

Bedrock topography and overburden thickness mapping, southern Ontario

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ABSTRACT

Bedrock elevation and drift thickness information is useful in bedrock aggregate resource assessments, groundwater studies, geotechnical work and other land-use applications. Recently, the Ontario Geological Survey has developed a protocol or methodology to generate regional bedrock elevation and overburden thickness maps using water well, geotechnical and petroleum drill records as well as geological observations for southern Ontario. This methodology followed a number of steps as follows. First, the data were filtered for problematic records and those that failed this process were flagged. Second, water wells were searched for an indication of bedrock and its depth below the ground surface. Using a translation table containing unique material combinations, the various layers identified in water wells were populated with either overburden 'O' or bedrock 'P' or 'Pr' for the Paleozoic or Precambrian. The bedrock depth was subsequently determined through a query routine. If 2 consecutive bedrock layers were encountered, the bedrock depth was taken as the top of the first bedrock layer. Otherwise, the bottom of the deepest overburden layer was treated as the bedrock depth. Water wells containing combinations with undefined or suspicious descriptions in the primary material field such as UNKNOWN TYPE, PREVIOUSLY DUG, SANDSTONE, SLATE and SOAPSTONE were inspected manually for bedrock depth. A search for inversed stratigraphy of Pr/P, i.e., Precambrian overlying Paleozoic was completed, and wells containing such stratigraphic violations were removed.

Next, the data set was used to interpolate an initial bedrock elevation surface or grid using the ESRI® ArcGIS® ordinary kriging function. Water wells not reaching bedrock but going below this elevation grid were selected and their depths used to push down the grid. The bedrock elevation grid was inspected at each stage to identify problems in the data set. Once problematic data were found and removed, kriging was repeated. For bedrock or thin-drift areas where the overburden cover is known to be less than 1 m thick and bedrock topography is directly reflected by the ground surface, the bedrock elevation surface was created by subtracting the known drift depths from the digital elevation model (DEM). Finally, an overburden thickness map was produced by subtracting the bedrock elevation grid from the DEM. Using this methodology, bedrock topography and overburden

thickness maps of southern Ontario were generated. New data, once available, will be used to update these maps in the future.

INTRODUCTION

This report outlines protocols and a methodology developed by the Ontario Geological Survey (OGS) to generate digital regional bedrock elevation and overburden thickness maps for southern Ontario. Advances in data storage and retrieval of the extensive petroleum, engineering and water well records as well as geological observations acquired over the last 50 years have made updated maps both timely and possible. Using ESRI® ArcGIS® analysis functions, such as kriging, these data can be integrated and analyzed to generate bedrock topography maps. The approximate thickness of the Quaternary sediments is determined by subtracting the bedrock elevation surface from the provincial digital elevation model (DEM).

Bedrock elevation and drift thickness information is important in bedrock aggregate resource assessments, groundwater studies, geotechnical work and other land-use applications. For instance, Ontario's current aggregate resources inventory mapping program, which was initiated in the late 1970s, assesses the aggregate resources for both naturally formed sand and gravels, and crushed stone derived from bedrock (Ontario Mineral Aggregate Working Party 1977; Cowan 1978; Kelly and Rowell 1995; Baker 2003). The resultant Aggregate Resources Inventory Paper (ARIP) publications form important components in municipal land-use planning and resource management to ensure that adequate resources of mineral aggregate remain available for future use. A key component of each ARIP is a bedrock resources map outlining areas of thin surficial sediment cover where bedrock aggregate resources can be obtained economically.

Since 2003, several pilot projects have been undertaken to develop drift thickness mapping for mineral aggregate and groundwater studies across southern Ontario (van Haaften et al. 2004; Gao et al. 2005; Shirota, Brunton and Kelly 2005). Feedback from users of the resultant maps has led to many improvements to the methodology. As a result, it was decided to expand the drift thickness mapping methodology to generate bedrock topography and overburden thickness maps of southern Ontario. The bedrock of southern Ontario comprises both Paleozoic sedimentary and Precambrian metamorphic

and igneous rocks (Ontario Geological Survey 1991; Johnson et al. 1992). Glaciations during the Quaternary period of the recent geological past resulted in both the physical erosion and sculpting of the bedrock surface and subsequent burial of much of the bedrock by variable thicknesses of till, clay, silt, sand and gravel deposits (Barnett, Cowan and Henry 1991; Barnett 1992; Ontario Geological Survey 2003). In comparison with previous bedrock topography studies (Karrow 1973; Chapman and Putnam 1984; Flint and Lolcama 1986; Eyles, Boyce and Mohajer 1993; Eyles et al. 1997; Brennand et al. 1998; Edgecombe 1999), additional quality control measures were undertaken so that problematic data could be identified and eliminated. As such, this new approach has enabled better delineation of the buried bedrock topography, in particular, the regional extent of significant buried valleys across southwestern Ontario.

This report focuses on the methodology itself, followed by a discussion on how to use the digital drift thickness maps to assist in bedrock aggregate resource assessment. Details are given in Appendix A on quality control and quality assurance (QA/QC) measures taken during the creation of the bedrock topography and overburden thickness maps of southern Ontario. The methodology consists of 4 components: (1) data acquisition; (2) data preparation and standardization; (3) bedrock surface interpolation; and (4) overburden thickness calculation, which are outlined in the subsequent parts of this report.

DATA ACQUISITION

For an area or region of interest, data within a surrounding buffer zone of at least 1 km width should be included in the working database. Data sources providing overburden thickness information include water wells, geotechnical boreholes, oil and gas wells, geological maps, DEM and data from other published and unpublished sources. Basic geological information such as geological formations and their contacts is extracted from published geological maps and reports. The Natural Resources and Values Information System data set is used to provide base map information such as lakes, municipal boundaries, roads and railways.

Water wells

The Ministry of the Environment (MOE) water wells contributed a large portion of the data used in the determination of the bedrock surface and drift thickness maps. Water well records describe each material stratum or layer using a combination of primary, secondary and tertiary materials. However, the data quality is inconsistent and the water wells frequently contain georeferencing errors and inaccurate descriptions or mis-used geologic terminology. Quality assurance/quality control of the water well data set is, therefore, critical and water wells that fail to pass the filtering process are excluded from kriging.

Geotechnical boreholes

The OGS houses the Urban Geology Automated Information System (UGAIS), a databank of geotechnical boreholes, assembled in the 1970s from various geology, hydrology and engineering related projects covering the Greater Toronto Area and other urban areas. This database includes a field indicating the depth of bedrock. This field and the DEM were used to calculate the bedrock elevations at each borehole location. Within the data set, georeferencing errors were noticed that were probably incorporated during data entry. A QA/QC check of this data set must be undertaken prior to use to screen out problematic data.

Oil and gas wells

Oil and gas drill records for Ontario, which are maintained by the Ontario Oil, Gas and Salt Resources Library, Ministry of Natural Resources (MNR), contain information on bedrock units and their relative depths. Recently, a digital database has been compiled by MNR and made available to clients. In this database, the bedrock surface is the top of the youngest bedrock unit encountered in each drill hole. However, in some cases, the drill record was found to have skipped some of the upper bedrock units making it difficult to define the true bedrock surface elevation. For this reason, this database was updated by MNR and a revised database including a field indicating bedrock subsurface elevations provided to the OGS.

Geological maps

Bedrock outcrop locations were retrieved from the surficial geology map of southern Ontario (Ontario Geological Survey 2003) and existing bedrock geology maps. The depth to bedrock is assigned as 0 m for bedrock outcrops. In addition to these point data, polygonal areas of exposed bedrock and thin drift where the overburden cover is known to be less than 1 m thick were added to the data set by converting each polygon to data points at a regularly spaced interval. In mapping the bedrock topography of southern Ontario, the data points were sampled at a grid spacing of approximately 400 by 500 m.

Occasionally, bedrock outcrops are recorded from steep slopes such as may occur at road cuts and along valley walls of deeply trenched flood gullies. In these cases, thick drift sediments may occur over bedrock. In areas where a fairly good density of boring data exists, such outcrops are well constrained. However, if inadequate drill holes exist, these outcrops can be over-weighted in the interpolating process, leading to exaggeration in the thin drift cover, in particular, this may occur in areas where high local relief exists. This problem was identified in the upper Beaver Valley where thick drift fills a deep and narrow valley but the map initially generated indicated an area with thin drift. The mapped outcrops were checked and compared with recent field observations in this area, leading to the removal of some data points (Armstrong, Ontario Geological Survey 2006, unpublished data). Also, a different interpolation approach, thickness kriging, was applied for this area (see discussion below for different methods of interpolation). No systematic ways have been found to screen out such outcrops. It is, therefore, highly recommended that users should analyze the data density and, if necessary, verify the key information on the generated maps particularly when large-scale map applications are intended.

Digital elevation model (DEM) and bathymetric data

A DEM is a grid of points, providing digital data on the ground surface relief. It is used to assign surface and water well strata elevations, and to calculate overburden thickness. The DEM used by the OGS for bedrock topography and overburden thickness mapping was generated and is maintained by MNR. The MNR also has a hydrologically manipulated DEM with actual stream elevations imposed on the surface. This

hydrologically adjusted version should not be used in the bedrock topography methodology outlined in this report.

In mapping the bedrock topography of southern Ontario, the elevation values of the ground surface in some areas were adjusted to the Shuttle Radar Topography Mission grid provided by the National Aeronautics and Space Administration (NASA) (2006). The elevation data (bathymetry) under Lake Erie and Lake St. Clair were provided by the National Oceanic and Atmospheric Administration (NOAA) (1999). The data sets from these sources were then combined and smoothed to create a continuous surface.

Other data sets

Readily-available, verified geological data, such as drilling records, should be incorporated into the working database from published and unpublished hydrogeology, groundwater and landfill-site investigations, municipal reports and academic studies. Bedrock outcrops and their locations recorded by geologists during the course of fieldwork provide important bedrock elevation information and should be incorporated into the overall data set.

In mapping the bedrock topography of southern Ontario, drilling records produced by the OGS and/or Geological Survey of Canada (GSC), some geophysical picks by OGS/GSC and bedrock outcrops recorded by OGS geologists during the course of their fieldwork were included. Because of a low data density, bedrock elevations were also extracted from 2 sand and gravel pits in the upper Beaver Valley (Ontario Geological Survey 1992; Jagger Hims and Ontario Geological Survey 2005, unpublished ARIP for Grey County). Also incorporated into the working database were borings from unpublished groundwater studies for the City of Hamilton (SNC Lavalin Engineers & Constructors 2004).

DATA PREPARATION AND STANDARDIZATION

Before being used for any map generation, the data must be properly filtered and standardized. Because of the large quantity of water wells available, it is a challenge as to how to filter out problematic data and determine bedrock depth for each location. In this

section, data filtering and bedrock determination will be described, followed by a discussion on data standardization.

Data filtering

The common problems associated with water well records are ambiguous UTM zones and datum, unreliable locations, material layers without depth values, wells located inside lakes and surface elevations inconsistent with DEM values. Water wells with these problems are eliminated from the working database.

Each water well record should be marked clearly with UTM zonation and datum. Those with North American Datum 1927 (NAD27) are converted to NAD83. Water wells lacking clear indications of UTM zones and datum are flagged and not utilized in kriging.

In the MOE database, water well records are all flagged with reliability codes (Table 1). For instance, codes 2 and 4 indicate location error margins of less than 2 and 10 m, respectively. Code 99 indicates that the location error is yet to be determined by MOE. For regional geological mapping, a 500 m error equates to a 1 cm deviation on 1:50 000 scale maps. For this reason, water wells with codes 2 to 9 inclusive were accepted and those coded with 10 or higher, i.e., over 500 m in error, rejected (Table 1). Applying these restrictions provides a database with a little over 350 000 water wells for southern Ontario.

Table 1. MOE water well georeferencing reliability and data suitability for bedrock topography mapping*.

MOE CODE	DESCRIPTION	NUMBER OF WELLS	PERCENTAGE (%)	ACCUMULATION (%)	SUITABILITY
2	Within 2 m	46	0.01	0.01	Yes
3	Within 5 m	1 279	0.24	0.24	Yes
4	Within 10 m	2 696	0.50	0.74	Yes
5	Within 20 m	730	0.13	0.88	Yes
6	Within 50 m	43 092	7.94	8.82	Yes
7	Within 100 m	137 206	25.29	34.11	Yes
8	Within 200 m	12 319	2.27	36.38	Yes
9	Within 500 m	156 691	28.88	65.26	Yes
10	Within 1000 m	6 236	1.15	66.40	No
11	Within 2000 m	1 534	0.28	66.69	No
12	Within 5000m	1 323	0.24	66.93	No
13	Within 10,000 m	565	0.10	67.04	No
99	Need Investigation	178 859	32.96	100.00	No
Total		542 576			

* As of June 2006

In some water well records, material layers don't have depth values. Without depth constraints, the layers 'float' without a fixed position in the succession of strata, thereby causing an incorrect allocation of the bedrock surface (Table 2). As such, water wells containing 'floating' layers were screened out.

Table 2. An example showing a gravel layer without depth 'floats' in the strata. In the left table, the well would be treated as a rock well. In the right, the same well is an overburden well not reaching bedrock.

Depth (m)	Material	Coding
3	Sand	O
	Gravel	O
7	Clay	O
9	Limestone	P

Depth (m)	Material	Coding
3	Sand	O
7	Clay	O
9	Limestone	P
	Gravel	O

Most of the ground elevations, as well as UTM co-ordinates for water wells, have been generated manually by MOE on 1:50 000 topographic maps which, for southern Ontario, have 10 m contour intervals. During this process, elevation errors could have potentially been introduced. Similar elevation errors may also occur with geotechnical boreholes. As a result, some of the recorded ground elevations are inconsistent with the DEM values. To filter out data with this problem, a difference between the record and the DEM of ± 10 m was used as the threshold to either accept or reject a record. In other words, those records with over ± 10 m difference between the well elevation and DEM elevation were regarded as problematic and removed.

Water wells with coordinates located inside lakes are regarded as erroneous and rejected. To remove these records, the NRVIS large lakes are used to clip them out. In southern Ontario, many wells are dug near lake shorelines. When plotted on a base map, they may fall a few meters into lakes due to the precision or lack of recorded coordinates. For this reason, only those wells that are more than 10 m away from lake shorelines (away from land) are rejected.

Bedrock determination: Preparing a translation table

Manually assigning the bedrock surface for each water well is time consuming and sometimes impractical due to the large number of water wells, often in the order of 10 000

to 100 000 for a report area. As such, a translation table is used that contains all of the unique water well layer combinations coded as either 'O' for overburden, and 'P' or 'Pr' for Paleozoic or Precambrian bedrock, respectively (Table 3). After populating the layers with this table, a pre-determined algorithm searches the water wells to establish the bedrock depth.

Table 3. Part of a translation table, showing the most frequent layer combinations for southern Ontario.

Water well count	%	Primary	Secondary	Tertiary	Bedrock Area	Coding
75 817	12.13	CLAY	Null	Null	Paleozoic	O
25 080	4.01	CLAY	STONES	Null	Paleozoic	O
12 508	2.00	CLAY	GRAVEL	Null	Paleozoic	O
6 029	0.96	CLAY	BOULDERS	Null	Paleozoic	O
5 649	0.90	CLAY	MEDIUM SAND	Null	Paleozoic	O
16 734	2.68	GRANITE	Null	Null	Precambrian	Pr
16 758	2.68	GRAVEL	Null	Null	Paleozoic	O
15 199	2.43	HARDPAN	Null	Null	Paleozoic	O
94 895	15.18	LIMESTONE	Null	Null	Paleozoic	P
7 498	1.20	LIMESTONE	HARD	Null	Paleozoic	P
12 159	1.94	MEDIUM SAND	Null	Null	Paleozoic	O
12 110	1.94	ROCK	Null	Null	Paleozoic	P
10 178	1.63	SAND	Null	Null	Paleozoic	O
28 309	4.53	SHALE	Null	Null	Paleozoic	P
36 332	5.81	TOPSOIL	Null	Null	Paleozoic	O
375 255	60.01					

Coding unique combinations relies on the assumption that the descriptions used by water well drillers refer to the same materials and correspond to geologic terminologies used by geologists. Sometimes, these descriptions are clear and sufficient to determine whether the stratum consists of overburden material such as GRAVEL and SAND or bedrock of LIMESTONE or SHALE, for example (Table 3). In other situations, comparing the water well locations with the local bedrock geology helps to flag material descriptions that may be questionable (Table 4). For instance, SLATE is frequently used by drillers for shale bedrock in areas of Paleozoic bedrock. A second example is SANDSTONE, which is often used to describe compact sandy clay till in southwestern Ontario.

Water wells containing combinations with undefined, ambiguous or questionable descriptions must be inspected and, if possible, assigned a bedrock depth manually

(Table 4). The primary clues used in manual assignment include the stratigraphy and geographic location of the well. Water well layers should be in the correct stratigraphic succession with Paleozoic always underlain by Precambrian bedrock in southern Ontario. A reversed sequence with Paleozoic underlying Precambrian bedrock is a violation of the stratigraphy, leading to exclusion of the related water wells from the data set. Geographic locations are important for manual inspection of water wells that contain questionable descriptions such as SANDSTONE. Numerous water wells containing this description are present across southern Ontario where only limited occurrences of sandstone bedrock exist. Comparison of the well locations with the underlying bedrock has proven useful in winnowing out some erroneous wells (see Appendix A).

As of June 2006, the OGS had received the updated MOE water well database that contains over 500 000 records (see Table 1). Of the 350 000 or so water wells that passed the filtering process described above, over 30 000 records were found to contain undefined or ambiguous layer combinations. Subsequently, they were hand-checked for bedrock depth or processed using specially designed routines. Readers should refer to Appendix A for details on the inspection procedures and manual assignment of bedrock depth.

Table 4. Coding MOE water well layers based on primary materials¹⁾. Those shaded are descriptions that need to be determined (TBD).

MOE Material Code	Primary Material	Coding		Remarks
		Paleozoic Area	Precambrian Area	
13	BOULDERS	O	O	
05	CLAY	O	O	
31	COARSE GRAVEL	O	O	
10	COARSE SAND	O	O	
01	FILL	O	O	Sometimes, man-made fill occurs deeper into bedrock, causing anomalous deep holes in the kriged bedrock surface. Remove water wells as necessary.
29	FINE GRAVEL	O	O	
08	FINE SAND	O	O	
11	GRAVEL	O	O	
14	HARDPAN	O	O	May mean hardened Palaeozoic bedrock layers, causing anomalies on the kriged bedrock surface. Look for clues from secondary material. Remove as necessary.
33	MARL	O	O	
30	MEDIUM GRAVEL	O	O	
09	MEDIUM SAND	O	O	

MOE Material Code	Primary Material	Coding		Remarks
		Paleozoic Area	Precambrian Area	
03	MUCK	O	O	
25	OVERBURDEN	O	O	
32	PEA GRAVEL	O	O	
04	PEAT	O	O	
07	QUICKSAND	O	O	
28	SAND	O	O	
06	SILT	O	O	
12	STONES	O	O	May mean bedrock, causing unrealistic deep holes in the kriged bedrock surface. Useful clues may come from the secondary material. All overburden wells bottomed by this description were screened out (see Appendix A).
33	TILL	O	O	
02	TOPSOIL	O	O	
35	WOOD FRAGMENTS	O	O	
47	SCHIST	O	Pr	All checked for southern Ontario
37	CHERT	P	P	Most inspected for southern Ontario
16	DOLOMITE	P	P	
40	FLINT	P	P	Most inspected for southern Ontario
15	LIMESTONE	P	P	
26	ROCK	P	Pr	
17	SHALE	P	P	
43	GYPSPUM	P	Pr	All checked for southern Ontario
19	SLATE	P	Pr	All checked for southern Ontario
48	SOAPSTONE	P	Pr	All checked for southern Ontario
39	FELDSPAR	Pr	Pr	
41	GNEISS	Pr	Pr	
21	GRANITE	Pr	Pr	
22	GREENSTONE	Pr	Pr	
46	QUARTZ	Pr	Pr	
20	QUARTZITE	Pr	Pr	
44	IRON FORMATION	Pr	Pr	
36	BASALT	TBD	Pr	All checked for southern Ontario
42	GREYWACKE	TBD	Pr	
45	MARBLE	TBD	Pr	All checked for southern Ontario
38	CONGLOMERATE	TBD	Pr	All checked for southern Ontario
18	SANDSTONE	TBD	Pr	All checked for southern Ontario
-		TBD	TBD	All checked for southern Ontario
27	**	TBD	TBD	All checked for southern Ontario
24	PREV. DRILLED	TBD	TBD	All checked for southern Ontario
23	PREVIOUSLY DUG	TBD	TBD	All checked for southern Ontario
00	UNKNOWN TYPE	TBD	TBD	All checked for southern Ontario

1) Manual assignment of bedrock depth for water wells containing TBD is detailed in Appendix A.

Bedrock determination: Computing algorithm

Once completed, the translation table is used to populate all of the well strata with either O, P or Pr. For each water well, the algorithm is designed to search for 2 consecutive bedrock layers of P and/or Pr. If no stratigraphic violation such as Pr/P occurs, the top of the first bedrock layer is the depth to bedrock at this location because 2 consecutive rock strata are considered a strong indication of true bedrock. It is unlikely that an incorrectly recorded boulder would occur twice in a row. Water wells reaching bedrock are referred to as rock wells.

If 2 consecutive bedrock strata are not found, the deepest stratum decides whether the well is a rock well or an overburden well not reaching bedrock. If the deepest stratum is bedrock, the top of this stratum becomes the bedrock depth at this location. If it is overburden, the well is considered to be an overburden well.

Erroneous, inversed stratigraphy of Pr/P, i.e., Precambrian overlying Paleozoic may exist in the succession of well layers after the coding process. A search is conducted and water wells containing such stratigraphic violations are removed.

Deep water wells in thin-drift areas

The existence of water wells with deep bedrock depths in thin-drift areas (< 1 m overburden) indicates a potential contradiction between the drilling record and geological observations. Since the surficial geology is mapped at a regional (1:50 000) rather than a local scale, it is quite possible that water wells reaching bedrock at greater depths (20 m for example) exist in a thin-drift area. Such wells can, if valid, be potentially used to define small bedrock depressions. It is, therefore, worth investigating whether these wells should be included in the kriging process or not. These records are manually checked and those that appear erroneous or questionable discarded.

For the current OGS aggregate resources inventory mapping program, drift thickness of 8 m is a threshold value in resource designation (Ontario Mineral Aggregate Working Party 1977; Cowan 1978; Kelly and Rowell 1995; Baker 2003). Bedrock polygons with less than 8 m drift cover are areas where crushed stone may be obtained at lower cost and, therefore, a high potential exists for resource protection, depending on aggregate

suitability of the rock. For this reason, water wells with bedrock depths deeper than 8 m in thin-drift areas, including those not reaching bedrock, were queried out and manually inspected. Geological maps outlining these areas include the 1:50 000 Surficial Geology of Southern Ontario and in areas where no 1:50 000 map coverage exists the 1:1000 000 Quaternary Geology of Ontario (Barnett, Cowan and Henry 1991; Ontario Geological Survey 2003).

Data standardization

All data points in the working database are standardized to contain UTM co-ordinates and bedrock elevations shown as metres above sea level (masl). The bedrock elevations are assigned or calculated as follows depending on the data type:

- For drilling records such as water wells, bedrock surface elevations are calculated as DEM elevation minus the depth to bedrock;
- For bedrock outcrops, bedrock surface elevations are assigned DEM values;
- For the artificial points converted from thin-drift areas (< 1 m overburden), bedrock surface elevations are calculated as DEM elevation minus 1 m.

In mapping the bedrock topography of southern Ontario, the working database was searched, and a number of data points, mostly water wells, were found to have duplicate locations. More than one or contradictory bedrock elevations with differences of up to 58 m were found at some of the duplicate locations. Duplicate data points with the same bedrock elevation or minor deviations are considered high-quality data because they corroborate the assigned bedrock depths at the same location. Those with a significant difference in bedrock depth are likely caused by errors such as misplaced georeferences, geological misinterpretation and, as discussed earlier, the use of ambiguous terminology; although the specific error sources for the discrepancy are difficult to determine. As such, well records at the duplicate locations with a difference exceeding 2 m in elevation were excluded from the data set (Table 5). For those with less than 2 m of difference, the average bedrock elevations were used. As a result, about 240 000 data points with

assigned bedrock elevations were obtained after the above data filtering and preparation procedures were carried out (Table 6).

Overburden wells are stored in a separate table. Their depth is used as the minimum bedrock elevation. Elevations are calculated as DEM elevations minus well depths. As will be discussed, overburden wells that go deeper than the initially kriged bedrock surface are selected for a 'push down' process. For mapping southern Ontario, a total of 16 212 wells (Table 6) were chosen after the QA/QC procedures as discussed in Appendix A were applied.

Table 5. Data removed due to contradictory bedrock elevations at duplicate locations.

Source	Count	Difference (m)
Water wells	3610	2 - 58
Oil and gas records	53	2 - 12
Geotechnical boreholes	34	2 - 14
GSC boreholes	17	2 - 4
Total	3714	

Table 6. Data used for mapping the bedrock topography of southern Ontario.

Source	Count
Geotechnical boreholes	14 252
Oil and gas wells	15 041
Outcrops	36 109
Water wells	164 883
Water wells (not reaching bedrock)	16 200
Other ¹⁾	6 685
Total	253 170

¹⁾ Consisting of approximately: 1700 OGS-GSC data points, mostly boreholes; 3000 borings from SNC Lavalin Engineers & Constructors (2004); and > 2000 duplicate points (*see* text for explanations).

BEDROCK SURFACE INTERPOLATION

Southern Ontario can be divided into thick and thin-drift areas based on the surficial geology (Ontario Geological Survey 2003). The thick drift areas are covered by over 1 m of overburden whereas those mapped as thin drift contain either exposed bedrock or bedrock with an overburden cover less than 1 m thick. In a thin-drift area, the relationship between the ground surface relief and bedrock topography is much stronger than in a thick drift

area. For this reason, different approaches, i.e., *elevation kriging* versus *thickness kriging*, are applied to these areas in bedrock surface interpolation.

THICK DRIFT AREAS: ELEVATION KRIGING

Initial kriging

Following data standardization, it is possible to interpolate the bedrock elevation surface or grid from all known bedrock elevation points. ESRI® ArcGIS® ordinary kriging is used for interpolation with a variable radius until the computing process finds 12 points or samples. The overall process in determining the bedrock topography involves kriging, QA/QC and re-kriging (Figure 1):

- (1) Kriging – This involves the generation of an initial bedrock elevation surface or grid from all bedrock elevation points in the working database.
- (2) QA/QC – The QA/QC process involves careful inspection of the initially kriged bedrock elevation surface in plan and perspective views. Particular attention is paid to water wells that define excessive peaks and holes. The database is then updated by reviewing and removing problematic data points or correcting problematic bedrock assignments in water wells.
- (3) Re-kriging – The ‘cleaned’ data set of bedrock elevation points is re-kringed to generate a refined bedrock elevation surface.

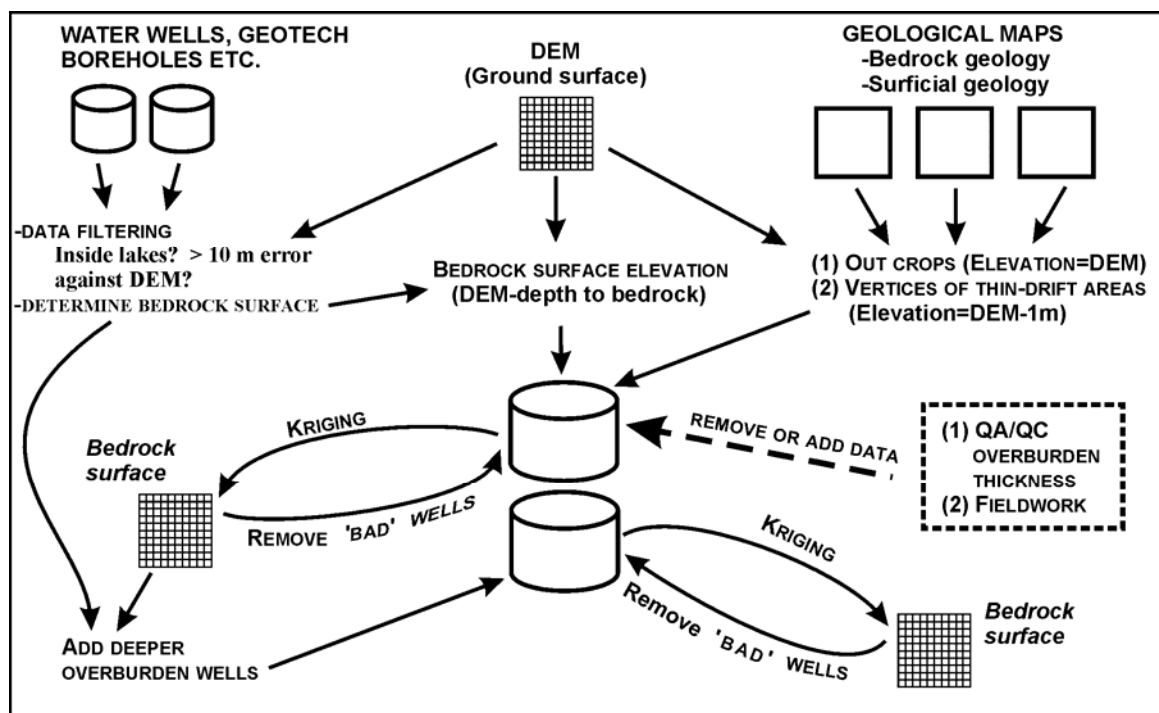


Figure 1. Flow chart outlining the key steps in bedrock elevation surface determination. After each kriging, problematic or 'bad' wells are removed and the surface is re-kriged. The QA/QC check on the overburden thickness map (*see* Figure 3) and subsequent fieldwork removes from or adds data to the database and the whole kriging process is re-initiated.

At the QA/QC stage, useful information sets that may assist the geologist to screen out problematic water wells include: (i) both rock and overburden water wells, (ii) bedrock and surficial geology maps, and (iii) a hillshade ground surface relief map derived from the DEM. Comparison of the water well bedrock layers with the local bedrock helps winnow out some problematic wells. For instance, well layers of SANDSTONE are treated as suspicious or invalid in an area underlain by shale or limestone bedrock, and water wells containing such descriptions may be eliminated. It is also useful to plot overburden wells adjacent to a rock well and compare their depths. If the rock well is outnumbered by overburden wells in the immediate vicinity, as is often the case, a highly pinched or raised bedrock point is considered suspect. The geologist should check the well records for possible misplacement of bedrock depth.

The ground surface relief and surficial geology may provide useful clues to 'bad' wells. For example, a bedrock surface peak defined by a single water well

containing shallow SANDSTONE as bedrock may be suspect. The location of such a well description on the Oak Ridges Moraine, for example, certainly indicates that such a description is erroneous. Consequently, the well is eliminated.

A typical problem related to erroneous geological interpretation is the presence of large boulders of the local bedrock in the drift sediment. These boulders may be mistaken by well drillers for bedrock, leading to erroneous bedrock peaks. During manual inspection of the data, the dimension or thickness of well layers may be used to differentiate a boulder from a true bedrock layer. For instance, it was found during the bedrock topography mapping process that many highly pinched peaks were actually caused by water wells containing, below overburden layers, a thin bottom layer of SHALE, LIMESTONE or GRANITE, ranging from a few centimeters to less than 3 m in thickness, whereas, adjacent water wells showed deeper bedrock depths. These thin layers likely represent boulders. As such, these water wells were rejected. Readers should refer to Appendix A for details on the quality control measures taken during the mapping process for the bedrock topography of southern Ontario.

Push down

Some of overburden water wells go deeper than the interpolated surface, suggesting that the bedrock surface should be deeper than that which has been interpolated at these points. As such, these deeper overburden wells are selected and appended to the interpolated data set, which is kriged again to honour them (Figure 1). This is often referred to as a 'push down' process. Again, anomalous peaks and depressions on the bedrock surface are checked. Problematic wells are removed and kriging is conducted to refine the bedrock elevation surface (Figure 1). The whole process can be summarized in the following steps:

- (1) Overburden wells selection - Overburden wells that extend below the kriged bedrock surface are selected and appended to the database.
- (2) Kriging – The data is kriged to generate a new bedrock elevation surface. This process uses the overburden wells to adjust or 'push down' the previously kriged bedrock surface.

- (3) QA/QC – Following kriging, a careful inspection of the kriged bedrock surface is completed. Attention is paid to water wells that highlight anomalous areas on the kriged bedrock surface.
- (4) Kriging – Once the data set has been cleaned, it is re-kriged to refine the bedrock elevation surface.

THIN-DRIFT AREAS: THICKNESS KRIGING

It was noticed during earlier pilot mapping projects that the drift thickness calculated from the kriged bedrock elevation surface failed to capture geological observations using the artificial data points converted from thin-drift areas at a grid spacing of approximately 400 m by 500 m (Figure 2A and B). This can be attributed to the local relief or unevenness of the ground surface. Theoretically, a good match could be achieved using all of the DEM data points available. Practically, however, it is rather inefficient for computers to process such a large data set.

For thin-drift areas where the overburden cover is known to be no more than 1 m thick, the bedrock surface is directly reflected by the ground surface. The bedrock elevation surface can be simply generated by subtracting the known drift depths from the DEM, a process referred to as thickness kriging. Using this kriging approach, which is more “depth-centric”, information from geological observations was incorporated (Figure 2D). Additional features such as depressions defined by drill records are also presented, thus refining the original geological maps (Figure 2D).

Thin-drift areas can be viewed as exposed bedrock covered by patchy drift sediments. For simplicity, the depth value used for subtraction from the DEM is 1 m or zero. Test runs were conducted using the value of 1 m and the calculated thickness under the 0 – 1 m category appears not to match the geological map (Figure 2C). On the other hand, the generated thickness using a value of zero captured the geological observations (Figure 2D). As such, this latter value was used to map the bedrock topography for the thin-drift areas of southern Ontario.

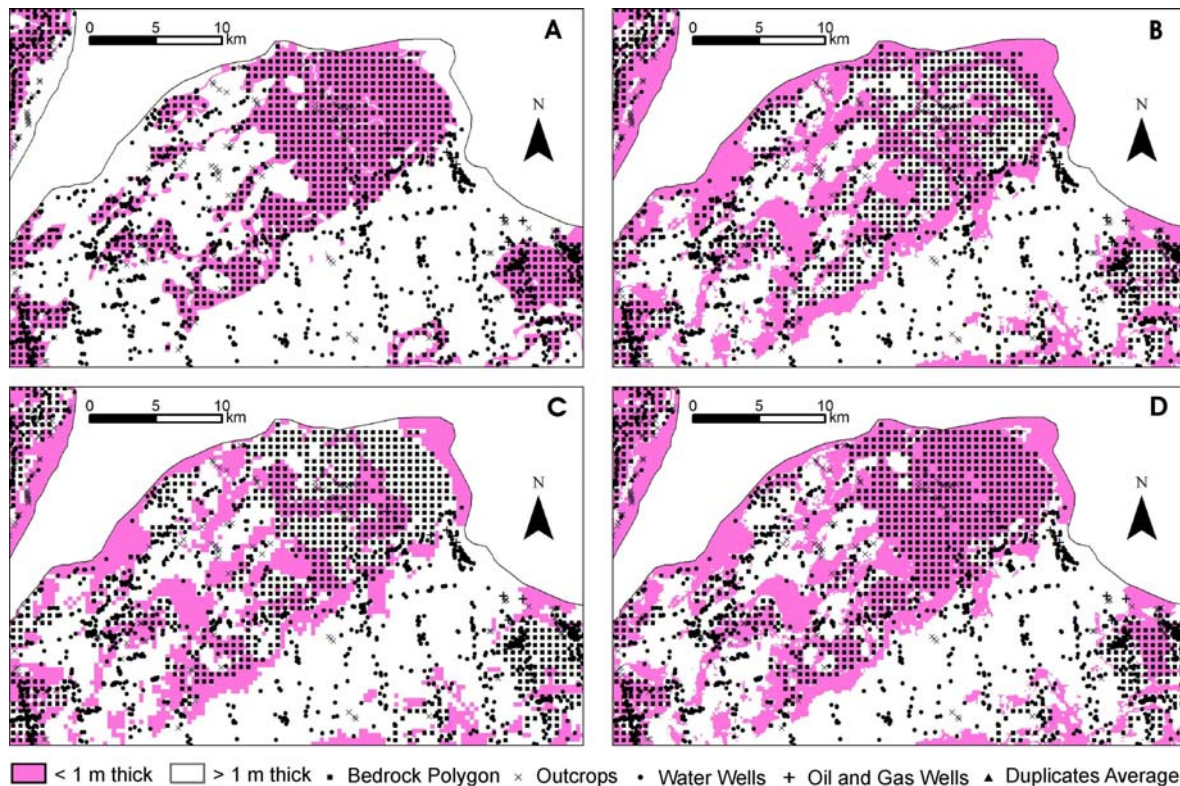


Figure 2. Thickness maps derived from different kriging approaches for thin-drift areas. A). Bedrock area mapped (Ontario Geological Survey 2003). B). Thickness after elevation kriging. C). After thickness kriging but with 1 m subtracted from DEM. Note maps from A and B fail to match the geological observations shown by A. D). After thickness kriging but with the value of 0 m used for subtraction. Note this map incorporates the geological observations.

COMBINING TWO SURFACES

To stitch together the bedrock elevation surfaces kriged by both methods, a buffer zone of 2-pixel width is created between them. The average elevations of the pixels are used to enforce a gradual change in elevation between these polygons. Pixel size is related to the intended map resolution. The bedrock elevation surface and drift thickness maps of southern Ontario were released as raster data sets with a spatial resolution of 0.005 decimal degrees, which equals approximately 500 m by 500 m of pixel size.

OVERBURDEN THICKNESS CALCULATION

The overburden thickness calculation is a simple subtraction between the kriged bedrock elevation surface and the DEM (Figure 3). However, negative values may arise from deficient data or sudden depressions in the DEM. Since all the data has been

standardized with DEM values, it is rare to have deficient data points that stand higher than DEM (refer to *Data Standardization*). More commonly, negative values arise in areas where sudden depressions in the DEM or ground surface exist. This may occur when a linear surface is interpolated or drawn between known data points across a steep escarpment or surface depression such as a river valley (Figure 4).

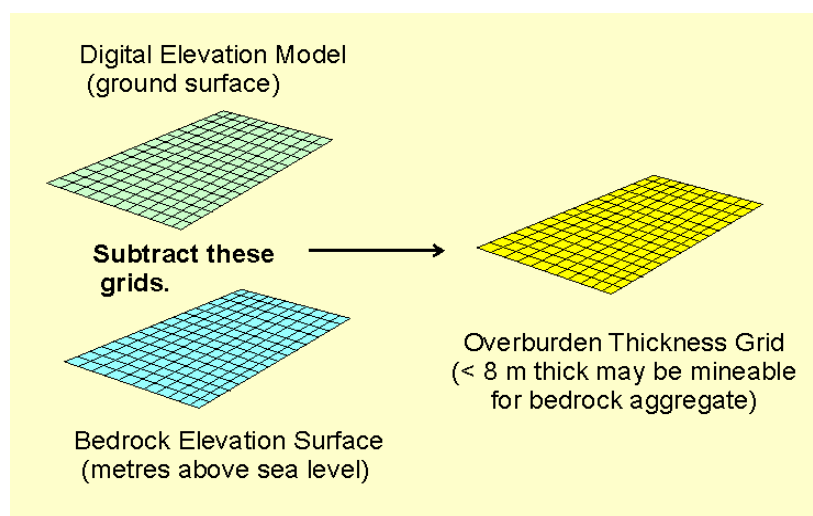


Figure 3. Overburden thickness calculated by subtracting the kriged bedrock elevation surface from the DEM (ground surface).

It is difficult, if not impossible, to collect enough data points along these areas to eliminate the negative values. On the other hand, an understanding of the landform and surficial geology of the study area is often helpful in rectifying problems. Negative values arise in thin-drift areas where rivers cut through the drift deposits. In thick overburden areas, however, this appears less likely to occur (Figure 4). Steep bedrock escarpments, such as the Niagara Escarpment, experience intense erosion and normally have a shallow cover of drift deposits. As such, any resulting negative values may be reclassified as thin-drift areas, e.g., 0 to 1 m. These areas may be verified during field investigations. The whole process can be summarized in the following steps:

- (1) Overburden thickness calculated by subtracting the kriged bedrock elevation surface from the DEM;

- (2) Reconciliation of negative thickness: Negative overburden values may be grouped into the 0-1 m category on a drift thickness map which is normally classified into 0-1 m, 1-8 m, 8-15 m and over 15 m drift thickness groups for OGS bedrock aggregate resource assessments.
- (3) QA/QC: QA/QC is completed by checking key water wells defining areas of interest.

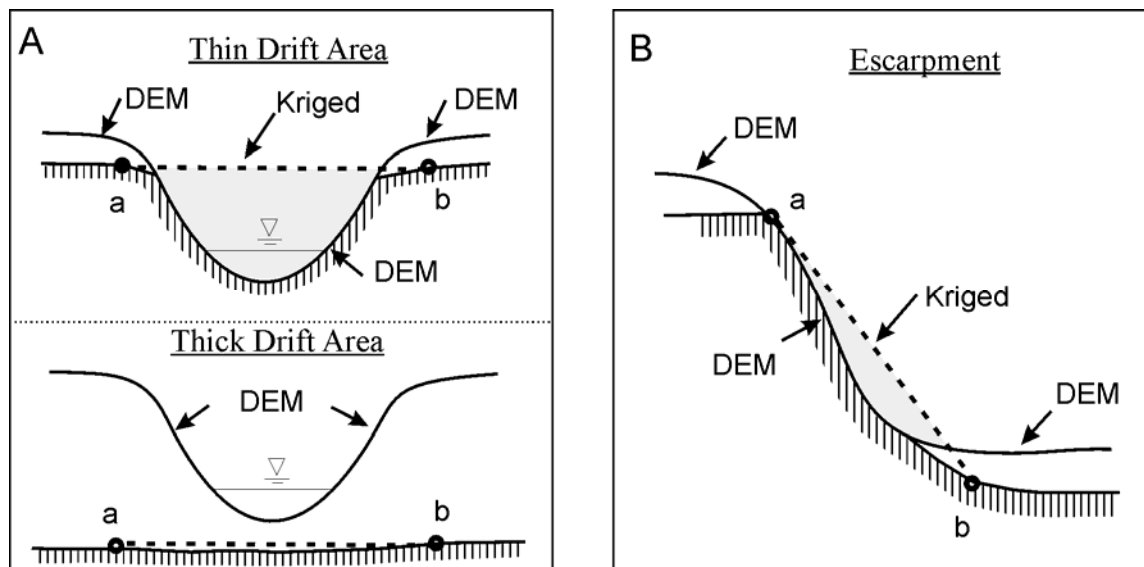


Figure 4. Schematic cross sections of areas where negative overburden thickness values (shaded area) typically arise after subtraction of a kriged bedrock surface from the ground surface or DEM. The dashed line represents the kriged surface between known bedrock data points *a* and *b*. A) Along a deep valley in an area covered by thin (top) and thick drift deposits (bottom). B) Along a steep escarpment.

Quality control is critical at this stage. For instance, OGS bedrock aggregate resource assessments focus on areas covered by less than 8 m of drift material where crushed stone may be obtained at lower cost. Water wells with incorrectly assigned bedrock depths can change the outline and areal extent of map polygons, regardless of how large the overall database is. Key water well/borehole logs located within and nearby thin drift areas with potential for bedrock aggregate resource protection are subjected to scrutiny to ensure that the delineation is reasonable. Problematic water wells are removed

from and new data, if available, appended to the database, leading to the re-initiation of the kriging process to generate refined maps (see Figure 1).

BEDROCK AGGREGATE RESOURCE ASSESSMENTS

One important application of the bedrock topography and drift thickness information is to assess bedrock aggregate resources, in particular, in southern Ontario where rapid development and ever growing demand for mineral aggregate requires high-quality aggregate maps so that balanced land-use plans can be developed. Bedrock resources for aggregate resources inventory papers (ARIP) are evaluated on the basis of drift thickness in conjunction with other considerations such as aggregate suitability, size, location, and natural and cultural constraints. Areas covered by less than 8 m of drift deposits may be selected for resource protection. Selected areas should contain sufficient data points to allow a reasonable interpretation of the geology. In line with the requirements for an ARIP, several key data layers are listed in Table 7.

Preliminary bedrock aggregate resource areas selected, based on drift thickness and aggregate suitability of the bedrock, are inspected and verified in the field. During fieldwork, collection of additional bedrock elevation information from outcrops and drilling activity requires an update of the working database, re-kriging of the bedrock elevation surface and re-calculation of drift thickness (see Figure 1).

Table 7. Key data layers proposed for a bedrock ARIP.

Data Layers	Description
SelectedBDResources	Selected areas with less than 8 m of drift, underlain by aggregate-suitable bedrock units. Attributed with tonnages, extracted areas and cultural setbacks for each polygon. Normally, the selected areas have undergone the editing process, such as merging and edge trimming.
BedrockResources	Polygons containing information on bedrock formations and drift thickness. This data layer is compiled from <i>DriftThick</i> and <i>GeoFormations</i> through the <i>intersect</i> process.
DriftThick	Drift thickness map from the kriging process. Polygons are categorized into 0 – 1 m, 1 – 8 m, 8 – 15 m and >15 m groups.
GeoFormations	Bedrock geology formations and their boundaries, including rock type, formation names and the estimate of thickness for the rock units.
QuarriesLicen	Licensed quarries, containing face heights (m), licensed areas (ha) and MNR licence ID.
QuarriesUnlicen	Unlicensed quarries, attributed with face heights (m).
SelectedWells_BD	Selected water wells containing MOE water well ID, depth to bedrock (m) and depth labels, e.g., 125 for depth to bedrock, 133+ for well total depth, not reaching bedrock.

CONCLUSIONS

Using the outlined methodology, the bedrock topography and drift thickness maps of southern Ontario were generated. The new approach provides the opportunity to integrate and analyse a variety of geo-data sets. This, in turn, allows the enhancement of map quality, increased confidence in geological interpretations, and efficiencies in data retrieval and manipulation. The intense use of multiple geo-data sets means that quality control is critical and challenging in order to maintain consistently high standards for the geological maps produced. Data sets, such as water wells, must be properly filtered and adequate quality control measures employed so that problematic data can be tracked, located and eliminated.

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APPENDIX A: BEDROCK TOPOGRAPHY AND DRIFT THICKNESS MAPPING: QUALITY CONTROL

Using the procedures described previously, the bedrock topography and drift thickness of southern Ontario were kriged and calculated. One of the major quality control and quality assurance (QA/QC) steps in this process was the manual assignment of bedrock depths to water wells containing undefined or questionable layers. Other important QA/QC measures included the inspection of anomalous peaks and holes on the kriged bedrock elevation surface and the critique of all wells with bedrock depths deeper than 8 m in thin-drift areas.

A1. Bedrock depth assignment for water wells containing undefined and questionable layers

To map the bedrock topography of southern Ontario, water wells containing undefined and ambiguous or questionable layer descriptions in primary material were processed separately and most of them assigned bedrock depths manually (Table A-1). Of the 350 000 or so water wells that passed the filtering process described in the main text (see Table 1), over 30 000 records containing undefined and ambiguous layer descriptions were queried out and inspected in a progressive order from southwestern to eastern Ontario. The following sections detail the steps and measures which were taken for the determination of bedrock depths.

Table A-1. To-be-determined (TBD), questionable or ambiguous descriptions of primary material in water well layers

MOE Material Code	Primary Material	Coding		Remarks
		Paleozoic	Precambrian	
00	UNKNOWN TYPE	TBD	TBD	Undefined
-		TBD	TBD	Undefined
27	**	TBD	TBD	Undefined
24	PREV. DRILLED	TBD	TBD	Undefined
23	PREVIOUSLY DUG	TBD	TBD	Undefined
43	GYP SUM	TBD	TBD	Ambiguous
18	SANDSTONE	TBD	Pr	Limited occurrence of sandstone bedrock in southern Ontario
38	CONGLOMERATE	TBD	Pr	Treated the same as SANDSTONE
19	SLATE	TBD	Pr	Questionable in Paleozoic bedrock area
47	SCHIST	TBD	Pr	Questionable in Paleozoic bedrock area
48	SOAPSTONE	TBD	Pr	Questionable in Paleozoic bedrock area

MOE Material Code	Primary Material	Coding		Remarks
		Paleozoic	Precambrian	
42	GREYWACKE	TBD	Pr	Questionable in Paleozoic bedrock area
36	BASALT	TBD	Pr	Questionable in Paleozoic bedrock area
44	IRON FORMATION	TBD	Pr	Ambiguous in Paleozoic bedrock area
45	MARBLE	TBD	Pr	Ambiguous in Paleozoic bedrock area

PREV. DRILLED or PREVIOUSLY DUG

During the coding process (see *Data Preparation and Standardization*), secondary or tertiary materials were used as clues to code combinations containing primary material PREV. DRILLED or PREVIOUSLY DUG. For instance, if the secondary material is GRAVEL, such a combination was assigned an O. Similarly, if the secondary material consists of LIMESTONE, the combination was coded with a P for bedrock.

Approximately 20 000 water wells containing such undefined combinations were identified in the database. In a water well layer sequence, a PREV. DRILLED or PREVIOUSLY DUG layer (X) is normally the uppermost layer. If underlain by an overburden layer (O), i.e., in a stratigraphic relation of X/O, this layer indicates overburden as illustrated by water well 2505178 in Table A-2. In this water well, the bedrock depth is defined beneath the layer of GRAVEL at 3.05 m below the ground surface. As such, water wells with such a stratigraphic relation were queried out and the combinations assigned an O.

After completing the above step, over 4300 water wells were left for inspection. Among them, the combinations are either underlain by bedrock layers (X/P, X/Pr), or are the only layers for the water wells or, less commonly, occur below other layers (O/X, P/X and Pr/X). With these stratigraphic relations, the bedrock surface could not be determined as in water wells 3004602 and 3007206 (Table A-2). As a result, these wells were removed.

Table A-2 Typical stratigraphic relations in water wells containing PREVIOUSLY DUG or PREV. DRILLED layers. Note the depth indicates the bottom of the water well layers.

Well ID	Layers	Well ID	Layers	Well ID	Layers
2505178	1.52 m: PREV. DRILLED	3004602	28.65 m: PREVIOUSLY DUG	3007206	9.14 m: PREV. DRILLED
	3.05 m: GRAVEL		31.7 m: SHALE		
	28.96 m: LIMESTONE				

UNKNOWN TYPE

Approximately, 1800 water wells contain undefined layers of UNKNOWN TYPE or layers marked by symbols of ‘**’ and ‘-’ without descriptions. These wells were checked using the layer stratigraphic relations, and where possible, the bedrock depth was assigned manually. If underlain by or imbedded with overburden layers in stratigraphic relations such as X/O and O/X/O, these layers (X) indicate overburden. If overlain by a bedrock layer (P/X or Pr/X), they were ascribed to bedrock and the bedrock depths were assigned. For instance, the depth to bedrock in water wells 4904552 and 6924677 containing UNKNOWN layers is clearly defined (Table A-3). The former reaches shale bedrock at 1.52 m below the ground surface, whereas, the latter is an overburden well not reaching bedrock.

The drift-bedrock contact cannot be determined for water wells if an UNKNOWN layer (X) occurs as the bottom bed and is overlain by overburden or underlain by a bedrock layer P or Pr (X/P or X/Pr), as illustrated by water wells 4904554 and 2104072 (Table A-3). Consequently, those wells were removed from the working database.

Table A-3. Typical stratigraphic relations in water wells containing layers UNKNOWN TYPE or layers marked by symbols ‘**’ and ‘-’ without descriptions

Well ID	Layers	Well ID	Layers	Well ID	Layers	Well ID	Layers
6924677	0 m: UNKNOWN TYPE	4904552	1.52 m: TOPSOIL	4904554	3.66 m: CLAY, SOFT	2104072	3.66 m: SAND
	2.13 m: CLAY		5.49 m: SHALE		11.89 m: CLAY,		11.58 m: CLAY
	2.44 m: UNKNOWN TYPE		7.01 m: UNKNOWN TYPE		19.81 m: UNKNOWN TYPE		12.8 m: UNKNOWN TYPE
	7.92 m: CLAY						20.73 m: LIMESTONE
	8.53 m: UNKNOWN TYPE						
	31.09 m: CLAY						

Ambiguous descriptions of primary material other than SANDSTONE

Water wells containing layers of ambiguous descriptions in primary material other than SANDSTONE were inspected and, if possible, the bedrock depth was assigned manually. To be specific, these descriptions include: BASALT, CONGLOMERATE, GREYWACKE, GYPSUM, IRON FORMATION, MARBLE, SLATE and SOAPSTONE in Paleozoic bedrock areas of southern Ontario. In addition, most of the water wells containing CHERT

and FLINT were checked in order to gain insight into the lithological terms used by water well drillers. The result was summarized in Table A-4.

Table A-4. Ambiguous descriptions of primary material and manually inspected water wells in Paleozoic bedrock area, southern Ontario

Primary material	Wells count	Remarks
SLATE	724	Bedrock. Mostly in southwestern and eastern Ontario. This description appears to be used by drillers for shale bedrock with parting structures.
SOAPSTONE	249	Bedrock. Mostly in southwestern Ontario, normally used by drillers for hard shale bedrock.
FLINT	99	Bedrock. Mostly in Onondaga Formation limestone in southern Niagara Peninsula.
CHERT	44	Bedrock in Bruce Peninsula where 31 water wells containing CHERT exist in the Guelph and Amabel Formations. The rest are used for lithology of gravel clasts. Inspection is recommended even if this description has been coded with P in Paleozoic bedrock areas.
MARBLE	13	In southwestern and central Ontario where thick drift exists, this description is frequently used to indicate lithology of gravel clasts. In eastern Ontario where shallow drift exists, water wells are often drilled through the Paleozoic to reach Precambrian bedrock where MARBLE does occur. Inspection is needed.
CONGLOMERATE	10	Treated the same as SANDSTONE. All located in southwestern and central Ontario and ascribed to overburden.
IRON FORMATION	10	Bedrock. Located in eastern Ontario or areas where Simcoe Group limestones border the Precambrian bedrock in central Ontario.
GYPSUM	9	Bedrock. Mostly in the Salina Formation.
BASALT	7	Treated as UNKNOWN TYPE. All in southwestern and central Ontario. Inspection is needed.
SCHIST	1	Layered clay.
GREYWACKE	0	Inspection is needed.
Total	1166	

SANDSTONE

If located in an area of Precambrian bedrock, SANDSTONE is normally treated as bedrock Pr (see Table 4). However, this description has been found to indicate both sandstone and compact sandy clay till in Paleozoic bedrock areas of southern Ontario. As such, care must be taken when the geological sediment it may represent is to be determined.

There are about 8200 records in the existing data set of water wells containing SANDSTONE (Figure A-1). In general, if overlain by a rock layer in a stratigraphic relation of P/X (X refers to SANDSTONE), this description was treated as bedrock and the bedrock depth for the water well was manually assigned. For other stratigraphic relations, information on the local bedrock geology was found useful for interpretation of this description. The *Bedrock Geology of Ontario* map at a scale of 1:1 000 000 was used for the bedrock formations (Ontario Geological Survey 1991). Also used was the draft version of the GIS Paleozoic geology map under construction which is based on published

1:50 000 maps for southern Ontario (D.K. Armstrong and J.E.P. Dodge, Ontario Geological Survey 2006, personal communication). Additional clues for the determination of lithology was derived from surficial geology maps. For instance, water wells on the Oak Ridges Moraine often contain descriptions of shallow SANDSTONE layers in an area where overburden is known to be very thick. Clearly, the well drillers have used this description locally to indicate glacial drift deposits rather than sandstone bedrock.

In southwestern and central Ontario where limestone, dolomite and shale bedrock units are predominant, the SANDSTONE description was treated as overburden. The exceptions are sandstones of the Lower Devonian Oriskany Formation and Springvale Member of the Bois Blanc Formation (Johnson et al. 1992). Along the Niagara Escarpment and in the Niagara Peninsula, the Whirlpool Formation sandstone occurs in the lower part of the Cataract Group. As such, SANDSTONE in water wells located in these areas of southern Ontario was ascribed to bedrock, and the subsequent rock depth assigned.

The Middle Ordovician Gull River limestone in the Simcoe Group sometime contains thin interbeds of quartz-rich sandstone. This formation is located along the northern and eastern margins of the Simcoe Group where it is underlain by the Shadow Lake Formation which contains dolomitic sandstone (Johnson et al. 1992). Because of this, many water wells containing SANDSTONE occur in this area of southern Ontario that borders the Precambrian Shield (Figure A-1). Thus, the SANDSTONE layer entry was ascribed to bedrock in these regions. East of the Simcoe Group numerous water wells containing SANDSTONE occur in eastern Ontario. In this region, dolomitic and quartz-rich sandstones commonly occur in rock formations of Middle and Lower Ordovician to Cambrian age including the Rockcliffe Formation, Beekmantown and Potsdam Groups. It was assumed that the drillers in this region have more experience in drilling sandstone bedrock than those in southwestern Ontario. For this reason, in eastern Ontario about 7000 water wells containing SANDSTONE were all coded for Paleozoic bedrock without further manual assignment for bedrock depth (Figure A-1). Among the 100 water wells or so randomly checked in the area underlain by the Beekmantown and Potsdam sandstones, the well layer sequences are characterized by a layer of SANDSTONE present at the base, consistent with the local bedrock (Table A-5). The common presence

of a CLAY cover as revealed by these wells is also consistent with the surficial geology in the region where early postglacial marine silt and clay exists (Chapman and Putnam 1984).

Table A-5. Water wells with layer sequences typically found in areas of sandstone and limestone bedrock in eastern Ontario					
Well ID	Layers	Well ID	Layers	Well ID	Layers
3501334	0.61 m: CLAY	3506393	8.23 m: CLAY	5602008	9.14 m: CLAY
	14.94 m: SANDSTONE		19.81 m: SANDSTONE		30.48 m: LIMESTONE
					47.24 m: SANDSTONE

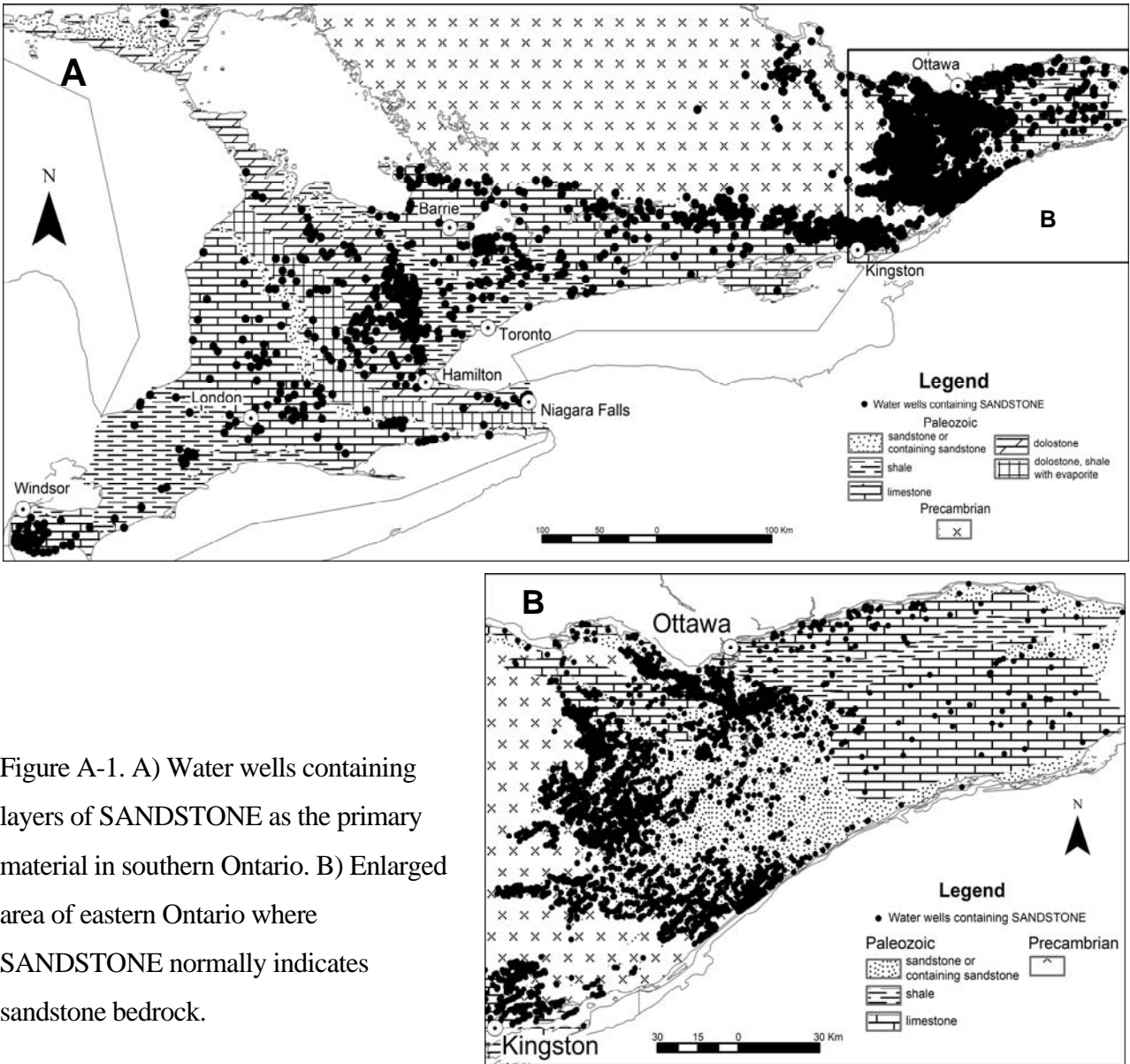


Figure A-1. A) Water wells containing layers of SANDSTONE as the primary material in southern Ontario. B) Enlarged area of eastern Ontario where SANDSTONE normally indicates sandstone bedrock.

A2. Anomalous peaks and holes on kriged bedrock surface

The initially kriged and down-pushed bedrock surface contained many excessive peaks and holes. More than 1200 data points that mark prominent anomalies and outline some large linear depression features were selected for inspection (Table A-6, Figure A-2). To aid the inspection process, records around each of the data points within a 1 km buffer zone were also queried out for comparison.

Table A-6. Inspected data points, southern Ontario

Source	Count	Removed	Bedrock depth Corrected
Water wells	775	169	2
Water wells (not reaching bedrock)	344	162	
Oil and gas wells	112	6	
Outcrops	26	12	
Geotechnical boreholes	3		
	1260	349	2

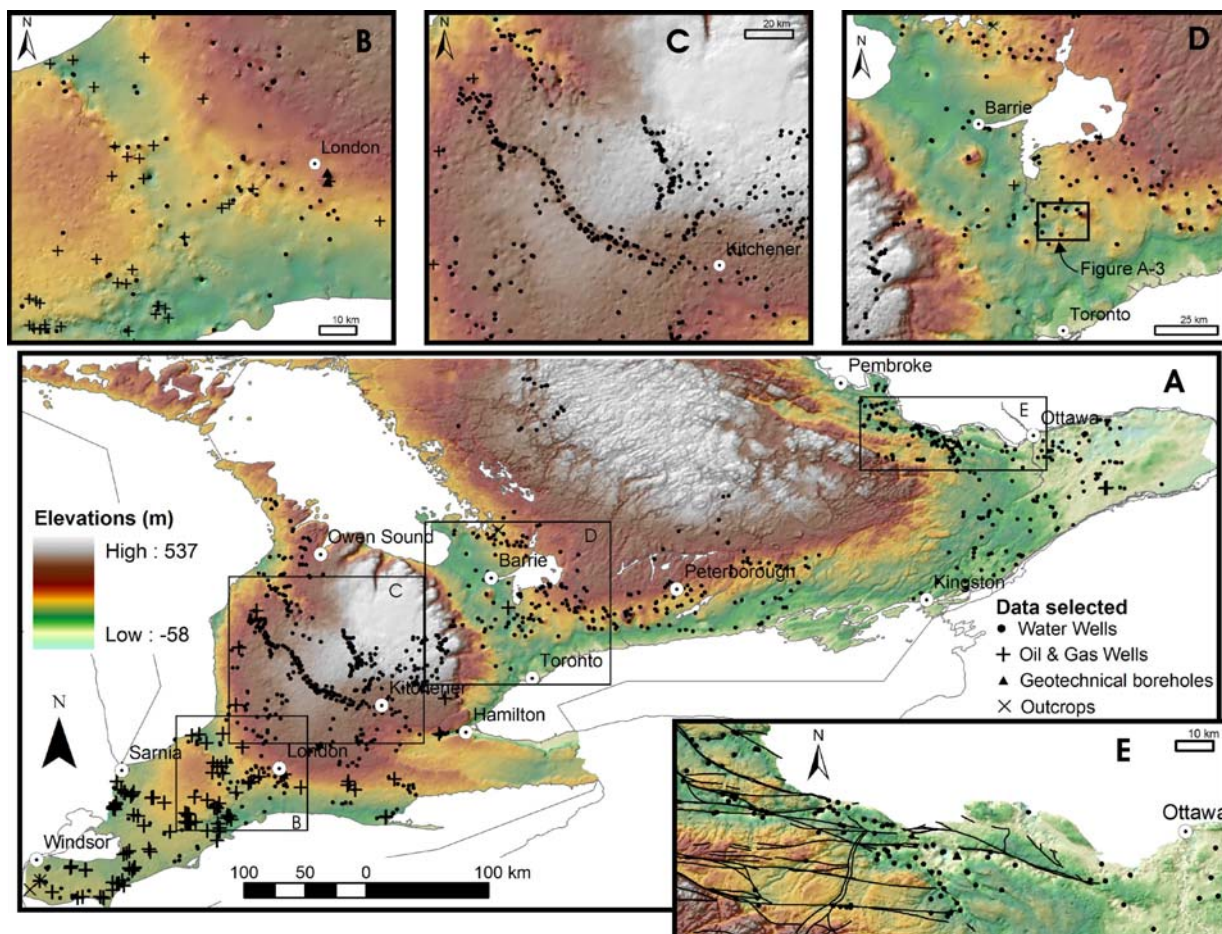


Figure A-2. Kriged bedrock surface and inspected data points that mark prominent peaks and holes in addition to some large linear features. A). Overview of southern Ontario. B). Close up of a NW-SE aligned valley, west of London. C). Close up of a deep, narrow valley, northwest of Kitchener. D). The buried Laurentian Valley. Boxed area is enlarged in Figure A-3. E). West of Ottawa, many deep holes exist along the geological faults (solid lines).

Water well logs were checked and compared with the adjacent data for possible erroneous bedrock depth assignment. It was found that the recorded thickness of layers and the material descriptions themselves often provided clues for winnowing out some of the problematic water wells. As a result, more than a quarter of the selected data points were screened out (Table A-6). Most problems were related to the misinterpretation of boulders as bedrock and the incorrect use of geologic terminology.

Many highly pinched peaks were caused by water wells containing, below overburden layers, a thin bottom layer of SHALE, LIMESTONE or GRANITE, ranging from a few centimeters to less than 3 m thickness. Frequently, the adjacent water wells showed

deeper bedrock depths. Examples are given in Figure A-3 where water wells 6900003, 6900376 and 6913380 are all characterised by thin bottom layers of SHALE or LIMESTONE with a recorded thickness of no more than 1 m. These thin layers likely represent boulders, but likely, have been mistakenly interpreted by drillers as bedrock. As such, these water wells were deleted.

There were numerous cases where STONES, although normally used by drillers for overburden, was found to indicate bedrock, thereby causing deep but unrealistic holes on the kriged bedrock surface. As exemplified by water well 1519357 (Table A-7), some drillers prefer using STONES in the primary material field for bedrock; in this case constructing a well log characterized by many layers of this description. In the previous automated process in coding and bedrock assignment, these layers were treated as overburden, thereby assigning unusually deep bedrock depths to the water wells. Many of the wells were mis-labeled as overburden wells not reaching the bedrock (Table A-7). When chosen for the push down process, such wells usually produce deep holes on the kriged bedrock surface. As such, over 3000 water wells bottomed by layers of STONES as the primary material were queried out and removed from the working database.

With the increased checking of water wells containing STONES, it became clear that entries in the secondary material field sometimes provided clues to define the lithology. For instance, if bedrock-like descriptions of the secondary material such as LIMESTONE or GRANITE were present, it was considered that the presence of overburden deposits was doubtful (Table A-7). More likely, these layers were considered to have been used by drillers to indicate bedrock. For simplicity, water wells of concern were deleted to eliminate any anomalous holes. In the future, it may be worthwhile to query out these layers and code them separately on the basis of their secondary material. This may reduce the amount of work for manual inspection but allow some of these water wells to be used which otherwise were removed.

Other material descriptions that were found occasionally to cause problems are HARDPAN and FILL. The former has been used in place by drillers to indicate hardened parts of Paleozoic bedrock layers. This may render the recognition of the bedrock-drift contact difficult although the zone of doubt is rarely more than a few meters thick. Clues from the secondary material were used to determine the true lithology, enabling the

rejection of some of the water wells that caused notable holes or peaks (Table A-7). Thick layers of FILL exceeding 20 m, for example, were occasionally found in water wells, penetrating deep into the bedrock. Such wells produced exaggerated overburden thickness and, as such, were removed from the data set.

When logging the water wells, drillers occasionally misuse the terms clay and shale bedrock. Misinterpretations or misidentifications of lithology, if it occurs, may lead to anomalous areas on the kriged bedrock surface. For instance, the 2 layers of SHALE in water well 6920788 (Figure A-3) appear dubious not only because they are unconfirmed by the adjacent water wells but also because this well, which caused an anomalous peak, is located on the Oak Ridges Moraine where the drift is known to be thick. Consequently, this well was removed.

The size or thickness of the well layers was often found to be very useful in winnowing out water wells with an erroneous bedrock depth assignment. Recorded, thick layers of LIMESTONE exceeding 20 m for example should be regarded as genuine Paleozoic bedrock even if they are underlain by thin layers of overburden such as CLAY. This is illustrated by water well 1403117 that reaches the LIMESTONE bedrock at depth of 1.52 m (Table A-8). In the automation process, however, the computer algorithm which searches for 2 consecutive bedrock layers skipped this layer, ascribing it to an overburden well not reaching bedrock. Consequently, a hole-like deep depression was created at this site.

Other data were also selected for inspection (Table A-6). The top of bedrock in oil and gas wells and geotechnical boreholes were difficult to verify because of the unavailability of actual log records. Requests were sent to the Ontario Oil, Gas and Salt Resources Library to review 6 oil and gas wells that generated prominent anomalies. It was reported that the top of bedrock in these records could not be verified (T. Carter, MNR 2006, personal communication). As a result, they were removed from the working database.

Table A-7. Typical problems related to the use of ambiguous or incorrect descriptions in water wells, southern Ontario*

Well ID	Layers	Well ID	Layers	Well ID	Layers
1519357	5.18 m: OVERBURDEN	4104330	49.99 m: CLAY, STONES	3503696	28.35 m: FILL
	17.37 m: STONES, LIMESTONE		71.93 m: HARDPAN, LIMESTONE		36.88 m: LIMESTONE
	18.29 m: STONES, LIMESTONE		73.15 m: LIMESTONE		
	148.44 m: STONES, LIMESTONE				
	151.79 m: STONES, SANDSTONE				
	153.92 m: STONES, LIMESTONE				

* **Bold italic** text indicates the correct uppermost rock layers. Note the 2 wells to the left were originally labeled as overburden wells not reaching bedrock.

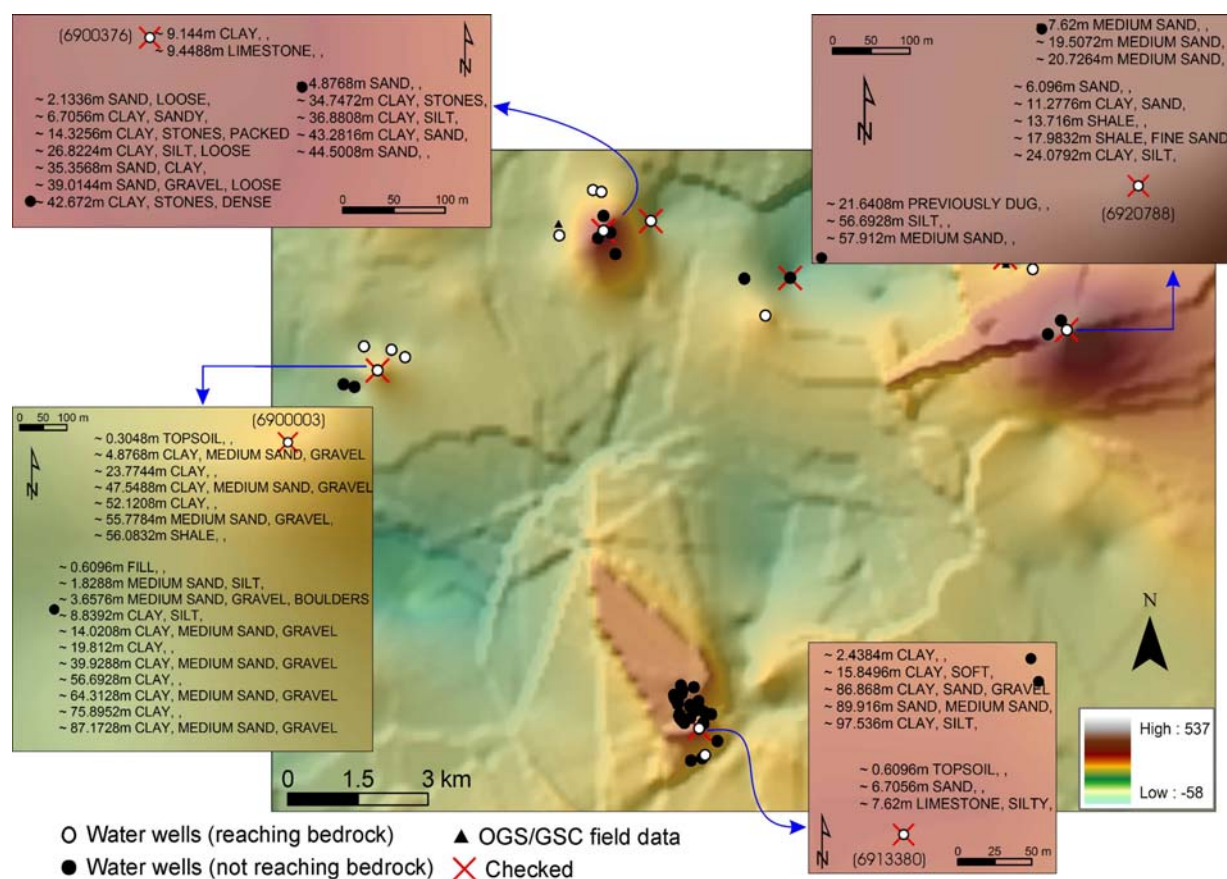


Figure A-3. Excessive peaks caused by water wells containing incorrectly interpreted dubious beds, York Region (see Figure A-2 for location). After closer inspection, the 4 water wells shown were removed.

A3. Deep water wells in thin-drift areas

After an inspection of anomalous areas on the kriged bedrock surface, 2286 water wells with a bedrock depth deeper than 8 m in thin-drift areas (< 1 m overburden) were queried out and manually checked (Figure A-4). Geological maps used to delineate thin-drift areas were the 1:50 000 scale Surficial Geology of Southern Ontario map and in areas where no 1:50 000 map coverage exists the 1:1 000 000 scale Quaternary Geology of Ontario (Barnett, Cowan and Henry 1991; Ontario Geological Survey 2003). After inspection, 181 wells were removed due mostly to the incorrect use of terminology or the misinterpretation of well layers. To illustrate, 3 records are shown in Table A-8. One well record illustrates the improper use of TOPSOIL, and the other two are related to misinterpretation of bedrock layers as CLAY.

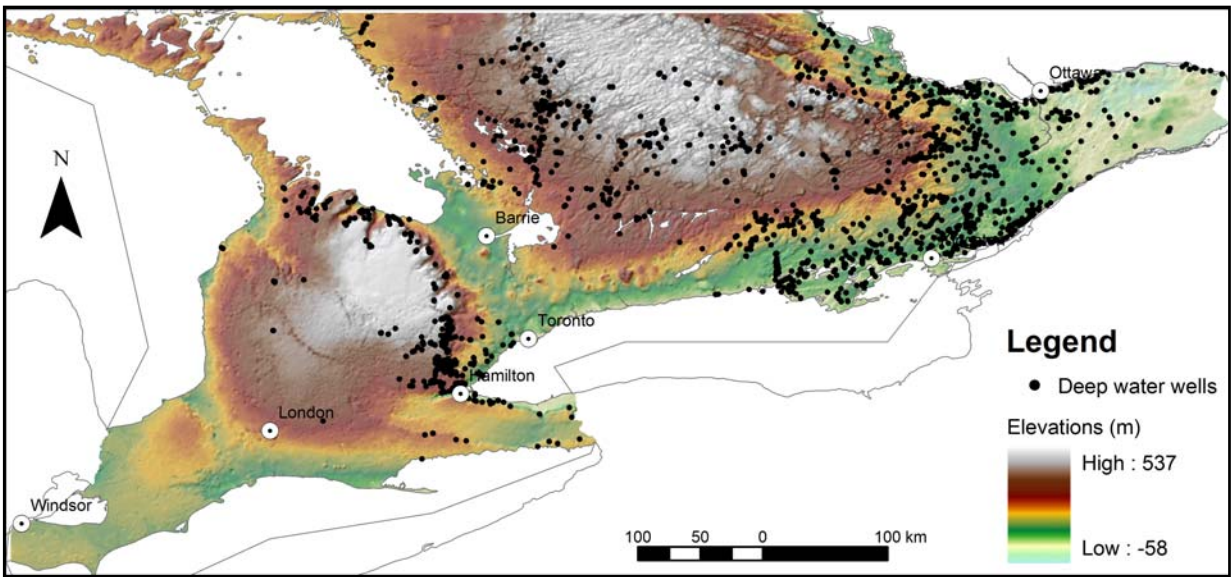


Figure A-4. Water wells with bedrock depth deeper than 8 m in thin drift areas, southern Ontario. Note these wells don’t include those that have been already removed as a result of previous inspection of anomalous areas in the kriged bedrock surface.

Table A-8. Mis-located bedrock depth in water wells due to erroneous geological interpretations or improper descriptions, southern Ontario*.

Well ID	Layers	Well ID	Layers	Well ID	Layers
4202259	3.05 m: SAND	1403117	1.54 m: TOPSOIL	4202150	0.61 m: TOPSOIL
	74.07 m: GRANITE		36.58 m: LIMESTONE		52.12 m: TOPSOIL, GRANITE
	74.37 m: CLAY		37.49 m: CLAY		
	96.62 m: GRANITE				

* Bold italic text indicates the correct uppermost rock layers. Note the 2 wells to the right were originally labeled as overburden wells not reaching bedrock.

A4. BEDROCK TOPOGRAPHY AND DRIFT THICKNESS OF SOUTHERN ONTARIO

After removal of the problematic data identified through the quality control steps as discussed above, the data set was re-kriged to produce the refined bedrock topography and the calculation of the drift thickness maps of southern Ontario (Figures A-5, A-6). Although a geologic interpretation of the topography of the bedrock subsurface will be given in a separate publication (*in preparation*), a comparison made with previous studies suggests that this new approach has enabled a better delineation of the buried bedrock topography, in particular, the regional extent of significant buried valleys across southwestern Ontario (e.g., Karrow 1973; Chapman and Putnam 1984; Flint and Lolcama 1985; Eyles, Boyce and Mohajer 1993; Eyles et al. 1997; Brennand et al. 1998; Edgecombe 1999). The information as included in this release may be used for groundwater studies, aggregate resource assessments, geotechnical work and other land-use applications. For technical specifications and recommendations as to how to use these maps, readers should refer to the *readme* file included in this release.

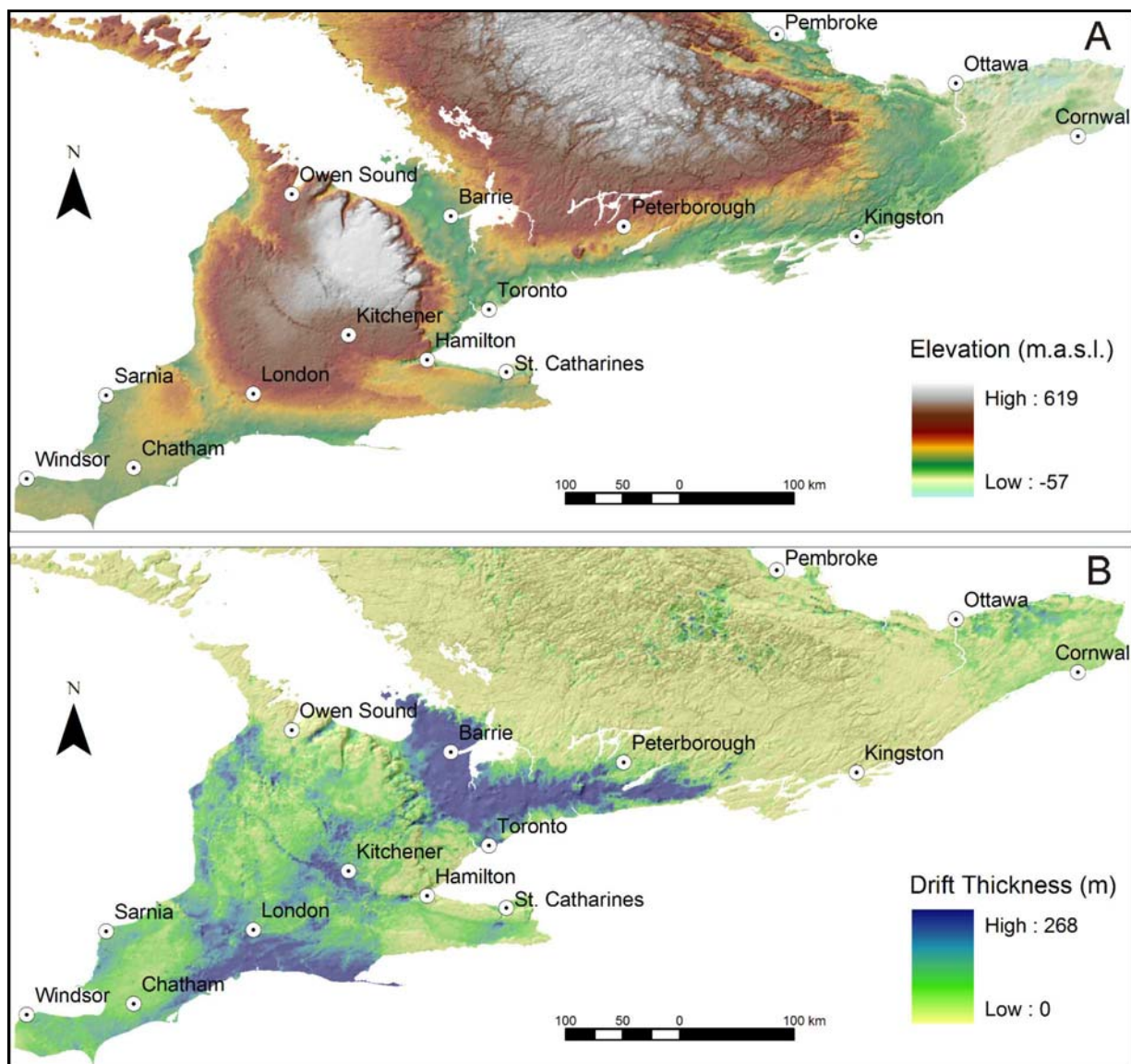


Figure A-5. Bedrock topography (A) and drift thickness (B) of southern Ontario.

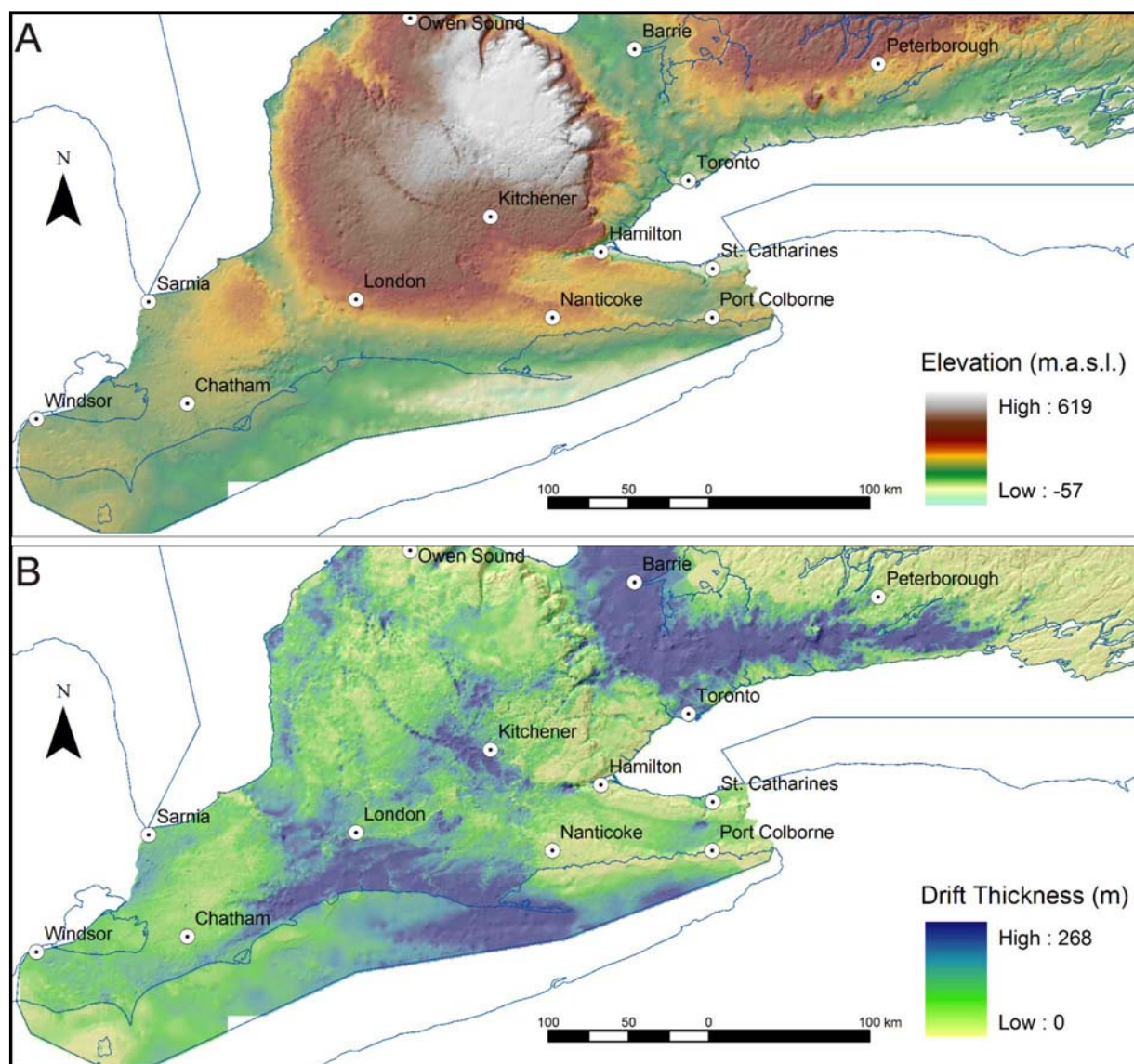


Figure A-6. Enlarged southwestern Ontario, showing the bedrock topography A) and drift thickness B) under Lake Erie.