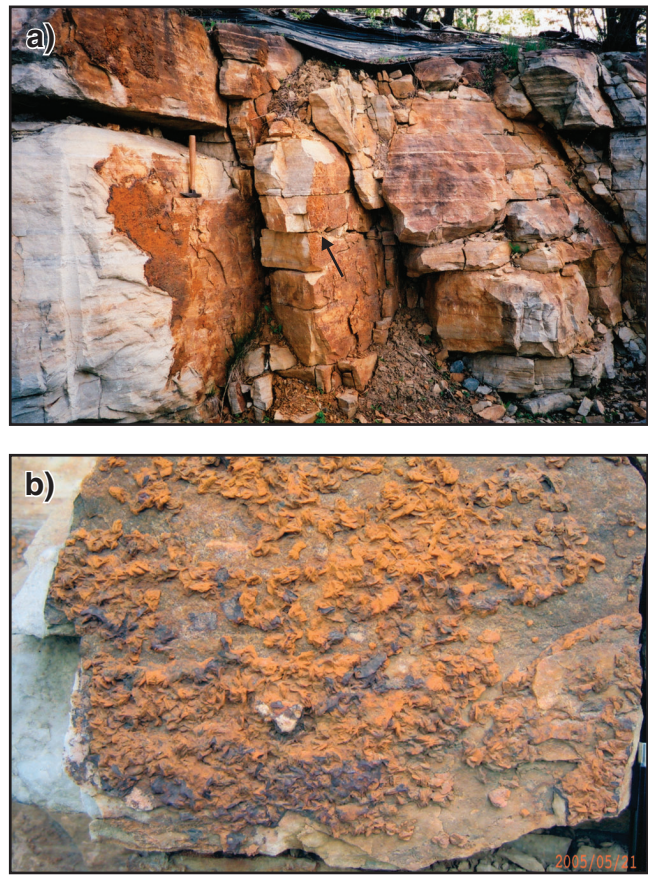


Figure 77. a) Normal faults intersecting Nepean Formation strata in the Kanata Centrum shopping centre, Ottawa, Ontario, at station O-5, are presumably splays emanating from the nearby Hazeldean Fault. Yellowish-orange deposits of goethite along each of the fracture surfaces are assumed to have precipitated from hydrothermal fluids moving along the fractures. The arrow points to the area shown in b) Photograph by B.V. Sanford. 2008-121 **b)** Detail of goethite deposits. Photograph by B.V. Sanford. 2008-122

The horizontal transport of the Potsdam Group across the basement surface in a west-northwest direction can be attributed to high regional stress fields associated with Taconian and/or Acadian orogenesis in progress from the early Middle Ordovician to the Late Devonian. A high-angle thrust striking at 270º that intersects the Keeseville Formation at an outlier in the Rock Island Road region of New York State, at station N-121, was likely associated with the same compressional events that triggered movements along the basement surface farther westward, as described above.

Brecciation of the basal strata of the Keeseville Formation occurred in a wide area bordering the St. Lawrence River in New York State soon after deposition. An example is seen at station N-87 near Chippewa Bay (Fig. 80; *see also* Selleck, 1978a).

Figure 78. Folded Covey Hill Formation strata on Highway 15, Ontario, near station O-27. Photograph courtesy of J.L. Wallach.

Figure 79. Unconformable contact between Precambrian rocks and the overlying Hannawa Falls Member of the Ausable Formation near Goose Bay, New York, on Route 12, at station N-54. Note the presence of drag folds in Precambrian metagranite that result from lateral west-northwest movement of the overlying Ausable Formation across the metagranite. Photograph courtesy of J.L. Wallach.

The tectonism that triggered the brecciation may have been a rejuvenation of the St. Lawrence River Fault (*see* Fig. 3), an event possibly coincident with initiation of Keeseville deposition and the outpouring of quartzite gravel in the Wellesley Island area, as noted at station N-4 (*see* Fig. 58a). Gentle folds in basal strata of the Nepean Formation were recognized locally in the western part of the Ottawa Embayment that do not appear to have affected strata higher in the formation. Such relatively minor folding along with basal brecciation and possible faulting as described above in the basal Keeseville Formation may be related to a tectonic event of some significance that occurred along the eastern margin of the continent during the Late Cambrian and/or Early Ordovician.

Previous workers, for example Kumarapelli and Saull (1966), emphasized the significance of anorogenic plate motions such as Mesozoic rifting to account for deformation of the St. Lawrence Platform. Undoubtedly, this event left

Figure 80. Intraformational breccia in basal sandstone of the Keeseville Formation near Chippewa Bay, New York, at station N-87. Photograph courtesy of J.L. Wallach.

some imprint on the region in terms of further rejuvenation of fracture systems and emplacement of dykes and plutons. However, previous investigations by the first author in the St. Lawrence, Arctic, and Hudson platforms suggest that by far the more intensive epeirogeny during the Phanerozoic began at the close of the Early Silurian and continued into the Late Silurian. This event radically changed the pattern of seaways that had previously inundated most of the Canadian Shield, and gave rise to rapid and deep subsidence of the cratonic and foreland basins during this period, i.e. the Michigan and Hudson Bay basins (Sanford, 1969, 1993b; Sanford and Grant, 1998). What effects these processes may have had on the Central Division of the St. Lawrence Platform is unclear. However, the very fact that Silurian rocks are nowhere present in the Ottawa Embayment or the Quebec Basin may be because this area was undergoing uplift and consequently Silurian strata were never deposited or were thin and quickly eroded. Intense deformation of Silurian rocks in Gaspésie (Bourque et al., 2001; Malo, 2001) and to a lesser extent in the Appalachian Basin (Ettensohn and Brett, 2002) indicates the broad regional extent of tectonism in progress during the Silurian. Accordingly, much of the post-Potsdam deformation of this region may have occurred during the Early to Late Silurian related to the continental-wide event that may have been triggered by continental collision and final closing of the Iapetus Ocean during an early phase of the Acadian Orogeny.

REFERENCES

Alling, H.L., 1919. Geology of the Lake Clear region; New York State Museum, Bulletin 207, v. 208, p. 111–145.

Anderson, K., 2004. Facies description and cementation history of the Cambro-Ordovician Nepean Formation; B.Sc. thesis, Carleton University, Ottawa, Ontario, 63 p.

Baer, A.J., Poole, W.H., and Sanford, B.V., 1977. Rivière Gatineau, Québec–Ontario Sheet 31; Geological Survey of Canada, Map 1334A, scale 1:1 000 000.

Baird, D.M., 1972. Geology of the National Capital area; 24th International Geological Congress, Montréal, Quebec, 24th Session, Field Excursion B-23-B-27, Guidebook, 32 p.

Baker, M.B., 1916. The geology of Kingston and vicinity; Ontario Bureau of Mines, 25th Annual Report, v. xxv, pt. III, p. 1–36.

Belyea, H.R., 1952. Deep wells and subsurface stratigraphy of part of the St. Lawrence Lowlands, Quebec; Geological Survey of Canada, Bulletin 22, 113 p.

Bouche, P., Giot, D., and Schmerber, G., 1975. Étude sédimentologique du Cambro-Ordovicien des Basses Terres du St. Laurent, Québec; Ministère des Richesses naturelles, Québec, Service de documentation technique, DP-375, 101 p.

Bourque, P-A., Malo, M., and Kirkwood, D., 2001. Stratigraphy, tectono-sedimentary evolution and paleogeography of the post-Taconian-pre-Carboniferous Gaspé Belt: an overview; Bulletin of Canadian Petroleum Geology, v. 49, no. 2, p. 186–201.

Brand, U. and Rust, B.R., 1977. The age and upper boundary of the Nepean Formation in its type section near Ottawa, Ontario; Canadian Journal of Earth Sciences, v. 14, p. 2002–2006.

Brown, L., Jensen, J., Kaufman, S., and Steiner, D., 1982. Rift structure beneath the Michigan Basin from COCORP profiling; Geology, v. 10, p. 645–649.

Card, K.D., Sanford, B.V., and Card, G.M., 1997. Controls on the emplacement of kimberlites and alkalic rock-carbonatite complexes in the Canadian Shield and surrounding regions; Exploration and Mining Geology, v. 6, no. 4, p. 285–296.

Carson, D.M., 1982. Preliminary report on the Paleozoic geology of the southern portion of the Ottawa–St. Lawrence Lowland, southern Ontario; Ontario Geological Survey, Open File Report 5385, 49 p.

Chadwick, G.H., 1915. Post-Ordovician deformation in the St. Lawrence Valley, New York; Geological Society of America, Bulletin 26, p. 287–294.

Chadwick, G.H., 1920. The Paleozoic rocks of the Canton Quadrangle; New York State Museum, Bulletin 217-218, Albany, New York, 60 p.

Clark, T.H., 1952. Montreal area, Laval and Lachine map-areas; Quebec Department of Mines, Geological Report 46, 159 p.

Clark, T.H., 1966. Châteauguay area; Châteauguay, Huntingdon, Beauharnois, Napierville and St. Jean counties; Quebec Department of Natural Resources, Geological Report 122, 63 p.

Clark, T.H., 1969. The Cambrian sandstones of the St. Lawrence Lowlands; Geological Association of Canada, Field Trip 8A, Guidebook, p. 21–36.

Clark, T.H., 1972. Région de Montréal; Ministère des Richesses naturelles, Rapport géologique/Geological Report 152, 244 p.

Cohee, G.V., 1945. Stratigraphy of Lower Ordovician and Cambrian rocks in the Michigan Basin; United States Department of the Interior, Geological Survey, Oil and Gas Investigations, Preliminary Chart 9.

Cole, J., 1999. Aeolian facies from the Cambro-Ordovician Nepean Formation, southeastern Ontario; B.Sc. thesis, Queen's University, Kingston, Ontario, 54 p.

Cumming, L.M., 1983. Lower Paleozoic autochthonous strata of the Strait of Belle Isle area; in Geology of the Strait of Belle Isle Area, Northwestern Insular Newfoundland, Southern Labrador, and Adjacent Quebec, Part 2; Geological Survey of Canada, Memoir 400, p. 75–108.

Cushing, H.P., 1901. Geology of Rand Hill and vicinity, Clinton Country; 19th Report of the State Geologist (for 1899), New York State Museum, 53rd Annual Report, Albany, New York, p. 39–82.

Cushing, H.P., 1908. Lower portion of the Paleozoic section in northwestern New York; Geological Society of America, v. 19, no. 7, p. 155–176.

Dean, S.L. and Baranoski, M.T., 2002. A look at western Ohio's Precambrian tectonic setting; Oil and Gas Journal, v. 100, no. 29, p. 34–40.

Dietrich, R.V., 1953. Conical and cylindrical structures in the Potsdam Sandstone, Redwood, New York; New York State Museum, Circular 34, 9 p.

Dix, G.R., Salad Hersi, O., and Nowlan, G.S., 2004. The Potsdam–Beekmantown Group boundary, Nepean Formation type section (Ottawa, Ontario): a cryptic sequence boundary, not a conformable transition; Canadian Journal of Earth Sciences, v. 41, p. 897–902.

Dobie, N., 2004. Depositional interpretation and sequence stratigraphic framework of the Nepean Foundation; B.Sc. thesis, University of Ottawa, Ottawa, Ontario, 44 p.

Donaldson, J.A. and Chiarenzelli, J.R., 2004. Precambrian basement and Cambrian-Ordovician strata, as displayed in three provincial parks of Canada; New York State Geological Association, 76th Annual Meeting, Field Trip A-1, Guidebook, (ed.) R. Badger, p. 63–78.

Donaldson, J.A. and Munro, I., 2002. Biofilm structures, trace fossils and stromatolites in early Paleozoic quartzarenite and carbonates of the Ottawa region, Ontario; in Program and Abstracts No. 12, (ed.) B.J. Dougherty and A.D. McCracken; Canadian Paleontology Conference, September 29–30, 2002.

Drahovzol, J.A., 1997. Proterozoic sequences and their implications for Precambrian and Cambrian geologic evolution of western Kentucky: evidence from seismic-reflection data; Seismological Research Letters, v. 68, no. 4, p. 553–566.

Drahovzal, J.A., Harris, D.C., Wickstrom, L.H., Walker, D., Baranoski, M.T., Keith, B., and Furer, L.C., 1992. The East Continental Rift Basin: a new discovery; Ohio Department of Natural Resources, Division of Geological Survey, Information Circular 57, 25 p.

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. 714–904.

Emmons, E., 1838. Report on the second geological district of the State of New York; New York Geological Survey, Report 2, p. 185–252.

Emmons, E., 1841. Proposed Keeseville Sandstone for parts of Potsdam: 5th Annual Report of the Survey, of the 2nd Geological District; New York Geologist Annual Report, 5th, p. 113–136.

Erickson, J.M., 1993. Cambro-Ordovician stratigraphy, sedimentation, and ichnobiology of the St. Lawrence Lowlands–Frontenac Arch to the Champlain Valley of New York; New York State Geological Association, 65th Annual Meeting, Field Trip A-3(1) Guidebook, p. 68–95.

Erickson, J.M. and Bjerstedt, T.W., 1993. Trace fossils and stratigraphy in the Potsdam and Theresa formations of the St. Lawrence Lowland, New York; New York State Geological Association, 65th Annual Meeting, Field Trip A-3(2) Guidebook, p. 97–119.

Erickson, J.M. and Fetterman, A.R., 1993. Distribution of trace fossils preserved in high energy deposits of the Potsdam sandstone, Champlain, New York; New York State Geological Association, 65th Annual Meeting, Field Trip A-3(4) Guidebook, p. 131–143.

Ettensohn, F.R. and Brett, C.E., 2002. Stratigraphic evidence from the Appalachian Basin for continuation of the Taconian Orogeny into Early Silurian time; Physics and Chemistry of the Earth, v. 27, no. 1, p. 279–288.

Findlay, R.G., 1968. Determination of the paleoenvironment of the Potsdam sandstone in the Kingston, Ontario, area; B.Sc. thesis, Queen's University, Kingston, Ontario, 37 p.

Fisher, D.W., 1956. The Cambrian System of New York State; Proceedings, 20th International Geological Congress, Part 2, Mexico City, Mexico, p. 321–351.

Fisher, D.W., 1968. Geology of the Plattsburgh and Rouses Point, New York–Vermont quadrangles; New York State Museum and Science Service, Map and Chart Series no. 10, 51 p.

Fisher, D.W., 1977. Correlation of the Hadrynian, Cambrian and Ordovician rocks in New York State; New York State Museum and Science Service, Map and Chart Series no. 25, 75 p.

Fisher, D.W., Isachsen, Y.W., and Rickard, L.V., 1970. Geologic map of New York State, Adirondack Sheet; New York State Museum and Science Service, Map and Chart Series no. 15; scale 1:250 000.

Forsyth, D.A.G., 1968. Studies in the Potsdam; B.Sc. thesis, Queen's University, Kingston, Ontario, 58 p.

Gaudette, H.E., Vitrac, A., and Allègre, C.J., 1981. North American Precambrian history recorded in a single sample high-resolution U-Pb systematics of the Potsdam sandstone detrital zircons, New York State; Earth and Planetary Science Letters, v. 54, no. 2, p. 248–260.

Getty, P.R. and Hagadorn, J.W., 2008. Reinterpretation of Climactichnites Logan 1860 to include subsurface burrows, and erection of Musculopodus for resting traces of the trailmaker; Journal of Paleontology, v. 82, no. 6, p. 1161–1172.

Getty, P.R. and Hagadorn, J.W., 2009. Palaeobiology of the Climactichnites tracemaker; Palaeontology, v. 52, no. 4, p. 753–778.

Globensky, Y., 1987. Géologie des basses-terres du Saint-Laurent; Gouvernement du Québec, Ministère de l'Énergie et des Ressources, MM 85-02, 63 p.

Goldring, W., 1931. Handbook of paleontology for beginners and amateurs, part 2: the formations; New York State Museum Handbook no. 10, The University of the State of New York, Albany, New York, 488 p.

Gower, C.F., 1986. Geology of the Double Mer, White Hills and surrounding region, Grenville Province, eastern Labrador; Geological Survey of Canada, Paper 86-15, 50 p.

Grady, W., 2002. Eight small steps, a fossil trackway near Kingston, Ontario; Canadian Geographical Journal, November/December 2002, p. 72–82

Grant, A.C., 1975. Seismic reconnaissance of Lake Melville, Labrador; Canadian Journal of Earth Sciences, v. 12, no. 12, p. 2103–2110.

Greggs, R.G. and Bond, I.J., 1972. A principal reference section proposed for the Nepean Formation of probable Tremadocian age near Ottawa, Ontario; Canadian Journal of Earth Sciences, v. 9, no. 5, p. 993–941.

Grier, M.E., 1993. Brittle faulting along the St. Lawrence Valley from Kingston to Cornwall; Atomic Energy Control Board, Ottawa, Ontario, Canada, Project No. 2.269.1 INFO 0578, 22 p, 1:250 000-scale geological map.

Gruhman, A.I. and Pederson, D.T., 1992. Boiling sand springs, Dismal River, Nebraska: Agents for formation of vertical cylindrical structures and geomorphic change; Geology, v. 20, p. 8–10

Hagadorn. J.W. and Belt, E.S., 2008. Stranded in upstate New York: Cambrian Scyphomedusae from the Potsdam Sandstone; Palaios, v. 23, p. 424–441. doi:10.2110/palo.2006.p06–104r

Hamblin, W.K., 1958. the Cambrian sandstones of northern Michigan; Michigan Department of Conservation, Geological Survey Division, Publication 51, 146 p.

Hawley, J.E. and Hart, R.C., 1934. Cylindrical structures in sandstones; Geological Society of America, Bulletin 46, p. 2008–2011.

Hilowle, M.A., Donaldson, J.A., and Arnott, R.W.C., 2000. Biofilm-mediated structures in quartzarenite of the Cambro-Ordovician Nepean Formation; GeoCanada 2000 — The Millennium Geoscience Summit, Calgary, Alberta, May 29–June 2, 2000; Conference CD, Abstract 868.

Hofmann, H.J., 1972. Stratigraphy of the Montreal area; International Geological Congress, 24th Session, Montréal, Quebec, Field Excursion B-03, 32 p.

Hunter, R.E., 1977. Basic types of stratification in small eolian dunes; Sedimentology, v. 24, p. 361–387.

Jackson, G.D., 1955. A petrographic study of part of the Potsdam sandstone, core from the Mallet Well, Ste. Thérèse, P.Q.; M.Sc. thesis, McGill University, Montréal, Quebec, 78 p.

J.L. Wallach Geosciences Inc. and MIR Télédétection Inc., 2004. Exploration for natural gas north and east of the Adirondack Dome in New York State. Phase I-Regional reconnaissance; New York State Energy Research and Development Authority, 81 p.

Kirwan, J.L., 1963. The age of the Nepean (Potsdam) Sandstone in eastern Ontario; American Journal of Science, v. 261, p. 108–110.

Knight, I., James, N.P., and Williams, H., 1995. Cambrian-Ordovician carbonate sequence (Humber Zone); *in* Chapter 3 of Geology of the Appalachian-Caledonian Orogen in Canada and Greenland, (ed.) H. Williams; Geological Survey of Canada, Geology of Canada, no. 6, p. 67–87 (*also* Geological Society of America, The Geology of North America, v. F-1, p. 67–87).

Krynine, P.D., 1948. Possible Algonkian in New York State; Geological Society of America, Bulletin 59, no. 12, p. 1333–1334 (abstract).

Kumarapelli, P.S. and Saull, V.A., 1966. The St. Lawrence valley system: a North American equivalent of the east African rift valley system; Canadian Journal of Earth Sciences, v. 3, no. 5, p. 639–658.

Kunert, M. and Coniglio, M., 2002. Origin of vertical shafts in bedrock along the Eramosa River valley near Guelph, southern Ontario; Canadian Journal of Earth Sciences, v. 39, p. 43–52.

Landing, E., Franzy, D.A., Hagadorn, J.W., Westrop, S.R., Kröger, B., and Dawson, J.C., 2007. Cambrian of east Laurentia: Field workshop in eastern New York and western Vermont; *in* Ediacarian-Ordovician of East Laurentia, C.W. Ford Memorial Volume, (ed.) E. Landing; 12th International Conference of the Cambrian Chronostratigraphy Workshop, New York State Museum Bulletin 51, p. 25–80.

Landing, E., Amati, L., and Franzi, D.A., 2009. Epeirogenic transgression near a triple junction: the oldest (latest early–middle Cambrian) marine onlap of cratonic New York and Quebec; Geological Magazine, v. 146, no. 4, p. 552–566. doi:10.1017/S0016756809006013

Lewis, D.W., 1965. Cambrian (pre-Beekmantown) sedimentation in southwestern Quebec with special reference to three deep wells near Montreal; Ph.D. thesis, McGill University, Montréal, Quebec, 329 p.

Lewis, T.L., 1963. A paleocurrent study of the Potsdam sandstones of New York, Quebec and Ontario; Ph.D. thesis, Ohio State University, Akron, Ohio, 148 p.

Liberty, B.A., 1967. Paleozoic stratigraphy of the Kingston area, Ontario; *in* Geology of Parts of Eastern Ontario and Western Quebec, (ed.) S.E. Genness; Geological Association of Canada-Mineralogical Association of Canada, Field Trip Guidebook, Kingston, Ontario, p. 167–182.

Liberty, B.A., 1971. Paleozoic geology of Wolfe Island, Bath, Sydenham and Gananoque map areas; Geological Survey of Canada, Paper 70-35, 12 p.

Logan, W.E., 1851. On the occurrence of a track and footprints of an animal in the Potsdam of Lower Canada; Geological Society of London, Quarterly Journal, v. 7, p. 247–252.

Logan, W.E., 1852. On the footprints occurring in the Potsdam Sandstone of Canada; Geological Society of London, Quarterly Journal, v. 8, p. 199–213.

Logan, W.E., 1863. Report on the Geology of Canada; Geological Survey of Canada, Report of Progress from Commencement to 1863.

Macey, G., 1970. Paleocurrent analysis and petrology of the Potsdam Sandstone in the Pointe aux Cascades-Île Perrôt; B.Sc. thesis, Loyola College, Concordia University, Montréal, Quebec, 33 p.

Malo, M., 2001. Late Silurian–Early Devonian tectono-sedimentary history of the Gaspé Belt in the Gaspé Peninsula: from a transtensional Salinic basin to an Acadian foreland basis; Bulletin of Canadian Petroleum Geology, v. 49, no. 2, p. 202–216.

Miser, H.D., 1935. Comment: "Cylindrical structures in sandstone" by J.E. Hawley and R.C. Hart; Geological Society of America, Bulletin 46, p. 2014–2015.

MacNaughton, R.B., Cole, J.M., Dalrymple, R.W., Braddy, S.J., Briggs, D.E.G., and Lukie, T.D., 2002. First steps on land: Arthropod trackways in Cambrian-Ordovician eolian sandstone, southeastern Ontario, Canada; Geology, v. 30, no. 5, p. 391–394.

Otvos, E.G., Jr., 1966. Sedimentary structures and depositional environments, Potsdam Formation, Upper Cambrian; American Association of Petroleum Geologists Bulletin, v. 50, no. 1, p. 159–185.

Owen, P., 1852. Description of the impressions and footprints of the Protichnites from the Potsdam Sandstone of Canada; Geological Society of London, Quarterly Journal, v. 8, p. 214–225.

Pettijohn, F.J., 1957. Sedimentary Rocks (second edition); Harper and Brothers, New York, 718 p.

Poole, W.H., Sanford, B.V., Williams, H., and Kelley, D.G., 1970. Geology of southeastern Canada; Chapter VI *in* Geology and Economic Minerals of Canada, (ed.) R.J.W. Douglas; Geological Survey of Canada, Economic Geology Report 1, p. 229–304.

Postel, A.W., Nelson, A.E., and Wiesnet, D.R., 1959. Geologic map of the Nicholsville quadrangle, New York; United States Geological Survey, Geologic Quadrangle Map GQ-123, scale 1:62 500.

Potter, P., 1996. Exploring the geology of The Cincinnati/Northern Kentucky region; Kentucky Geological Survey, Special Publication 22, 115 p.

Reed, J.C., 1934. Geology of the Potsdam Quadrangle, New York; New York State Museum, Bulletin 297, p. 5–65.

Richard, B.H., Wolfe, P.J., and Potter, P., 1997. Pre-Mount Simon basins of western Ohio; Geological Society of America, Special Paper 312, p. 243–252.

Rickard, L.V., 1973. Stratigraphy and structure of the subsurface Cambrian and Ordovician carbonates of New York; New York State Museum and Science Service, Map and Chart Series no.18, Albany, New York, 26 p.

Roliff, W.A., 1954. The Pre-Middle Ordovician rocks of southwestern Ontario; Proceedings of the Geological Association of Canada, v. 6, pt. 2, p. 103–109.

Roliff, W.A., 1968, Stratigraphic and environmental studies of the Potsdam Group, St. Lawrence Lowland — eastern Canada; Ph.D. thesis, University of London, London, England, 89 p.

Sahakian, A.S., 1963. Paleocurrent study of the Potsdam Sandstone of New York and Quebec; Ph.D. thesis, Harvard University, Cambridge, Massachusetts, 118 p.

Salad Hersi, O. and Lavoie, D., 2000a. Pre-Cairnside Formation carbonate-rich sandstone: evidence for a Cambrian carbonate platform in southwestern Quebec?; Geological Survey of Canada, Current Research 2000-D3, 8 p.

Salad Hersi, O. and Lavoie, D., 2000b. Lithostratigraphic revision of the Upper Cambrian Cairnside Formation, upper Potsdam Group, southwestern Quebec; Geological Survey of Canada, Current Research 2000-D4, 8 p.

Salad Hersi, O., Lavoie, D., Hilowle, M.A., and Nowlan, G.S., 2002. Subaerial unconformity at the Potsdam-Beekmantown contact in the Quebec Reentrant: regional significance for the Laurentian continental margin history; Bulletin of Canadian Petroleum Geology, v. 50, no. 3, p. 419–440.

Sanford, B.V., 1969. Silurian of southwestern Ontario; Proceedings, Ontario Petroleum Institute Annual Meeting, p. 1–44.

Sanford, B.V., 1987. Paleozoic geology of the Hudson Platform; *in* Sedimentary Basins and Basin Forming Mechanisms, (ed.) C. Beaumont and A.J. Tankard; Canadian Society of Petroleum Geology, Memoir 12, p. 483–505.

Sanford, B.V., 1993a. St. Lawrence Platform — Introduction; Chapter 10 *in* Sedimentary Cover of the Craton in Canada, (ed.) D.F. Stott and J.D. Aitken; Geological Survey of Canada, Geology of Canada, no. 5, p. 709–722 (*also* Geological Society of America, The Geology of North America, v. D-1, p. 709–722).

Sanford, B.V., 1993b. St. Lawrence Platform — Geology; Chapter 11 *in* Sedimentary Cover of the Craton in Canada, (ed.) D.F. Stott and J.D. Aitken; Geological Survey of Canada, Geology of Canada, no. 5, p. 723–786 (*also* Geological Society of America, The Geology of North America, v. D-1, p. 723–786).

Sanford, B.V., 1993c. Stratigraphic and structural framework of upper Middle Ordovician rocks in the Head Lake–Burleigh Falls area of southcentral Ontario; Géographie physique et Quaternaire, v. 47, no. 3, p. 253–268.

Sanford, B.V., 1998. Geology and oil and gas possibilities of the Gulf of St. Lawrence region — southeastern Canada; Geological Survey of Canada, Open File 3632, 63 p.

Sanford, B.V., 2007. Stratigraphic and structural framework of the Potsdam Group in eastern Ontario; Ph.D. thesis, University of Ottawa, Ottawa, Ontario, 222 p.

Sanford, B.V. and Grant, A.C., 1990. New findings relating to the stratigraphy of the Hudson Platform; *in* Current Research, Part D; Geological Survey of Canada, Paper 90-10, p. 17–30.

Sanford, B.V. and Grant, A.C., 1998. Paleozoic and Mesozoic geology of the Hudson and southeast Arctic Platform; Geological Survey of Canada, Open File 3595, scale 1:2 500 000.

Sanford, B.V. and Quillian, R.G., 1959. Subsurface stratigraphy of Upper Cambrian rocks in southwestern Ontario; Geological Survey of Canada, Paper 58-112, 33 p.

Sanford, B.V., Thompson, F.J., and McFall, G.H., 1985. Plate tectonics — A possible controlling mechanism in the development of hydrocarbon traps in southwestern Ontario; Bulletin of Canadian Petroleum Geology, v. 33, p. 52–71.

Santos, J.O.S., Hartman, L.A., McNaughton, N.J., Easton, R.M., Rea, R.G., and Potter, P., 2002. Sensitive high resolution ion microprobe (SHRIMP) detrital zircon geochronology provides new evidence for a hidden Neoproterozoic foreland basin to the Grenville Orogen in the eastern Midwest, U.S.A.; Canadian Journal of Earth Sciences, v. 39, no. 10, p. 1505–1515.

Selleck, B.W., 1975. Paleoenvironment and petrography of the Potsdam Sandstone, Theresa Formation and Ogdensburg Dolomite (U. Camb.–L. Ord.) of the southwestern St. Lawrence Valley, New York; Ph.D. thesis, University of Rochester, Rochester, New York, 185 p.

Selleck, B.W., 1978a. Syndepositional brecciation in the Potsdam Sandstone of northern New York State; Journal of Sedimentary Petrology, v. 48, p. 1177–1184.

Selleck, B.W., 1978b. Paleoenvironments of the Potsdam Sandstone and Theresa Formation of the southwestern St. Lawrence Lowlands; New York State Geological Association, 28th Annual Conference Field Trip Guidebook, September 1978, Syracuse, New York, p. 173–188.

Selleck, B.W., 1993. Sedimentology and diagenesis of the Potsdam sandstone and Theresa formations, southwestern St. Lawrence Valley; New York State Geological Association, 65th Annual Meeting, Field Trip Guidebook, p. 219–228.

Shrake, D., Wolfe, P.J., Richard, H., MacSwinford, E., Wickstrom, L.H., Potter, P.E., and Sitler, G.W., 1990. Lithologic and geophysical description of a continuously cored hole in Warren country, Ohio, including description of the Middle Run Formation (Precambrian ?) and a seismic profile across the core site; State of Ohio, Department of Natural Resources, Division of Geological Survey, 11 p.

Sitter, S.S., 1960. A study of the Potsdam sandstone in the vicinity of Kingston, Ontario; B.Sc. thesis, Queen's University, Kingston, Ontario, 46 p.

Smith, G.L., Byers, C.W., and Dott, R.H., Jr., 1993. Sequence stratigraphy of the Lower Ordovician Prairie du Chien Group on the Wisconsin Arch and in the Michigan Basin; American Association of Petroleum Geologists Bulletin, v. 77, no. 1, p. 49–67.

Stevenson, I.M., 1967. Goose Bay map area, Labrador; Geological Survey of Canada, Paper 67-33, 12 p.

Stevenson, I.M., 1970. Rigolet and Groswater Bay map-areas, Newfoundland (Labrador) 13J, 13I; Geological Survey of Canada, Paper 69-48, 24 p.

Van Ingen, G., 1902. The Potsdam Sandstone of the Lake Champlain Basin; *in* Report of the State Paleontologist (for 1901), New York State Museum Bulletin 52, Albany, New York, p. 529–545.

Waterfall, R.G., 1968. Soft-sediment deformation in the Nepean Formation, Ottawa, Ontario; B.Sc. thesis, Department of Geology, Carleton University, Ottawa, Ontario, 48 p.

Wheeler, J.O., Hoffman, P.F., Card, K.D., Davidson, A., Sanford, B.V., Okulitch, A.V., and Roest, W.R., 1996. Geological Map of Canada; Geological Survey of Canada, Map 1860A, scale 1:5 000 000.

Wiesnet, D.R., 1961. Composition, grain size, roundness and sphericity of the Potsdam Sandstone (Cambrian) in northeastern New York; Journal of Sedimentary Petrology, v. 31, p. 5–14.

Wiesnet, D.R. and Clark, T.H., 1966. The bedrock structure of Covey Hill and vicinity, northern New York and southern Quebec; United States Geological Survey, Professional Paper 550-D, p. D35–D38.

Williams, D.A. and Wolf, R.R., 1984a. Paleozoic geology of the Carleton Place area, southern Ontario; Ontario Geological Survey, Map P.2725, scale 1:50 000.

Williams, D.A. and Wolf, R.R., 1984b. Paleozoic geology of the Westport area, Southern Ontario; Ontario Geological Survey, Map P.2723, scale 1:50 000.

Williams, D.A. and Wolf, R.R., 1984c. Paleozoic geology of the Perth area, southern Ontario; Ontario Geological Survey, Map P.2724, scale 1:50 0000.

Williams, D.A., Rae, A.M., and Wolf, R.R., 1984a. Paleozoic geology of the Ottawa area, southern Ontario; Ontario Geological Survey, Map P.2716, scale 1:50 000.

Williams, D.A., Rae, A.M., and Wolf, R.R., 1985a. Paleozoic geology of the Alexandria–Vaudeuil area, southern Ontario; Ontario Geological Survey, Map P.2719, scale 1:50 000.

Williams, D.A., Rae, A.M., and Wolf, R.R., 1985b. Paleozoic geology of the Russell–Thurso area, southern Ontario; Ontario Geological Survey, Map P.2717, scale 1:50 000.

Williams, D.A., Telford, P.G., McCracken, A.D., and Brunton, F.R., 1992. Cambrian–Ordovician geology of the Ottawa region; Geological Association of Canada, Paleontology Division, Canadian Paleontology Conference, Field Trip Guidebook no. 2, 51 p.

Williams, D.A., Wolf, R.R., and Rae, A.M., 1984b. Paleozoic geology of the Arnprior–Quyon area, southern Ontario; Ontario Geological Survey, Map P.2726, scale 1:50 000.

Williams, H., Kumarapeli, P.S., and Knight, I., 1995. Upper Precambrian–Lower Cambrian clastic sedimentary and volcanic rocks (Humber Zone); *in* Chapter 3 of Geology of the Appalachian-Caledonian Orogen in Canada and Greenland, (ed.) H. Williams; Geological Survey of Canada, Geology of Canada, no. 6, p. 61–67 (*also* Geological Society of America, The Geology of North America, v. F-1, p. 61–67).

Wilson, A.E., 1937. Erosional intervals indicated by contacts in the vicinity of Ottawa, Ontario; Royal Society of Canada, Proceedings and Transactions, 3rd series, 31 Sect. IV, p. 45–60.

Wilson, A.E., 1946. Geology of the Ottawa–St. Lawrence Lowland, Ontario and Quebec; Geological Survey of Canada, Memoir 241, 66 p.

Wilson, A.E., 1956. A guide to the geology of the Ottawa District; The Canadian Field-Naturalist, v. 70, no. 1, 68 p.

Winder, C.G. and Sanford, B.V., 1972. Stratigraphy and paleontology of the Paleozoic rocks of southern Ontario; International Geological Congress, Montréal, Quebec, 24th Session, Field Excursion A-45-C45, 74 p.

Wolf, R.R. and Dalrymple, R.W., 1984. Sedimentology of the Cambro-Ordovician sandstones of eastern Ontario; Ontario Geological Survey, Miscellaneous Paper 121, p. 240–252.

Appendix A

Location of field stations

Station.number	Area	1:250 000 map sheet	UTM location	Rocks exposed
Ontario				
O-1*	Rockland	Ottawa 31G	476500E; 5041500N	Covey Hill/Nepean
O-2*	Ottawa	Ottawa 31G	432050E; 5019700N	Nepean
O-3*	Ottawa	Ottawa 31G	432100E; 5018900N	Nepean
O-4	Ottawa	Ottawa 31G	428410E; 5017535N	Nepean
O-5	Ottawa	Ottawa 31G	428532E; 5017954N	Nepean
O-6*	Ottawa	Ottawa 31G	437841E; 5016272N	Nepean/March
O-7*	Ottawa	Ottawa 31G	456144E; 5017333N	Nepean/March
O-8	Almonte	Pembrooke 31F	404546E; 5007349N	Nepean
O-9	Almonte	Pembrooke 31F	404625E; 5007425N	Nepean/March
O-10	Mississippi Lake	Pembrooke 31F	408250E; 4995900N	Nepean
O-11	Mississippi Lake	Pembrooke 31F	402823E; 4985611N	Nepean/March
O-12*	Mississippi Lake	Pembrooke 31F	406721E; 4987232N	PE/Nepean
O-13	Mississippi Lake	Pembrooke 31F	406324E; 4985609N	Nepean/March
O-14*	Rideau Ferry	Kingston 31C	405884E; 4967820N	Covey Hill
O-15	Rideau Ferry	Kingston 31C	405560E; 4969200N	Nepean
O-16*	Rideau Ferry	Kingston 31C	408423E; 4967610N	Covey Hill/Nepean
O-17*	Otter Lake	Kingston 31C	412659E; 4959755N	Covey Hill/Nepean
O-18*	Briton Bay	Kingston 31C	406309E; 4958089N	Covey Hill
O-19	Briton Bay	Kingston 31C	407450E; 4955000N	Covey Hill
O-20	Portland	Kingston 31C	408050E; 4952939N	Nepean
O-21	Crosby	Kingston 31C	400635E; 4942884N	Nepean
O-22	Crosby	Kingston 31C	400801E; 4942483N	Nepean
O-23*	Elgin	Kingston 31C	402834E; 4940012N	PE/Covey Hill
O-24	Elgin	Kingston 31C	403630E; 4939348N	Nepean/March
O-25	Elgin	Kingston 31C	404200E; 4938450N	Nepean
O-26	Elgin	Kingston 31C	404100E; 4936450N	Nepean
O-27*	Jones Falls	Kingston 31C	404090E; 4934500N	PE/Covey Hill
O-28	Jones Falls	Kingston 31C	401924E; 4933165N	Covey Hill
O-29*	Jones Falls	Kingston 31C	401956E; 4932350N	Covey Hill
O-30*	Elgin	Kingston 31C	406002E; 4936441N	Covey Hill
O-31	Elgin	Kingston 31C	406186E; 4938443N	Nepean
O-32	Elgin	Kingston 31C	405450E; 4943000N	Nepean
O-33*	Philipsville	Kingston 31C	409459E; 4943600N	Nepean/March
O-34	Philipsville	Kingston 31C	410200E; 4926500N	Covey Hill
O-35*	Delta	Kingston 31C	410302E; 4942614N	Covey Hill
O-36	Delta	Kingston 31C	410906E; 4941216N	Nepean
O-37	Delta	Kingston 31C	412637E; 4939140N	Covey Hill
O-38	Delta	Kingston 31C	413074E; 4938852N	Nepean
O-39	Charleston Lake	Kingston 31C	418470E; 4937296N	Nepean
O-40	Charleston Lake	Kingston 31C	416993E; 4937131N	Nepean
O-41	Charleston Lake	Kingston 31C	415940E; 4937026N	Nepean
O-42	Lyndhurst	Kingston 31C	411789E; 4935700N	Nepean
O-43	Lyndhurst	Kingston 31C	411723E; 4935120N	Covey Hill
O-44	Lyndhurst	Kingston 31C	411073E; 4934054N	Nepean
O-45	Charleston Lake	Kingston 31C	419521E; 4936705N	Covey Hill
O-46	Charleston Lake	Kingston 31C	419020E; 4934942N	(?) Nepean
O-47*	Davis Lock	Kingston 31C	397051E; 4936100N	Covey Hill
O-48	Lansdowne	Ogdensburg 31B	420310E; 4916935N	Nepean
O-49	Lansdowne	Kingston 31C	418837E; 4918914N	Nepean
O-50	Lansdowne	Kingston 31C	414065E; 4918878N	Nepean
O-51	Gananoque	Kingston 31C	409935E; 4911053N	PE/Nepean
O-52	Gananoque	Kingston 31C	409758E; 4910883N	Covey Hill
O-53	Gananoque	Kingston 31C	400334E; 4907867N	Nepean
O-54	Ganonoque	Kingston 31C	394883E; 4905508N	Nepean
O-55*	Kingston	Kingston 31C	389600E; 4902020N	PE/Abbey Dawn/ Gull River
O-56*	Sunbury	Kingston 31C	389520E; 4912016N	Covey Hill
O-57*	Sunbury	Kingston 31C	390789E; 4912949N	PE/Covey Hill/Nepean
O-58	Sunbury	Kingston 31C	387666E; 4914267N	Covey Hill
O-59	Sunbury	Kingston 31C	388789E; 4915324N	Covey Hill
O-60	Charleston Lake	Kingston 31C	418797E; 4929750N	Covey Hill
O-61*	Charleston Lake	Kingston 31C	417600E; 4928400N	Covey Hill
O-62	Lyn	Ogdensburg 31B	437243E; 4936854N	Nepean

* Denotes key sections

Appendix A (cont.)

Station.number	Area	1:250 000 map sheet	UTM location	Rocks exposed
O-63	Lyn	Ogdensburg 31B	437740E; 4935927N	Nepean
O-64*	Lyn	Ogdensburg 31B	438347E; 4936282N	PE/Abbey Dawn/ Covey Hill/Nepean
O-65*	Butternut Bay	Odgensburg 31B	436810E; 4929860N	PE/Abbey Dawn/March
O-66*	Athens	Odgensburg 31B	427442E; 4937404N	Abbey Dawn/ Covey Hill/Nepean
O-67*	Salem	Kingston 31E	383200E; 4945200N	Covey Hill
O-68	Fermoy	Kingston 31E	381500E; 4945750N	Covey Hill
O-69	Ellisville	Kingston 31E	408560E; 4926077N	Covey Hill
O-70*	Sunbury	Kingston 31E	393900E; 4916616N	Covey Hill/Nepean
Quebec				
Q-1*	Gatineau	Ottawa 31G	451415E; 5037084N	PE/Cairnside
Q-2*	Perrôt Island	Montreal 31H	581310E; 5026470N	Covey Hill
Q-3*	Perrôt Island	Montreal 31H	581570E; 5026290N	Covey Hill
Q-4*	Perrôt Island	Montreal 31H	589550E; 5023950N	Cairnside (Nepean)
Q-5*	Covey Hill	Montreal 31H	596274E; 4988706N	Covey Hill
Q-6*	Covey Hill	Montreal 31H	591518E; 4987409N	Covey Hill
Q-7*	Covey Hill	Montreal 31H	594549E; 4985743N	Covey Hill
Q-8*	Covey Hill	Montreal 31H	597199E; 4985419N	Covey Hill
Q-9*	Saint Pierre	Montreal 31H	587545E; 4996190N	Cairnside
Q-10*	Saint Pierre	Montreal 31H	591017E; 4995515N	Covey Hill
Q-11*	Bridgetown	Montreal 31H	582697E; 4986664N	Cairnside
Q-12*	Saint-Jean Chrysostone	Montreal 31H	597337E; 4994954N	Covey Hill
Q-13*	Covey Hill	Montreal 31H	591513E; 4987598N	Covey Hill
Q-14*	Covey Hill	Montreal 31H	592857E; 4985700N	Covey Hill
Q-15*	Covey Hill	Montreal 31H	594549E; 4985748N	Covey Hill
Q-16	Gatineau	Ottawa 31H	446205E; 5038084N	Cairnside (Nepean)
Q-17	Masson	Ottawa 31H	466857E; 5043434N	Cairnside (Nepean)
Q-18*	Covey Hill	Montreal 31H	598734E; 4984332N	Covey Hill/Cairnside
Q-19*	Covey Hill	Montreal 31H	599249E; 4985006N	Covey Hill
New York				
N-1	Clayton	Kingston 31C	413205E; 4898240N	Keeseville
N-2	Thousand Is. Park	Kingston 31C	419304E; 4907018N	Keeseville
N-3	Alexandria Bay	Ogdensburg 31B	420556E; 4905987N	Keeseville
N-4*	Thousand Is. Park	Kingston 31C	419488E; 4907450N	Keeseville
N-5	Alexandria Bay	Ogdensburg 31B	420262E; 4902815N	Keeseville
N-6	Alexandria Bay	Ogdensburg 31B	422933E; 4900909N	Keeseville
N-7	Alexandria Bay	Ogdensburg 31B	425754E; 4904193N	Ausable
N-8	Alexandria Bay	Ogdensburg 31B	428739E; 4905147N	Ausable
N-9	Alexandria Bay	Ogdensburg 31B	428935E; 4905017N	Ausable
N-10	Alexandria Bay	Ogdensburg 31B	428384E; 4907702N	Keeseville
N-11	Alexandria Bay	Ogdensburg 31B	427991E; 4907977N	Keeseville
N-12	Alexandria Bay	Ogdensburg 31B	428485E; 4910354N	Keeseville
N-13*	Alexandria Bay	Ogdensburg 31B	430059E; 4910604N	PE/Ausable/ Keeseville
N-14	Alexandria Bay	Ogdensburg 31B	430118E; 4910676N	Ausable
N-15	Theresa	Ogdensburg 31B	434505E; 4895625N	Ausable
N-16	Theresa	Ogdensburg 31B	433836E; 4895550N	Keeseville
N-17*	Theresa	Ogdensburg 31B	434488E; 4897850N	Ausable/Keeseville
N-18*	Theresa	Ogdensburg 31B	436714E; 4896198N	PE/Ausable/ Keeseville
N-19	Theresa	Ogdensburg 31B	436921E; 4895947N	Ausable
N-20	Theresa	Ogdensburg 31B	437978E; 4895623N	Ausble
N-21	Theresa	Ogdensburg 31B	438215E; 4895477N	Ausable
N-22	Theresa	Ogdensburg 31B	439458E; 4897770N	Ausable
N-23	Theresa	Ogdensburg 31B	434704E; 4899215N	Keeseville
N-24	Theresa	Ogdensburg 31B	434755E; 4899329N	Keeseville
N-25	Theresa	Ogdensburg 31B	436162E; 4899223N	Ausable
N-26	Theresa	Ogdensburg 31B	436256E; 4899636N	Ausable
N-27	Redwood	Ogdensburg 31B	436411E; 4900145N	Keeseville
N-28	Redwood	Ogdensburg 31B	436662E; 4901203N	Ausable
N-29	Redwood	Ogdensburg 31B	435984E; 4901647N	Keeseville
N-30	Redwood	Ogdensburg 31B	435725E; 4901811N	Keeseville
N-31	Redwood	Ogdensburg 31B	436926E; 4901307N	Ausable

* Denotes key sections

Appendix A (cont.)

Station.number	Area	1:250 000 map sheet	UTM location	Rocks exposed
N-32	Redwood	Ogdensburg 31B	437705E; 4901711N	Ausable
N-33	Redwood	Ogdensburg 31B	437829E; 4901779N	Ausable
N-34	Redwood	Ogdensburg 31B	438035E; 4901897N	Ausable
N-35	Redwood	Ogdensburg 31B	438709E; 4902532N	Ausable
N-36	Redwood	Ogdensburg 31B	439147E; 4903800N	Ausable
N-37	Redwood	Ogdensburg 31B	436930E; 4904803N	Keeseville
N-38	Redwood	Ogdensburg 31B	435946E; 4905890N	Keeseville
N-39*	Redwood	Ogdensburg 31B	435146E; 4905627N	Ausable/Keeseville
N-40	Redwood	Ogdensburg 31B	435066E; 4905605N	Ausable
N-41	Redwood	Ogdensburg 31B	431709E; 4905645N	Keeseville
N-42	Redwood	Ogdensburg 31B	435912E; 4906623N	Keeseville
N-43	Redwood	Ogdensburg 31B	435923E; 4906911N	Ausable
N-44	Redwood	Ogdensburg 31B	436197E; 4904606N	Keeseville
N-45	Redwood	Ogdensburg 31B	433100E; 4906750N	Keeseville
N-46	Redwood	Ogdensburg 31B	433389E; 4906856N	Keeseville
N-47	Redwood	Ogdensburg 31B	433151E; 4907815N	Keeseville
N-48	Redwood	Ogdensburg 31B	433450E; 4908167N	Keeseville
N-49	Redwood	Ogdensburg 31B	433645E; 4908566N	Ausable
N-50	Redwood	Ogdensburg 31B	433612E; 4908694N	Keeseville
N-51	Redwood	Ogdensburg 31B	433597E; 4908778N	Keeseville
N-52	Redwood	Ogdensburg 31B	433586E; 4909113N	Keeseville
N-53	Redwood	Ogdensburg 31B	432072E; 4912176N	Ausable
N-54*	Redwood	Ogdensburg 31B	433061E; 4913021N	Ausable
N-55	Redwood	Ogdensburg 31B	433135E; 4913112N	Ausable
N-56	Redwood	Ogdensburg 31B	437279E; 4908026N	Ausable
N-57	Redwood	Ogdensburg 31B	437437E; 4908477N	Ausable
N-58*	Redwood	Ogdensburg 31B	437087E; 4908957N	Ausable
N-59	Redwood	Ogdensburg 31B	435716E; 4910730N	Ausable
N-60	Redwood	Ogdensburg 31B	435692E; 4911863N	Ausable
N-61	Redwood	Ogdensburg 31B	435928E; 4912880N	Ausable
N-62	Redwood	Ogdensburg 31B	436180E; 4913100N	Keeseville
N-63	Redwood	Ogdensburg 31B	431971E; 4902089N	Keeseville
N-64	Redwood	Ogdensburg 31B	433098E; 4910209N	Keeseville
N-65	Muskellunge Lake	Ogdensburg 31B	440275E; 4905331N	Keeseville
N-66	Muskellunge Lake	Ogdensburg 31B	440604E; 4905628N	Keeseville
N-67	Muskellunge Lake	Ogdensburg 31B	440712E; 4905786N	Ausable
N-68	Muskellunge Lake	Ogdensburg 31B	441080E; 4906012N	Ausable
N-69	Muskellunge Lake	Ogdensburg 31B	440454E; 4906588N	Keeseville
N-70	Muskellunge Lake	Ogdensburg 31B	440538E; 4906968N	Keeseville
N-71	Muskellunge Lake	Ogdensburg 31B	440748E; 4906166N	Ausable
N-72	Chippewa Bay	Ogdensburg 31B	439850E; 4914411N	Ausable
N-73*	Hammond	Ogdensburg 31B	440606E; 4915124N	Ausable/Keeseville
N-74	Hammond	Ogdensburg 31B	441971E; 4916836N	Ausable
N-75	Hammond	Ogdensburg 31B	442480E; 4917865N	Ausable
N-76	Hammond	Ogdensburg 31B	443393E; 4918878N	Ausable
N-77	Hammond	Ogdensburg 31B	443719E; 4919166N	Ausable
N-78	Hammond	Ogdensburg 31B	443794E; 4919361N	Keeseville
N-79	Hammond	Ogdensburg 31B	444462E; 4916673N	Ausable
N-80*	Chippewa Bay	Ogdensburg 31B	437384E; 4917814N	Ausable/Keeseville
N-81	Chippewa Bay	Ogdensburg 31B	437890E; 4918254N	Keeseville
N-82	Chippewa Bay	Ogdensburg 31B	438149E; 4918634N	Keeseville
N-83	Chippewa Bay	Ogdensburg 31B	438480E; 4918955N	Keeseville
N-84	Chippewa Bay	Ogdensburg 31B	438315E; 4919418N	Ausable
N-85	Chippewa Bay	Ogdensburg 31B	438570E; 4919804N	Ausable
N-86	Chippewa Bay	Ogdensburg 31B	438934E; 4919411N	Keeseville
N-87	Chippewa Bay	Ogdensburg 31B	439209E; 4919663N	Keeseville
N-88*	Chippewa Bay	Ogdensburg 31B	439278E; 4919731N	Ausable/Keeseville
N-89*	Chippewa Bay	Ogdensburg 31B	439288E; 4924031N	Ausable/Keeseville/ Theresa
N-90*	Chippewa Bay	Ogdensburg 31B	438760E; 4925121N	Theresa/Keeseville/ Ausable
N-91	Hammond	Ogdensburg 31B	440433E; 4921840N	Ausable/Keeseville
N-92	Hammond	Ogdensburg 31B	440539E; 4922566N	Ausable
N-93	Hammond	Ogdensburg 31B	440530E; 4922668N	Ausable
N-94	Hammond	Ogdensburg 31B	442006E; 4924341N	Ausable

* Denotes key sections

Appendix A (cont.)

Station.number	Area	1:250 000 map sheet	UTM location	Rocks exposed
N-95	Hammond	Ogdensburg 31B	445882E; 4922357N	Ausable
N-96*	Hammond	Ogdensburg 31B	446373E; 4922953N	Ausable/Keeseville
N-97	Hammond	Ogdensburg 31B	446578E; 4923110N	Keeseville
N-98	Hammond	Ogdensburg 31B	447499E; 4924216N	Ausable
N-99	Hammond	Ogdensburg 31B	446402E; 4926357N	Keeseville
N-100	Hammond	Ogdensburg 31B	446662E; 4926671N	Keeseville
M-101	Hammond	Ogdensburg 31B	445788E; 4927349N	Keeseville
N-102	Morristown	Ogdensburg 31B	440406E; 4929246N	Keeseville
N-103	Morristown	Ogdensburg 31B	445809E; 4934582N	Keeseville
N-104	Morristown	Ogdensburg 31B	446606E; 4935379N	Keeseville
N-105	Morristown	Ogdensburg 31B	448359E; 4928892N	Keeseville
N-106	Morristown	Ogdensburg 31B	450050E; 4928069N	Keeseville
N-107	Morristown	Ogdensburg 31B	450218E; 4927773N	Ausable
N-108	Edwardsville	Ogdensburg 31B	452619E; 4930495N	Keeseville
N-109*	Edwardsville	Ogdensburg 31B	453297E; 4930718N	Ausable/Keeseville
N-110	Edwardsville	Ogdensburg 31B	450697E; 4933896N	Keeseville
N-111	Edwardsville	Ogdensburg 31B	450876E; 4934094N	Keeseville
N-112	Edwardsville	Ogdensburg 31B	451129E; 4934422N	Keeseville
N-113	Edwardsville	Ogdensburg 31B	451726E; 4934628N	Keeseville
N-114	Edwardsville	Ogdensburg 31B	451519E; 4935293N	Keeseville
N-115	Edwardsville	Ogdensburg 31B	455999E; 4933455N	Keeseville
N-116	Edwardsville	Ogdensburg 31B	456995E; 4934122N	Keeseville
N-117	Edwardsville	Ogdensburg 31B	458036E; 4934915N	Keeseville
N-118	Edwardsville	Ogdensburg 31B	459204E; 4935637N	Ausable
N-119	Pope Mills	Ogdensburg 31B	456417E; 4926460N	Ausable
N-120	Pope Mills	Ogdensburg 31B	456703E; 4926599N	Ausable
N-121*	Richville	Ogdensburg 31B	463926E; 4915442N	Keeseville
N-122	Richville	Ogdensburg 31B	463682E; 4922324N	Ausable
N-123*	Hannawa Falls	Ogdensburg 31B	502050E; 4941190N	Ausable
N-124*	Brasher Falls	Ogdensburg 31B	517980E; 4968500N	Keeseville
N-125*	Constable	Ogdensburg 31B	553696E; 4971879N	Keeseville
N-126*	Burke	Ogdensburg 31B	565430E; 4972473N	Keeseville
N-127	Burke	Ogdensburg 31B	565785E; 4971310N	Keeseville
N-128*	Chasm Falls	Ogdensburg 31B	566954E; 4967703N	Ausable
N-129*	Chasm Falls	Ogdensburg 31B	567998E; 4968956N	Ausable
N-130*	Chateaguay	Ogdensburg 31B	571974E; 4972971N	Ausable/Keeseville
N-131*	Chateaguay	Ogdensburg 31B	578785E; 4976078N	Keeseville
N-132*	Chateaguay	Ogdensburg 31B	578778E; 4979604N	Keeseville
N-133	Churubusco	Lake Champlain	582737E; 4981990N	Keeseville
N-134	Churubusco	Lake Champlain	583518E; 4983199N	Keeseville
N-135*	Churubusco	Lake Champlain	584315E; 4977184N	Keeseville
N-136	Churubusco	Lake Champlain	581184E; 4976195N	Keeseville
N-137*	Churubusco	Lake Champlain	581656E; 4971344N	Ausable
N-138*	Churubusco	Lake Champlain	585876E; 4970137N	Ausable
N-139*	Churubusco	Lake Champlain	585348E; 4970049N	Ausable
N-140	Churubusco	Lake Champlain	587600E; 4968450N	Ausable
N-141*	Ellenburg Mtn.	Lake Champlain	593181E; 4965010N	Ausable
N-142	Ellenburg Depot	Lake Champlain	590072E; 4969810N	Ausable
N-143	Ellenburg Depot	Lake Champlain	589017E; 4970697N	Ausable
N-144*	Ellenburg Depot	Lake Champlain	589064E; 4972032N	Ausable
N-145*	Ellenburg Depot	Lake Champlain	589743E; 4979189N	Keeseville
N-146	Ellenburg Depot	Lake Champlain	591428E; 4979433N	Keeseville
N-147	Ellenburg Depot	Lake Champlain	590915E; 4979343N	Keeseville
N-148	Ellenburg Depot	Lake Champlain	596610E; 4982047N	Keeseville
N-149	Ellenburg Depot	Lake Champlain	598309E; 4983144N	Keeseville
N-150	Ellenburg Depot	Lake Champlain	598066E; 4981369N	Keeseville
N-151	Ellenburg Depot	Lake Champlain	595774E; 4980909N	Keeseville
N-152*	Ellenburg Depot	Lake Champlain	594209E; 4979592N	Ausable
N-153	Ellenburg Depot	Lake Champlain	597236E; 4979213N	Keeseville
N-154	Altona	Lake Champlain	599401E; 4979574N	Keeseville
N-155	Ellenburg Depot	Lake Champlain	595555E; 4977612N	Keeseville
N-156	Ellenburg Depot	Lake Champlain	594556E; 4978002N	Keeseville
N-157	Ellenburg Depot	Lake Champlain	594450E; 4977900N	Keeseville
N-158	Ellenburg Depot	Lake Champlain	593135E; 4976775N	Keeseville
N-159	Ellenburg Depot	Lake Champlain	595059E; 4974729N	Keeseville

* Denotes key sections

Appendix A (cont.)

Station.number	Area	1:250 000 map sheet	UTM location	Rocks exposed
N-160	Altona	Lake Champlain	599432E; 4975691N	Keeseville
N-161	Altona	Lake Champlain	599828E; 4974794N	Keeseville
N-162	Ellenburg Depot	Lake Champlain	596210E; 4973222N	Keeseville
N-163	Ellenburg Depot	Lake Champlain	593907E; 4971267N	Keeseville
N-164	Ellenburg Depot	Lake Champlain	594489E; 4970981N	Keeseville
N-165	Ellenburg Depot	Lake Champlain	595811E; 4969857N	Keeseville
N-166*	Ellenburg Mtn.	Lake Champlain	596018E; 4968465N	Keeseville
N-167	Jericho	Lake Champlain	599273E; 4962400N	Ausable
N-168	Jericho	Lake Champlain	599369E; 4962704N	Ausable
N-169	Jerricho	Lake Champlain	601528E; 4968118N	Keeseville
N-170	Altona	Lake Champlain	602060E; 4971946N	Keeseville
N-171	Altona	Lake Champlain	602346E; 4973096N	Keeseville
N-172	Altona	Lake Champlain	604900E; 4972691N	Keeseville
N-173	Jericho	Lake Champlain	605432E; 4969668N	Keeseville
N-174	Altona	Lake Champlain	607122E; 4970443N	Keeseville
N-175	Altona	Lake Champlain	606129E; 4970511N	Keeseville
N-176*	Altona	Lake Champlain	606954E; 4971427N	Keeseville
N-177	Altona	Lake Champlain	607553E; 4975171N	Keeseville
N-178*	Altona	Lake Champlain	607489E; 4975630N	Keeseville
N-179	Altona	Lake Champlain	607190E; 4978930N	Keeseville
N-180	Mooers	Lake Champlain	610124E; 4978132N	Keeseville
N-181	Mooers	Lake Champlain	612041E; 4979382N	Keeseville
N-182	Mooers	Lake Champlain	613126E; 4979347N	Keeseville
N-183	Mooers	Lake Champlain	612853E; 4976017N	Keeseville
N-184	Jericho	Lake Champlain	606289E; 4965515N	Ausable
N-185	Jericho	Lake Champlain	607555E; 4965482N	Ausable
N-186*	Jericho	Lake Champlain	604306E; 4964042N	Ausable
N-187*	Jericho	Lake Champlain	605142E; 4962498N	Ausable
N-188	Jericho	Lake Champlain	606978E; 4960323N	Ausable
N-189*	West Chazy	Lake Champlain	608938E; 4957860N	Ausable
N-190	Morrisonville	Lake Champlain	609246E; 4951133N	Keeseville
N-191	West Chazy	Lake Champlain	611762E; 4962600N	Ausable
N-192	West Chazy	Lake Champlain	612700E; 4963200N	Keeseville
N-193*	West Chazy	Lake Champlain	613796E; 4964152N	Ausable
N-194	West Chazy	Lake Champlain	614374E; 4964172N	Ausable
N-195	West Chazy	Lake Champlain	611737E; 4963573N	Ausable
N-196	West Chazy	Lake Champlain	610304E; 4963728N	Ausable
N-197	West Chazy	Lake Champlain	609699E; 4964098N	Ausable
N-198	West Chazy	Lake Champlain	616944E; 4968144N	Ausable
N-199	West Chazy	Lake Champlain	616369E; 4968938N	Ausable
N-200*	West Chazy	Lake Champlain	615750E; 4968866N	Ausable
N-201	West Chazy	Lake Champlain	614318E; 4968853N	Ausable
N-202	West Chazy	Lake Champlain	614200E; 4970000N	Ausable
N-203	West Chazy	Lake Champlain	615550E; 4977500N	Ausable
N-204*	Mooers	Lake Champlain	614909E; 4972049N	Keeseville
N-205*	Mooers	Lake Champlain	618328E; 4972073N	Keeseville
N-206	Champlain	Lake Champlain	622187E; 4979788N	Keeseville
N-207*	Champlain	Lake Champlain	622809E; 4979680N	Keeseville
N-208	Champlain	Lake Champlain	624093E; 4977938N	Keeseville
N-209	Champlain	Lake Champlain	623165E; 4976259N	Keeseville
N-210	Champlain	Lake Champlain	623409E; 4972324N	Keeseville
N-211	Morrisonville	Lake Champlain	614416E; 4942797N	Keeseville
N-212*	Keeseville	Lake Champlain	619272E; 4939112N	Ausable
N-213	Keeseville	Lake Champlain	622365E; 4931219N	Keeseville
N-214	Keeseville	Lake Champlain	622110E; 4931262N	Keeseville
N-215*	Keeseville	Lake Champlain	621058E; 4929472N	Keeseville
N-216	Mooers	Lake Champlain	615414E; 4981345N	Keeseville
N-217	Champlain	Lake Champlain	618515E; 4982820N	Keeseville
N-218	Ellenburg Depot	Lake Champlain	595590E; 4981707N	Ausable
N-219*	West Chazy	Lake Champlain	613202E; 4964127N	Ausable

* Denotes key sections

Appendix B

Location of boreholes

Ontario	UTM location	Thickness of Potsdam Group
O-1 Dominion Observatory No. 1	443950E; 5026500N	31 m
O-2 GSC Lebreton No. 1	445500E; 5028100N	78 m
O-3 GSC Russell No. 1	469150E; 5017450N	144 m
O-4 Imperial Oil Ltd., Laggan No.1	521325E; 5026350N	310+ m
O-5 GSC McCrimmon No. 1	520250E; 5030200N	256+ m
O-6 Consumers Gas No. 12023	520333E; 5030981N	339 m

Quebec	UTM location	Thickness of Potsdam Group
Q-1 Gastem – Dundee No. 1	544391E; 4989999N	166+ m
Q-2 Gastem – Dundee No. 2	544254E; 4990442N	97+ m
Q-3 Montreal No. 1	577490E; 5014092N	439+ m
Q-4 St. Lawrence River No. 1	577025E; 5013642N	603+ m
Q-5 Oka No. 8	577150E; 5047500N	320+ m
Q-6 Mallet Test No. 1	590508E; 5057823N	519+ m
Q-7 Quonto-International St. Vincent de Paul No. 1	604418E; 5055374N	516 m
Q-8 Quonto-International Mascouche No. 1	610070E; 5066362N	365 m

Contents
This CD-ROM contains the full contents of Bulletin 597 in .pdf format, including any maps or oversized figures.

System requirements
PC with 486 or greater processor, or Mac® with OS® X v. 10.2.2 or later; Adobe® Reader® v. 6.0 (included for both PC and Mac) or later; video resolution of 1280 x 1024.

Quick start
This is a Windows®-based autoplay disk. Should the autoplay fail, navigate to the root of your CD-ROM drive and double-click on the autoplay.exe file. Mac® users must use this method to begin.

****

Contenu
Ce CD-ROM renferme le contenu intégral du Bulletin 597 en format .pdf, y compris les figures surdimensionnées ou les cartes, s'il y a lieu.

Configuration requise
PC avec processeur 486 ou plus rapide, ou Mac® avec OS® X v. 10.2.2 ou ultérieure; Reader® v. 6 d'Adobe® (fourni pour PC et Mac) ou version ultérieure; résolution vidéo de 1280 x 1024.

Démarrage rapide
Ceci est un disque à lancement automatique pour les systèmes d'exploitation Windows®. Si le lancement automatique ne fonctionne pas, allez au répertoire principal du CD-ROM et faites un double clic sur le fichier autoplay.exe. Les utilisateurs de systèmes Mac® doivent procéder de cette façon pour débuter la consultation.