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Detailed outcrop and core measured sections of Upper Cambrian and Middle Ordovician sandstones (and associated facies), southwestern Ontario

A.P. Hamblin

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ABSTRACT

Upper Cambrian and Middle Ordovician units, particularly the Potsdam and Shadow Lake sandstone units, of southwestern Ontario may harbour potential for natural gas resources, groundwater resources, Carbon Capture and Storage (CCS), and/or toxic waste disposal, but have not been fully studied in detail over the region. This report presents 5 outcrop and 16 core measured sections of these strata, descriptions of the facies encountered, and a few comments on their resource potential. Potsdam (Mount Simon) Formation facies include dominant thick bedded medium to coarse sandstone, arkosic coarse sandstone to conglomerate, and minor dark siltstone and dolostone, interpreted to represent deposition in a shallow nearshore to shoreline setting during initial upper Cambrian transgression. Theresa (Eau Claire) Formation facies include interbedded sandy dolostone and dolomitic fine to medium grained sandstone and minor bioturbated siltstone, interpreted to represent shallow subtidal to nearshore deposition. Shadow Lake Formation facies include dominant well sorted medium grained sandstone, poorly sorted fine to coarse sandstone, reddish mottled mudstone, and grey siltstone interbedded with greenish calcisiltite/limestone/dolostone in the upper parts of the formation. This suite is interpreted to represent deposition in shallow nearshore, shoreline and subaerial environments during the initial Middle Ordovician regional transgression over the peneplained Precambrian and Upper Cambrian unconformity surface, from which the detritus was derived. The porous and permeable Potsdam Formation yields oil and gas, and may provide further unstudied potential for hydrocarbons, groundwater, CCS or toxic waste disposal. The Shadow Lake Formation is not currently recognized to produce hydrocarbons (although these strata are in reservoir continuity with productive Cambrian units in places), but harbours significant unevaluated potential for oil and gas, groundwater and perhaps CCS.

INTRODUCTION

Upper Cambrian and Middle Ordovician sandstone units of southwestern Ontario are of interest due to their natural gas potential, their aquifer potential and their potential as deep storage reservoirs for toxic waste disposal. These strata were described in a series of 5 outcrops, located near the margin of the exposed Precambrian Shield, and 16 subsurface cores, scattered through southwestern Ontario. The Upper Cambrian Potsdam/Mt. Simon unit occurs in 10 cores, the Upper Cambrian Theresa/Eau Claire carbonates occur in 5 cores and the Middle Ordovician Shadow Lake Formation occurs in 5 outcrops and 8 cores (Fig. 1; Figs. 3-23).

REGIONAL TECTONIC AND STRATIGRAPHIC SETTING

Tectonic Setting

Southwestern Ontario is located between two major Paleozoic sedimentary basins, the Appalachian Basin to the south and east, and the Michigan Basin to the west, straddling the broad basement high of the Algonquin Arch (Armstrong and Carter, 2010). According to Sanford *et al.* (1985), the tectonic events in the Appalachian Orogen, epeirogeny on the craton and lower Paleozoic depositional succession of southern Ontario were all controlled by large-scale plate motions, which resulted in periodic rejuvenation of basement blocks on deep-seated fracture systems and subsidence of intervening circular basins. Their Tectonic Cycle I (late Precambrian to late Paleozoic) began with the creation of passive margin conditions, continued with separation during Late Precambrian to early Ordovician time, and concluded with active closure and collision during later Paleozoic time (Sanford et al., 1985). Howell and van der Pluijm (1990) concurred with the concept of relating Arch uplift and episodic cratonic basin subsidence to orogenic phases in the Appalachians, and suggested that the pre-Taconian Upper Cambrian/Lower Ordovician stratigraphic sequence accumulated in an elongate

NE/SW-trending trough in the location of the later Michigan Basin, possibly as a northern extension of the Reelfoot Rift. Tectonic movements during the Taconic Orogeny at the craton margin were transmitted through the craton by tilting of fault-bounded mega-blocks and expressed as uplift along arches on dominant NE and NW trends, and as corresponding downwarp of intervening cratonic basins (Sanford *et al.*, 1985).

During the early Paleozoic the NE-SW-oriented Algonquin Arch was a broad, subdued platform between the more rapidly subsiding Michigan Basin to the west and the Appalachian Basin to the east (Bailey and Cochrane, 1984; Sanford *et al.*, 1985). It also separates the northern Bruce basement mega-block (with simple uniform E-W fracture system) from the southern Niagara basement mega-block (with complex multiple sets of fractures cutting it into a maze of smaller blocks) (Sanford *et al.*, 1985). During the Early Ordovician (the earliest phase of the Taconian Orogeny), Arch rejuvenation and fault-bounded uplift induced erosion of previously more extensive Upper Cambrian/Lower Ordovician strata from the crest, resulting in Cambrian erosional edges bounded by fault line scarps and basement blocks along the southern flank of the Algonquin Arch (Bailey and Cochrane, 1984; Sanford *et al.*, 1985). This is the regional-scale, pre-Tippecanoe, or "Knox", Unconformity which truncates all Upper Cambrian strata in southern Ontario, and elsewhere in the northern Appalachians (e.g. Fowler *et al.*, 1995) (Fig. 1).

Stratigraphic Setting

During Early Paleozoic time, Southwestern Ontario was located at about 15^{o} S paleolatitude, at the margin of a tropical sea. The present-day Precambrian surface slopes away from the Shield except for the mildly positive Algonquin Arch, and the Palaeozoic succession of southern Ontario (approximately 1400 m thick) dips gently away to the south, west and southwest (Roliff, 1954; Sanford and Quillian, 1959; Armstrong and Carter, 2010). During early Paleozoic time the Precambrian surface was likely similar to its present-day configuration, and irregularities on this surface are reflected far up into the stratigraphy (Sanford and Quillian, 1959). There is commonly development of a widespread regolith zone of highly-weathered granitic detritus mantling the Precambrian surface, known to drillers as "the Arkose" (Bailey and Cochrane, 1984).

As the Upper Cambrian sea transgressed from the Appalachian Geosyncline through southern Ontario up the flanks of the subdued Algonquin Arch, the depositional units thinned, but likely covered the structure, resulting in an overall transgressive succession of marine sandstone and dolomite resting unconformably on basement (Roliff, 1954; Poole *et al.*, 1968). However, these strata, the Sauk Sequence of Sloss (1963), were eroded from the Arch crest during a phase of Early Ordovician uplift, marine regression and subaerial erosion, resulting in the development of the sub-Tippecanoe Sequence (of Sloss, 1963) "Knox Unconformity" (Bailey and Cochrane, 1984a, Coniglio et al., 1990) (Fig. 2). This surface was subsequently transgressed and overlapped by Middle Ordovician units of the Black River Group (Cohee, 1948; Poole *et al.*, 1968; Bailey and Cochrane, 1984) (Fig. 2). At the crest of the Algonquin Arch, Middle Ordovician rocks rest directly on Precambrian basement (Cohee, 1948; Roliff, 1954) (Fig. 2). Currently, Upper Cambrian strata comprise about 1% of the Palaeozoic rock volume and occur over only about 50% of the area of southwestern Ontario (Sanford and Quillian, 1959). These strata range 0-60 m thick over an area of about 25000 sq. km, where preserved beneath Middle Ordovician carbonates, and are thickest in the Lake Huron and Lake Erie areas in the far western and southern parts of the province (Roliff, 1954). The entire Upper Cambrian section, representing the only preserved portion of the Sauk Sequence in southwestern Ontario, thins by both onlap and erosion onto both flanks of the Algonquin Arch (Bailey and Cochrane, 1984) (Fig. 2).

The Middle Ordovician strata of the Tippecanoe Sequence overlie the "Knox Unconformity" and overlap progressively older Cambrian units toward the crest of the Arch (Armstrong and Carter, 2010) (Figs. 1, 2). The subsequent Middle Ordovician Tippecanoe regional transgression was caused by one of the greatest eustatic sea level rises in geological history, and resulted in a general Black

River/Trenton sequence of depositional environments from basal transgressive shoreline/tidal flat clastics and carbonates to lagoonal carbonates to offshore carbonates (Coniglio *et al.*, 1990). The offshore direction was generally to the southeast (Coniglio *et al.*, 1990). In central Ontario, the Precambrian basement had irregular but low relief with knobs up to 100 m high, onlapped progressively by Ordovician units (Coniglio *et al.*, 1990). The basal transgressive sandstone of the Black River Group, the Shadow Lake Formation, is absent over the top of many of these and over the top of the Algonquin Arch, but still present over large areas (Fig. 2). In southwestern Ontario Ordovician units onlapped, and were derived from, Upper Cambrian units or the Precambrian peneplain (Trevail, 1990). Thus, lithology, thickness and depositional environment are very variable, depending on paleotopography and sediment source (Coniglio *et al.*, 1990; Trevail, 1990). The Black River Group generally comprises arkosic sandstones and sandy mudstones near the base (Shadow Lake Formation) and sandy dolostones upward (Gull River Formation) (Roliff, 1954; Armstrong and Carter, 2010).

Summaries of the geological literature for both Upper Cambrian and Middle Ordovician sandstone units were provided by Hamblin (1998a, 1998b), and references therein. In addition, Hamblin (1998c) provided a summary of literature for equivalent strata in the Ottawa Embayment to the east of the Frontenac Arch. The most modern, comprehensive and exhaustive summary of information on all Paleozoic units in Southern Ontario was provided by Armstrong and Carter (2010). In many older subsurface wells, a unit referred to as "Basal Beds" is logged overlying basement, which may be uppermost Upper Cambrian in age, or may be the basal Middle Ordovician Shadow Lake Formation (Roliff, 1954; Bailey and Cochrane, 1984).

UPPER CAMBRIAN POTSDAM (MOUNT SIMON) FORMATION

Distribution

At the base of the Phanerozoic section of southwestern Ontario are up to 50 m of white to greenish or locally reddish orthoquartzitic sandstone, overlapped by Ordovician units, which is traditionally referred to the Potsdam Formation in the southeast, and the Mount Simon Formation in the northwest (Poole *et al.*, 1968). The Potsdam may be equivalent to the Nepean Formation which outcrops along both edges of the Frontenac Arch in eastern Ontario (Armstrong and Carter, 2010).

The Potsdam was named by Emmons (1838) with a type locality in New York, but an Ontario type locality was designated near Kingston, and even Logan recognized the extension of this unit to the southern side of the Frontenac Axis (Winder, 1961). Sanford and Quillian (1959) used this name for basal quartzose sandstone, with a basal boulder conglomerate, unconformably overlying basement in the subsurface east of 81° W longitude (i.e. east of London). They recognized a lower white unit and upper red unit, possibly separated by an unconformity in the Kingston area, with the upper portion conformable with the overlying Middle Ordovician Black River limestone (Winder, 1961). This term is essentially an Appalachian Basin name.

The Mount Simon was named by Walcott for sandstones lying on basement in Wisconsin and was traced into southwestern Ontario by Cohee (1948) and Roliff (1954), where Liberty (1955) designated a reference well near Simcoe (U.S. Steel #1, Norfolk Co., Charlotteville Twp, 21-I). Although the Mount Simon does not outcrop in Ontario (Armstrong and Carter, 2010), Sanford and Quillian (1959) applied the name to all basal white to grey quartzose sandstone in the subsurface west of 81° W longitude (i.e. west of London), and suggested equivalence to the Potsdam Formation to the east. The Mount Simon rests unconformably on Precambrian basement, is overlain by the Theresa/Eau Claire or overlapped by the Middle Ordovician, and is presumed (but not proven) to be of Upper Cambrian age (Cohee, 1948; Roliff, 1954; Liberty, 1955). This term is essentially a Michigan Basin term.

The erosionally truncated edges of the Potsdam (Mount Simon) rim the Algonquin Arch in the subsurface from Manitoulin Island, down the western shore of Lake Huron, and around the northern shore of Lake Erie, and therefore the unit underlies much of southwestern Ontario (Liberty, 1955; Winder, 1961). In Canada, it is thickest and deepest at the International Boundary (thickening into the U.S.) and thins inland through the adjacent counties to subcrop beneath the sub-Middle Ordovician unconformity (Cohee, 1948; Liberty and Bolton, 1971). Armstrong and Carter (2010) designated a reference well and core for Upper Cambrian units: Pembina Central Lake Erie 185-M-3, and OGS 82-3 Yarmouth (Port Stanley) (which is part of this study), respectively.

Lithology

The Potsdam (Mount Simon) comprises light grey to white, well sorted, friable, medium to coarse quartzose sandstone with minor thin beds of brown fine crystalline sandy dolostone and minor shale increasing toward the top (Cohee, 1948; Roliff, 1954; Liberty, 1955; Armstrong and Carter, 2010). A thin arkosic sandstone commonly occurs at the base, overlying Precambrian basement (Sanford and Quillian, 1959). Quartz grains are subangular to subrounded, with rounding and frosting increasing upward, and trace glauconite is ubiquitous (Roliff, 1954; Sanford and Quillian, 1959; Liberty and Bolton, 1971).

Facies Present in Cores

Thin Bedded, Poorly Sorted, Arkosic Coarse Sandstone to Conglomerate

Thin beds of grey, reddish or greenish, pebbly coarse- to very coarse-grained sandstone to sandy pebble conglomerate occur at the base of the Potsdam /Mount Simon formations in some cores. These typically occur immediately above the fractured, weathered unconformity surface at the top of the Precambrian, overlying pinkish grey granite or granitic gneiss. These conglomerates are massive, poorly sorted, and matrix-supported with angular to subangular granitic clasts floating in a sandy or silty matrix. They fill fractures and irregularities in the basement surface and are porous and friable.

Thick Bedded, Fine to Coarse Grained Sandstone with Thin Silty Partings

The most common facies in the Potsdam and Mount Simon formations (comprising 80-90% of the formation at any given location) is represented by thick beds of grey to greenish grey to reddish grey, fine- to coarse-grained sandstone, typically medium- to coarse-grained, uniform, well sorted, rounded to subrounded quartz sandstone with dolomitic or siliceous cement. This facies commonly occurs in multi-storied, thick fining-upward units, commonly with sharp, erosive bases lined with stringers of coarse sand granules, feldspar pebbles or mudstone rip-up clasts. Low angle lamination and trough cross bedding are ubiquitous, with some ripple cross lamination, contorted lamination, silty partings, and common vertical to sub-horizontal burrows, especially in finer grained examples. Finer grained examples also are typically thinner bedded and may be interbedded with siltstone/mudstone beds.

Dark Siltstone to Mudstone with Thin Sandstone Beds

Rare, thin beds of grey to dark grey or greenish, sandy siltstone and silty mudstone occur in a few cores of Potsdam/Mount Simon. These are typically interbedded with coarser lithologies. Most are well-bioturbated with abundant horizontal burrows, and include very thin sandy streaks or a few floating granule to pebble clasts. In the Port Stanley core, this facies immediately overlies the weathered Precambrian unconformity surface, and fills fractures and irregularities in this surface.

Dark Sandy Dolostone and Stromatolite Horizons

In several cores, thin beds of grey to dark brownish grey, sandy dolostone occur, typically interbedded with coarser sandstones and dolomitic sandstones. They are commonly bioturbated, but may be thinly laminated. In OPG Core DGR-2, three isolated grey, sandy, stromatolitic horizons occur in the upper half of the Mount Simon Formation. They are separated by thin dark grey sandy siltstone beds, and are underlain by coarse-grained sandstone and overlain by fine to medium grained sandstone.

Environments of Deposition

The facies described for the Potsdam /Mount Simon formations are interpreted to represent deposition in a fairly energetic, primarily nearshore shallow marine and shoreline environment, during early Phanerozoic transgression of the exposed, weathered, low-topography, peneplained Precambrian unconformity surface. The massive coarse facies which commonly immediately overlies this surface is interpreted to represent regolith, reworked regolith, and possibly alluvial sediments deposited in the initial stages of this transgression. The thin silty/muddy beds, minor carbonates and stromatolitic horizons represent lower energy areas or periods of deposition within this shallow marine setting.

UPPER CAMBRIAN THERESA (EAU CLAIRE) FORMATION

Distribution

Stratigraphically overlying the Potsdam (Mount Simon) Formation through part of southwestern Ontario are up to 75 m of dolostone and sandy dolostone, truncated and overlapped by Middle Ordovician units (Roliff, 1954), named the Theresa Formation. These rocks overlap the Potsdam (Mount Simon) toward the Algonquin Arch to lie unconformably on Precambrian basement (Poole *et al.*, 1968). The Theresa Formation, an Appalachian Basin term, was designated at a type locality in New York, and Sanford and Quillian (1959) suggested the name only be used east of 81^{o} W longitude (i.e. east of London), based on observational evidence. There are no outcrops of Theresa in Ontario, but it is present in the subsurface in the Niagara Peninsula/Lake Ontario area, thinning to a subcrop truncation edge to the west (Sanford and Quillian, 1959).

The Eau Claire Formation, a Michigan Basin sandstone and lesser dolostone unit, was traced into southwestern Ontario by Cohee (1948) and Roliff (1954). Sanford and Quillian (1959) suggested the name only be used west of 81^{o} W longitude (i.e. west of London), based on observational evidence. There are no outcrops of Eau Claire in Ontario, but it is present as a thin wedge in the subsurface of the Lake Huron/Bruce Peninsula, and Lambton/Essex/Kent Co./Lake Erie areas where it overlaps the Mount Simon and thins to a subcrop truncation edge toward the crest of the Algonquin Arch (Cohee, 1948; Sanford and Quillian, 1959; Liberty and Bolton, 1971; Armstrong and Carter, 2010). The Theresa and Eau Claire are considered as approximately equivalent (Winder, 1961), although no proven ages exist (Liberty and Bolton, 1971.). Armstrong and Carter (2010) designated a reference well and core for Upper Cambrian units, as stated above.

Lithology

The Theresa (Eau Claire) Formation comprises grey to pinkish grey, fine to medium crystalline dolostone, sandy dolostone, argillaceous dolostone, and fine- to coarse-grained sandstone (Cohee, 1948; Roliff, 1954; Sanford and Quillian, 1959; Armstrong and Carter, 2010). Where resting on basement, there may be a basal, reddish arkosic sandstone, with abundant authigenic potassium feldspar, related to formation water migration along the unconformity (Sanford and Quillian, 1959; Liberty and Bolton, 1971; Armstrong and Carter, 2010). The proportion of dolostone increases upward and may be glauconitic near the top, especially to the west (Sanford and Quillian, 1959; Winder, 1961). Quartz grains are rounded and frosted (Sanford and Quillian, 1959; Liberty and Bolton, 1971).

Facies Present in Cores

Grey Fine to Coarse Crystalline Sandy Dolostone

Thick beds of grey, mottled, fine to medium (coarse in places) crystalline dolostone to sandy dolostone are ubiquitous and the dominant lithofacies of the Theresa/Eau Claire. Interbedding of finer and coarser beds is common. In addition, these dolostone beds are commonly interbedded with the dolomitic sandstone facies. Bed bases and tops are generally sharp, and thickness ranges up to 3 m, but is typically 30-50 cm. Finer grained beds are typically thinner and may be interbedded with silty beds. Stylolites, silty/muddy partings, bioturbation, vugs and low angle lamination are common. Convolute lamination and brecciation occur in several cores. Glauconitic horizons are present in several cores.

Grey Fine to Medium Grained Dolomitic Sandstone

Thin to thick beds of pale grey, fine- to medium-grained, well sorted dolomitic sandstone represent the second most common facies of the Theresa/Eau Claire. Interbedding of different grain sizes is common, and this facies is commonly interbedded with the dolostone facies. Individual beds typically have sharp bases and tops, and may fine upward. Beds are typically 10-50 cm thick, but may range up to 1 m in thickness. Low angle lamination, ripples, and trough cross bedding are common, and burrowing and convolute lamination occur in places.

Thin Bioturbated Calcareous Siltstone

Beds and partings of grey to greenish grey, calcareous siltstone/mudstone are uncommon, but occur in a few cores, interbedded with the other more dominant facies. Bed thickness ranges 1-20 cm, but is typically 2-8 cm. These units are generally thoroughly bioturbated.

Environments of Deposition

The facies described for the Theresa/Eau Claire are interpreted to represent deposition in a fairly energetic, clear, shallow subtidal to nearshore/shoreline marine environment, in a mixed carbonate/clastic setting where some sedimentary mixture of terrigenous (shoreline and aeolian) clastic material was common. The thin silty/muddy beds represent lower energy areas or periods of deposition within this shallow marine setting.

LITTLE FALLS (TREMPELEAU) FORMATION

These units represent the youngest Upper Cambrian rocks in the area, but occur only under Lakes Erie and Huron near the International Boundary, wedging out toward land (Sanford and Quillian, 1959; Poole *et al.*, 1968). The Little Falls occurs in only one well in Lake Erie and is about 30 m thick (Poole *et al.*, 1968). The units overlie, and may overlap, the Theresa (Eau Claire). The lithology is a distinctive buff grey, fine to medium crystalline dolostone, locally sandy (Sanford and Quillian, 1959). No outcrops or cores in this study included this unit.

BASAL SANDSTONE/GRANITE WASH PROBLEM

From the basinal flanks, toward the crest of the Arch, the above stratigraphic units are less distinct and transgressive winnowing apparently produced thin sandy shoreward equivalents of all the units (Bailey and Cochrane, 1984). Sandstones of this type, of Theresa (Eau Claire) age, are apparently finer grained and better sorted than those of Potsdam (Mount Simon) or earlier vintage, but can result in difficult correlation problems (Bailey and Cochrane, 1984). Armstrong and Carter (2010) suggested that these reddish sandstones, characterized by fresh potassium feldspar crystals, are related to formation water migration along the unconformity. In addition, on the crestal areas of the Arch, isolated patches of sandstone of unknown (Upper Cambrian, Lower Ordovician or Middle Ordovician) age occur, and can be very porous and prospective (Bailey and Cochrane, 1984).

MIDDLE ORDOVICIAN SHADOW LAKE FORMATION

Definition

The term Shadow Lake was first proposed by Okulitch (1939) for the Middle Ordovician age "basal beds", unconformably resting on Precambrian basement at the type locality on Highway 35, 6 km north of Coboconk at Shadow Lake (Winder, 1961) (included in this study). In most parts of Ontario, except for the Ottawa Embayment, the unit is the lowest Ordovician present, marking the base of the Tippecanoe Sequence of Sloss (1963) (Fig. 1). It unconformably overlies Precambrian basement, or where Cambrian rocks are present, the Shadow Lake Formation unconformably overlies the truncated edges of progressively younger Upper Cambrian units away from the Canadian Shield (Liberty, 1955; Armstrong and Carter, 2010). It yields Black River age conodonts and passes conformably upward into the Gull River limestones, of definite Black River age (Williams and Telford, 1986).

Distribution and Thickness

The Shadow Lake includes red arkose, green shale and grey dolostone overlying the Precambrian. It was previously designated the "Rideau Formation" by Winder (1955) but Caley and Liberty (1957) suggested the Rideau was simply a facies of the Shadow Lake (Winder, 1961). The Shadow Lake is somewhat discontinuous, its presence and thickness determined by the paleotopographic relief on the underlying Precambrian erosional surface in most areas (Liberty, 1955). Thickness ranges 0-15 m, thickest in depressions on the unconformity (Liberty, 1955; Winder, 1961; Armstrong and Carter, 2010) which may have had up to 25 m of local relief (Caley and Liberty, 1950). The upper contact with the limestone and dolostone of the overlying Gull River Formation ranges from sharp to gradational (Armstrong and Carter, 2010). It is exposed sporadically in the Kawartha Lakes area in a band along the edge of the Shield (Winder, 1961). It is best seen at 1) the type section on Highway 35 north of Coboconk, 2) at the Marmoraton Iron Mine, 3) on Highway 36 near Burleigh Falls, 4) at Waubaushene, 5) just north of Seabright, and 6) on the northwest shore of Head Lake (Liberty, 1955; Coniglio *et al.*, 1990). Several of these outcrops are included in this study, and the Marmoraton Mine outcrop is also described by Armstrong and Carter (2010).

Traces of the Shadow Lake have been recorded in the subsurface of the Bruce Peninsula (Liberty and Bolton, 1971), Toronto, Niagara and London areas (Winder, 1961) (Fig. 1), where it commonly overlies and truncates Cambrian units (Roliff, 1954; Liberty, 1955). Bailey and Cochrane (1984b) used the Shadow Lake as a consistent and easily-identified marker in subsurface correlations. Trevail (1990) described good cores of Shadow Lake in the London area from three wells: OGS 82-3 Yarmouth 3-9-I, Canada Cities Service et al. South Dorchester 1-10-VIII and 8-7-VII where it is typified by a distinct high radioactivity response on the Gamma Ray log. Eight cores of Shadow Lake are described in this study, and several reference cores and well logs were designated by Armstrong and Carter (2010): OGS 83-3 (Pickering) and OGS 82-3 Yarmouth (Port Stanley) (included in this study), respectively.

Lithology

In general the formation consists of arkosic sandstone and green or red shale with embedded quartz grains (Caley and Liberty, 1950; Liberty, 1955). Silty to sandy dolostone may be present in minor amounts, generally as part of the transition upward to the Gull River Formation (Williams and Telford, 1986). Sandstones are greenish-grey, friable and loose, rounded, arkosic, calcareous and fine to coarse grained (Caley and Liberty, 1950). A few scattered Precambrian pebbles are common. The sandstones are typically overlain by red and green shale with embedded, frosted, rounded quartz grains and minor thin limestone or dolostone interbeds (Caley and Liberty, 1950). In subsurface well cuttings the sand commonly dominates because the shale is washed away. Dolostone beds are fine crystalline and greenish grey (Williams and Telford, 1986).

In south central Ontario the Shadow Lake lithology is summarized by Coniglio *et al.* (1990) as follows (Fig. 2). The unit generally comprises lower arkosic conglomerate and coarse sandstone grading up into interbedded silty dolomitic and calcareous sandstone and terrigenous mudstone. The basal contact is sharp and unconformable; the upper contact is gradational with upward increase of sandy dolostone and limestone into the Gull River. Sedimentary structures include planar and cross lamination, ripples, mudcracks, *Skolithos* and other burrows. Mottling of reddish and greenish colours is commonly due to burrowing. A sparse fauna of a few conodonts, lingulid and strophomenid brachiopods, bivalves, fish teeth and ostracods suggests a lower Black River age, diachronous across the province with the oldest to the south and southeast.

In the subsurface of southwestern Ontario, Trevail (1990) described and interpreted three lithofacies, as follows. Directly overlying the unconformity, green poorly to well sorted, thoroughly bioturbated, medium to coarse grained glauconitic sandstones deposited in a low energy shallow marine setting. Sediment was primarily derived from eroded upper Cambrian rocks, but abundant frosted and pitted coarse quartz grains suggest aeolian input as a secondary sediment source. Secondly, interbedded dark green to black laminated siltstone and greenish, burrowed fine to medium sandstone occurs higher in the Shadow Lake. Sand grains are 90% monocrystalline quartz, subrounded to subangular and set in a matrix of dolomite and illite. Black shale rip-ups and pyrite blebs are common and the facies was likely deposited in a quiet, possibly anoxic, shallow marine setting subject to periodic high energy storms. Thirdly, brown grey, fossiliferous medium to coarse sandstone with broken shell fragments is locally present at the top.

Facies Present in Outcrops and Cores

Thick-Bedded, Poorly-Sorted Very Fine to Coarse Sandstone

Thick beds of grey, reddish or greenish, poorly to fairly sorted, massive, arkosic, friable, argillaceous pebbly sandstone commonly drape the weathered, fractured and irregular Precambrian unconformity surface, or the Knox unconformity surface at the top of the Cambrian. Grain size ranges from very fine silty sandstone to granulestone, typically medium- to coarse-grained, and floating angular sand- to pebble-sized clasts of pink granite or gneiss derived from the underlying weathered basement are abundant. Grain size may fine upward from the sharp base to a sharp or gradational top. Red and green angular mudstone clasts and burrows are rarely present. This facies represents only about 5% of Shadow Lake deposits.

Thin-Bedded, Well-Sorted Very Fine to Coarse Sandstone

The most common facies in the Shadow Lake Formation comprises grey, thinly to thickly bedded, well sorted, fine- to coarse-grained dolomitic sandstone. The average grain size is medium-grained sandstone. This facies typically occurs in sharp, erosively-based, fining-upward units from 1 to 5 m thick, although units with no obvious grain size trend are also present. Erosive bases may be lined with mudstone rip-up clasts or granules and pebbles, and angular granules of granite, quartz and feldspar are scattered throughout the unit thickness in some examples. Low angle lamination and trough cross bedding are ubiquitous, and ripple cross lamination, contorted lamination and silty partings occur in the upper parts of fining-upward units. Subhorizontal to subvertical burrows also occur in the upper parts of many units, especially associated with silty partings and interbeds.

Red/Green Mottled Mudstone to Silty Sandstone

In a few outcrops and cores, thin units of red, greenish grey, or red/green-mottled sandy siltstone to silty sandstone are present. These siltstones are uniform, massive, blocky, fractured, have gradational boundaries and appear to display vertical pedogenic structures. One example displays mudcracks, interpreted as desiccation cracks, and another is brecciated. Occurrences of this facies are associated with the dominant sandstone facies and represent about 5% of Shadow Lake deposits.

Grey Siltstone with Thin Sandstone Beds

In three cores, units of grey calcareous sandy siltstone, with discontinuous thin beds of calcareous, very fine grained sandstone, are present. These siltstones are well bioturbated with abundant small horizontal burrows. In one example, shell fragments float in the matrix. This facies is associated with the limestone/dolostone facies.

Grey/Green/Brown Limestone and Dolostone

A common facies throughout the Shadow Lake Formation comprises greyish to greenish to brownish calcisiltite, limestone and sandy dolostone. This facies is most common in the upper parts of the formation, and is intimately interbedded with other facies, representing about 20% of Shadow Lake deposits. These units are generally fine crystalline, thin to thick bedded, may be laminated, and commonly include thin stringers of sand grains, and/or floating sand grains scattered throughout. Mudstone partings, stylolites, burrows and evaporite crystal molds also occur. In one core there are several thin stromatolite horizons and in one outcrop, polygonal mudcracks, interpreted as desiccation cracks, and ripple marks are present.

Environments of Deposition

The facies described for the Shadow Lake Formation are interpreted to represent deposition in a fairly energetic, primarily shallow nearshore marine to subaerial environment, during the Middle Ordovician transgression of the exposed, weathered, low-topography, Upper Cambrian and Precambrian peneplained unconformity surface. The massive coarse facies, which commonly immediately and unconformably overlies the Upper Cambrian and Precambrian erosional surfaces, is interpreted to represent regolith, reworked regolith, and possibly alluvial sediments deposited in the initial stages of this transgression. The predominant sandstone facies appears to include a mix of fluvial, shoreline and nearshore shallow marine depositional environments, intricately interbedded with the other facies during the complex transgression which spread over the low-topography unconformity surface. Thin occurrences of reddish pedogenic siltstone represent subaerial deposition and soil-forming processes adjacent to shoreline and alluvial settings. The thin burrowed silty/muddy beds, and sandy carbonates and stromatolitic horizons represent lower energy areas or periods of deposition, within the nearshore shallow marine setting.

The Shadow Lake Formation represents complex shallow marine and shoreline to subaerial environments, developed as the Middle Ordovician Tippecanoe sea advanced over the Precambrian/Cambrian erosional surface and washed the weathered detritus into the paleotopographic depressions. It appears to comprise a thin, possibly discontinuous, fan-like transgressive wedge of widely-varied lithologies and facies, extending out from the adjacent Precambrian Shield (which is exposed immediately east and north of the outcrop belt), and from the then-exposed Cambrian units overlying the Algonquin Arch. The depositional setting was likely nearshore marine and subaerial, and likely includes a complex mixture of regolith, aeolian, alluvial, shoreline and shallow marine deposits, reworked during transgression.

RESOURCE POTENTIAL

Exploration History of Upper Cambrian Strata

The Upper Cambrian units of southwestern Ontario have proven oil and gas reserves (about 13% of Ontario gas; Powell *et al.*, 1984), and represent the last "frontier in conventional hydrocarbon exploration in the province (Sanford, 1989, *pers. comm.*). In addition, these units have currently un-evaluated capacity for salt water injection, gas storage and toxic waste disposal (Sanford, 1989, *pers. comm.*). All hydrocarbon reservoirs discovered to date occur in dolostones Theresa Formation) and dolomitic sandstone (Potsdam Formation) units near the updip truncated erosional edge of Cambrian strata along the southern flank of the Algonquin Arch (Powell *et al.*, 1984) (Fig. 2). The Cambro-Ordovician succession of southwestern Ontario is thermally marginally mature (C.A.I. = 2-2.5, i.e. 60-90 burial temperature) (Legall *et al.*, 1981; Barker and Pollack, 1984). Cambrian oils were sourced from the upper Ordovician Collingwood marine shale (Powell *et al.*, 1984), whereas there is no presently known source for Cambrian gas (Barker and Pollack, 1984).

In southwestern Ontario, oil was first discovered in Cambrian rocks at Romney in 1923, downdip of the erosional edge in porosity/permeability pinchouts in interbedded dolostone and sandstone of the Theresa Formation (Poole *et al.*, 1968). Gas was first discovered at Electric in 1948, with initial flows of 600 Mcf/d from Potsdam (Mount Simon) sandstones (Roliff, 1954). Discovery of oil at the erosional truncation edge of the Potsdam in 1960 at Gobles initiated a round of deep drilling in southwestern Ontario which resulted in further discoveries (Poole *et al.*, 1968). Attention was again focused on the deep Ordovician and Cambrian targets during the 1980's, particularly in Kent, Elgin and Sussex Counties, and the adjoining offshore areas of Lake Erie. This has again resulted in a number of new oil and gas discoveries and field extensions. Cambrian oil pools average 1.57 million barrels reserves, 23% recovery factor, 1803 acres area, producing from reservoirs with about 10 % porosity and 45 md permeability (Daily Oil Bulletin, June 4, 1986). The most recent published mean volume estimate for Cambrian oil discovered reserve is ~5 x 10^6 m^3, and the estimated mean remaining undiscovered potential is a very minor 0.08 x 10^6 m^3 (Osadetz et al., 1996). For Cambrian natural gas, the most recent published mean volume estimate for discovered reserve is ~ 1044 x 10^6 m^3 (Osadetz et al., 1996). No estimate of remaining undiscovered gas potential was supplied.

Traps and Reservoirs in the Upper Cambrian

Cambrian units represent some of the earliest-exploited and most prolific hydrocarbon producers in Ontario. Structural, stratigraphic, erosional truncation and porosity/permeability pinchout mechanisms all play parts in trapping oil and gas in Cambrian units (Bailey and Cochrane, 1984; Powell *et al.*, 1984; Barker and Pollack, 1984). For all play types, the untested areas are large, and potential is significant (Bailey and Cochrane, 1984).

Porous Cambrian units pinch out updip against the Precambrian surface and are top-sealed by the overlapping Shadow Lake Formation, such as at Gobles and Innerkip (Bailey and Cochrane, 1984; Armstrong and Carter, 2010). Structurally-based mechanisms related to basement block normal faulting appear to be the main controlling factors (Roliff, 1954; Bailey and Cochrane, 1984; Sanford *et al.*, 1985; Sanford, 1989, *pers. comm.*; Armstrong and Carter, 2010). For most Cambrian fields, the main traps involve basement tilt-fault blocks of various scales formed in the Early Ordovician rejuvenation of the Algonquin Arch, and reactivated in Late Ordovician, Silurian and Devonian times (Bailey and Cochrane, 1984; Sanford *et al.*, 1985). For example, the Clearville Field traps oil in Upper Cambrian sandstone and dolostone at the northern uplifted side of a triangular-shaped block and is sealed by juxtaposition against Middle Ordovician limestone (Sanford *et al.*, 1985). Some blocks may have been active during deposition, and erosional paleotopography at the overlying unconformity surface may have created stratigraphic traps as noted in northwestern Pennsylvania (Pees and Fox, 1990). In Ohio and New York Cambrian sandstones have porosities averaging 8-12 % (up to 15%), isolated rich source rock intervals (T.O.C. 3.6-4.8 % in the oil window) and pool reserves averaging 300-400 MMcf/well (ranging 75 MMcf/well to 1Bcf/ well) (Petzet, 1991; Robinson, 1991).

Where present at, or near, the surface in central Ontario near the outcrop edge of the Canadian Shield, porous and permeable Cambrian units may likewise harbour significant groundwater resources. Similarly, the presence of these porous and permeable Cambrian units at significant depth may present opportunities for CCS or toxic waste disposal.

Resource Potential of Shadow Lake Formation

Caley (1961) mentioned that the "basal beds" of the Toronto-Hamilton area may be potential hydrocarbon reservoirs, and Bailey and Cochrane (1984b) suggested that sandstone beds in the Shadow Lake may have hydrocarbon potential but are likely in reservoir continuity with underlying Cambrian units, where present. Regionally, the Shadow Lake is not yet a significant producer of hydrocarbons, nor a significant groundwater aquifer (Armstrong and Carter, 2010). However, in the

Innerkip area, Shadow Lake sandstones in porosity/permeability communication with underlying productive Cambrian sandstones do produce natural gas, and may represent a currently under-explored potential play (Armstrong and Carter, 2010), with much more potential than previously recognized. CCS is also possible. Where present at, or near, the surface in central Ontario near the outcrop edge of the Canadian Shield and in the shallow subsurface, the Shadow Lake may also harbour significant groundwater resources. At this time, further speculation regarding these possibilities is premature.

CONCLUSION

The Upper Cambrian and Middle Ordovician sandstones of southwestern Ontario include facies with potential to be significant hydrocarbon reservoirs. Well-sorted, fine- to coarse-grained sandstone, of shallow marine to shoreline origin, occurs over a reasonable area and provides reservoir potential in these units. The Upper Cambrian Potsdam Formation (and possibly the Middle Ordovician Shadow Lake Formation) already produce hydrocarbons from several known pools. These same facies, under the right conditions, may also have potential for groundwater, carbon capture and storage, and/or toxic waste disposal. Further study of the stratigraphy, sedimentology, mineralogy and reservoir characteristics of these units will lead to better understanding of the possibilities.

ACKNOWLEDGEMENTS

I would like to thank Derek Armstrong, Terry Carter and Rob MacNaughton for helpful discussions and guidance on the subject of the Lower Paleozoic strata of southwestern Ontario over a period of years. The manuscript was reviewed and improved by Rob MacNaughton. The figures were drafted with great patience and professional expertise by Elizabeth Macey. Denise Then handled the final assembly and production of the Open File. Many thanks to all of you.

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23. Ontario Power Generation Core DGR-2.

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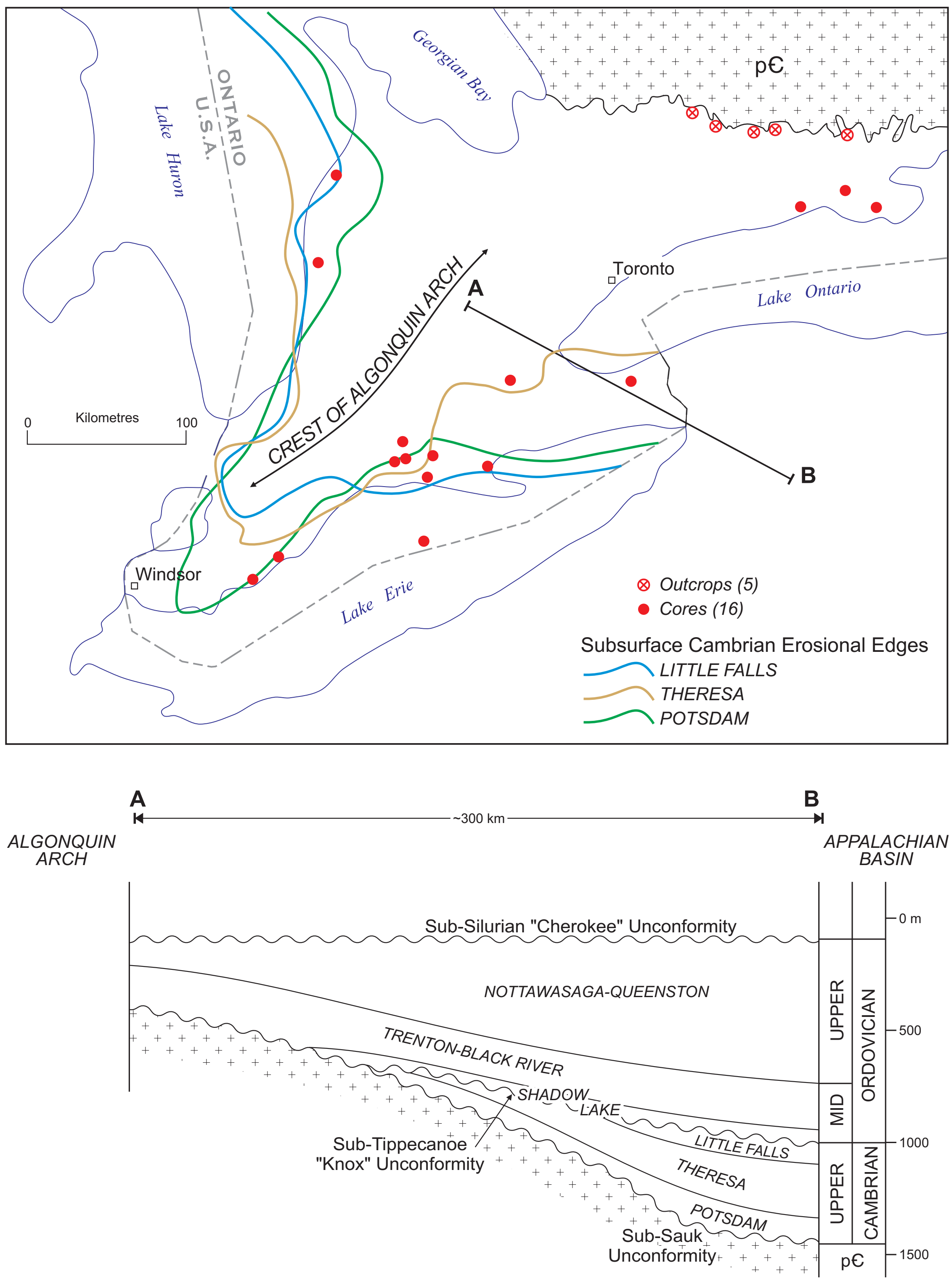

Figure 1. Distribution of Upper Cambrian strata of Southwestern Ontario, and outcrop and core locations (modified from Sanford and Quillian, 1954; Poole et al., 1968; Hamblin, 1998b)

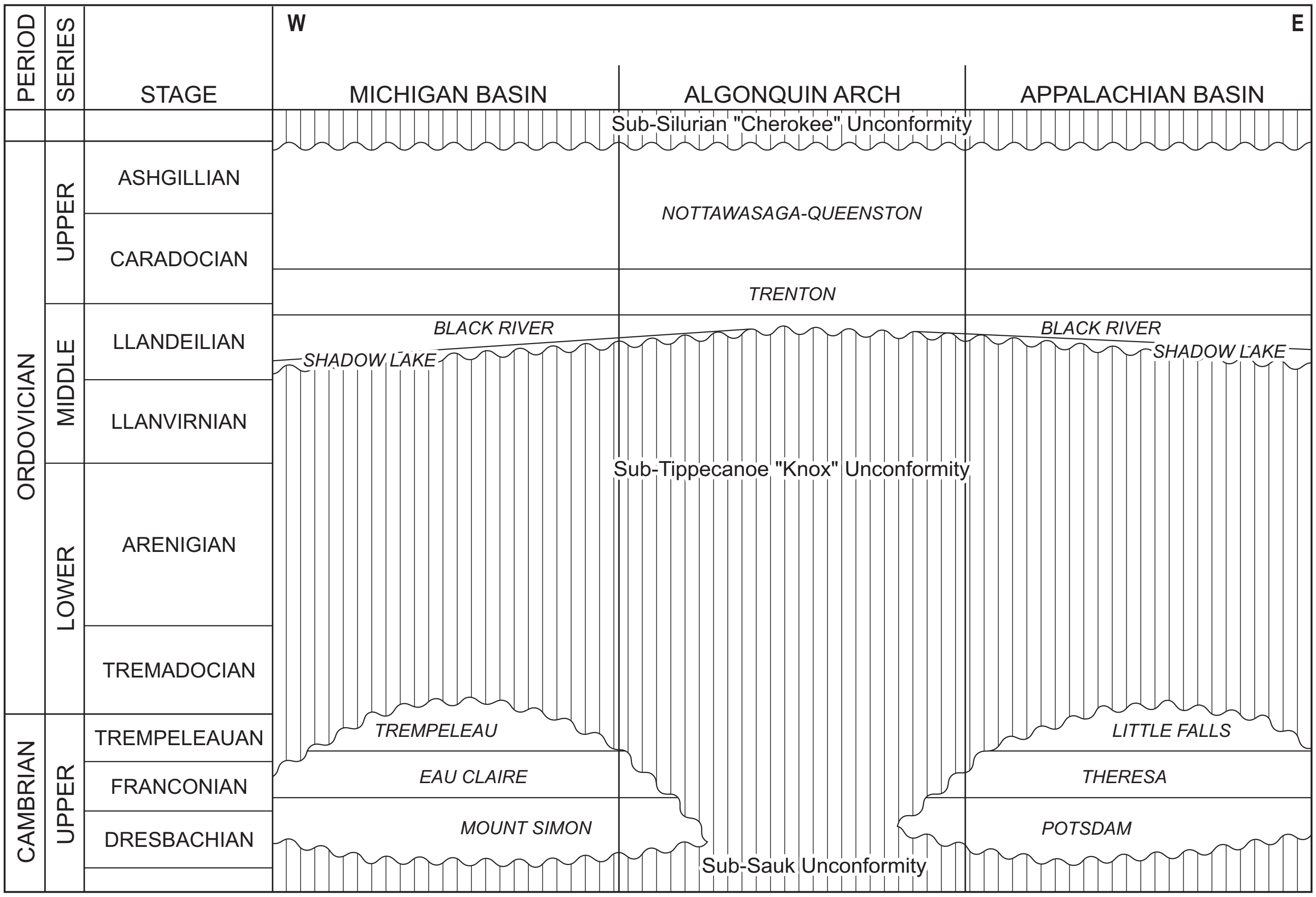

Figure 2. Schematic stratigraphic columns for Cambrian and Ordovician strata of Southwestern Ontario (modified from Hamblin, 1998a, 1998b)

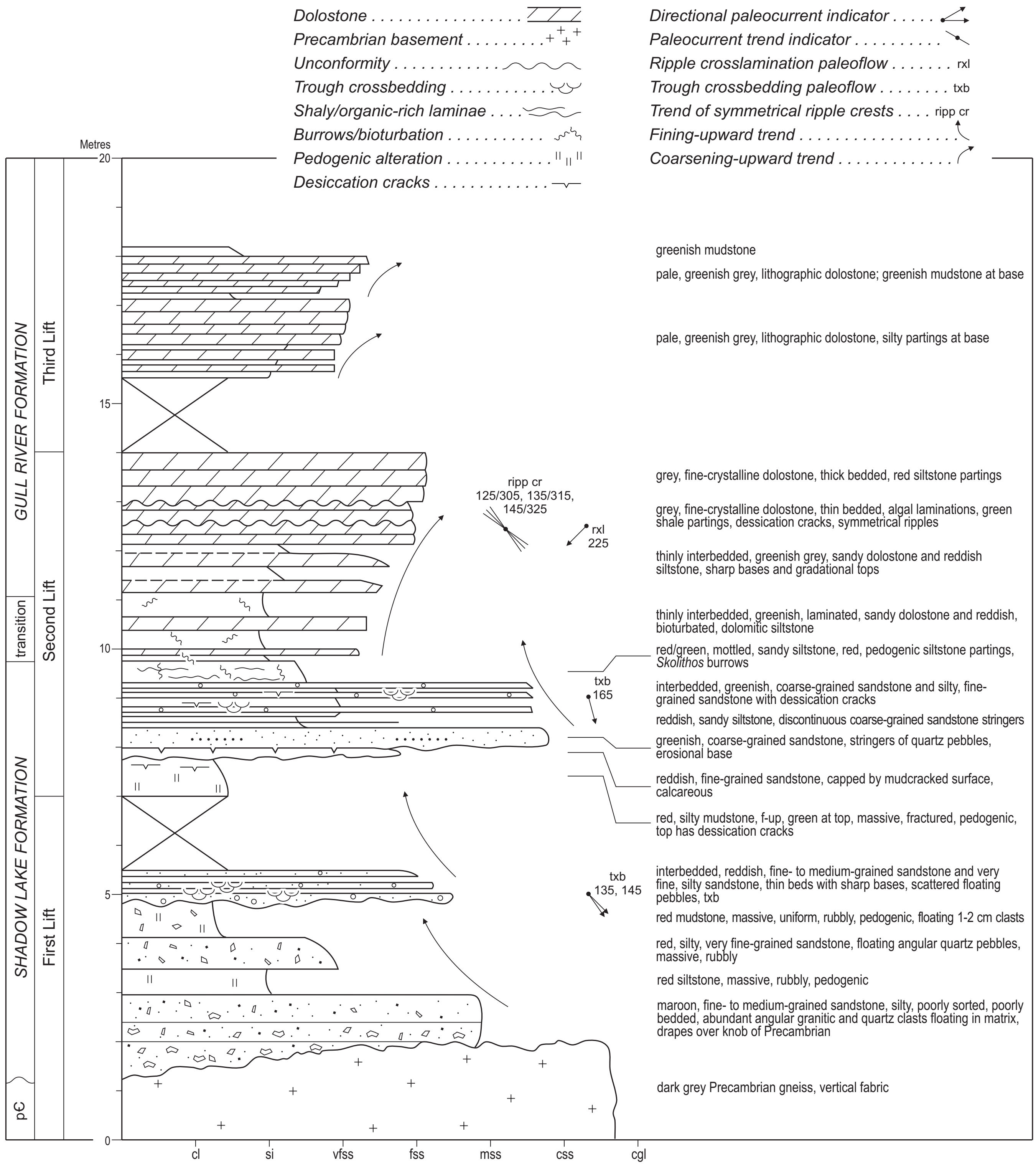

Figure 3. Marmoraton Iron Mine (Abandoned)
Shadow Lake Formation – Gull Lake Formation
East of Marmora, south of Highway 7
NTS 31C/5 (Campbellford); 44°29'N, 77°40'W; UTM Zone 18: 288 936E, 4928 302N

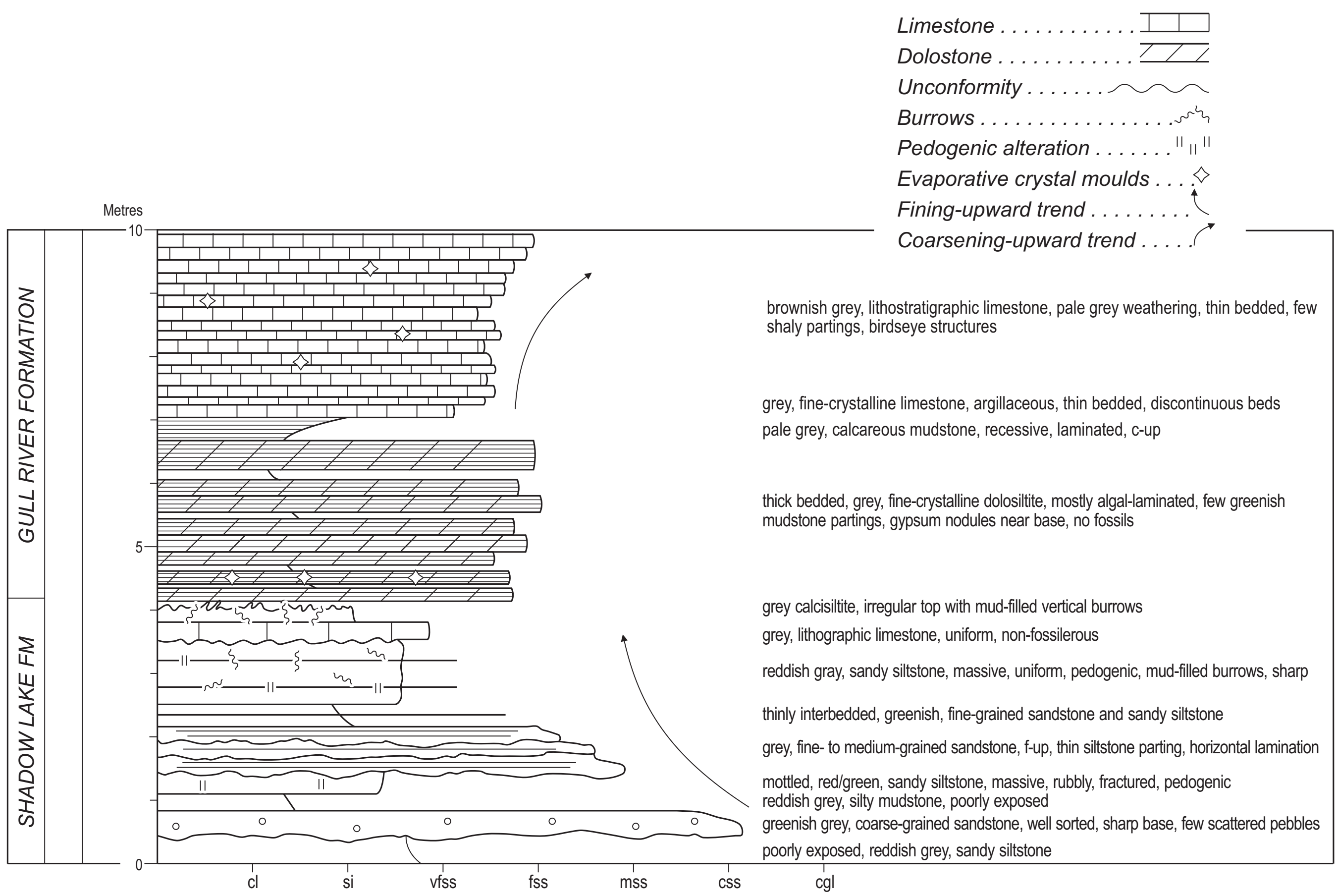

Figure 4. Highway 35
5 km north of Coboconk
Shadow Lake Formation – Gull River Formation
44°39'N, 78°48'W; UTM Zone 17: 674 110E, 4 952 160N

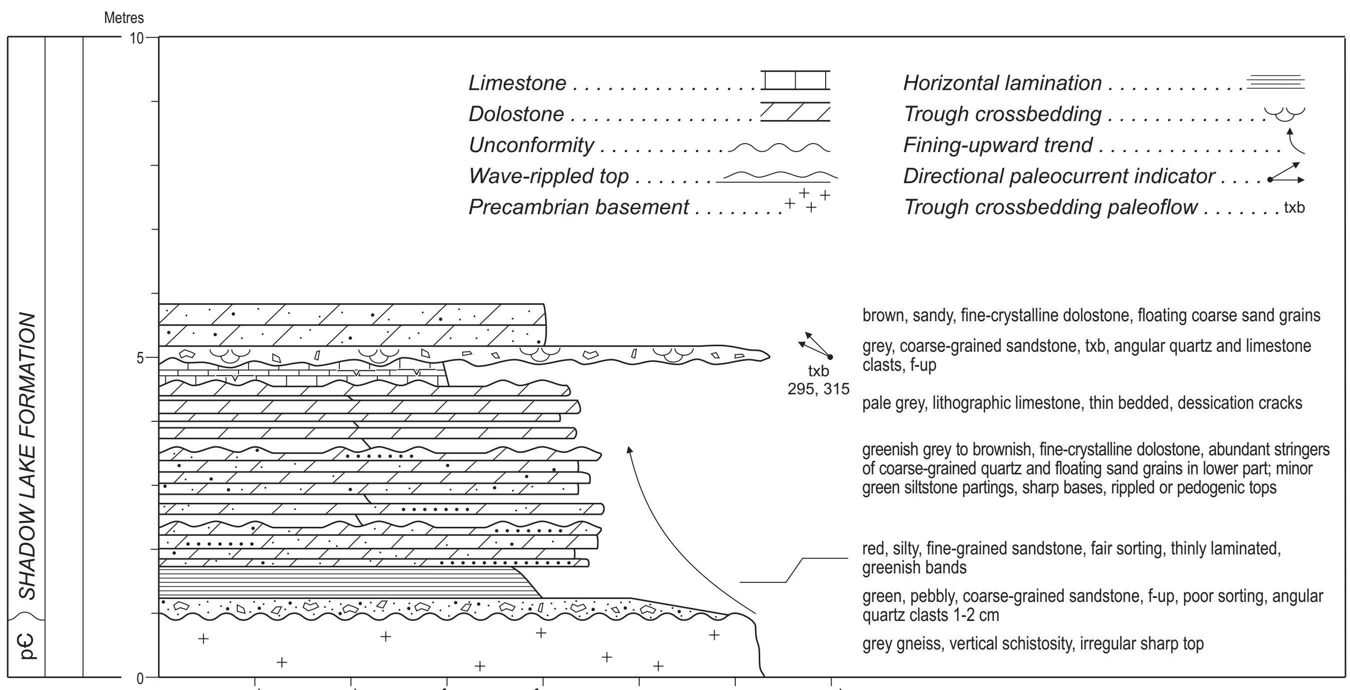

Figure 5. Highway 36 Roadcut
North of Burleigh Falls
Shadow Lake Formation
44°34'N, 78°14'W; UTM Zone 17: 718 462E, 4 939 925N

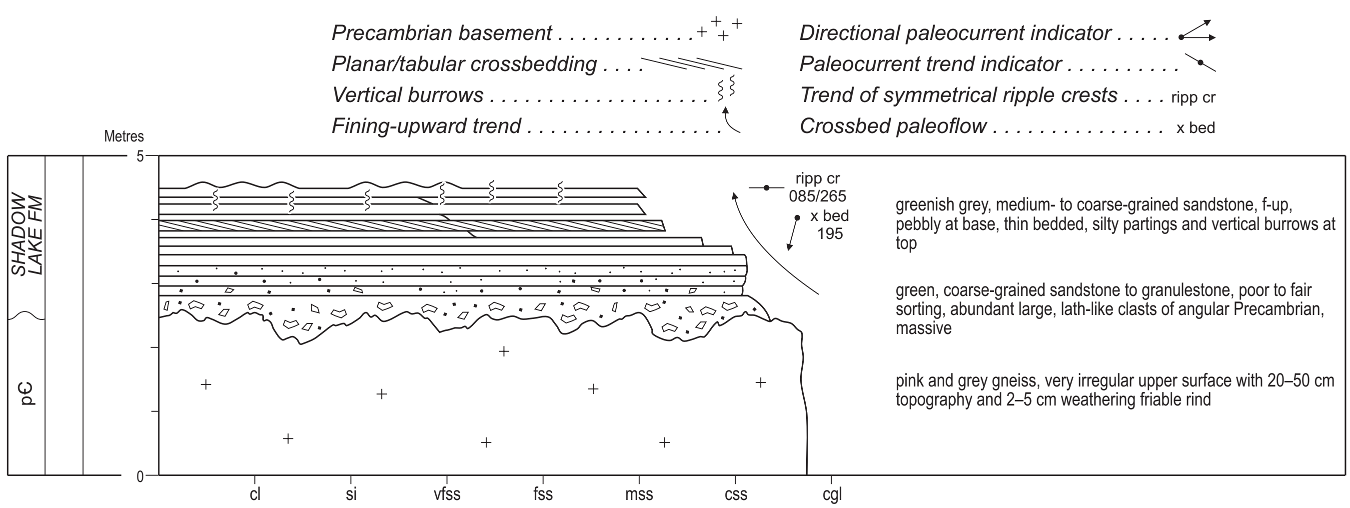

Figure 6. Inverary Roadcut
Battersea Road, 1 km east of Inverary
Precambrian – Shadow Lake Formation
44°23'N, 76°28'W; UTM Zone 18: 383 627E, 4 928 298N

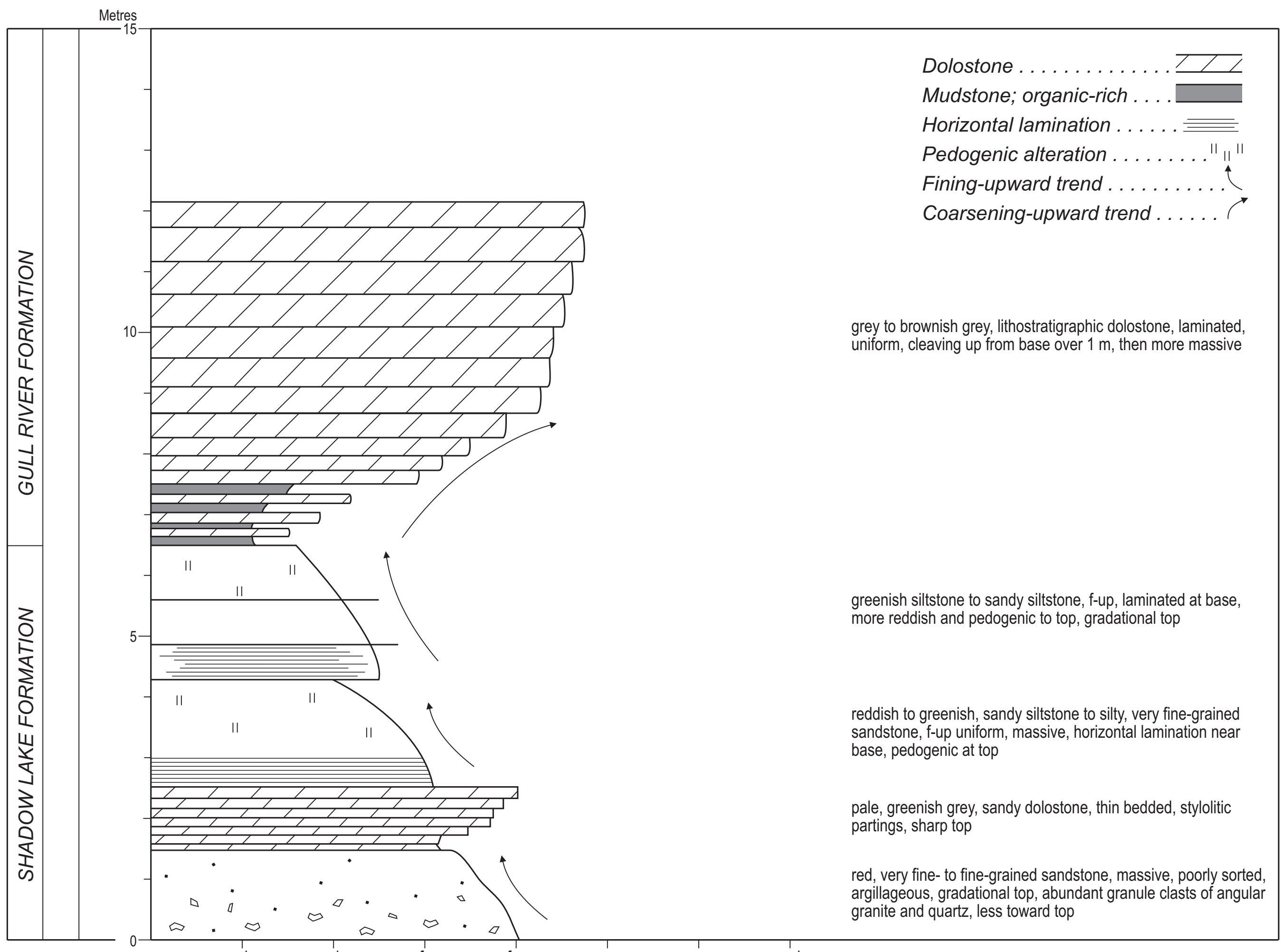

Figure 7. Jeff Parnell Quarry Coreholes (Composite of 3 close-spaced cores)
Shadow Lake Formation – Gull River Formation
Cavendish Township, Peterborough County
44°42'N, 78°24'W

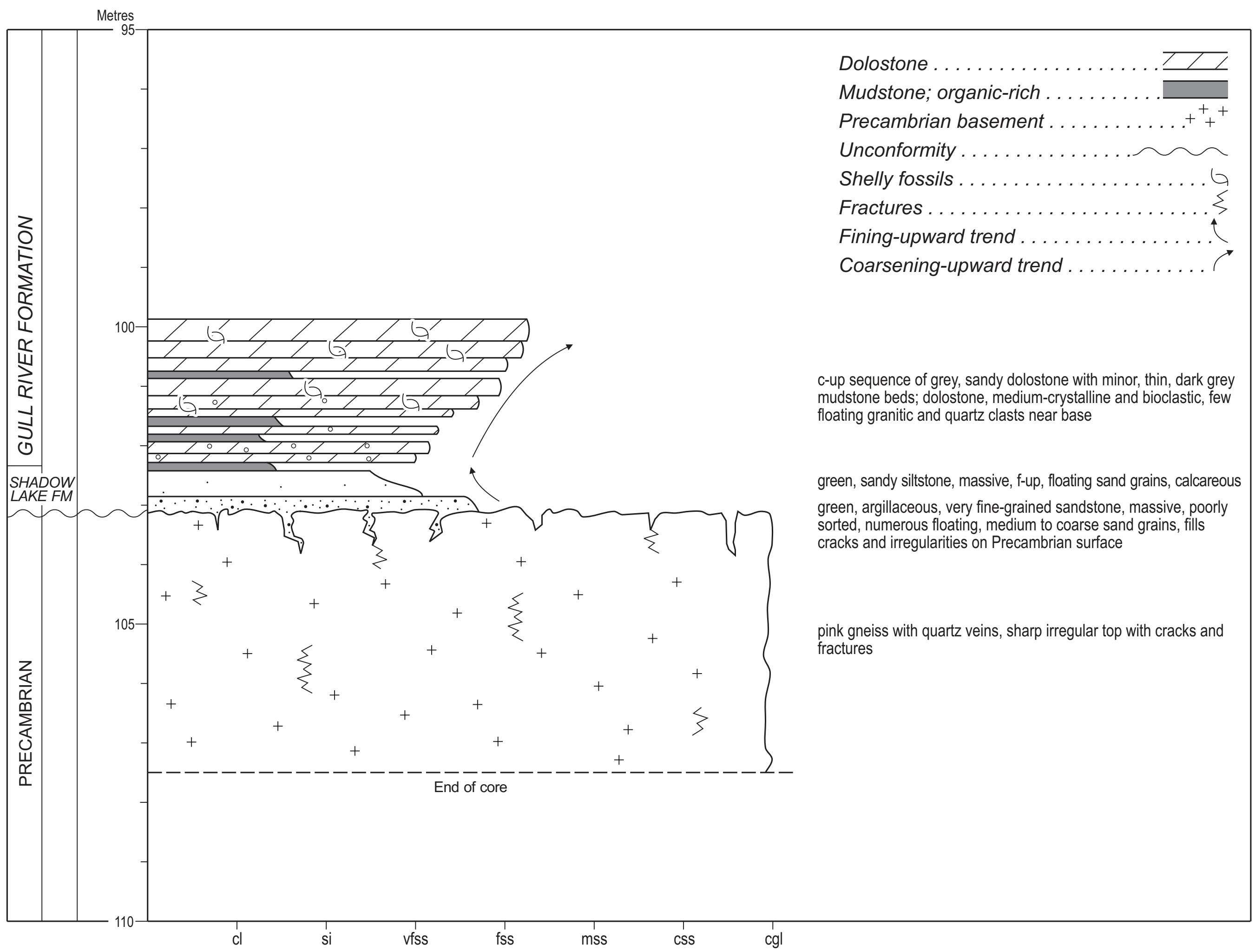

Figure 8. South Fredricksburg Bath Hole, Two 373 (1981)
Precambrian–Shadow Lake Formation–Gull River Formation
Lot 18, Concession I, South Fredricksburg Township, Prince Edward County
44°08'40"N, 76°50'43"W; UTM Zone 18: 352 250E, 4 889 250N

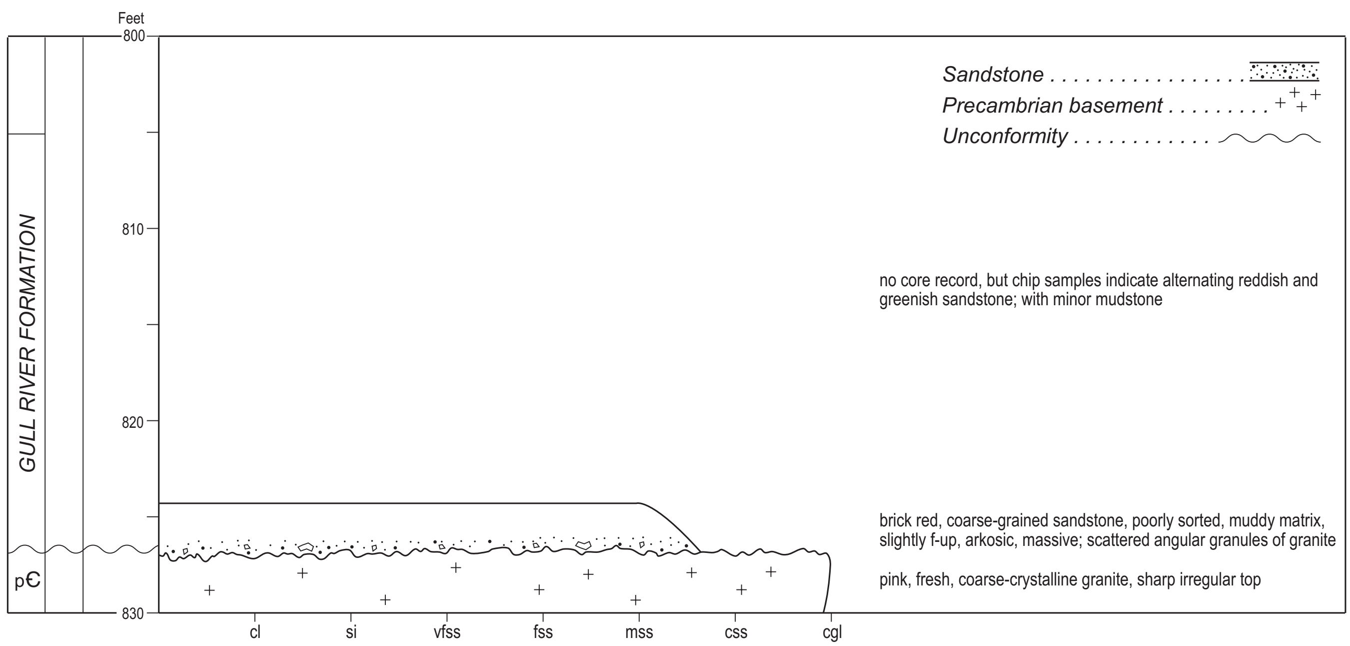

Figure 9. Jalore Mining Co., Port Hope #1 (Port Hope Core)
Precambrian–Shadow Lake Formation
Lot 18, Concession III, Hope Township, Durham County
(OMNR core record 171)
43°58'52"N, 78°22'26"W; UTM Zone 17: 710 600E, 4 873 150N

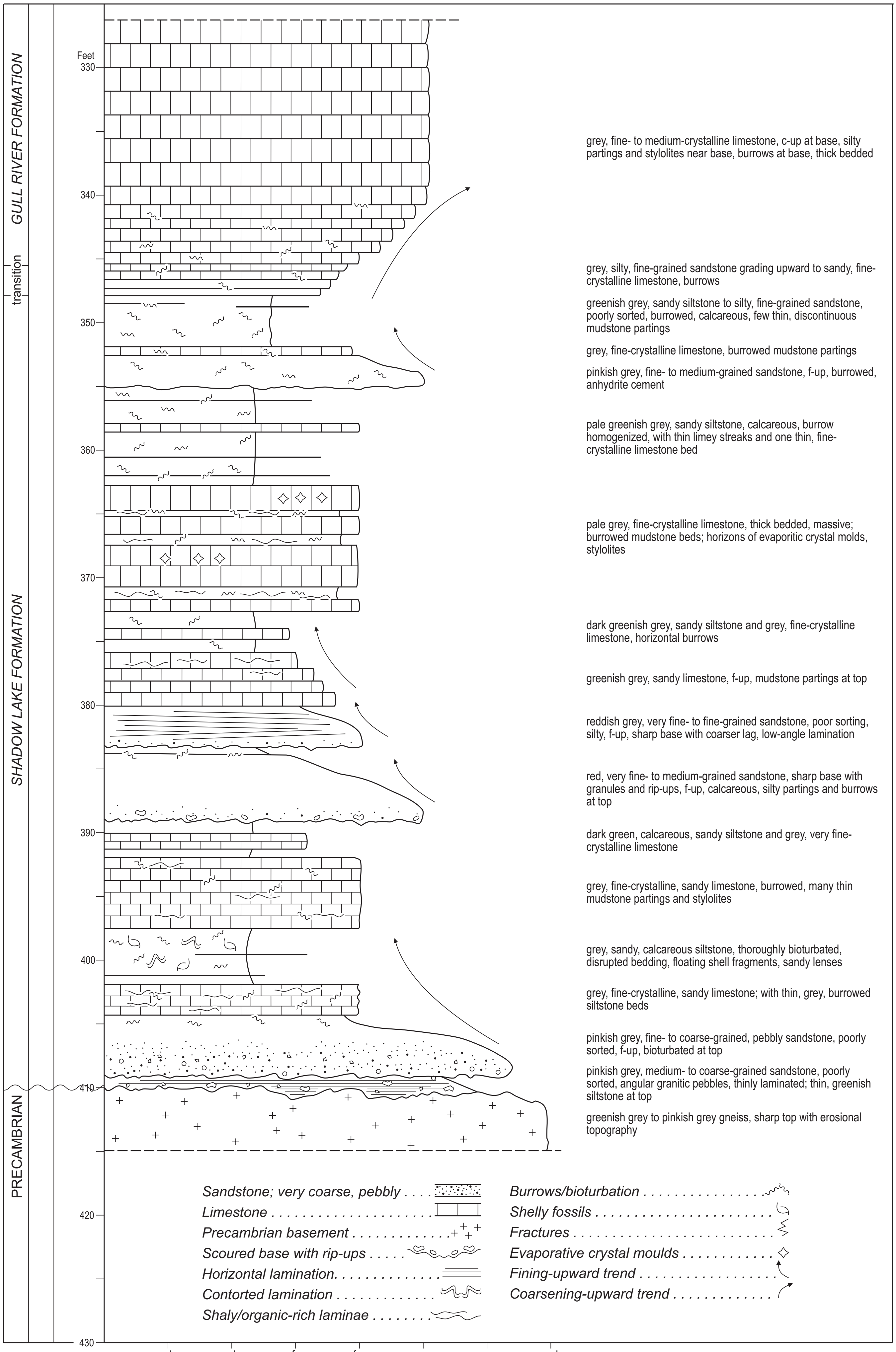

Figure 10. Consumer's Gas #16065
Precambrian–Shadow Lake Formation–Gull River Formation
Lot 4, Concession III, Murray Township, Northumberland County
TD 457', KB 315', RR 68/08/10 (OMNR core record 550)
44°08'07.2"N, 77°36'07.1"W

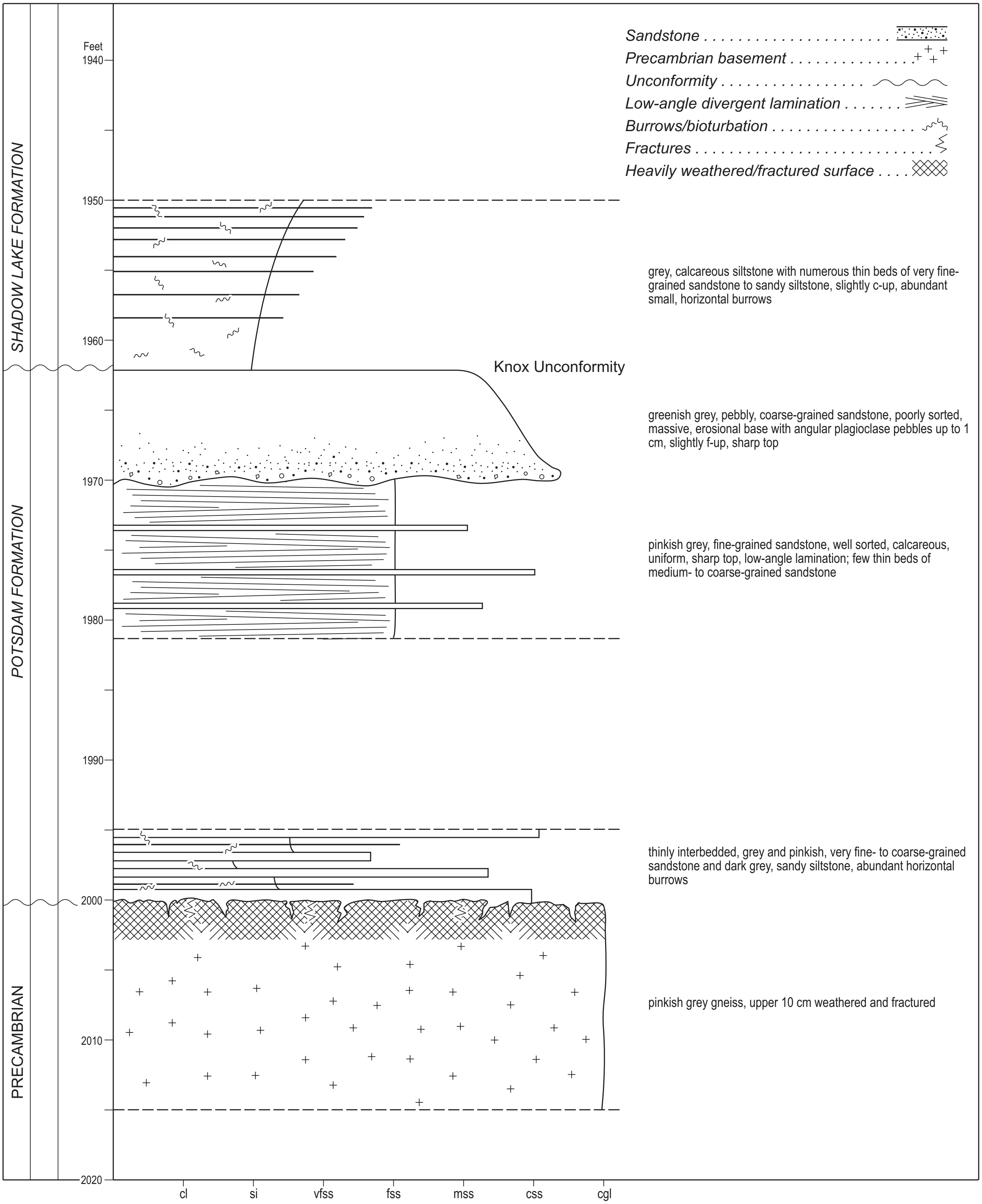

Figure 11. Imperial Saltfleet #11-1 (1965)
Precambrian – Potsdam Formation – Shadow Lake Formation
Lot 11, Concession I, Saltfleet Township, Wentworth County
TD 2005', KB 275', RR 65/01/20 (OMNR core record 891)
43°13'24.2"N, 79°40'44.3"W

Figure 12. U.S. Steel DDH #1
Lot 21, Concession I, Charlotteville Township, Norfolk County
Precambrian – Potsdam Formation – Theresa Formation – Shadow Lake Formation – Gull River Formation
TD 5616', KB 705', RR 52/01/01, (OMNR core record 100)
42°44'26.3"N, 80°17'41.8"W

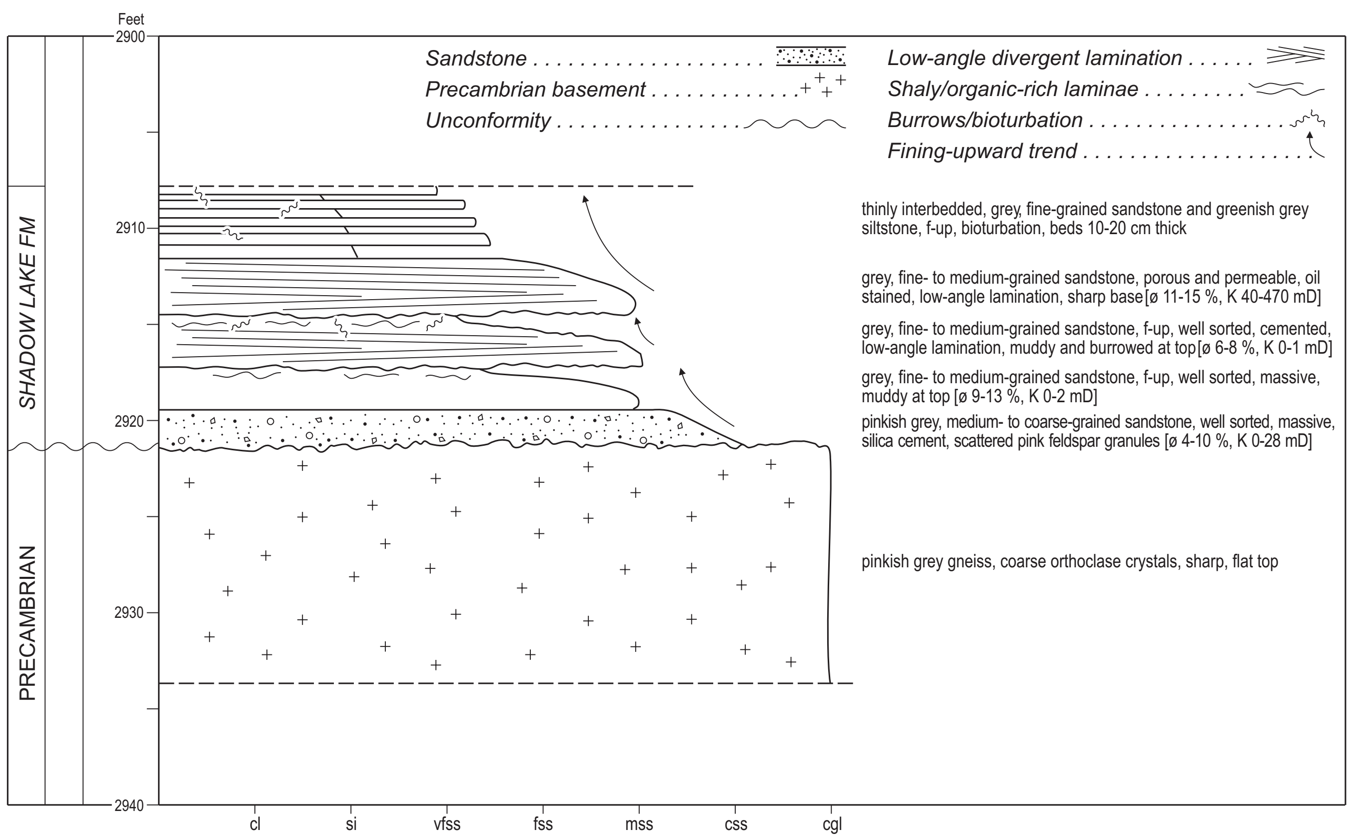

Figure 13. Canadian Kewanee Ltd Gobles #29
Precambrian–Shadow Lake Formation
Lot 21, Concession I, Burford Township, Brant County
T 001718 (OMNR core record 268)
43°08'50.9"N, 80°34'42.9"W

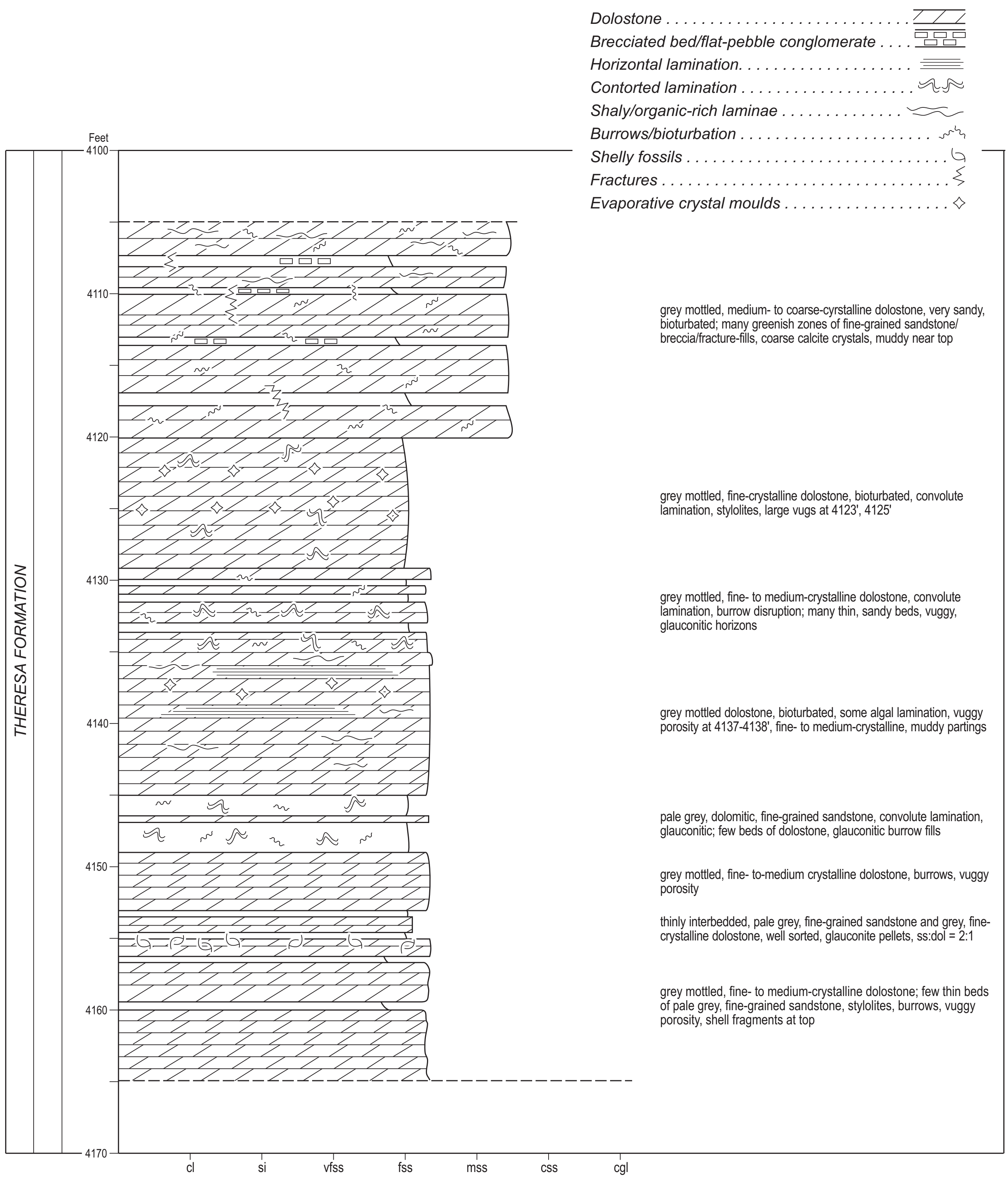

Figure 14. Consumer's Pan Am Lake Erie #13039 (1968)
Theresa Formation
Block 156, Lake Erie County
(OMNR core record 857)
42°21'59.5"N, 80°49'28.5"W

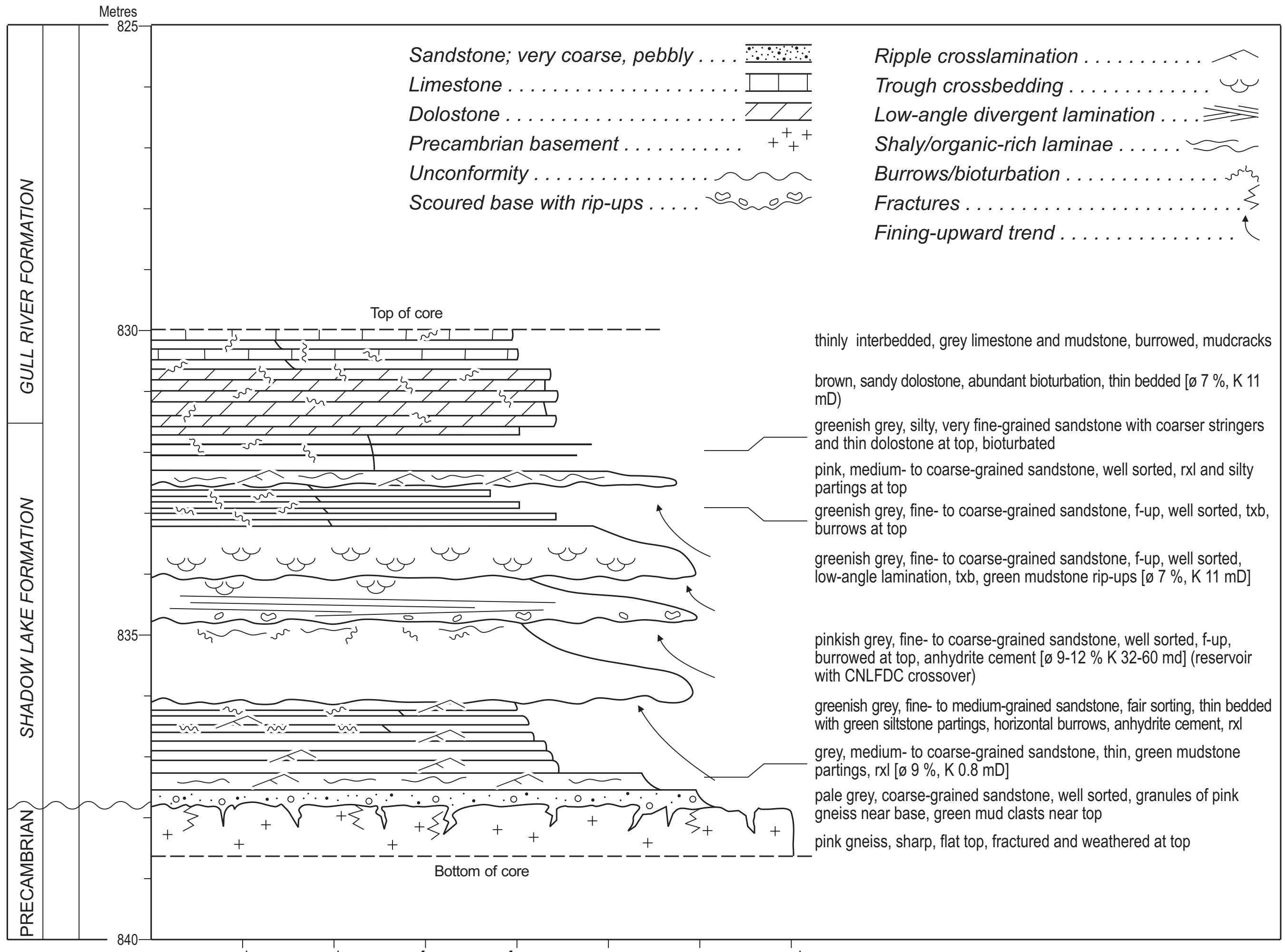

Figure 15. Cambright 76 Blenheim 2-17-X (1999)
Precambrian – Shadow Lake Formation – Gull River Formation
Lot 17, Concession X, Blenheim Township, Oxford County
T 008297 (OMNR core record 1086)
43°16'43.7"N, 80°36'13.5"W

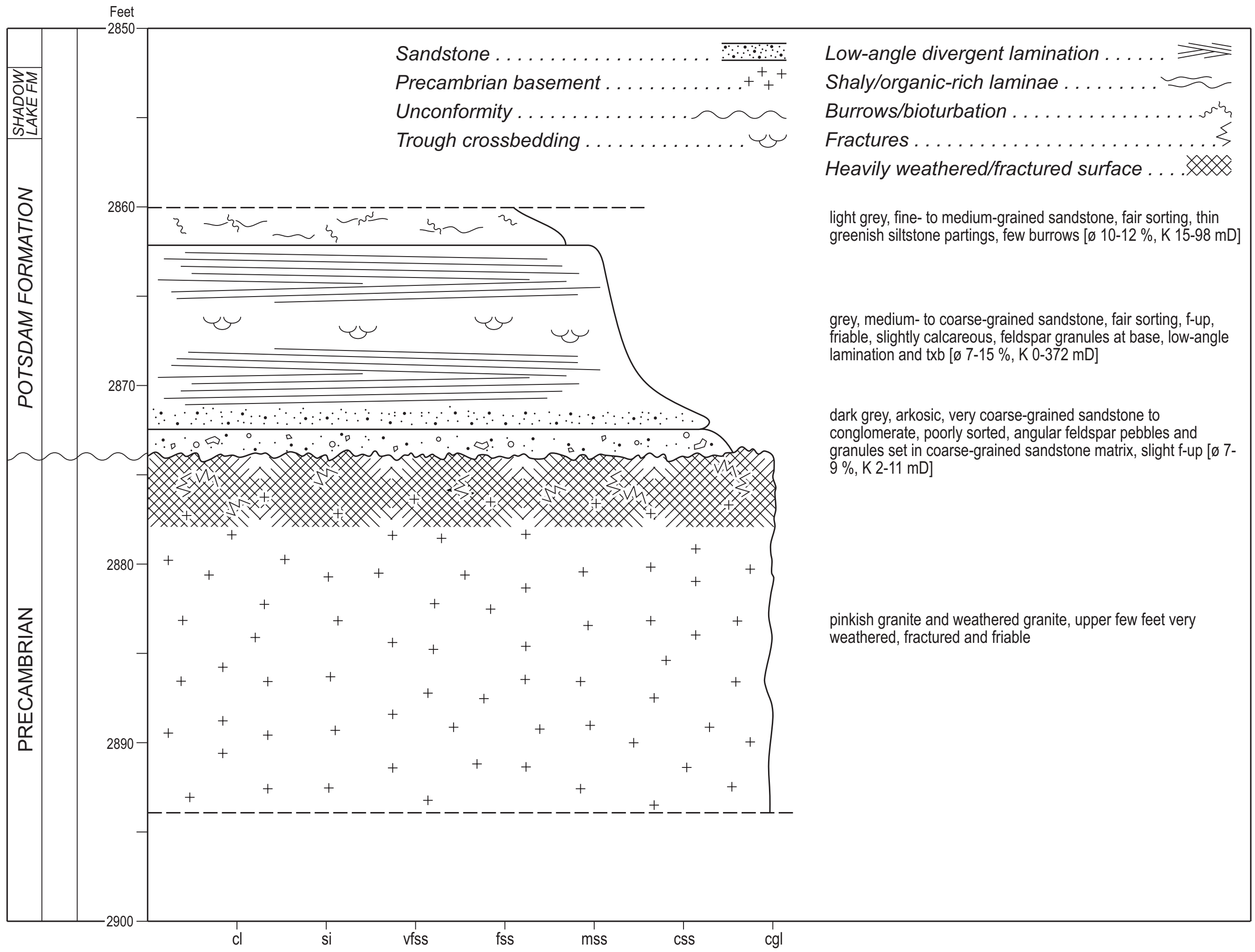

Figure 16. Kewanee Gobles #41 (1965)
Precambrian – Potsdam Formation
Lot 16, Concession I, BlenheimTownship, Oxford County
TD 2895', KB 899', RR 65/02/10 (OMNR core record 374)
43°09'44.2"N, 80°33'10.4"W

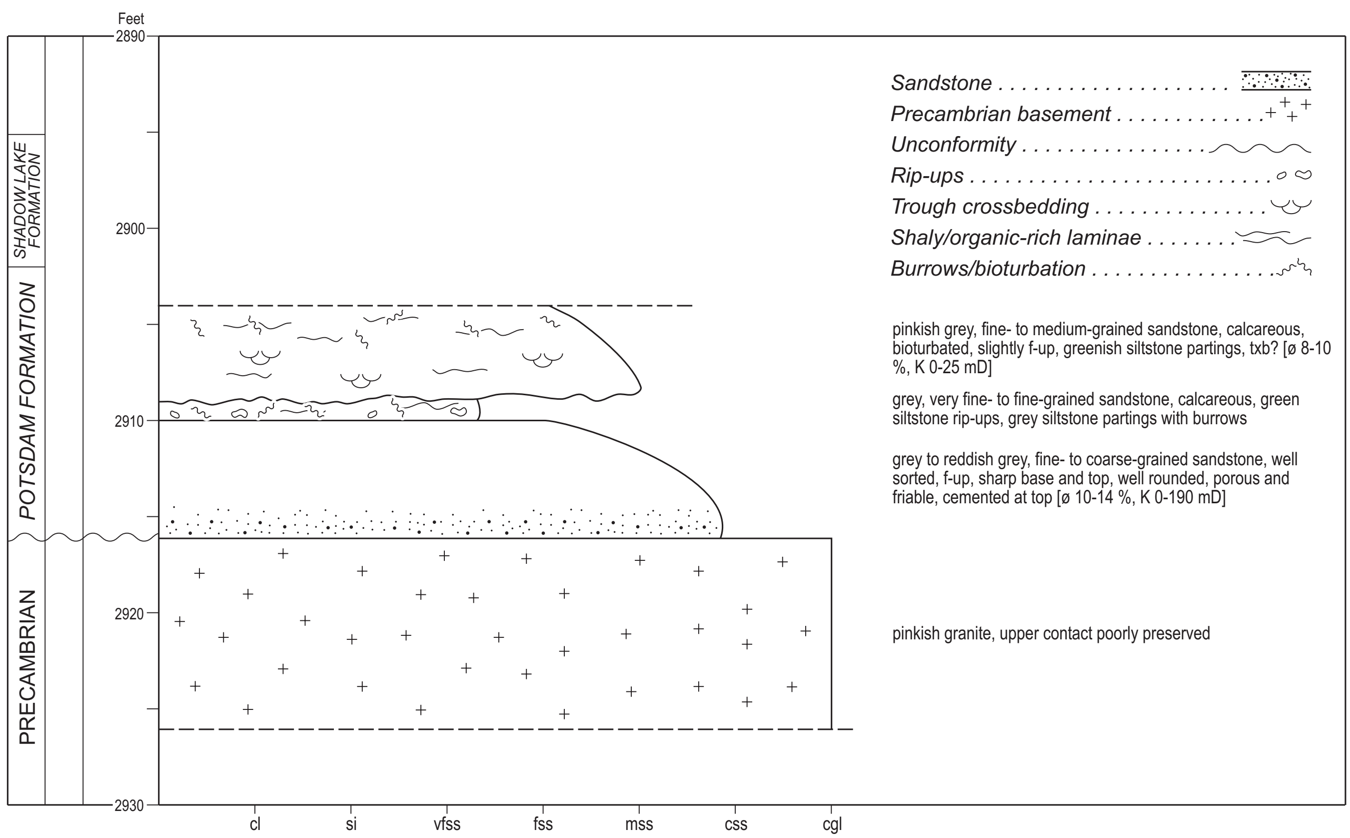

Figure 17. Imperial #792 Gobles #5 (1961)
Precambrian – Potsdam Formation
Lot 21, Concession I, Blenheim Township, Oxford County
TD 2926' KB 938' RR 61/09/23 (OMNR core record 574)
43°09'23.2"N, 80°35'17.4"W

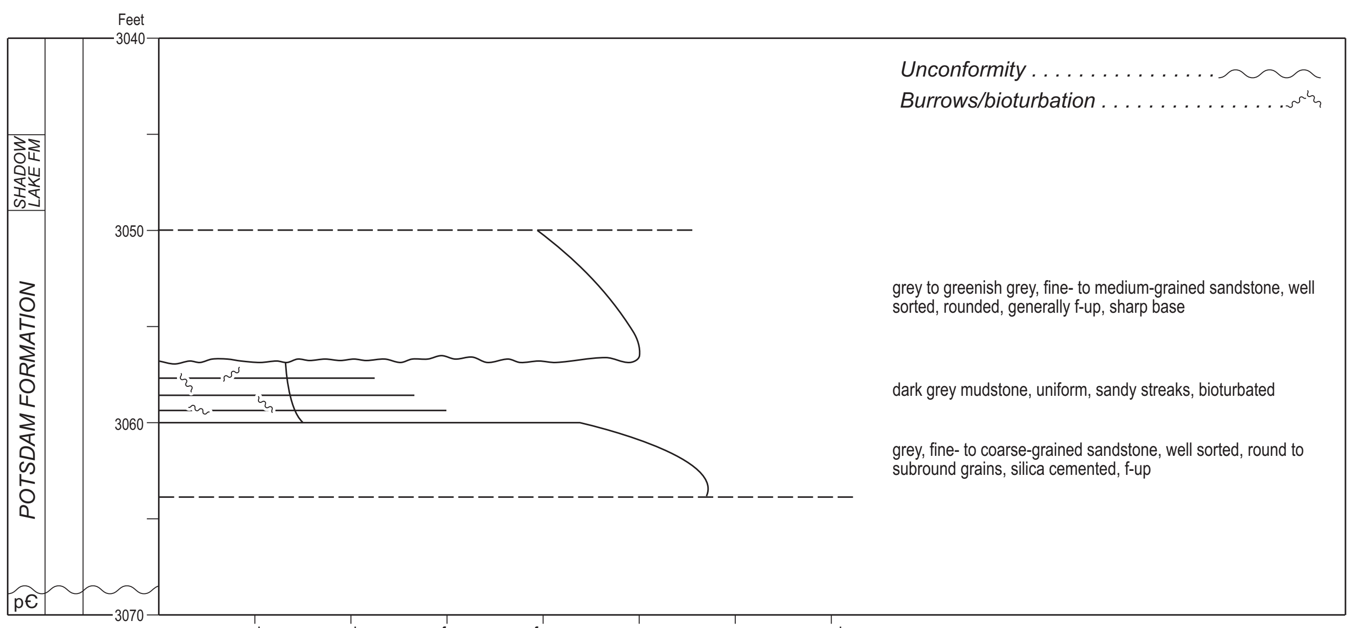

Figure 18. Imperial #842 Hill #1 (Imperial North Norwich 4-II,1963)
Potsdam Formation
Lot 1, Concession II, North Norwich Township, Oxford County
TD 3071', KB 866', RR 63/04/20 (OMNR core record 560)
43°01'51.2"N, 80°35'13.3"W

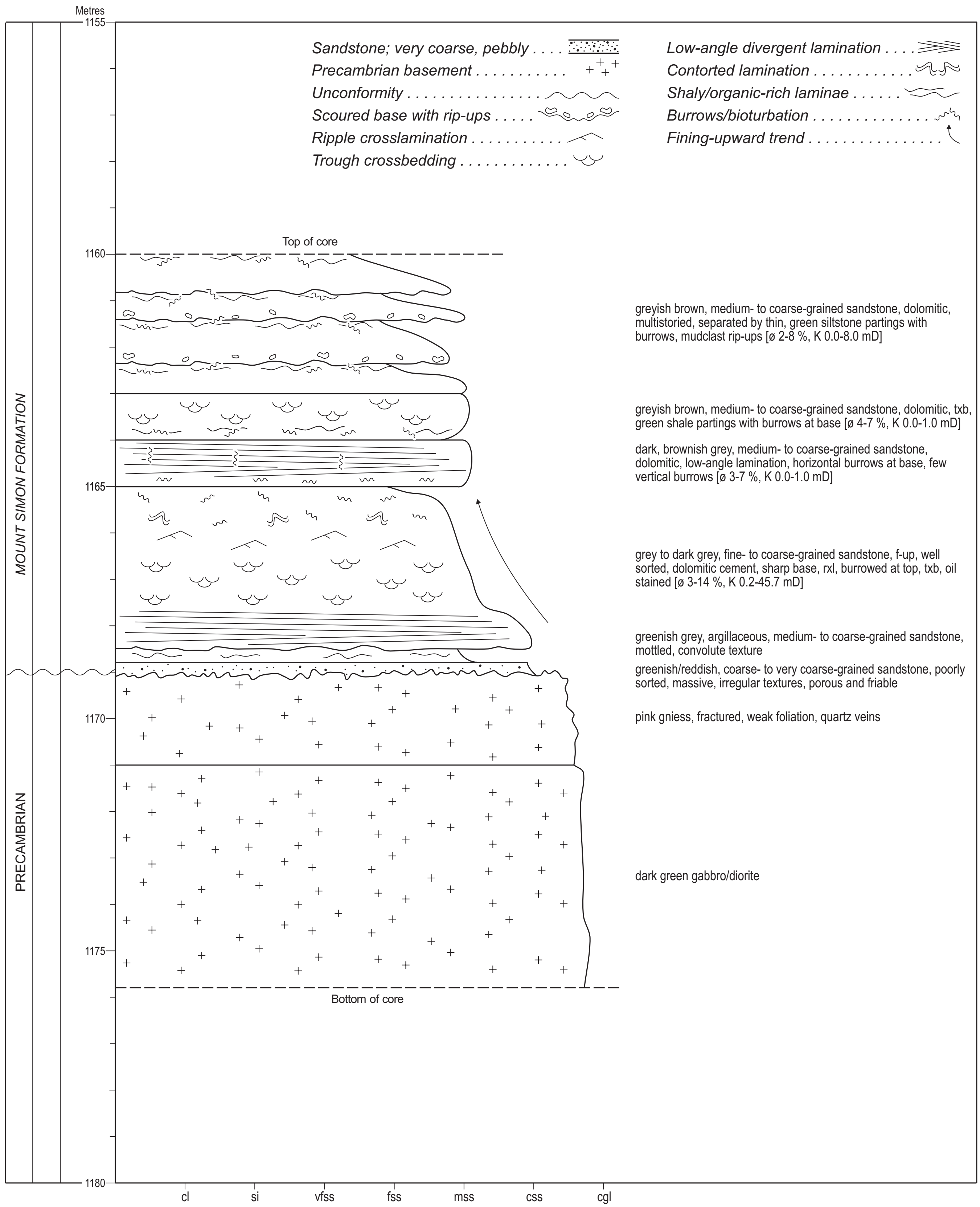

Figure 19. RAM BP #5 (1988)
Precambrian – Mount Simon Formation
Lot 17, Concession XIII, Raleigh Township, Kent County
(OMNR core record 986)
42°17'36.2"N, 82°07'41.7"W

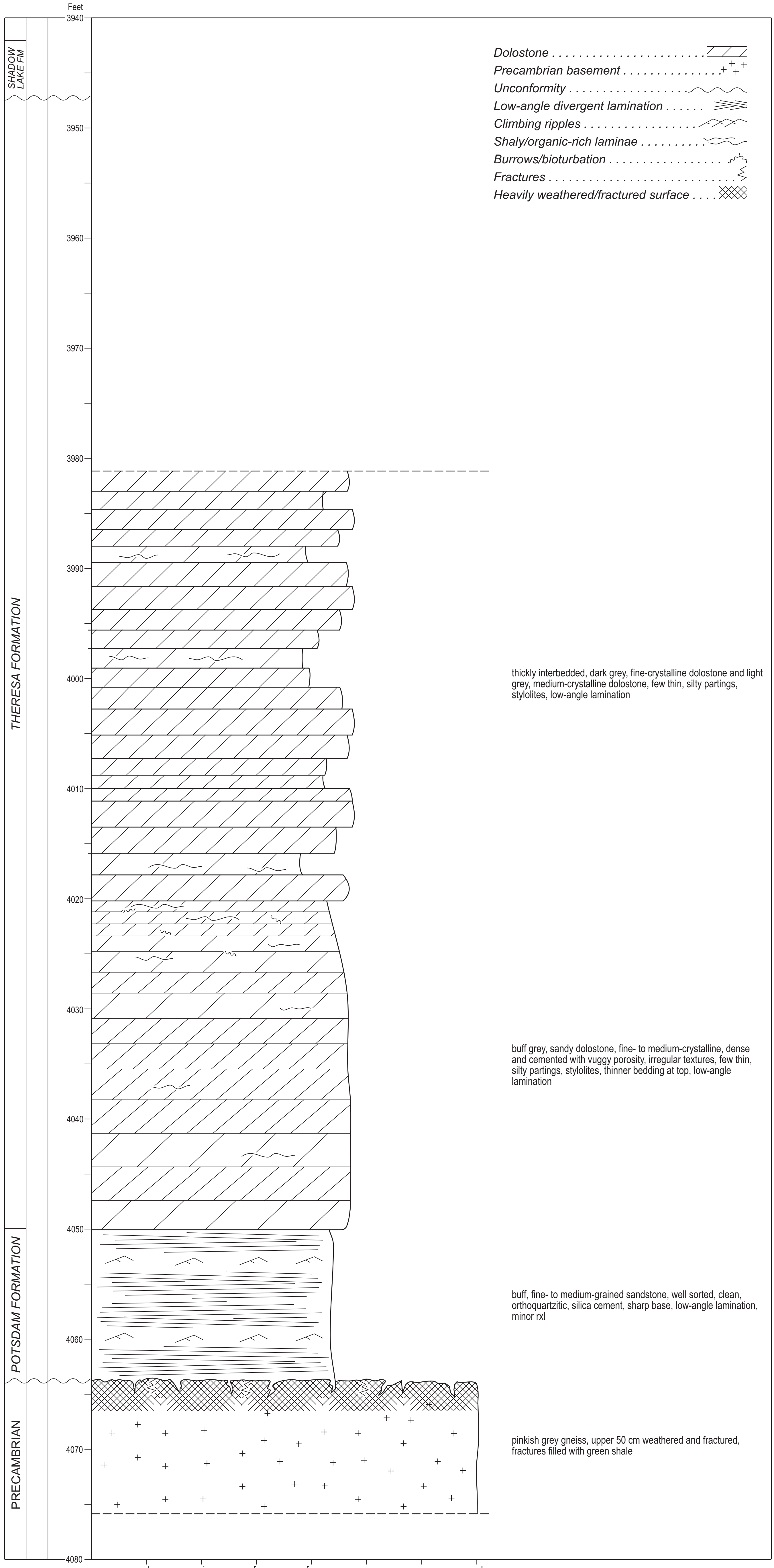

Figure 20. Imperial Orford 8-57 (1964)
Precambrian – Potsdam Formation – Theresa Formation
Lot 57, Concession N.T.R., Orford Township, Kent County
TD 4077', KB 656', RR 64/01/29 (OMNR core record 275)
42°28'24.6"N, 81°42'21.6"W

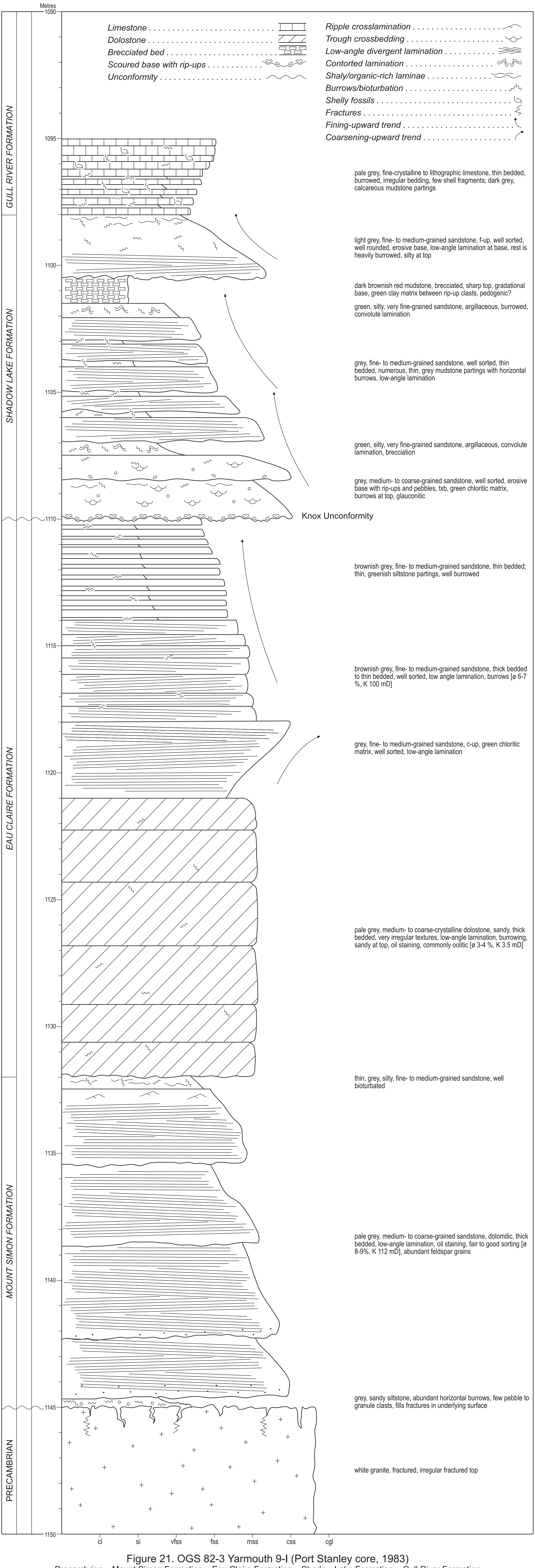

Figure 21. OGS 82-3 Yarmouth 9-I (Port Stanley core, 1983)
Precambrian – Mount Simon Formation – Eau Claire Formation – Shadow Lake Formation – Gull River Formation
Lot 9, Concession I, Tract 3, Yarmouth Township, Elgin County
TD 1168.5 m, KB 213.5 m, RR 83/03/11
42°40'13"N, 81°09'47"W; 211.4 m asl (OMNR core record 861)

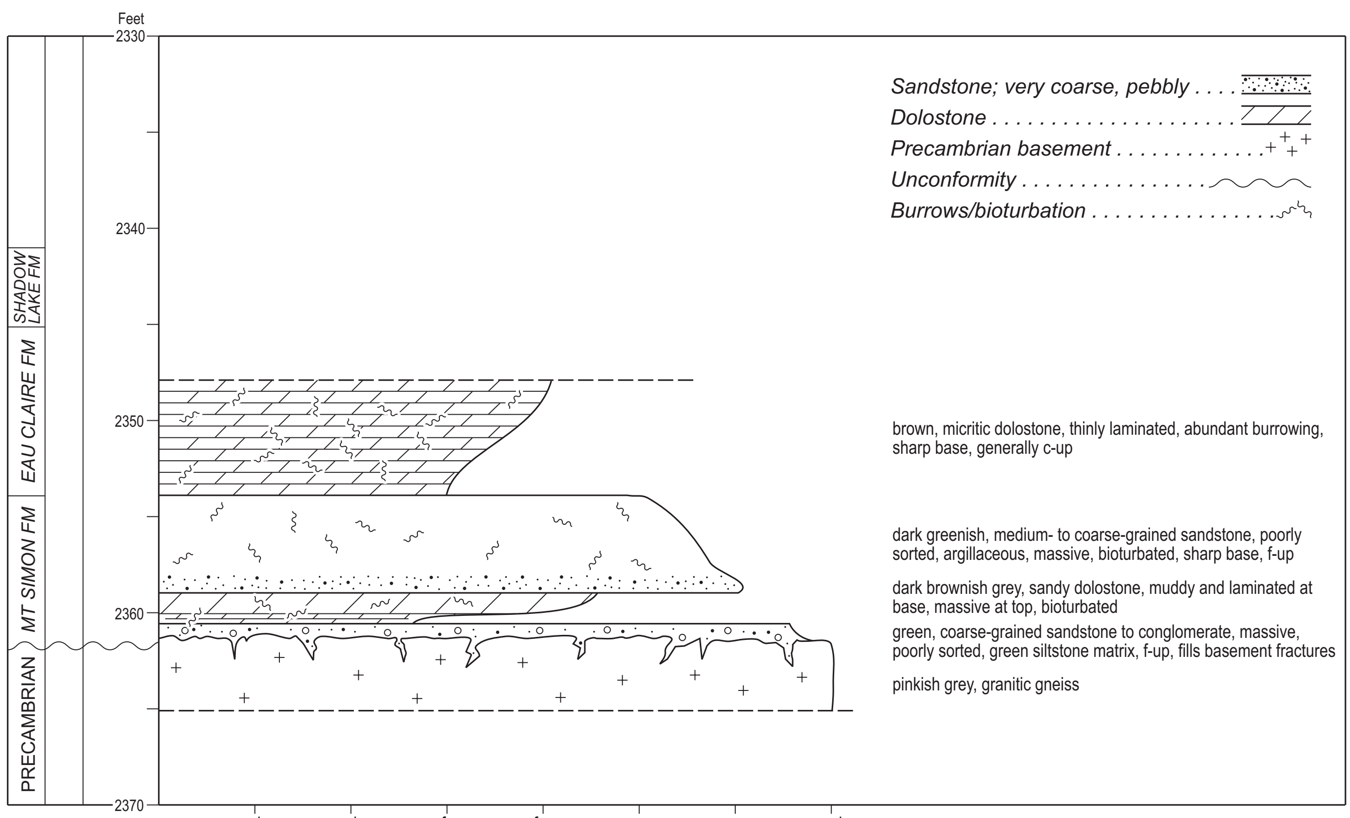

Figure 22. BP TRIAD Saugeen 29-II(A) (1964)
Precambrian – Mount Simon Formation – Eau Claire Formation
County Bruce, Township Saugeen, Lot 29, Concession II
TD 2370', KB 799', RR 64/08/02 (OMNR core record 985)
44°20'59.7"N, 81°20'08.7"W

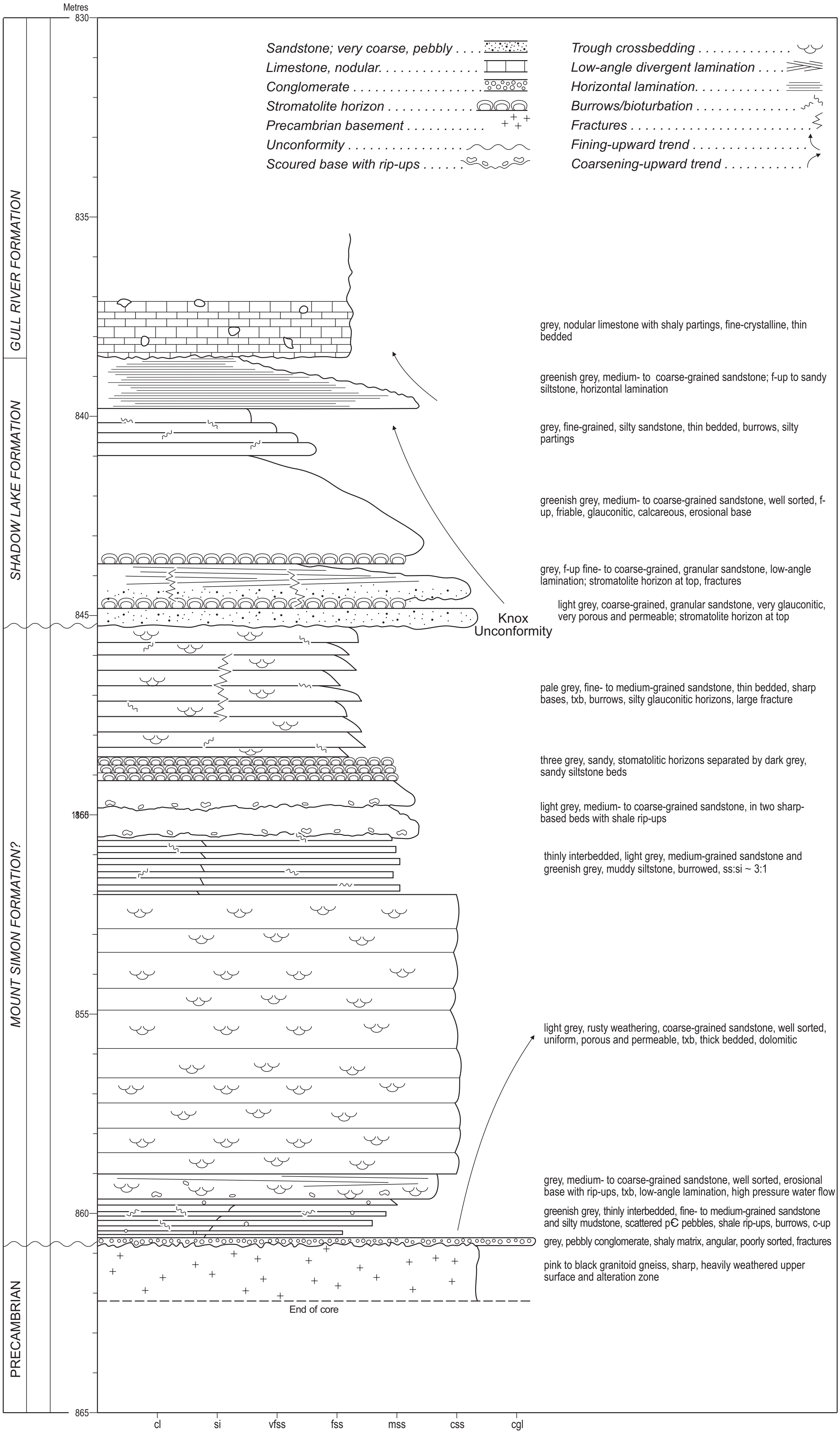

Figure 23. Ontario Power Generation Core DGR-2
Precambrian – Mount SimonFormation? – Shadow Lake Formation – Gull River Formation
Lot 20, Concession Lake Range, Bruce Township, Bruce County
TD 862.2 m, KB 187.9 m, RR 07/08/03
44°19'16.7"N, 81°34'27.3"W; UTM Zone 17: 454 208E, 4 907 720N