Grant 187 Sedimentology of the Cambro-Ordovician Sandstones of Eastern Ontario

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ABSTRACT

Sandstones of the Cambro-Ordovician Potsdam Group which outcrop on the Frontenac Axis, north and east of Kingston, Ontario, can be subdivided into the 'Covey Hill' and overlying Nepean Formations. Isolated outliers of pebbly arkose and feldspathic conglomerate that are preserved within down-faulted blocks northeast of Big Rideau Lake are tentatively correlated with the Covey Hill Formation of Quebec. The well-sorted quartz arenites of the Nepean Formation outcrop more extensively, providing excellent exposures for study.

Two terrestrial and two marine facies have been identified from these units. The poorly-sorted, and commonly cross-bedded, pebbly arkoses and conglomerates of the 'Covey Hill' formation are interpreted to represent a proximal braided fluvial environment. The sequence of structures suggests that sedimentation was influenced by movement on the nearby Rideau Lake Fault. The second terrestrial facies is characterized by very large, simple cross beds composed of medium-grained, well sorted and rounded quartz grains, interbedded with thin, unsorted conglomerates. The cross beds display a variety of small features including adhesion ripples, wave ripples and arthropod crawling traces (*Protichnites*), and are considered to represent a coastal dune complex that was locally cut by fluvial channels, and periodically flooded by marine waters.

The third and most extensively-developed facies is composed of cyclically-interbedded cross-bedded and bioturbated quartz arenites. A typical cycle is 1-3 m thick and consists of a basal erosion surface overlain by small-scale cross-bedding and ripple cross-lamination, which passes upward into totally bioturbated sandstone. The sequence of structures suggests that these cycles represent the repeated progradation of a subtidal to intertidal-flat environment. The final facies includes all of the scattered outcrops of marine sandstone which do not fit into the third facies. It includes trough cross-bedded and parallel-bedded quartz arenites, and represents an (at present) undifferentiated nearshore facies in which beach, foreshore, tidal inlet and offshore bar deposits may be present. Initial results from this study suggest that the second and third facies have the greatest potential for high quality silica.

INTRODUCTION

OBJECTIVES

Sandstones of the Cambro-Ordovician Potsdam Group of eastern Ontario have long been considered as a possible source of silica (Cole 1923). Over the last few years renewed interest in these sandstones has led to considerable drilling and sampling by both government agencies and industry (Powell and Klugman 1979; Klugman and Yen 1980; Collings and Andrews 1983; Kingston and Papertzian 1983), and in 1982, the W.R. Barnes Company Limited removed 30,000 tonnes of silica sandstone from their Storrington Township (Frontenac County) quarry, north of Kingston, for processing in their plant at Waterdown, Ontario (Kingston and Papertzian 1983). Silica has many industrial applications: it is a primary ingredient in the production of glass, concrete products, enamel paint, ferrosilicon and silicon carbide, and is an abrasive agent in soap and scouring pads (Vos 1981). Canadian consumption totalled more than 3.5 million tonnes in 1980. Less than 2.3 million tonnes of silica ore was mined in Canada so that more than $10 million worth of silica was imported (Boyd 1982).

The study summarized here was initiated to assist in the evaluation of the silica sand potential of the Potsdam Group sandstones by determining the depositional processes and environments which produced them. The determination of the geographic and stratigraphic distribution of the environmental facies will also aid in extending and predicting occurrences of high quality silica sand.

STUDY AREA

The area under investigation extends north and east of Kingston, Ontario, and occupies the roughly triangular area between Kingston, Brockville, and Big Rideau Lake (Figure 1). This area straddles the Frontenac Axis and includes the southwestern margin of the Ottawa Valley. The Paleozoic rocks in this region have been examined recently by the Ontario Geological Survey (Carson 1982a,b; Wolf and Williams 1984a,b). These maps, with certain revisions required by the additional work reported here, provide the basis for this study. Natural and man-made exposures of the Potsdam Group sandstones are scattered and sparse

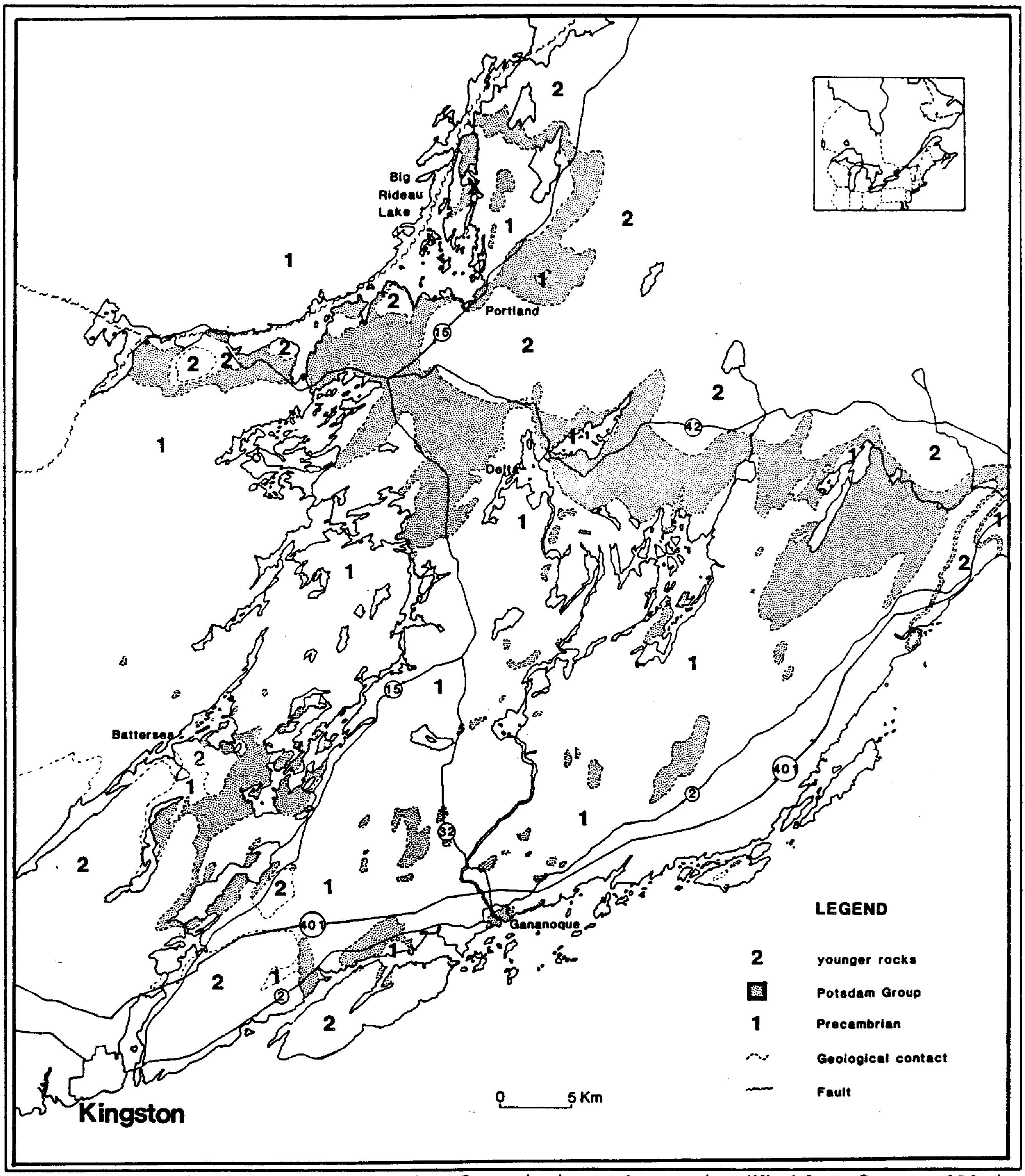

Figure 1. Areal distribution of the Potsdam Group in the study area (modified from Carson 1982a,b and Wolf and Williams 1984a,b). X - Mill Pond Quarry.

on the Frontenac Axis in the southern and central portions of the map-area, and most exposures do not exceed 2 m in thickness, except in the Battersea area. In the northeastern part of the map-area, however, continuous exposure, which exceeds 20 m in height in many places, exists along the Precambrian-Paleozoic contact.

METHODOLOGY

Approximately 70% of the available outcrops have been studied in detail; the remainder have also been examined in an earlier reconnaissance survey. Detailed studies were conducted in the Battersea area, west and east of Delta, in the Gananoque area, and in the Big Rideau Lake area. The remaining areas of exposure will be examined in the second field season of this study.

Over 130 outcrops showing more than 2 m of section were measured and described on a bed by bed basis. The data recorded included: bed thickness and its lateral variability; vertical trends in bedding thickness; nature of bedding plane contacts; grain size and sorting; variations in grain size through the beds; grain roundness and mineralogy, especially in the gravel sizes; rock colour; and the nature of any sedimentary structures present. The description of physical structures included: size of structures and vertical trends in size; direction of cross-bed dips; shape and orientation of ripple marks and other bedding-plane structures; lateral variations of structures within beds; and vertical changes in the types of structures present. In addition, biological structures were recorded, including the degree of bioturbation in each bed and the nature of any body and trace fossils found.

Samples were collected from representative locations for X-ray radiographs, geochemical analysis, and petrographic examination. From the more than 200 samples collected, 45 thin sections were made. Of these, detailed petrographic analyses, including point counts, have been made on 15 thin sections (Dorr 1984). An initial 20 samples have been submitted for geochemical analysis, with each sample being analyzed for silica, iron, calcium, aluminum, magnesium, sodium, potassium, and titanium. Approximately 25 slabs from apparently structureless sandstones will be X-rayed to search for any fine structures.

GENERAL GEOLOGY

The term 'Potsdam Sandstone' was first introduced by Emmons (1838) for a succession of sandstones in Potsdam County, New York, and Logan (1863) extended the term to include lithologically similar rocks in Frontenac and Leeds Counties, Ontario. Since then, many workers in both Canada and the United States have used the term Potsdam for any basal Cambro-Ordovician sandstone, regardless of lithology (Wright 1923; Keith 1949; Liberty 1972). In New York, Quebec, and Ontario, the current practice is to use the term Potsdam Group for all of the Cambro-Ordovician sandstones, and then to subdivide the Group into formations on a local basis (Fisher 1977; Globensky 1981, 1982a,b; Wolf and Williams 1984a,b)

The Potsdam Group forms the basal Paleozoic unit in eastern Ontario, unconformably overlying the Precambrian and conformably overlain by sandy dolostones and dolostones of the Beekmantown Group (Table 1). In eastern Ontario the Potsdam Group can be divided into two formations based on distinct lithological differences, the lower, 'Covey Hill' formation and the overlying Nepean Formation (Williams and Wolf 1982) (Table 1).

Several isolated outcrops in the Big Rideau Lake area, most of which are found in a down-faulted block, have been tentatively assigned to the Covey Hill Formation, a formation originally described from the Montreal area (Clark 1966). The Big Rideau Lake outcrops consist of massive to poorly stratified, arkosic conglomerates and cross-stratified pebbly arkoses, similar to exposures of the Covey Hill Formation near Montreal. Earlier workers were either unable to correlate these outcrops (Wilson and Dugas 1961), or believed them to be equivalent to the Middle Ordovician Shadow Lake Formation (Wynne-Edwards 1967). Based on its stratigraphic position in water-well records, and the lack of Phanerozoic lithologies in the clasts of the conglomerates, this unit is considered by the authors to be post-Grenville and pre-Nepean in age. Though lithologically and stratigraphically similar to the Montreal outcrops, the correlation remains tentative due to the distance from Quebec and the isolated and discontinuous nature of the outcrops in Ontario. The 'Covey Hill' formation in Ontario unconformably overlies the Precambrian and, while the upper contact is not exposed at Big Rideau Lake, an exposure of a similar conglomerate at Jones Falls is unconformably overlain by quartz arenites of the Nepean Formation.

The Nepean Formation was introduced by Wilson (1946) for the quartz arenites which lie directly on the Precambrian in the Ottawa area where the 'Covey Hill' formation is generally absent, due to either pre-Nepean erosion or non-deposition. The Nepean Formation was named for Nepean Township where large quarries were developed for the building stone which was used for the Parliament Buildings in Ottawa. Because these quarries have been either partially or totally filled, Greggs and Bond (1972, 1977) proposed that the nearby roadcut on the Queensway (Highway 417), west of Ottawa, be designated as a principal reference section. Later, Brand and Rust (1977a,b) recognized the contact between the Nepean Formation and the overlying March Formation in this section, and proposed that it be designated as the type section for the Nepean Formation.

In the immediate Kingston area it is more difficult to divide the Potsdam Group due to the more variable and scattered nature of the outcrops. The rocks in this area, however, are all quartz arenites and, thus, can be assigned to the Nepean Formation. As will be seen later in this report, the sedimentary structures within the quartz arenites in the Kingston area are very different from the structures found in the typical Nepean Sandstone of the Ottawa - St. Lawrence Lowlands. Further study may result in further subdivision of the Nepean Formation.

In eastern Ontario the upper portion of the Nepean Formation is Lower Ordovician (Tremadocian) in age, based on a sparse conodont fauna (Brand and Rust 1977a), whereas the stratigraphically-equivalent unit in northern New York State (Keeseville Formation) is Upper Cambrian (Canadian) in age, based on trilobite assemblages (Fisher 1977). This indicates that at least the upper part of the Potsdam Group is diachronous (changes age) northward from New York to Ontario. The exact position of the Cambrian-Ordovician boundary in Ontario cannot be precisely determined due to the lack of diagnostic fossils in the lower portion of the Potsdam Group.

TABLE 1. CAMBRO-ORDOVICIAN STRATIGRAPHY OF THE OTTAWA-ST. LAWRENCE LOWLANDS (AFTER WOLF AND WILLIAMS 1984A,B).

Middle Ordovician	Ottawa Group	
	Chazy Group	
Lower Ordovician	Beekmantown Group	Oxford Formation
		March Formation
Upper Cambrian	Potsdam Group	Nepean Formation
		'Covey Hill' formation
PRECAMBRIAN		

DEPOSITIONAL ENVIRONMENTS

The sandstones of the Potsdam Group have long been regarded simplistically as an undifferentiated blanket of nearshore sandstones, produced during the marine transgression of the Precambrian surface. During the initial field season, examination of outcrops has shown that the Potsdam Group in eastern Ontario is actually a complex mosaic of several different terrestrial and marine facies. Two terrestrial and two marine environments have been identified to date, each of which can be further subdivided into distinct components. A summary of the results has recently been presented (Wolf and Dalrymple 1984); these provisional findings are presented below.

FACIES 1 – PEBBLY ARKOSES AND CONGLOMERATES

This facies is restricted to the 'Covey Hill' formation, and is dominantly found in the Big Rideau Lake area, although a few additional outcrops are scattered throughout the study area (Figure 2). A readily accessible quarry located near the Mill Pond Conservation Area, on lot 6, concessions II and III of South Burgess Township in Leeds County (Figure 1), provides a representative section over 13 m thick (Figure 3). The Mill Pond quarry, like most outcrops of this facies, is found in a downfaulted block that includes Big Rideau Lake and which is bounded by the Rideau Lake Fault (Wynne-Edwards 1967) on the northwest and by the Briton Bay Fault (Wolf and Williams 1984a) to the east. A detailed study of this quarry formed the basis for a B.Sc. thesis by Dorr (1984) under the supervision of the authors. Some of these results, together with additional observations, are summarized below.

Description

This facies is characterized by poorly sorted, massive to cross-stratified, feldspathic conglomerates and cross-stratified pebbly arkoses. The Mill Pond quarry section can be divided into five erosionally-bounded units, based on grain size and sedimentary structures (Figure 3). These units are organized into two generally fining upwards sequences, each with a discrete, unimodal paleocurrent orientation, based on pebble imbrication and cross-bed dips: units 1 to 3 with an easterly flow; and units 4 and 5 with a northerly paleocurrent direction (Figure 3). The lower sequence also displays a minor coarsening upwards sequence in unit 2.

The pebble to cobble conglomerates of units 1, 4, and the upper part of unit 2 consist of poorly-sorted, dominantly subround to round clasts of quartzite set in a matrix of feldspathic coarse sand and fine pebbles. Unstable lithologies such as feldspathic gneiss, marble, and schist compose, on average, about 12% of the clasts in unit 1, but decrease in abundance up section to 5-6% in unit 4 (Figure 3). Similarly, the matrix of these conglomerates also becomes more mature (less potassium-feldspar, plagioclase, and lithic fragments) up section. Sedimentary structures in the conglomerates range from massive (no structures) to crude horizontal bedding and cross-stratification.

The sandy lower portion of unit 2, and units 3 and 5, are characterized by poorly-sorted, pebbly arkoses. As in the conglomerates, the unstable components decrease in abundance up section (Figure 3). In unit 2, the sandstones are horizontally stratified and grade upwards into the overlying horizontally stratified conglomerates. Large-scale (0.5 to 1.9 m thick) planar cross beds occupy the lower portion of unit 3, and are erosionally overlain by smaller-scale trough cross beds.

Interpretation

The presence of poorly stratified conglomerates, the size of the cross beds, the consistently uni-directional paleocurrents, and the poorly sorted, immature character of the sediments all suggest that this facies was formed in a setting transitional between a distal, flow-dominated alluvial fan and a proximal braided fluvial environment. The fining upward sequences visible in the Mill Pond quarry also show a strong similarity to the braided river facies models of Miall (1977, 1978) and Rust (1978). A beach to nearshore origin is incompatible with the poor sorting, immature mineralogy, and the type and scale of the sedimentary structures.

The massive to stratified conglomerates of units 1 and 4 are considered to represent longitudinal bars formed during high flood stage. The cross-stratified conglomerates of unit 4 probably represent the preserved lee faces of these bars, whereas the structureless to crudely horizontally-stratified beds may be due to high rates of deposition by a rapidly waning flow which did not allow significant sorting. The imbrication of the cobbles in these deposits indicates the paleoslope at the time of deposition better than cross beds do (Collinson 1970); therefore, the general paleoslope was eastward in unit 2 and northward in unit 4. Miall (1977) noted that longitudinal bar formation occurs most commonly in proximal, gravelly braided rivers.

The planar cross beds of units 3 and 5 are interpreted to have been formed by the migration of transverse bars in a more distal setting (Miall 1977). In unit 3, the upward transition from planar to trough cross beds, and the corresponding decrease in set size, suggests either that water depth over the top of the underlying transverse bar was sufficient to allow sinuous bedforms to form on it (Miall 1977), or that channels filled with sinuous bedforms cut across the top of the transverse bars at a later time. Unit 5 probably represents the deposits of smaller transverse bars driven over the longitudinal bar of unit 4 in the manner described by Cant and Walker (1978). The coarsening-upward sequence of horizontal stratification in unit 2 may represent a channel fill formed under upper flow re-

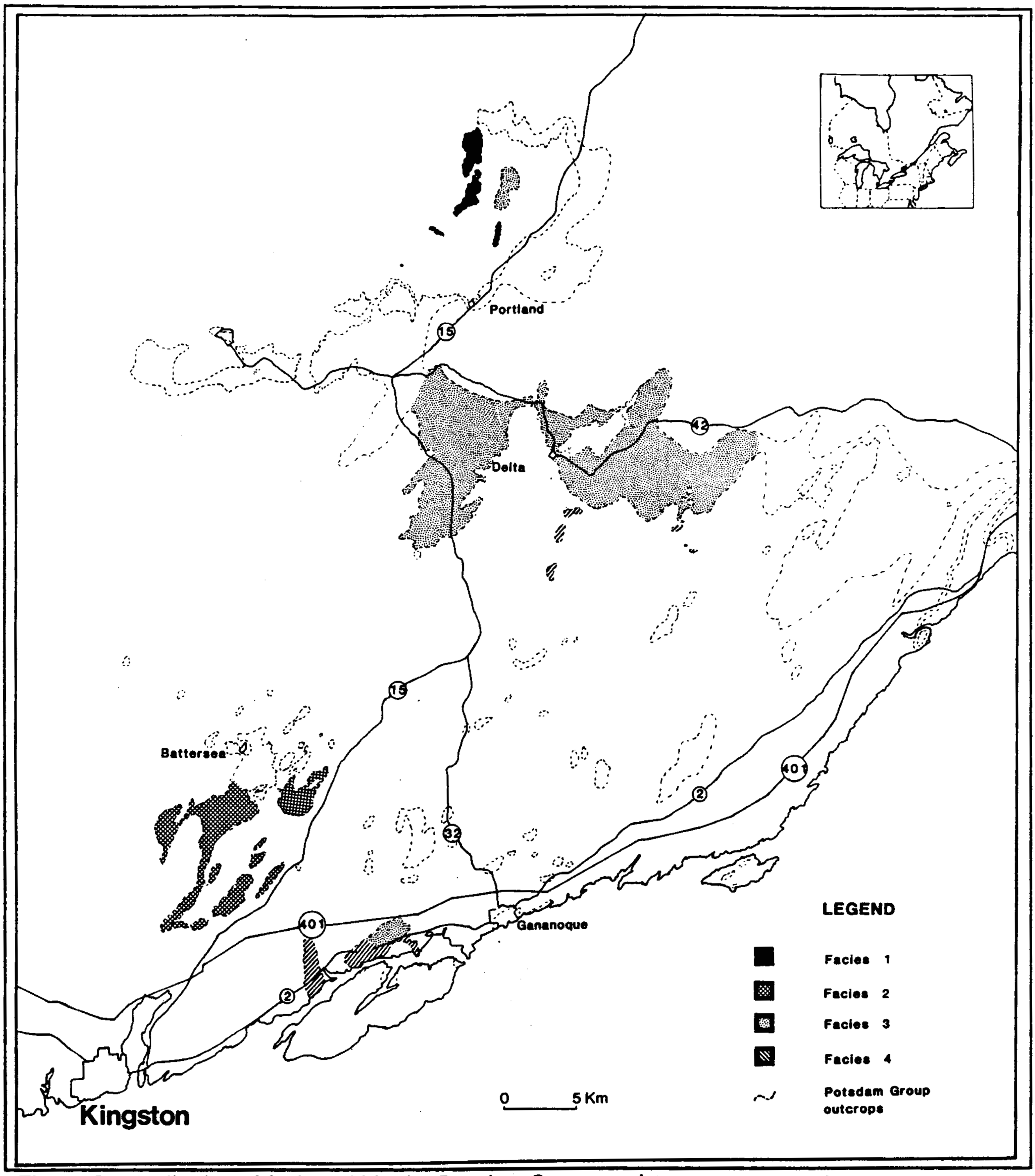

Figure 2. Distribution of facies within the Potsdam Group sandstones.

gime conditions. The upward increase in grain size may be due to either a progressive increase in flow velocity as the channel was re-occupied, or to rejuvenation of the source area.

The upward-fining sequences of units 1 to 3 and 4 to 5, the immaturity of the rock fragments, and the close proximity to the major Rideau Lake Fault system strongly suggest that deposition of this facies was controlled by movement of the fault. Repeated uplift would explain the repetition of the sequences. Initial uplift would cause deposition of the coarse-grained, proximal conglomerates, and then, as the source area became subdued, the decreasing relief would result in a transition to more distal, sandy environments (Steel *et al.* 1977). Alternatively, the sequences could result from the avulsive switching of alluvial fan lobes and their subsequent, gradual abandonment (Steel and Aasheim 1978). The upward increase in sediment maturity indicates that less first-cycle debris was supplied to the fluvial system, and that the amount of reworking increased through time.

A paleohydraulic reconstruction, based on the grain size and the scale of the sedimentary structures observed, suggests a channel depth on the order of 4 m. The resulting fluvial system would have had a drainage basin approximately half the size of the present day Saskatchewan River system (Dorr 1984). The large size of the river system and the apparently-contradictory, proximal nature of the sediments is presumably the result of local fault control on sedimentation. The large river size also suggests that the 'Covey

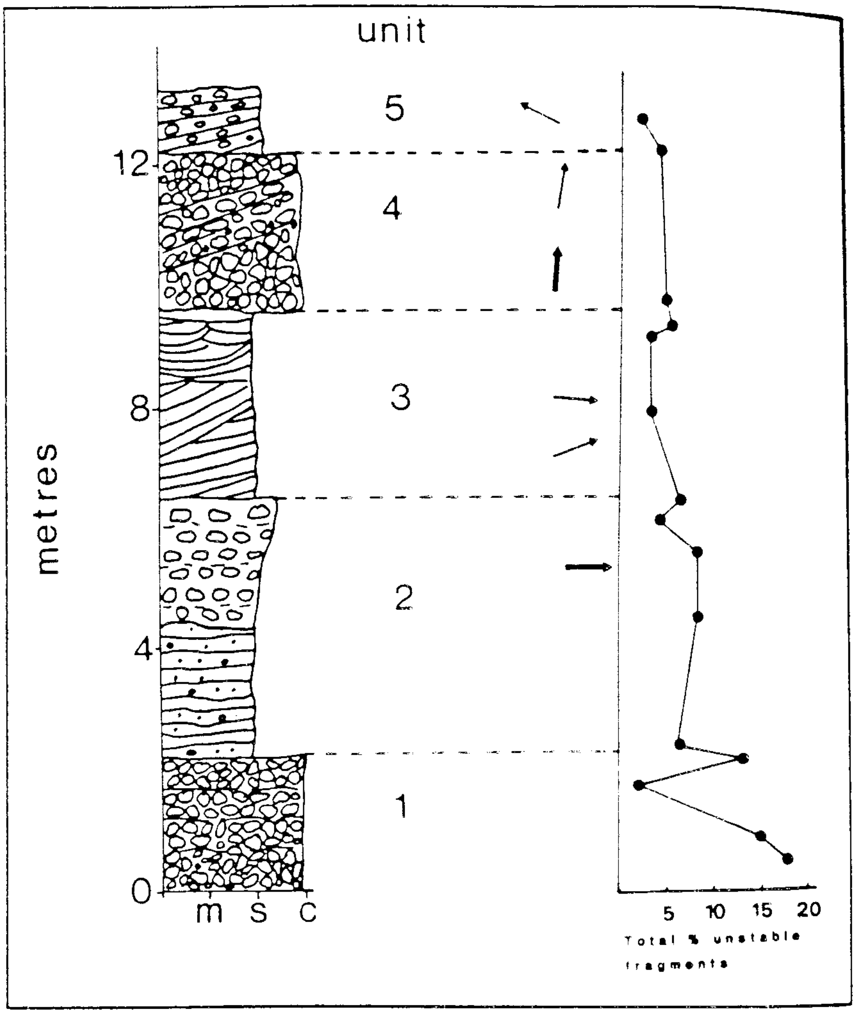

Figure 3. Stratigraphic section of the Facies 1 conglomerates and sandstones in the Mill Pond quarry (modified from Dorr 1984). Paleocurrent directions shown by arrows: thick arrows - pebble imbrications; thin arrows - cross-bed dips. At the base of the stratigraphic column, grain size: m = mud, s = sand, and c = conglomerate.

Hill formation would originally have covered a much more extensive portion of eastern Ontario, and beyond. The scarcity of such outcrop today is due to either pre- or post-Nepean erosion.

FACIES 2 -- VERY LARGE-SCALE CROSS-BEDDED SANDSTONE

A large area of exposure of Facies 2 occurs northeast of Kingston, in the Battersea area, with smaller outcrops around Delta (Figure 2). This facies is provisionally placed in the Nepean Formation on the basis of its quartz content, although its distinctive characteristics might allow it to be considered as a separate unit. In most places where it is exposed, this facies immediately overlies the Precambrian and sits in low areas between Precambrian highs; this is especially noticeable in the Delta area. In one exposure east of Battersea, a unit of apparently marine sandstone is in fault contact with rocks of Facies 2, which are situated on the presumed down-thrown side of the fault. This indicates that Facies 2 may overlie the marine beds at least locally. Throughout most of the study area however, it would appear that the rocks of Facies 2 lie stratigraphically below typical marine Nepean Sandstone, though no exposures have been found to date to substantiate this.

Description

This facies is dominated by very large, simple cross beds which have long sweeping toesets and bottomsets; in general, only the toe and bottomsets are exposed, and less commonly the lower portion of the foresets. The thickness of individual sets ranges from 2 to 10 m, but they were undoubtedly larger as the maximum thickness is generally controlled by the height of the available outcrop. Most of the sets are transitional in shape between planar and trough cross beds; some of the planar sets may, however, be part of very large troughs, as some troughs over 20 m wide have been measured. Cross-bed dip and trough axis orientations indicate a dominant paleocurrent flow toward the southwest. Approximately one-quarter of the set boundaries show little or no change in grain size or sorting from one set to the next. More commonly though, thin quartz-pebble horizons occur either at the top of the underlying set or at the base of the overlying set. In a few cases, lenses and thin sheets of poorly-sorted and unstratified, polymictic conglomerate separate the cross beds. At one locality, the uppermost 5 to 7 cm of a set is deep purple, in sharp contrast to the normal white to cream colour.

The cross beds are composed of very regular laminae of well-sorted, well-rounded, medium-grained quartz. Individual laminae can sometimes be traced for several 10s to 100s of centimetres. In places where there is clean, relatively unweathered exposure, faint, low-angle, climbing translatent laminae (Hunter 1977a,b) were observed. Small reverse faults with displacements of a few centimetres are common in the bottomsets of some of the larger cross-bed sets. Bedding-plane exposures of bottom and toesets locally display several significant features including: slightly sinuous, wave ripple marks; the trace fossil *Protichnites,* a crawling trace formed by a large arthropod; and, closely associated with this trace in one place, wart-like, low-amplitude ripple marks which are similar to the adhesion structures described by Kocurek and Fielder (1982).

Interpretation

The features observed in this facies suggest that these very large scale, cross-bedded quartz arenites were deposited in an aeolian dune complex. The size and style of the cross beds is similar to aeolian dune structures described from both modern (Tsoar 1982) and ancient (McKee 1979) examples. The climbing translatent structures which are formed by climbing wind ripples (Hunter 1977a,b), and the adhesion ripples (features formed when wind-blown sand is deposited on a wet surface; Kocurek and Fielder 1982) provide confirmation of the aeolian origin of these cross beds. Grain flow and avalanche deposits, which Hunter (1977a,b) described as being characteristic of aeolian deposits, are absent, but this may be because these structures normally form in the upper part of foresets which are not preserved in the outcrops studied to date.

The conglomeratic lenses present between the cross beds are interpreted to have been formed by small streams which occupied the interdune areas. The larger sheets of conglomerate may have been deposited by flash floods. Reworking of the fluvial deposits by the wind would produce a deflation lag of quartz pebbles which would then line the set boundaries after the next sand dune had advanced over the lag surface. A long period of interdune weathering might also be responsible for the dark purple zone at the top of one of the cross-bed sets, although this colouration might also be diagenetic in origin.

The occurrence of wave ripple marks and marine arthropod crawling traces can be reconciled with the aeolian interpretation by suggesting that the dunes constituted a coastal dune complex in which some of the interdune areas were periodically flooded by sea water. The close association of the crawling traces with the adhesion ripples suggest that the arthropod may have been stranded on the lower dune surface when the marine waters receded. Further work is needed to substantiate this as the occurrence of a subaerial arthropod trace of Late Cambrian - Early Ordovician age has significant implications for the paleoecological tolerances of these primitive organisms.

The only reasonable alternative to an aeolian origin for these cross beds is that they are the deposits of large, shallow marine sand waves, such as those described from the North Sea, Georges Bank, and the east coast of southern Africa (Allen 1980). Recent studies of modern (Dalrymple 1984) and ancient (Allen and Homewood 1984; Blakey 1984) sand waves, as well as theoretical models (Allen 1980), have shown, however, that the internal structures of marine sand waves are highly complex, reflecting the fluctuating nature of the tidal and storm currents which generate them. In addition, marine sand waves would not contain climbing translatent strata or adhesion ripples. Thus, based on the various features observed in this facies, the aeolian interpretation is favoured.

FACIES 3 – ALTERNATING CROSS–BEDDED AND BIOTURBATED SANDSTONES

Facies 3 represents those rocks which are typically regarded as the Nepean Formation. Within the study area this facies occurs predominantly in the northeast, along the margin of the Ottawa - St. Lawrence Lowlands around Delta (Figure 2). Commonly, a thin, discontinuous horizon of quartz pebble and cobble conglomerate with a matrix of well-rounded, medium-grained, quartz arenite immediately overlies the Precambrian at the base of this facies. The quartz-rich nature of these conglomerates distinguishes them from those of Facies 1.

Description

Facies 3 consists of laterally continuous beds of quartz arenite which show a cyclic alternation between cross-bedded and bioturbated sandstone. The cross-bedded units begin with a sharp, erosional base and pass gradationally upwards into totally bioturbated beds. Complete cycles are 1 to 3 m thick, though in many cases the cycles are incomplete. The cross-bedded portion of the cycle is usually whiter, thicker, and more resistant to weathering than the bioturbated intervals. This gives the outcrops of this facies a distinctive repetition of dark-coloured recessive units and lighter, resistant beds. Both the cross-bedded and bioturbated beds are composed of fine- to medium-grained, well-sorted and well-rounded, quartz grains cemented by silica. In cycles higher in the formation, calcareous and dolomitic cements are also present, particularly in the bioturbated units.

The lower portion of each cycle is characterized by small-scale (30 to 50 cm) planar and trough cross beds which generally pass abruptly upwards into ripple cross-laminated sandstone. Formsets of megaripples are present in some sections. The cross beds commonly display bipolar, 'herringbone', cross-bed dips, usually oriented east-west. Reactivation surfaces are abundant within the cross beds, and several may occur in a single set, spaced several 10s of centimetres apart. Discrete vertical burrows of *Skolithos* sp., *Diplocraterion* sp., and *Monocraterion* sp. commonly penetrate the cross beds. In cases where a cycle terminates at this level, the upper surface may have areas covered by symmetrical wave ripple marks.

In complete cycles, the degree of burrowing increases rapidly upwards. The degree of bioturbation in the upper part of the cycles varies from approximately 50% by volume to almost 100% so that all sedimentary structures are obliterated. No identifiable trace fossils have yet been recovered from these highly burrowed intervals. On some bedding plane surfaces disarticulated lingulid brachiopods were found. Rarely, distinct erosional surfaces separate the bioturbated beds. At one locality near Phillipsville, a zone of disrupted laminae caps the burrowed beds. The nature of the laminae suggests collapse into small cavities.

Interpretation

The vertical sequence of structures, the herringbone cross beds, the reactivation surfaces and the trace and body fossils indicate that this facies was deposited in a marine environment influenced by tidal currents. Each cycle is interpreted to represent a minor transgression, which is preserved only as an erosional surface, followed by progradation of a sandy tidal flat environment. A subtidal to lower intertidal setting is envisioned for the lower portion of the cycle. Here, megaripples and/or sand waves capped by ripples formed under the influence of the tidal currents. As progradation continued and the water depth shallowed, energy levels and the rate of sediment movement decreased allowing organisms to colonize the sandy substrate in greater numbers. The completely bioturbated sandstones probably represent deposition under such quiet conditions in an upper intertidal environment. The disrupted laminae which cap the cycle at the Phillipsville locality may represent the collapse of overlying sand into cavities formed by the dissolution of evaporites, such as gypsum or halite (B.W. Selleck, Colgate University, personal communication 1983), which might have formed in the supratidal zone (Thompson 1968). The next cycle would begin with another minor transgression, which might erode some of the upper sediments of the previous sequence.

Most of the facies models proposed for tidal flat progradation contain significant amounts of mud in the upper intertidal zone (Reineck 1972; Reineck and Singh 1980). The lack of shale in Facies 3 does not detract seriously from the above interpretation however, as the absence of mud-sized terrigenous clastics is a feature that is common to many Cambro-Ordovician sequences on the North American craton (Byers and Dott 1981), and many other deposits of this age, which are interpreted as intertidal in origin, also lack shale (Barnes and Klein 1975; Jansa 1975).

FACIES 4 – HORIZONTAL AND TROUGH CROSS-STRATIFIED SANDSTONE

This final facies groups those outcrops which cannot be assigned to Facies 3. In general, these outcrops are scattered and poorly exposed, and most occur in the southern part of the map-area; exposures between Kingston and Gananoque, as well as some south of Delta, are placed in this facies (Figure 2). These outcrops generally have not been investigated in detail, but the variety of structures and sequences already seen ensure that this facies will be subdivided further after more study. Only two of the more widespread subfacies will be described.

Description

The most extensive subfacies is a trough cross-bedded quartz arenite. The individual sets vary from 0.3 to 0.5 m in thickness, and occur in co-sets several metres thick, which are separated by thin, continuous, quartz pebble horizons. Measurements of the trough axes indicate a uni-directional paleocurrent flow to the south-southwest. Discrete burrows of *Skolithos* are present, and small lenses of ripple cross lamination occur between the trough cross beds in a few places. West of Gananoque this subfacies usually rests on the Precambrian and is overlain by burrowed quartz arenites of Facies 3 (Figure 2).

A second subfacies occurs west of Gananoque, underlying trough cross-bedded sandstone. This subfacies consists of horizontally-bedded quartz arenite, with occasional ripple and megaripple formsets randomly interbedded. No dominant paleocurrent direction was determined from the few measurements taken. Thin, continuous layers of quartz granules and pebbles subdivide this subfacies into several similar units. No trace fossils have been observed.

Interpretation

Due to the variable nature of the several subfacies and the lack of detailed observations, this facies is provisionally considered to be an undifferentiated nearshore deposit. The trough cross-bedded sandstone might have accumulated in tidal inlet and/or offshore bar settings, while the horizontally-bedded sandstone could be a beach to foreshore deposit. Undoubtedly, this facies will be subdivided into a variety of nearshore environments with more study.

SUMMARY AND DISCUSSION OF SILICA POTENTIAL

The sandstones of the Potsdam Group can be divided into four facies representing two terrestrial environments (braided fluvial and aeolian), and at least two marine environments (subtidal to intertidal and nearshore), which are organized into a complex depositional mosaic. Alluvial fan/braided fluvial sequences, the deposition of which was locally influenced by syn-depositional tectonic activity, mantled portions of the Precambrian surface prior to the Late Cambrian transgression. Along the advancing shoreline, a coastal dune complex, that was cut by gravelly streams, developed in the arid to semi-arid climate that is indicated by the possible evaporite-dissolution features in Facies 3. As the transgression progressed, coastal erosion reworked most of these terrestrial sediments into the various marine sandstones described above, and only locally have the terrestrial deposits survived. If the aeolian-on-marine stratigraphy is confirmed by further work, then at least one period of relative sea level fall is indicated; such an event is also suggested by the presence of silcrete breccias in the Potsdam sandstones of northern New York State (Selleck 1978). This sea-level fluctuation would raise the possibility of additional, complex interfingering of the depositional environments. A close modern analogue, in which the sea is transgressing over an irregular bedrock surface, is the Atlantic coast of Nova Scotia (Boyd *et al.* 1983). The general suite of environments is similar in the two cases, but differences exist because of the presence of mud, vegetation and a humid climate in the Nova Scotia example.

Figure 2 shows the geographic distribution of the four facies as known to date. From this it appears that the terrestrial facies are preferentially preserved along the crest of the Frontenac Axis, whereas the marine facies are exposed primarily along the flanks, and especially to the northeast. This configuration could be interpreted to suggest that the crest of the axis was not transgressed until later in the Ordovician. It is likely, however, that these terrestrial deposits preferentially escaped erosion by the transgressing sea because of their sheltered position in topographic or structural depressions, and that subsequent erosion has removed any overlying marine sandstones that were once present on the axis. The large area of marine sandstone that occurs on the western flank of the Frontenac Axis in upper New York State (Selleck 1975) supports this alternative.

Very little work has yet been undertaken on the relationship between the depositional facies and silica-sand potential, but a few preliminary comments are possible. Correlation of the sample locations of various published chemical analyses (Cole 1923; Keith 1949; Powell and Klugman 1979) with the known facies distribution (Figure 2) indicates that the highest silica values are found in Facies 2 (aeolian) and Facies 3 (subtidal to intertidal). In addition, the W.R. Barnes Company Limited's silica quarry in Storrington Township is located in the large-scale aeolian cross beds of Facies 2, while the proposed Angelstone Company Limited operation near Delta is in Facies 3 sandstones. It is clear from the petrographic examination of the Facies 1 fluvial sandstones that the initial sediment derived from the Canadian Shield was immature, and that a portion, but not all, of the quartz enrichment was accomplished by fluvial action. The final purification must, therefore, have taken place either in an aeolian environment and/or in the nearshore region of the transgressing sea. The relative role of these environments in the production of quartz-rich sandstones may be clarified when the stratigraphic relationship between the aeolian and marine facies is established. It may be that aeolian sands derived from marine sediments, which were themselves reworked from fluvial deposits, are the purest quartz sandstones.

FUTURE STUDY

Approximately 30% of the significant outcrops in the study area remain to be examined in detail; the main areas to be studied are located around Brockville and Westport, and in the region between Gananoque and Delta. The major concerns will be to complete the delineation of the facies distributions (Figure 2) and to provide a satisfactory subdivision and interpretation of Facies 4 (undifferentiated nearshore). Evidence to confirm and/or modify the provisional interpretations of the other facies will also be sought in the remaining outcrops.

When the facies subdivision and interpretation is complete, the emphasis will switch to a more rigorous evaluation of the factors controlling silica content. Systematic sampling of all of the facies for geochemical analysis will continue, to complement those samples already being processed. Further thin section analyses will also be undertaken. The geochemical and petrographic data will then be integrated with the environmental interpretations to determine the influence of depositional processes on silica distribution. These data should lead to the development of a set of guidelines to be used in the exploration for silica deposits.

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REFERENCES

Allen, J.R.L.
1980: Sand Waves: a Model of Origin and Internal Structure; Sedimentary Geology, Volume 26, p.281-328.

Allen, P.A., and Homewood, P.
1984: Evolution and Mechanics of a Miocene Tidal Sandwave; Sedimentology, Volume 31, p.63-81.

Barnes, J.J. and Klein, G. deV.
1975: Tidal Deposits in the Zabriskie Quartzite (Cambrian), Eastern California and Western Nevada; p.163-169 *in* Tidal Deposits: a Casebook of Recent Examples and Fossil Counterparts, edited by R.N. Ginsburg, Springer-Verlag, Berlin, 428p.

Blakey, R.C.
1984: Marine Sand-wave Complex in the Permian of Central Arizona; Journal of Sedimentary Petrology, Volume 54., p.29-51.

Boyd, B.W.
1982: Silica: p.405-409 *in* Canadian Minerals Yearbook, 1980, Energy, Mines and Resources Canada, Mineral Report 30, 563p.

Boyd, R., Bowen, A.J., and Hall, R.K.
1983: Transgressive Coastal Sedimentation Along the Eastern Shore, Nova Scotia (abstract); Geological Society of America, Abstracts with Programs, Volume 15, p.194.

Brand, U., and Rust, B.R.
1977a: The Age and Upper Boundary of the Nepean Formation in its Type Section near Ottawa, Ontario; Canadian Journal of Earth Sciences, Volume 14, p.2002-2006.
1977b: The Age and Upper Boundary of the Nepean Formation in its Type Section near Ottawa, Ontario: Reply to Greggs and Bond: Canadian Journal of Earth Sciences, Volume 14, p.2671-2673.

Byers, C.W., and Dott, R.H., Jr.
1981: SEPM Research Conference on Modern Shelf and Ancient Cratonic Sedimentation - The Orthoquartzite-Carbonate Suite Revisited; Journal of Sedimentary Petrology, Volume 51, p.329-347.

Cant, D.J., and Walker, R.G.
1978: Fluvial Processes and Resulting Facies Sequences in the Sandy Braided South Saskatchewan River; Sedimentology, Volume 25, p.625-648.

Carson, D.M.
1982a: Paleozoic Geology of the Brockville-Mallorytown Area, Southern Ontario; Ontario Geological Survey, Preliminary Map P.2495, Geological Series, Scale 1:50 000.
1982b: Paleozoic Geology of the Gananoque-Wolfe Island Area, Southern Ontario: Ontario Geological Survey, Preliminary Map P.2496, Geological Series, Scale 1:50 000.

Clark, T.H.
1966: Chateauguay Area: Quebec Department of Natural Resources, Geological Report 122, 63p.

Cole, L.H.
1923: Silica in Canada, Its Occurrence, Exploitation and Uses; Canada Department of Mines, Number 555, Part 1, 126p.

Collings, R.K., and Andrews, P.R.A.
1983: Potsdam Sandstone of Ontario as Glass and Foundry Glass (Abstract); Canadian Institute of Mining and Metallurgy, Bulletin, Volume 76, p.72-73.

Collinson, J.D.
1970: Bedforms of the Tena River, Norway; Geographisca Annaler, Volume 52A, p.31-55.

Dalrymple, R.W.
1984: Morphology and Internal Structure of Sandwaves in the Bay of Fundy: Sedimentology, Volume 31, p.365-382.

Dorr, J.J.
1984: The Sedimentological Study of the Feldspathic Conglomerates and Sandstones of the Big Rideau Lake Area, Ontario: unpublished B.Sc. Thesis, Queen's University, Kingston, Ontario, 98p.

Emmons, E.
1838: Report of the Second Geological District of the State of New York; New York State Geological Survey, Second Annual Report, 214p.

Fisher, D.W.
1977: Correlation of the Hadrynian, Cambrian, and Ordovician Rocks of New York State; New York State Museum, Map and Chart Series, Number 25, 75p.

Globensky, Y.
1981: Region de Huntingdon; Ministere de L'Energie et des Ressources, Service des Leves Geologiques, Rapport Geologique 198, 53p.
1982a: Region de Lachute; Ministere de L'Energie et des Ressources, Service des Leves Geologiques, Rapport Geologique 200, 67p.
1982b: Region de Vaudreuil; Ministere de L'Energie et des Ressources, Service des Leves Geologiques, Rapport Geologique 199, 59p.

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, Volume 9, p.933-941.
1977: The Age and Upper Boundary of the Nepean Formation in its Type Section near Ottawa, Ontario: Discussion of Brand and Rust: Canadian Journal of Earth Sciences, Volume 14, p.2669-2671.

Hunter, R.E.
1977a: Basic Types of Stratification in Small Eolian Dunes; Sedimentology Volume 24, p.361-387.
1977b: Terminology of Cross-stratified Sedimentary Layers and Climbing-ripple Structures; Journal of Sedimentary Petrology, Volume 47, p.697-706.

Jansa, L.F.
1975: Tidal Deposits in the Monkman Quartzite (Lower Ordovician) Northeastern British Columbia, Canada; p.153-161, *in* Tidal Deposits: A Casebook of Recent Examples and Fossil Counterparts, edited by R.N. Ginsburg, Springer-Verlag, Berlin, 428p.

Keith, M.L.
1949: Sandstone as a Source of Silica Sands in Southeastern Ontario; Ontario Department of Mines, Annual Report for 1946, Volume 55, Part 5, 36p.

Kingston, P.W., and Papertzian, V.C.
1983 1982 Report of the Eastern Region Resident Geologist; p.179-191, *in* Report of Activities, Regional and Resident Geologists, 1982, edited by C.R. Kustra, Ontario Geological Survey, Miscellaneous Paper 107, 211p.

Klugman, M.A., and Yen, W.T.
1980: Silica Sand Potential in Eastern Ontario, Preliminary Report 2 - Beneficiation; Ontario Geological Survey, Open File Report 5305, 39p.