Hydrogeology of the Potsdam Sandstone in Northern New York

John H. Williams, Richard J. Reynolds, David A. Franzi, Edwin A. Romanowicz, and Frederick L. Paillet

Abstract: The Potsdam Sandstone of Cambrian age forms a transboundary aquifer that extends across northern New York and into southern Quebec. The Potsdam Sandstone is a gently dipping sequence of arkose, subarkose, and orthoquartzite that unconformably overlies Precambrian metamorphic bedrock. The Potsdam irregularly grades upward over a thickness of 450 m from a heterogeneous feldspathic and argillaceous rock to a homogeneous, quartz-rich and matrix-poor rock. The hydrogeological framework of the Potsdam Sandstone was investigated through an analysis of records from 1,500 wells and geophysical logs from 40 wells, and through compilation of GIS coverages of bedrock and surficial geology, examination of bedrock cores, and construction of hydrogeological sections. The upper several metres of the sandstone typically is weathered and fractured and, where saturated, readily transmits groundwater. Bedding-related fractures in the sandstone commonly form sub-horizontal flow zones of relatively high transmissivity. The vertical distribution of sub-horizontal flow zones is variable; spacings of less than 10 m are common. Transmissivity of individual flow zones may be more than 100 m^2/d but typically is less than 10 m^2/d. High angle fractures, including joints and faults, locally provide vertical hydraulic connection between flow zones. Hydraulic head gradients in the aquifer commonly are downward; a laterally extensive series of sub-horizontal flow zones serve as drains for the groundwater flow system. Vertical hydraulic head differences between shallow and deep flow zones range from 1 m to more than 20 m. The maximum head differences are in recharge areas upgradient from the area where the Chateauguay and Chazy Rivers, and their tributaries, have cut into till and bedrock. Till overlies the sandstone in much of the study area; its thickness is generally greatest in the western part, where it may exceed 50 m. A discontinuous belt of bedrock pavements stripped of glacial drift extends across the eastern part of the study area; the largest of these is Altona Flat Rock. Most recharge to the sandstone aquifer occurs in areas of thin, discontinuous till and exposed bedrock; little recharge occurs in areas where this unit is overlain by thick till and clay. Discharge from the sandstone aquifer provides stream and river baseflow and is the source of many springs. A series of springs that are used for municipal bottled water and fish-hatchery supply discharge from 1,000 to 5,000 L/min adjacent to several tributaries east of the Chateauguay River. The major recharge areas for the Chateauguay springs are probably upgradient to the southeast, where the till cover is thin or absent.

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Résumé : Le grès de Potsdam du Cambrien constitue un aquifère transfrontalier qui s'étend du nord de l'état de New York jusqu'au sud du Québec. Le grès de Potsdam est une séquence sub-horizontale d'arkoses, de subarkoses et d'orthoquartzites qui repose en discordance sur le socle métamorphique précambrien. Le Potsdam évolue vers le haut à travers une séquence de 450 m à partir d'une roche hétérogène feldspathique et argileuse vers une roche homogène riche en quartz à peu de matrice. Le cadre hydrogéologique du grès de Potsdam fut examiné grâce à l'analyse des descriptions de 1 500 puits et des logs géophysiques de 40 puits, à la compilation de couvertures DIG de la géologie de surface et du roc, à l'examen de carottes de forage, et avec l'élaboration de coupes hydrogéologiques types. Les premiers quelques mètres du grès sont typiquement altérés et fracturés et, quand ils sont saturés, transmettent l'eau facilement. Des fractures de litage dans le grès forment souvent des zones d'écoulement sub-horizontales à transmissivité relativement élevé. La distribution verticale des zones d'écoulement sub-horizontales est variable, un espacement de moins de 10 m est fréquent. La transmissivité des zones individuelles peut être de plus de 100 m^2/d mais le plus souvent est de moins de 10 m^2/d. Localement, des fractures sub-verticales, incluant des joints et des failles, constituent les connexions entre les différentes zones d'écoulement. Les gradients hydrauliques dans l'aquifère sont le plus souvent vers le bas et les zones d'écoulement sub-horizontales latéralement étendues agissent comme des drains pour le système d'écoulement souterrain. Les différences de charges hydrauliques verticales entre les zones d'écoulement superficielles et profondes varient entre 1 m et 20 m. Les différences de charge hydraulique les plus grandes sont dans les zones de recharge en amont de la région ou les rivières Châteauguay et Chazy, ainsi que leurs affluents, aient creusé dans le till et le roc. Du till repose sur le grès sur une grande portion de la région à l'étude et il est généralement plus épais dans la partie occidentale où il peut présenter des épaisseurs dépassant 50 m. Une zone discontinue d'affleurements dénudés de recouvrement glaciaire est exposé dans la partie orientale de la zone d'étude dont la plus étendue est Altona Flat Rock. La plus grande partie de la recharge de l'aquifère de grès s'effectue dans les régions riches en affleurements et à couverture mince de till et d'argile. Les résurgences de l'aquifère de grès fournissent les débits de base des cours d'eau et rivières et créent plusieurs sources. Une suite de sources, qui sont utilisées pour l'alimentation municipale, l'embouteillage et la pisciculture émergent, avec des débits entre 1 000 et 5 000 L/min, le long de plusieurs des affluents orientaux de la rivière Châteauguay. Les principales zones de recharge des sources Châteauguay sont probablement en amont vers le sud-est, là ou le couvert de till est mince ou absent.

Introduction

The Potsdam Sandstone of Cambrian age forms a transboundary aquifer in northern New York and southern Quebec. In 2003, the Geological Survey of Canada (GSC) and the Quebec Ministry of Sustainable Development, Environment, and Parks (Ministère du Développement durable, de l'Environnement et des Parcs du Québec; MDDEP) began a four year hydrogeological assessment of the Potsdam Sandstone and younger carbonate bedrock in the Chateauguay River basin in Quebec. In 2005, the U.S. Geological Survey (USGS), in collaboration with these agencies, began a two-year compilation of hydrogeological data to characterize the Potsdam sandstone aquifer in a 1,000 km^2 area on the United States side of the border (Figure 1).

This paper presents results of the Potsdam Sandstone investigation in northern New York conducted in collaboration with the Canadian investigation in Quebec. It describes the bedrock and surficial geology of the study area, and discusses the hydrogeology of the Potsdam sandstone aquifer, including representative hydrogeological logs and sections.

Previous Investigations

Relatively little has been published on the hydrogeology of the Potsdam Sandstone in northern New York to date. Nelson *et al*. (1956) and Postel *et al*. (1956)

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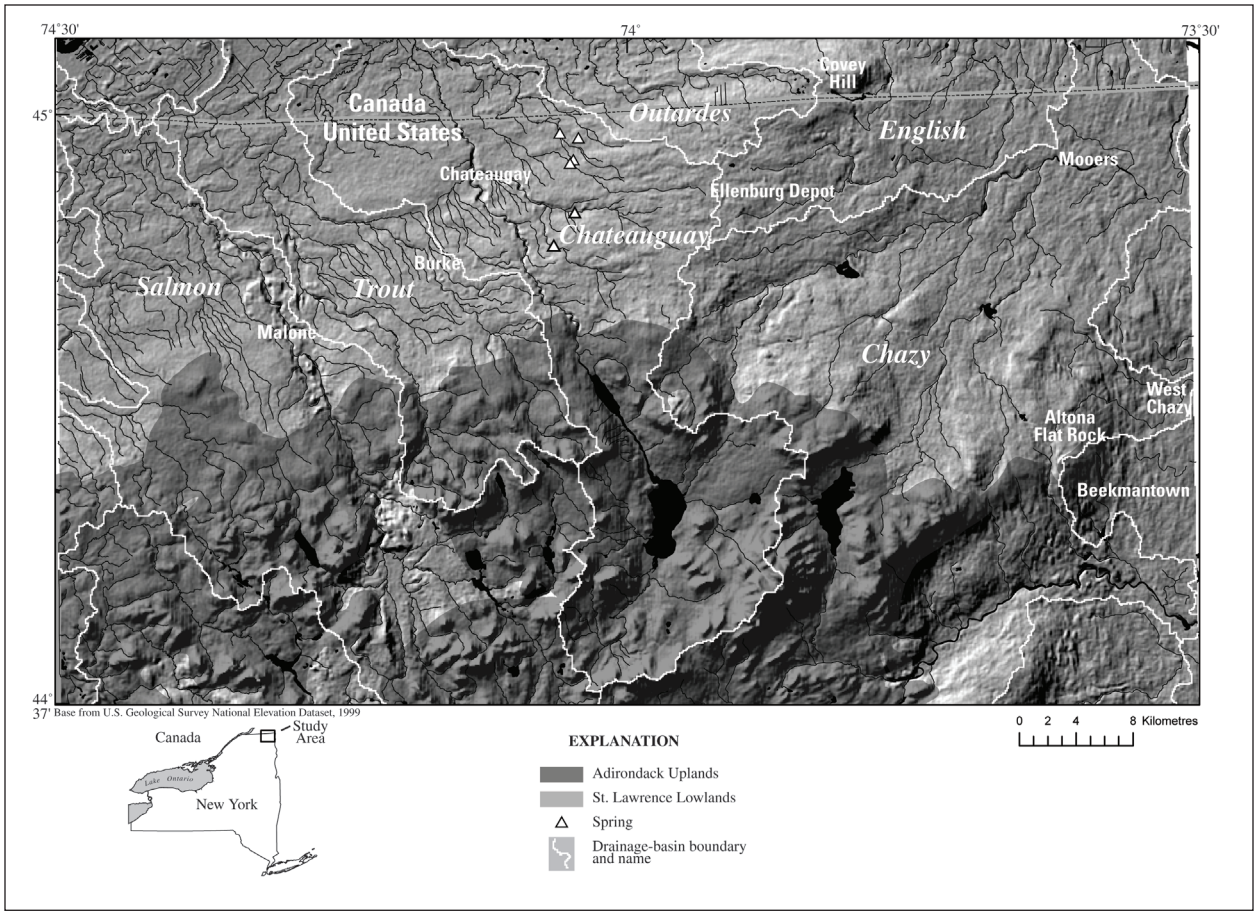

Figure 1. Drainage basin names and boundaries, and locations of pertinent geographic features in the study area, northern New York and southern Quebec.

mapped the bedrock geology of the Chateauguay and Malone areas, respectively (Figure 1). Wiesnet (1961) investigated the petrology of the Potsdam Sandstone and compiled a bedrock geology map of the Mooers area. Clark (1966) mapped the bedrock geology of the Chateauguay area in southern Quebec. Wiesnet and Clark (1966) combined their respective work in northern New York and southern Quebec to produce a transboundary bedrock map and discussed the geologic structure near Covey Hill. The bedrock geology map for New York was published by Fisher and others (1970) and that for Quebec was published by Globensky (1987). Landing *et al.* (2007; 2009) examined the stratigraphy of the Potsdam Sandstone and surrounding rocks in northern New York and Quebec. Recently published work by Sanford and Arnot (2010) describes the stratigraphic and structural framework of the Potsdam Sandstone in eastern Ontario, western Quebec, and northern New York.

MacClintock and Stewart (1965) and Denny (1974) mapped the surficial geology of the northern Adirondack Uplands and St. Lawrence Lowlands, and Woodworth (1905) and Denny (1967; 1970; 1974) mapped the surficial geology of the northeastern Adirondack Uplands and Champlain Lowlands. Cadwell and Pair (1991) compiled the surficial geology for the Adirondack Sheet of the Surficial Geology Map of New York. Franzi *et al.* (2002; 2007) described the glacial drift deposits and landforms in the region.

Methods of Investigation

Hydrogeological data on the Potsdam Sandstone aquifer were compiled from published bedrock

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and surficial geology maps, from well, spring, and streamflow records, as well as from geophysical logs. Additional features such as brittle-bedrock structures (Isachsen and McKendree, 1977), bedrock outcrops with lithologic descriptions (Wiesnet, 1961), and bedding orientations (Nelson *et al.*, 1956; Postel *et al.*, 1956) were added to the Geographic Information Systems (GIS) coverage of bedrock geology, which had been previously digitized from the published New York State map (Fisher *et al.*, 1970). Images of published bedrock geology maps by Weisnet and Clark (1966) and Clark (1966) were georeferenced and used to help interpret bedrock lithology and structure near the New York – Quebec border. GIS coverages for surficial geology, digitized from published maps by MacClintock and Stewart (1965), Denny (1974), and Cadwell and Pair (1991), were combined with new subsurface data on the character and thickness of the glacial drift deposits; these data were obtained from well logs that were collected as part of this investigation.

Also incorporated in this investigation were results from hydrogeological research conducted by the State University of New York at Plattsburgh (SUNY Plattsburgh) since the early 1990s at Altona Flat Rock and in the Little Chazy River basin (Figure 1). As part of this research, a total of 24 observation wells, ranging in depth from 4.5 to 140 m and having shallow surface casing, were drilled in the Altona Flat Rock area. The Little Chazy River basin has been instrumented with three recording meteorological stations and a nested series of 16 streamflow gauging stations.

Hydrogeological information on more than 1,400 predominantly domestic water-supply wells was compiled as part of this investigation. The well records were obtained through the New York State Department of Environmental Conservation Water Well Driller Registration Program, which began in 2000. Well locations were derived from driller-reported GPS (global positioning system) coordinates, sketch maps, and (or) street addresses. The well records contain information regarding well and casing depths, water levels, yields, and drilling logs, but only about one-quarter of the well records included drilling logs with usable descriptions of the glacial drift and (or) bedrock lithology and thickness. Well records from hydrogeological consultant reports, and logs made for prospective and abandoned Atlas missile silos, water-supply development, and groundwater contaminant investigations also were collected and compiled.

In total, about 1,500 new well records were entered into the USGS National Water Information System (NWIS) database. The drilling and hydrogeological logs were used to classify the character and thickness of the surficial materials into five categories: bedrock at or near land surface, sand and gravel, thin till, thick till with some sand and gravel, and thick till and clay; those logs also were used to classify the dominant sandstone lithology penetrated by the wells. Bedrock core from two 60 m deep wells at the abandoned missile silo site near Ellenburg Depot were obtained and studied. High-yielding springs were inventoried in the field, and the discharges from two of them, the Village of Chateauguay spring and the New York State Fish Hatchery spring near Chateauguay, were measured.

Caliper, gamma, fluid resistivity, temperature and flow logs were collected under ambient conditions from 24 wells at Altona Flat Rock, 12 wells at Ellenburg Depot, and four other wells. Acoustic televiewer, wellbore deviation, and pumped flow logs also were collected from most of the wells, and optical televiewer and magnetic susceptibility logs were collected from several wells. The ambient and pumped flow data were collected and analyzed by methods described by Paillet (2000) to estimate the transmissivity and hydraulic head of flow zones penetrated by the logged wells.

Bedrock Geology

The Potsdam Sandstone forms the base of the early Paleozoic transgressive passive-margin sedimentary rock sequence in northern New York (Clark, 1966; Otvos, 1966; Bjerstedt and Erickson, 1989; Hersi *et al.*, 2002; 2003). The formation lies unconformably over Precambrian metamorphic rocks and grades upward to the dolomitic sandstones and sandy dolostones of the overlying Theresa Formation (Figure 2). The Potsdam Sandstone irregularly grades upward from a heterogeneous feldspathic and argillaceous rock to a homogeneous, quartz-rich and matrix-poor rock. A composite of gamma logs from selected wells in northern New York and southern Quebec (Figure 2) reflects the upward decrease in feldspathic and argillaceous content in the Potsdam Sandstone.

Fisher *et al.* (1971) recognized three lithostratigraphic units in the Potsdam Sandstone: the Allens Falls, Ausable, and Keeseville Members (from base to top). The bedrock geology map for New

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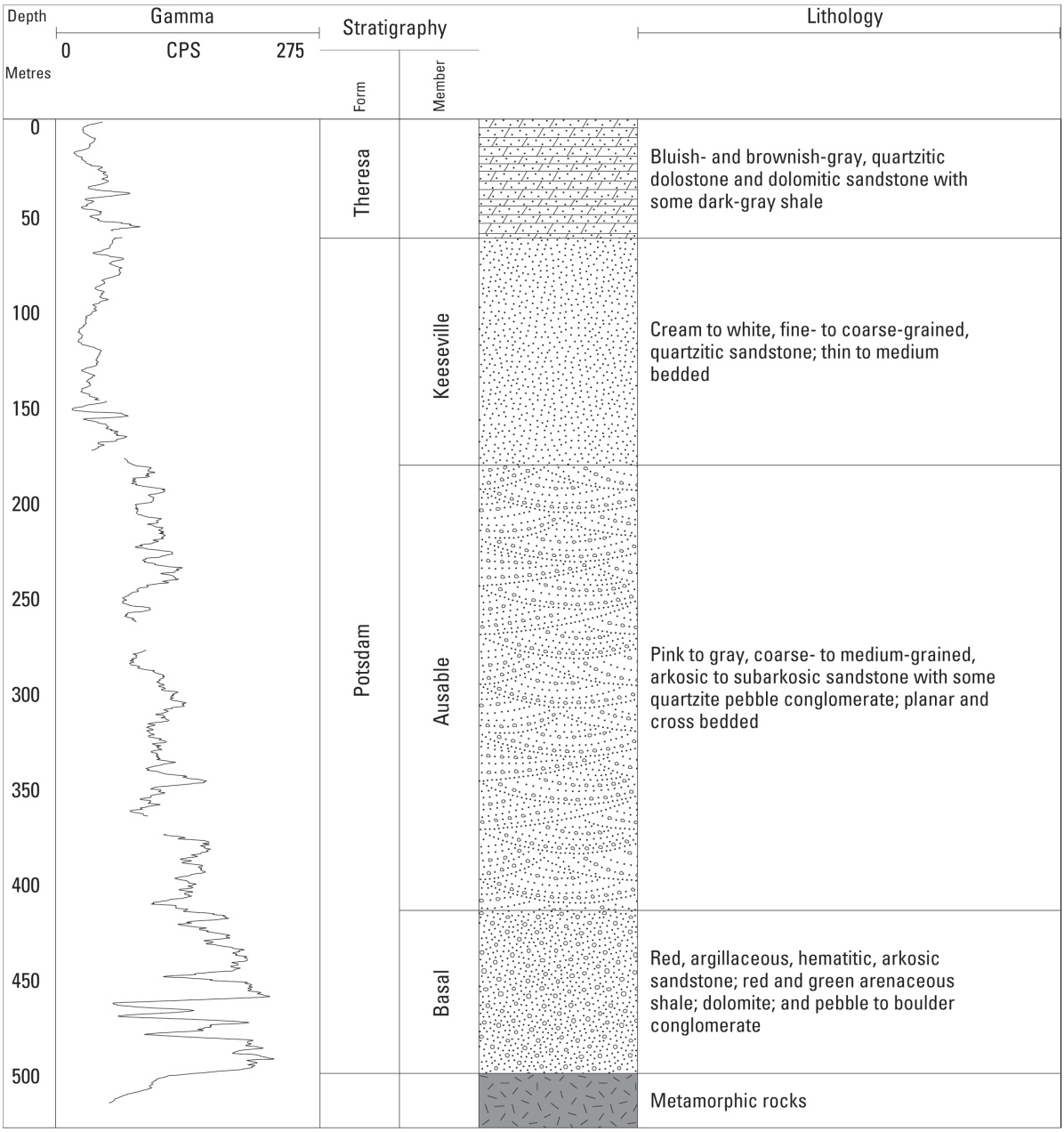

Figure 2. Stratigraphy and composite of gamma logs of the Potsdam Sandstone, northern New York and southern Quebec.

York of Fisher *et al*. (1970) did not map the Potsdam Sandstone Members as separate units.

The basal member of the Potsdam Sandstone, which is the Allens Falls Member of Krynine (1948) and also the Nicholville of Postel *et al*. (1959), is exposed in sparse outcrops in the eastern part of the study area. Fisher (1968) describes the unit as consisting of interbedded maroon or dusky red, hematitic, feldspathic, micaceous and quartzitic sandstone and shale. About 80 m of the Allens Falls Member, predominantly maroon micaceous, dolomitic fine sandstone, siltstone and shale with interbeds of sandy and shaly dolostone and dolostone, were penetrated between the Ausable Member and

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Precambrian metamorphic bedrock in a 140 m deep well drilled at Altona Flat Rock (Figures 2 and 3). The contact of the Allens Falls Member with the Ausable, observed only in the drilling and geophysical logs from the Altona deep well, is gradational. The gamma log reflects the heterogeneous composition of the Allens Falls Member and the general upward decrease in feldspathic and argillaceous content, whereas the magnetic susceptibility log reflects the general upward decrease in magnetite and other related heavy minerals. Recently published work by Landing *et al*. (2007; 2009) identified the shale- and siltstone-dominated unit that lies between the Ausable Member of the Potsdam Sandstone and the Precambrian metamorphic rocks as a new stratigraphic unit, the Altona Formation.

The Ausable Member consists predominantly of pale red to light gray, thinly to massively bedded, planar- and cross-bedded, poorly sorted, arkosic and subarkosic sandstone and conglomerate with some intra-formational conglomerate and thin mudstone interbeds (Wiesnet, 1961; Fisher, 1968; and Lewis, 1971). The Ausable Member irregularly grades upward to the pinkish gray to light gray, thinly to medium bedded, moderately to well sorted, medium to fine grained orthoquartzite of the Keeseville Member (Figure 2) (Fisher, 1968). The Keeseville Member grades upward into the dolomitic sandstones and sandy dolostones of the Theresa Formation. The Theresa Formation is distinguished from the Potsdam Sandstone by its limited feldspar content, absence of zircon, and greater rounding of the quartz particles (Wiesnet, 1961). Fisher (1968) proposed a total thickness of 450 m for the Potsdam Sandstone in the northern Champlain Lowland just east of the study area. The composite of the gamma logs (Figure 2) indicates an approximate thickness of 250 m for the Ausable Member, 100 m for the Keeseville Member, and 50 to 100 m for the Allens Falls Member in the study area.

The southern extent of the Potsdam Sandstone is marked by the Adirondack Uplands, except for a few outliers within the uplands (Figure 4). In general, bedding in the Potsdam Sandstone gently dips northwestward west of the Chambly Arch and northeastward east of the Arch (Fisher *et al*., 1971). The contact of the Potsdam with the Theresa Formation is in the northeast and northwest corners of the study area near the New York–Quebec border. The sandstone lithologies penetrated in the Potsdam by wells and observed in outcrops generally are distributed as expected; arkose is dominant near the Adirondack Uplands, orthoquartzite is dominant near contacts with the Theresa Formation, and subarkose is present in between (Figure 4). Discrepancies in this general distribution may be related to the interbedded nature and lateral variability of the Potsdam Sandstone lithologies, as well as to structural complications related to folds and faults, and the inherent subjectivity of reported drilling logs.

In Quebec, the arkose and subarkose of the Covey Hill Formation and orthoquartizite of the Cairnside Formation form the Potsdam Group (Lewis, 1971; Globensky, 1987; Hersi *et al*., 2002; and Sanford and Arnot, 2010). Contacts for the Potsdam Sandstones and younger stratigraphic units on the current geological maps of New York (Fisher *et al*., 1970) and Quebec (Globensky, 1987) do not match across the New York–Quebec border. The discrepancies may be partly explained by the differences in the stratigraphic classification among investigators. Wiesnet and Clark (1965) mapped folds and faults at and west of Covey Hill, which implies that some offsets may be structurally related.

Surficial Geology

Sedimentary bedrock in the study area is discontinuously overlain by till; fluvial, deltaic, and beach sand and gravel; and lacustrine and marine silt and clay of Pleistocene age (Figure 5). Till is the most widespread glacial deposit in the study area and is generally thickest in the western half of the study area, where its thickness may exceed 50 m. Thick till also is present in the southeast corner of the study area near Beekmantown, where many wells penetrate thicknesses of as much as 60 m. Till is generally thin in the northeastern part of the study area, except in areas underlain by drumlins (Denny, 1970). The area of thin till contains large areas of exposed bedrock that together are known as Flat Rock, a discontinuous, 30 km long, 5 km wide belt of bedrock pavements created by the catastrophic drainage of proglacial Lake Iroquois and post-Iroquois proglacial lakes during the Late Wisconsinan deglaciation of the region (Franzi *et al*., 2002).

Sand and gravel deposits of beach or deltaic origin are present in the study area and are largely associated

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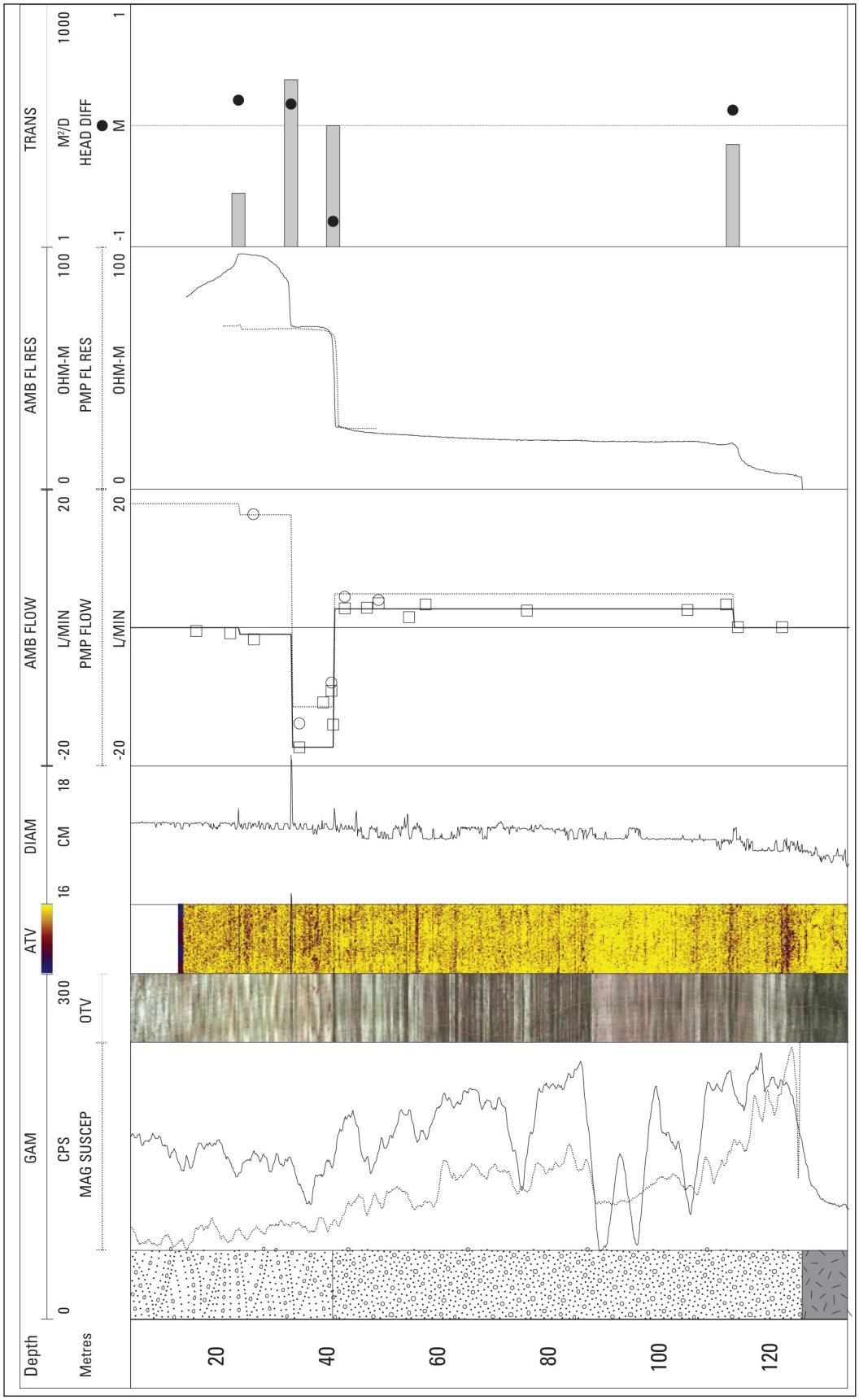

Figure 3. Geophysical logs of a well that penetrated the lower Potsdam Sandstone at Altona Flat Rock (Location shown on Figure 1). Log abbreviations are as follows: GAM, gamma (counts per second); MAG SUSCEP, magnetic susceptibility (values increase to the right); OTV, optical televiewer; ATV, acoustic televiewer; AMB FLOW, ambient flow (litres per minute); PMP FLOW, pumped flow (litres per minute); AMB FL RES, ambient-fluid resistivity (ohm-metres); TRANS, flow zone transmissivity (metres squared per day); and HEAD DIFF, difference between flow zone and composite head (metres).

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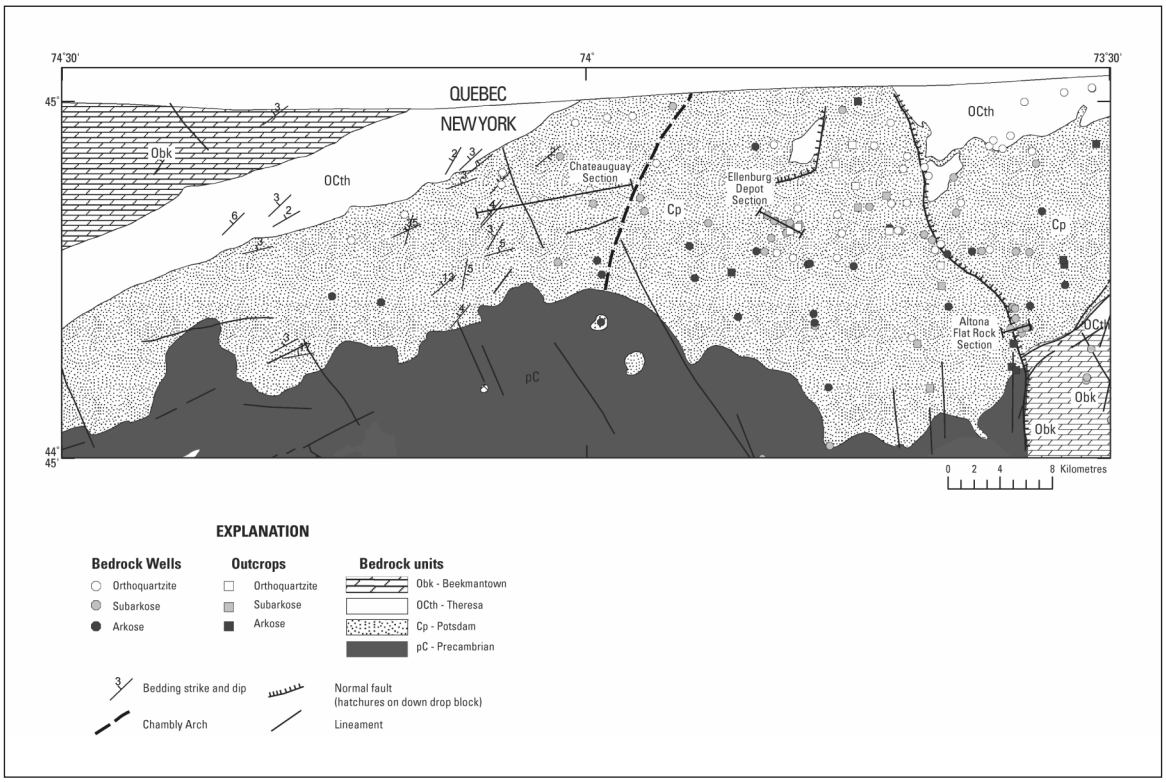

Figure 4. Bedrock geology of the study area, northern New York (modified from Nelson *et al*. (1956), Postel *et al*. (1956), Fisher *et al*. (1970), and Isachsen and McKendree (1977)).

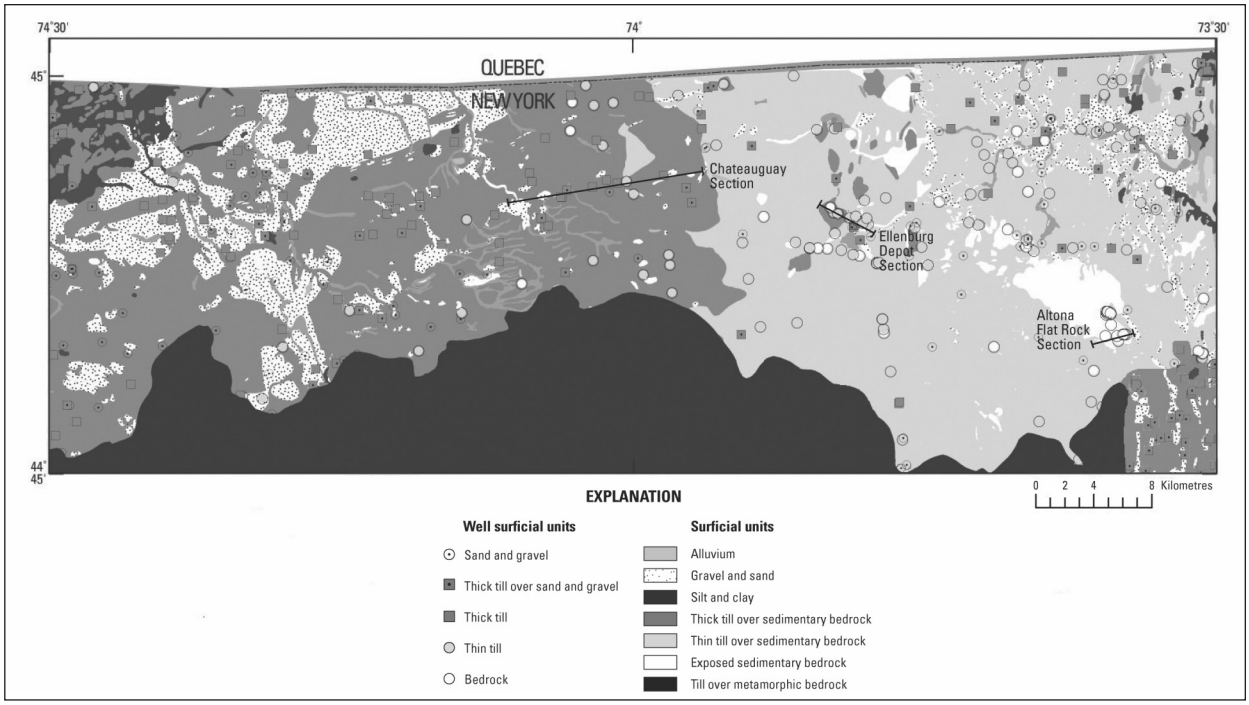

Figure 5. Surficial geology of the study area, northern New York (modified from MacClintock and Stewart (1965), Denny (1974), and Cadwell and Pair (1991)).

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with proglacial Lake Iroquois. A large area of beach gravel and dune sand is present in northwestern part of the study area and extends northeastward into Quebec (Figure 5). The beach deposits resulted largely from wave action in the Champlain Sea, which winnowed fine-grained sediment from littoral-zone deposits and left the coarse sand and gravel behind as a lag deposit (MacClintock and Stewart, 1965). The beach sand and gravel forms a veneer generally less than 3 m thick that overlies till; drilling logs indicate that the underlying till in this area is 12 to 40 m thick. MacClintock and Stewart (1965) mapped several deltas that consist chiefly of pebbly sand and were built into the shallow Champlain Sea by northward flowing streams carrying glacial meltwater. An example of these deposits is present in the western part of the study area at Malone, where a large delta just north of the town marks the extent of a proglacial lake shoreline (Figure 5). Upstream (south) from this delta, the Salmon River valley is filled with kame terrace deposits of sand and gravel. This is the largest area of ice-contact sand and gravel that has been mapped in the study area. Smaller, isolated kames are scattered throughout the study area.

A group of unique glacial features in the central part of the study area are the Chateauguay Channels, mapped and described by MacClintock and Stewart (1965) (Figure 5). These features consist of a series of ice-marginal drainage channels that generally slope westward at oblique angles to the present-day topographic slope. The channels are cut into the underlying till and are partly filled with cobble and boulder lag deposits. The channels range from 8 to 23 m deep and from 90 to 120 m wide, and occur as short, relatively straight or gently curved segments that range in length from a few tens of metres to a kilometre or two. The lower part of the channel system terminates at the former shoreline of proglacial Lake Iroquois (MacClintock and Stewart, 1965). The logs of several wells drilled through or adjacent to these channels indicate that they are underlain by varying thicknesses of sand, gravel, and cobbles that locally rest directly on bedrock. Denny (1974) suggested that the channel system mapped by MacClintock and Stewart (1965) may extend farther eastward as far as the divide between the St. Lawrence (Chateauguay River) and Champlain (Chazy and English Rivers) basins.

Hydrogeology

The Potsdam Sandstone forms a fractured rock aquifer of regional extent. As in most bedrock, the upper several metres typically is weathered and fractured and, where saturated, readily transmits groundwater. Bedding-related fractures commonly form sub-horizontal flow zones of relatively high transmissivity. The vertical distribution of flow zones is variable; spacings of less than 10 m are common. Transmissivity of individual flow zones may exceed 100 m^2/d but typically is less than 10 m^2/d. Joints and high angle faults locally form hydraulic connections between sub-horizontal flow zones. The 60 m deep, 24 m diameter shaft excavation at the missile silo site near Mooers (Figure 1) intersected a near vertical fault in the Keeseville Sandstone (U.S. Army Corps of Engineers, 1962).

Most recharge to the Potsdam Sandstone aquifer occurs in areas of thin, discontinuous till and exposed bedrock; little recharge occurs in areas where it is overlain by thick till and clay. Discharge from the sandstone aquifer provides stream and river baseflow and is the source of many springs.

The median well depth, casing depth, and yield reported for wells completed in the Potsdam Sandstone are 35 m, 6.7 m, and 75 L/min, respectively. Well depths range from 9 to 110 m, and casing depths range from 1 to 33 m. Domestic wells reportedly yield as much as 750 L/min. The median well yield for the three principal sandstone lithologies, and the number of wells used to calculate the median, are as follows: arkose, 75 L/min (54 wells); subarkose, 55 L/min (77 wells); and orthoquartzite, 85 L/min (41 wells).

Lateral continuity of flow zones in Potsdam Sandstone has been documented by multiple-well aquifer tests near Covey Hill, on the Quebec side of the border (Figure 1), where water levels at observation wells as far as 1,000 m from pumping wells were affected (Nastev *et al.*, 2008). Hydrogeologic information from three selected areas in northern New York supports the presence of laterally extensive flow zones in the Potsdam Sandstone.

Altona Flat Rock

Altona Flat Rock is the largest of the discontinuous belt of bedrock pavements that extend from Covey Hill southeastward to the Champlain Valley (Figures

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1 and 5). Much of the Altona Flat Rock area is drained by the Little Chazy River, which originates in upland forests in the northeastern foothills of the Adirondack Uplands and flows eastward across the Champlain Lowland before discharging into Lake Champlain. The river descends steeply at an average gradient of 18 m/km from the eastern margin of Altona Flat Rock into the Champlain Lowland near West Chazy. The Champlain Lowland is characterized by low relief, thick lacustrine and marine deposits, and an average stream gradient of about 2.5 m/km.

Baseflow analyses of the Little Chazy River (Hoenwarter *et al*., 2004; Cubley, *et al*., 2005; Lehman *et al*., 2006) indicate that streamflow gains and losses are not uniform in this river's basin. Gaining conditions predominate in the headwater tributaries, whereas losing conditions occur where the Little Chazy River traverses Altona Flat Rock (Franzi and Adams, 1999). The Little Chazy River may lose more than half of its summer baseflow in this reach as it recharges the sandstone aquifer. Baseflow increases as the river descends from Altona Flat Rock into the Champlain Lowland; here it is fed by direct discharge from the Potsdam Sandstone and by inflow from several springs along this reach. Some springs discharge more than 1,000 L/min. During low flow conditions in late summer, nearly all baseflow of Little Chazy River is generated in this reach (Lehman *et al*., 2006).

Bedding in the Potsdam Sandstone gently dips to the northeast at Altona Flat Rock, and extensive exposures of the arkosic and subarkosic sandstone of the Ausable Member are present. A 140 m deep well that started in the Ausable Member penetrated 80 m of the Allens Falls Member before it penetrated metamorphic bedrock at 126 m (Figures 2 and 6). Correlation of gamma logs from wells on either side of the normal fault bordering the Champlain Lowland (Figures 4 and 6) suggests 100 m of vertical offset in the bedrock units.

The 140 m deep well at Altona Flat Rock intersected four flow zones: two in the Ausable unit with transmissivities of 5 and 120 m^2/d, a zone near the Ausable-Allens Falls Member contact with a transmissivity of 32 m^2/d, and a zone in the lower part of the Allens Falls unit with a transmissivity of 18 m^2/d (Figure 3). Hydraulic heads in the shallow and deep zones were 1 m higher than in the flow zone near the Ausable-Allens Falls contact.

The most transmissive flow zone in the deep well is intersected at the same stratigraphic horizon by two shallow upslope wells (Figure 6). The vertical offset of the flow zone between the deep and shallow wells is greater than would be expected from the dip of bedding exposed at the surface and thus suggests the presence of a minor normal fault. The transient response of flow in the deep well during pumping of one of the shallow wells indicates a vertical connection between the flow zone and zones above and below it; this is consistent with the presence of a high angle fracture zone such as a normal fault.

The average vertical spacing between flow zones in the 24 shallow flowmetered wells at Altona Flat Rock is 10.7 m. Transmissivity of the zones ranges from less than 1 to more than 100 m^2/d, with a median of 8 m^2/d. Hydraulic head in wells that penetrated multiple zones was 1 to 2 m higher in the upper zone than in the lower zone. A confined aquifer response and a metre of drawdown were measured in observation wells 100 to 200 m from wells pumping at low rates.

Hydrographs from wells at Altona Flat Rock indicate a range of aquifer conditions in the Potsdam Sandstone. Hydrographs showing rapid responses to precipitation suggest fractured zones that are well connected with the shallow flow system and with surface water (Figure 7a). Hydrographs from other wells show less variability and longer lag times; a response typical of semi-confined and confined aquifers (Figure 7b). Hydrographs from some of the wells show a threshold water level (Figure 7c), whereby water levels remain at relatively shallow depths with little fluctuation for most of the year, but during prolonged dry periods, typically during the late summer, drop below the threshold level and fall rapidly, by as much as 7 m over a few days. The threshold water level appears to be fairly constant at each well with this hydrograph pattern. Water levels at these wells recover rapidly after recharge to an elevation above the threshold. These hydrographs reflect rapid recharge during wet periods from near-surface fractures connected to ephemeral and intermittent surface water sources. Depletion of these sources during dry periods allows water levels to drop precipitously in response to the lower hydraulic heads in the deeper fractured zones.

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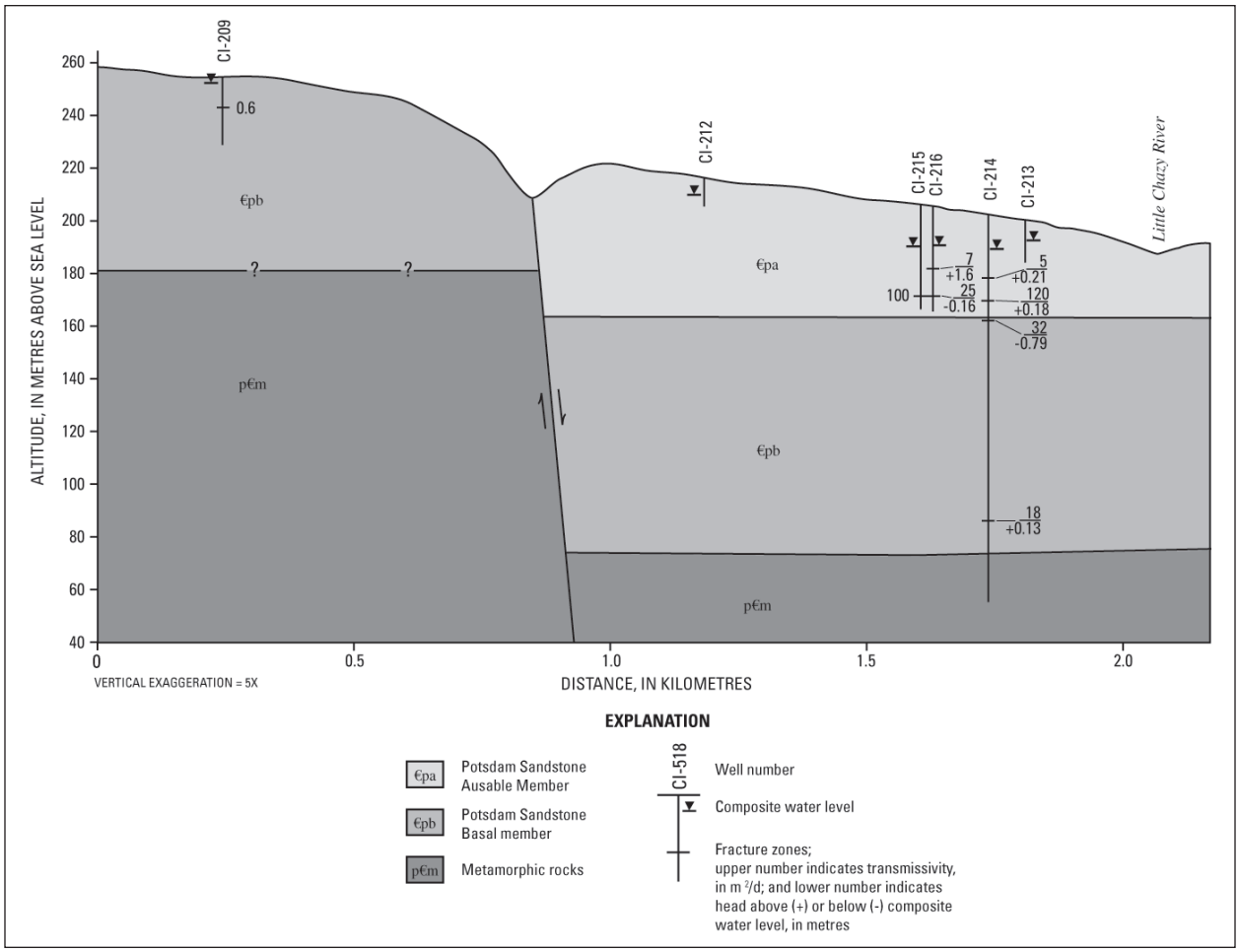

Figure 6. Hydrogeological section of Altona Flat Rock area, northern New York (location of section is shown in Figures 4 and 5).

Ellenburg Depot Area

The Potsdam Sandstone in the Ellenburg Depot area dips gently to the northeast. The sandstone is discontinuously overlain by thin till; small patches of thicker till are present locally, and most of these patches cover only a few square kilometres (MacClintock and Stewart, 1965). Ice-contact deposits of sand and gravel form a 4 km long ridge known as the Ellenburg moraine, which is cut by the North Branch of the Great Chazy River. The North Branch flows on bedrock ledges formed by thick-bedded, resistant orthoquartzite beds that result in several small waterfalls.

A laterally extensive fractured zone near the Ausable-Keeseville contact was penetrated by eight wells drilled along a 600 m long transect from an upland recharge area to the North Branch discharge area (Figure 8). The wells penetrated shallow and deep flow zones in the sandstone; average vertical spacing between flow zones was 8.8 m. Each of the wells penetrated a fractured zone with low hydraulic head at an elevation of about 245 m above sea level. Flowmeter measurements under ambient measurements in the open hole wells indicated downward flows at rates greater 4 L/min from shallow fractures (260 to 290 m above sea level) to the 245 m zone. In the well furthest upgradient, about half of the downward flow from shallow fractures was received by a zone at 275 m above sea level, and the rest of the flow was received by the 245 m zone. The 245 m zone penetrated by the deep well nearest the river received upward flow from a fracture at 215 m above sea level in addition to downward flow from shallow fractures. Core and geophysical log analyses indicate that the fractured

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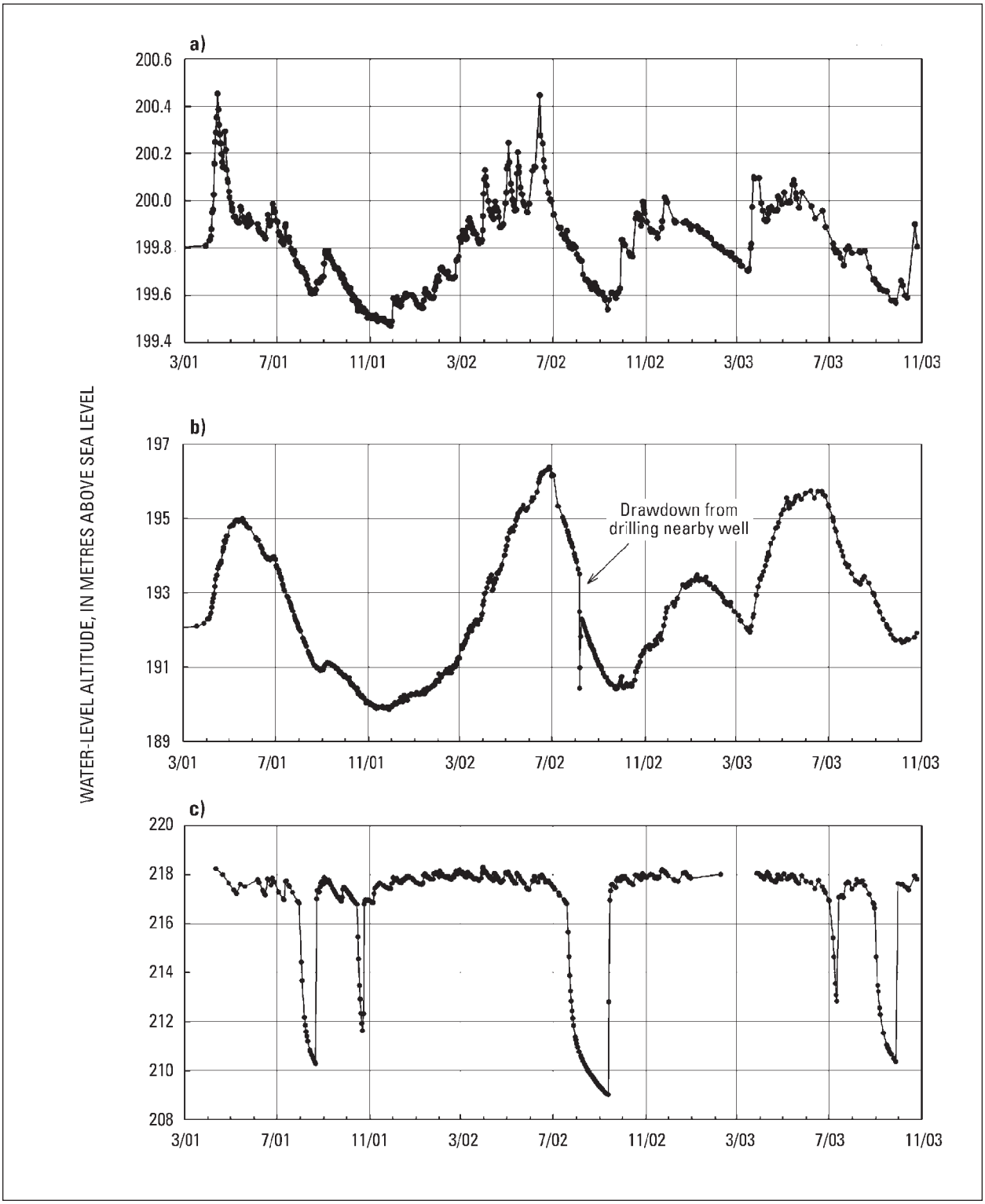

Figure 7. Hydrographs (March 2001 through November 2003) from selected wells at Altona Flat Rock showing: a) rapid response of a shallow system, b) subdued response of a semi-confined to confined system, and c) threshold response related to connection with ephemeral surface water.

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zone at 245 m above sea level consists of a series of sub-horizontal fractures associated with thin, coarse-grained beds that are present within thicker bedded and well-cemented orthoquartizite.

Hydraulic head differences between the shallow zones (260 to 290 m above sea level) and the zone at 245 m may have been about 10 m, according to a model analysis of these ambient downward flows. A second set of ambient flowmeter measurements collected in the furthest upgradient well, when its composite water level was 2.5 m higher than during the previous measurements, indicated downward flows at rates of less than 0.2 L/min. Comparison of the flow measurements under these low and high water level conditions suggests that the deep fractures receive little recharge during dry periods but continue to drain, and thereby, create the maximum downward hydraulic gradients in the sandstone aquifer.

Chateauguay Area

The Potsdam Sandstone in the Chateauguay area dips gently to the northwest. It is overlain by till, typically 15 m to more than 50 m thick, from just east of the Chateauguay River to the drainage divide of the Salmon River to the west (Figures 1 and 5). The till contains scattered thin beds of sand and gravel, most commonly near the contact with the underlying bedrock. The till thins along a bedrock high to the east-northeast, and near the Chateauguay River's eastern drainage divides with the English and Chazy Rivers. A network of ice-marginal channels, diagonal to the present day topographic slope, are cut at least 8 m into till and, toward the east, close to or into bedrock. Deltaic sands grading to a series of proglacial lake levels overlie the till locally. Postglacial erosion has carved a deep gorge along the Chateauguay River through the till and 15 to 30 m into the underlying sandstone. The bottom of the Chateauguay bedrock gorge drops northward from 290 to 170 m above sea level along its 8 km reach.

A series of major springs, which are used for municipal, bottled-water, and fish-hatchery supply, discharge from 1,000 to 5,000 L/min from the Potsdam Sandstone adjacent to several tributaries east of the Chateauguay River (Figures 1 and 9). The springs align roughly in a north-south direction over a distance of 8 km and range from 320 to 170 m

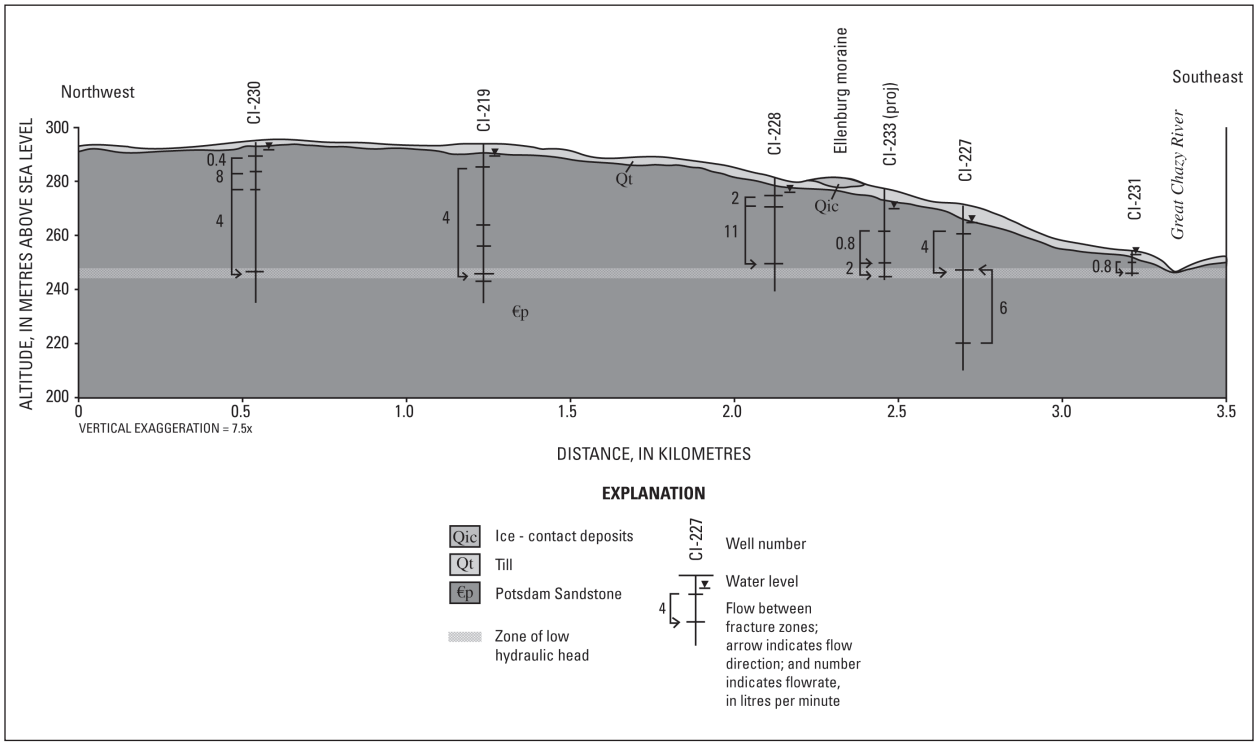

Figure 8. Hydrogeological section of Ellenburg Depot area, northern New York (location of section is shown in Figures 4 and 5).

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above sea level with vertical spacing ranging from 15 to 45 m. Drilling and geophysical logs indicate that wells in this area penetrate a series of sub-horizontal fracture zones with differing hydraulic heads. Water levels in wells completed in shallow, fractured bedrock are less than 10 m below land surface, whereas those in wells that tap deeper fractures are typically more than 30 m below land surface. Drillers report zones of lost circulation in many deep wells; cascading water is common in wells that penetrate both shallow and deep flow zones. The ambient flowmeter log of a deep well east of Chateauguay, which had a composite water level of 35 m below land surface, revealed the presence of downward flow to a fractured zone of low hydraulic head at 84 m below land surface.

The average vertical spacing between flow zones in two flowmetered wells that penetrated the orthoquartzite of the Keeseville Member is 7 m. The median transmissivity of the flow zones in one of these wells, where the orthoquartzite is overlain by little or no till, is 34 m^2/d, whereas the median transmissivity of the flow zones in the other well, where the orthoquartzite is overlain by thick till, is 1.4 m^2/d. The hydraulic head in the deep bedrock fractures in a cluster of three wells at the thick till site near Burke was 18 m lower than the head near the top of fractured bedrock, and 26 m lower than the head in the surficial sand (Figure 10).

The hydrogeologic investigations in the Ellenburg Depot area to the east and the Covey Hill area in southern Quebec (Nastev *et al.*, 2008) indicate the presence of areally extensive bedding-related fracture zones in the Potsdam Sandstone aquifer. These and similar observations from the Chateauguay area are consistent with a conceptual model wherein the Chateauguay springs and bedrock gorge are points of discharge for a gently dipping series of transmissive fracture zones. The major recharge areas for the springs are presumably upgradient to the southeast, where the till cover is thin or absent. The abandoned ice-marginal channels, where cut into or close to bedrock, may serve as focused points of recharge.

Summary and Conclusions

The Potsdam Sandstone forms a regional transboundary aquifer in northern New York and southern Quebec. The Potsdam Sandstone is a gently dipping sequence

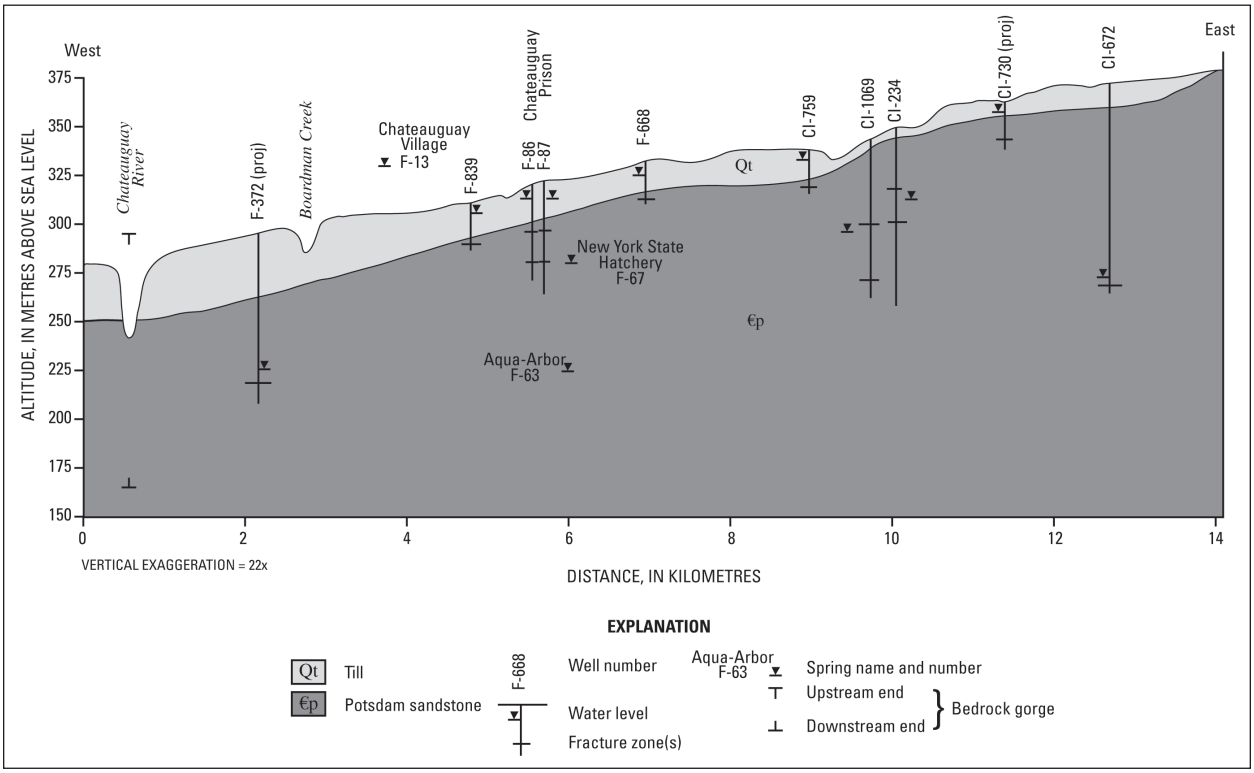

Figure 9. Hydrogeological section of the Chateauguay area, northern New York. (location of section is shown in Figures 4 and 5).

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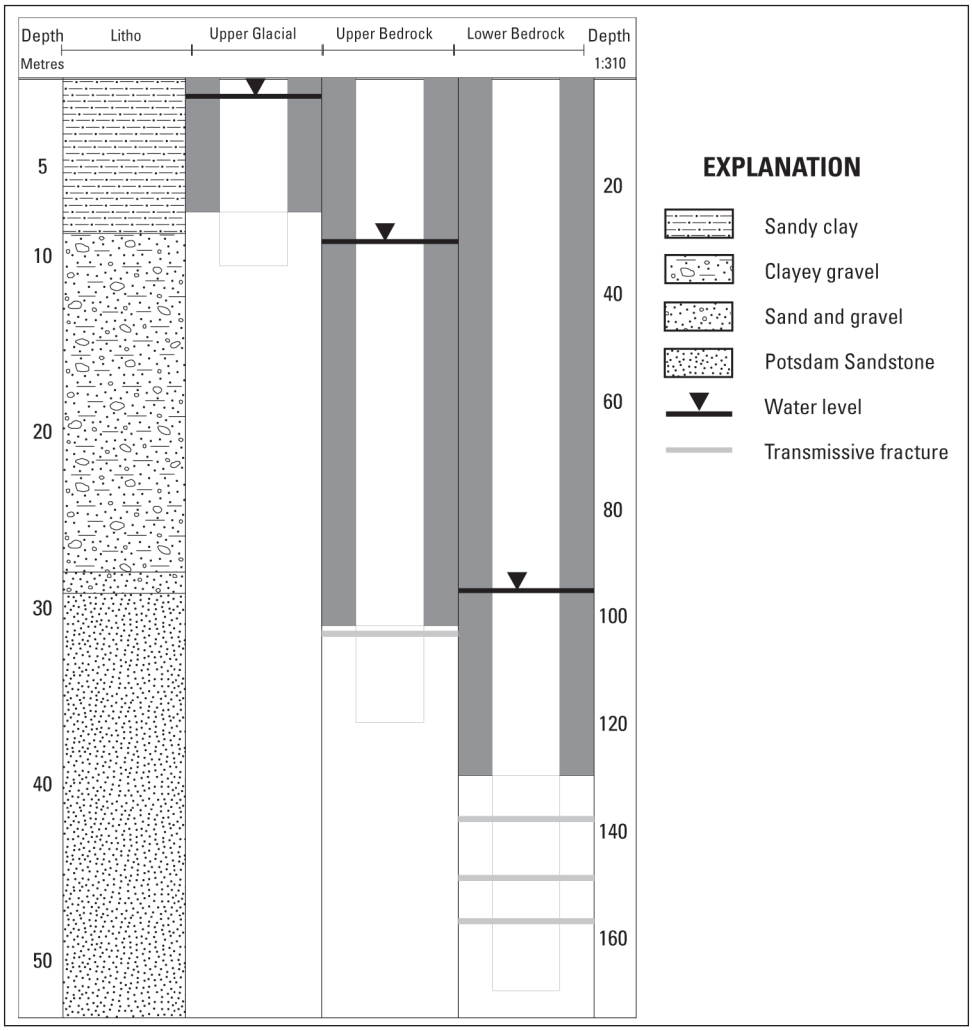

Figure 10. Construction, lithology and water levels (April 2006) in a well cluster near Burke, northern New York (location shown on Figure 1).

of arkose, subarkose, and orthoquartzite that unconformably overlies Precambrian metamorphic bedrock. The Potsdam Sandstone irregularly grades upward over a thickness of 450 m from a heterogeneous feldspathic and argillaceous rock to a homogeneous, quartz-rich and matrix-poor rock.

Analyses of data from 1,500 well records and core, geophysical, and flowmeter logs indicate that bedding-related fractures in the Potsdam Sandstone commonly form sub-horizontal flow zones of relatively high transmissivity. The upper several metres of the sandstone also tend to be weathered and fractured and, where saturated, readily transmit groundwater. High angle fractures, including joints and faults, locally provide vertical hydraulic connection between sub-horizontal zones. The vertical distribution of the sub-horizontal flow zones is highly variable; spacings of less than 10 m are common. Transmissivity of individual flow zones typically is less than 10 m^2/d but may exceed 100 m^2/d locally. Hydraulic head gradients in the Potsdam Sandstone aquifer commonly are downward, with laterally extensive series of sub-horizontal flow zones serving as drains for the groundwater flow system. Vertical hydraulic head differences between shallow and deep flow zones range from 1 m to more than 20 m. The maximum head differences are in recharge areas upgradient from the area in which the Chateauguay and Chazy Rivers, and their tributaries, have cut into till and bedrock.

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Till overlies the Potsdam Sandstone in much of the study area and is generally thickest in the western part, where its thickness may exceed 50 m. A discontinuous belt of bedrock pavements stripped of glacial drift deposits extends across the eastern part of the study area; the largest of these stripped areas is Altona Flat Rock. Most recharge to the Potsdam Sandstone aquifer occurs in areas of thin, discontinuous till and exposed bedrock; little recharge occurs where the aquifer is overlain by thick till and clay. Discharge from the sandstone aquifer provides stream and river baseflow, and is the source of many springs. Under summer baseflow conditions, a Chazy River tributary loses flow and recharges the Potsdam Sandstone aquifer as it crosses Altona Flat Rock, but then gains flow as it descends into the Champlain Lowland, and is fed by direct discharge from the sandstone and by inflow from several springs, some of which discharge more than 1,000 L/min. A series of major springs that are used for municipal, bottled-water, and fish-hatchery supply discharge from 1,000 to 5,000 L/min adjacent to several tributaries east of the Chateauguay River. The major recharge areas for the Chateauguay springs are probably upgradient and to the southeast, where the till cover is thin or absent. Abandoned ice-marginal channels, where cut into or close to bedrock, may serve as focused points of recharge.

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