3D geological model of a deltaic aquifer system formed in a buried channel of the St. Lawrence River in Quebec City, Canada.

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ABSTRACT
Quaternary sediments in the vicinity of Quebec City are the result of a uniquely complex erosional and depositional system. The recent discovery of a deltaic aquifer system covered by intertidal silts (aquitard) in a buried channel of the Proto St. Lawrence River illustrates the importance of understanding the rapid paleoenvironmental changes induced by late- and postglacial relative sea level changes. These have a direct bearing on deltaic sediment architecture and hence on the distribution of hydraulic properties in the buried valley aquifer. A 3D geological model was developed to define the subsurface distribution of the hydrostratigraphic units and allows the interpolation of hydraulic properties in a regional framework incorporating the observed hydrofacies distribution.

RÉSUMÉ
L'architecture des sédiments quaternaires dans les environs de la ville de Québec résulte de l'évolution complexe d'un système d'érosion-sédimentation marine, estuarienne et fluviale. La découverte récente d'un delta enfoui sous la Basse ville de Québec illustre l'importance de bien comprendre les changements rapides des conditions paléoenvironnementales. Ces conditions ont une influence directe sur la structure sédimentaire de même que sur la distribution des propriétés hydrauliques. Un modèle géologique 3D permet de définir les limites spatiales des différentes unités hydrostatigraphiques, et ainsi contraindre l'interpolation des propriétés hydrauliques à l'intérieur des différents hydrofacies.

1 INTRODUCTION

Since the 1980s, computer-aided design has allowed the simulation of increasingly complex 3D structures. Many fields, from medicine to biology and geology, use this technology to represent objects in three dimensions (Kolterman and Gorelick, 1996). In Quaternary sediment aquifers, stratigraphic architecture and the associated 3D distribution of hydraulic properties are the required inputs for modelling the aquifer behaviour (Domenico and Schwartz, 1990). However, the integration of data from multiple sources and uneven quality required to construct a 3D model in glaciated regions involves a good understanding of the geological complexity.

The last deglaciation in the vicinity of Quebec City was marked by rapid changes in ice dynamics (Parent et Occhietti, 1999; Paradis and Bolduc, 1999) and at least a few sea level fluctuations (Dionne 2001). The recent discovery of a deltaic aquifer system covered by a sheet of intertidal silts (aquitard) in a buried channel of the early St. Lawrence River illustrates the importance of understanding rapid paleoenvironmental changes induced by late- and postglacial relative sea level (RSL) changes. Due to the rapid succession and variability of sedimentary environments, characterizing this buried deltaic system represents a challenge, particularly the interpolation of hydraulic properties.

2 STUDY AREA

Quebec City is located on the north shore of the St. Lawrence River at the convergence point of the Appalachian Highlands, the central St. Lawrence Lowlands and the Laurentian Highlands (Figure 1). The narrowing and rising of the St. Lawrence valley floor in the study area played a major role on deglaciation patterns and on the ensuing marine invasion in the Central St. Lawrence Lowlands. Nearby highland regions are covered by thin and fairly discontinuous glacial sediments, which were locally winnowed and reworked by the action of waves below marine limit (180-210 m ASL). Local bodies of glaciofluvial sediments occur mainly but not exclusively above marine limit (Bolduc *et al.*, 2003).

In the vicinity of Quebec City, the valley is partly covered by marine, fluvial and intertidal sediments that were deposited by a uniquely complex suite of Late Quaternary erosional and depositional systems. Initially, the system was controlled by rapid glacial isostatic uplift and emergence of the sill separating the Champlain Sea basin from the Goldthwait Sea basin.

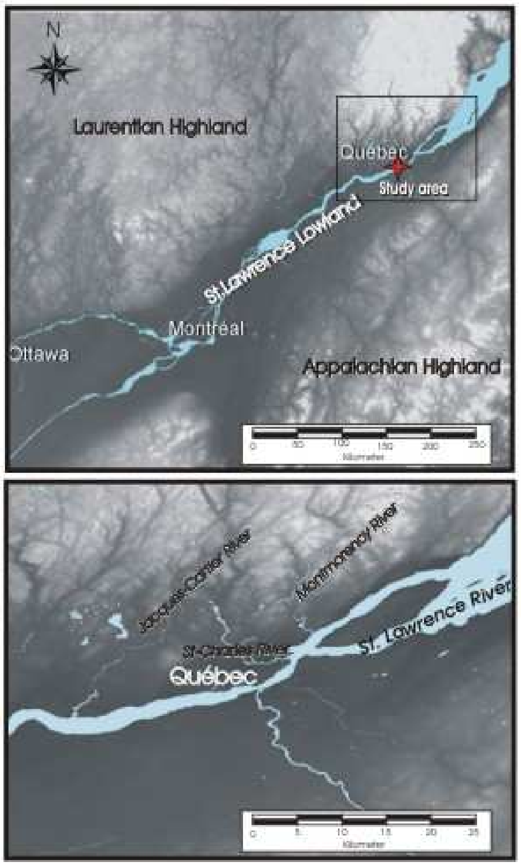

Figure 1. Location of the study area.

Subsequently, in middle to late Holocene time, the system was controlled by second order RSL fluctuations, as observed by Dionne (2001) in the St. Lawrence Estuary.

The erosional and depositional record in the vicinity of Quebec City results from the interplay of the three major rivers of the region: the Proto-St. Lawrence River and its two main local northern affluents, the Jacques-Cartier and Montmorency rivers.

3 METHODS

3.1 3D model

Geological survey records are the first source of information in the elaboration of a 3D geological model. Discontinuous data such as borehole records, testhole data, grain size characteristics or sedimentary structures are used to complement this information. Other sources such as engineering reports or geophysical surveys can complete the information (Kaufman and Martin, 2008). In addition to over 5000 archived boreholes that were compiled, new data consisting of 11 new boreholes, 40 seismic profiles and 300 ambient noise (HVSR) measurements were acquired and integrated through a gOcad platform to construct the 3D framework model. Interpretative information contained in geological maps (Bolduc et al., 2003) was also used in the integration process.

Following the quality assessment of subsurface data as proposed by Ross et al. (2005), cross-sections were prepared as an intermediate step in the construction of the 3D model. Standardized well markers were then placed on the well logs and used to constrain the interpolation of geological surfaces. When needed, control points were also added to optimize interpolation. These surfaces are subsequently employed as common limits of geological regions during construction of the voxet model. The 3D grids regions are used to create hydraulic sub-units for hydrofacies interpolation.

3.2 Hydrofacies

Forthcoming hydrogeological data will also be integrated to the 3D model during the next phase of the project, although their number, spatial distribution and quality will probably not be sufficient to efficiently characterize the entire site. To overcome this and to provide better insight into the distribution of hydraulic properties, the Quebec City area is compared to a nearby site (Valcartier Garrison), where deltaic depositional environments are quite similar, and for which an extensive characterization has been conducted (Lefebvre et al., 2004).

In the Quebec City buried delta, 11 cone penetration tests (CPT) were carried out during the summer of 2007. Each stratigraphic interpretation was correlated with samples from a borehole dug next to the testhole. Valcartier hydrofacies defined by Ouellon et *al* (2008) could be identified on the basis of CPT responses (Fauveau 2006). Limits used to recognize hydrofacies at Valcartier from CPT using the Eslami and Fellenius (2004) interpretation chart were modified to adapt them to the Quebec City setting (Figure 2). The limit of hydrofacies 1 was modified to exclude a coarse sand units found in the Quebec City delta area. This is because the tip stress log of this unit is lower than 3.9 (top limit of hydrofacies 1 in Fauveau (2006)) and should be placed in hydrofacies 4 instead of hydrofacies 1. The new proposed limit is the line between sand and finer sediment in the Eslami and Fellenius chart (Figure 2).

Hydrofacies 1 represents the aquitard units while hydrofacies 2 to 4 represent the deltaic unit, from the finer to the coarser grain sizes. The 5th hydrofacies contains glacial units and other unclassified sediments. At this point, we consider the hydraulic properties as similar in both deltas. Future work will allow testing of this preliminary assessment.

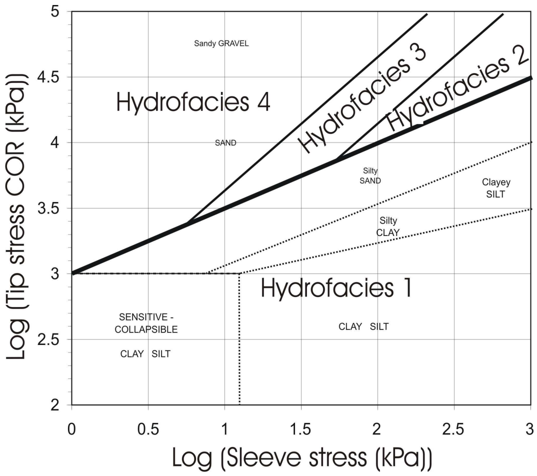

Figure 2. Hydrofacies interpretation based on the Eslami and Fellenius chart (modified from Ouellon, 2006).

Table 1. Description of hydrofacies (modified from Ouellon *et al.*, 2006)

Hydrofacies	Description
1	Clay, silts, sandy silt
2	Fine sand to silty sands
3	Fine to medium sands
4	Medium to coarse sands, gravelly sands, sandy gravel, gravels
5	Diamictons, Till

4 RESULTS

4.1 3D model

Figure 3 shows the total thickness of surficial sediments in the study area and the location of vertical cross-sections cutting across the 3D geological model shown on Figure 4.

The 3D model of Quebec City shows the complex architecture of Quaternary sediments in the main buried valley as well as in adjacent terrains. The top of bedrock surface displays a twin-branched valley underlying the lower town (Figure 3). The south branch is shown in Figure 4. Stratified sediments of presumed pre-Late Wisconsinan age are preserved in the deepest part of the valley. A continuous till unit is observed covering up this older interglacial or interstadial sand and the underlying glacial unit. Till topography is mostly parallel to the rock surface.

The 3D sedimentary architecture reveals a large subsurface deltaic complex that was emplaced at the mouth of an early channel of the St. Lawrence River as it entered the Goldthwait Sea about 10 000 years BP to 8 700 years BP. As a nearly continuous sheet of intertidal silts covers this deltaic unit, it had remained unrecognized as such until now. Interestingly a sand unit had been described by Cockburn (1984) in a geotechnical review of the area. Marine silty clays can be observed in a few boreholes below the delta. The main deltaic body consists of sand and gravelly sand with observed thicknesses ranging from 10 to 30 m. The heterogeneity of borehole descriptions and the difficulty of interpolating contacts between boreholes are the main challenges when constructing such a sophisticated 3D stratigraphic model. For example, expected medium-scale features such as gravelly channels or fine sand to silt lenses are difficult to trace laterally. Figure 4 illustrates grain size zones observed in some deltaic sub-units.

As freshwaters from Lake *Lampsilis*, the successor basin of the Champlain Sea, discharged into the Goldthwait Sea, a series of large estuarine channels were incised through the Quebec City sill during regressive stages

4.2 CPT description

An example of stratigraphic description with the corresponding hydrofacies determined from CPT is shown in Figure 5. The intertidal silt aquitard is well represented by hydrofacies 1. At a depth of about 2 to 4 m, a transitional unit is evidenced between the intertidal silt and typical deltaic units. High hydrofacies heterogeneity is observed in the deltaic unit. However, materials tend to become coarser with depth at this site.

Borehole heterogeneity shown in Figure 6 illustrates a high variability in the distribution of hydrostratigraphic units. For example, the thickness of the intertidal silt unit ranges from less than 1 m at the periphery to over 4 m in the central area. Locally, regressive sandy beach-ridge is observed in borehole FL07-15.

5 DISCUSSION

5.1 Geological framework model

Paleo-environmental changes since the last glaciation were controlled by complex interactions between ice retreat, marine incursion and subsequent regression. Located at the junction between the Champlain Sea and Goldthwait Sea basins, the Quebec City sill had an important role in the daily exchange of water between the two basins, particularly as water levels fell. High energy benthic environments were created and these had a major impact on sedimentation patterns across much of the region.

The early, main and late phases of the Champlain Sea and the ensuing Lake *Lampsilis* are currently interpreted as recording a fairly regular drop of sea level (Parent and Occhietti, 1999). Until now, the available data didn't allow the detection of second-order sea level fluctuations. The presence of multiple low-level terraces in the St. Lawrence Lowland

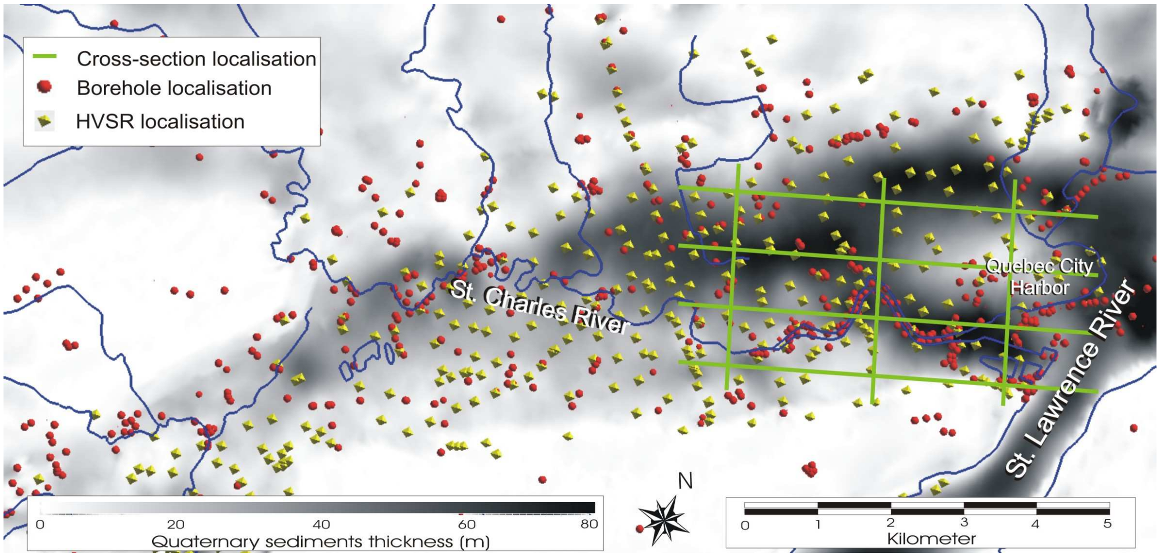

Figure 3. Quaternary sediment thickness of the Quebec City delta.

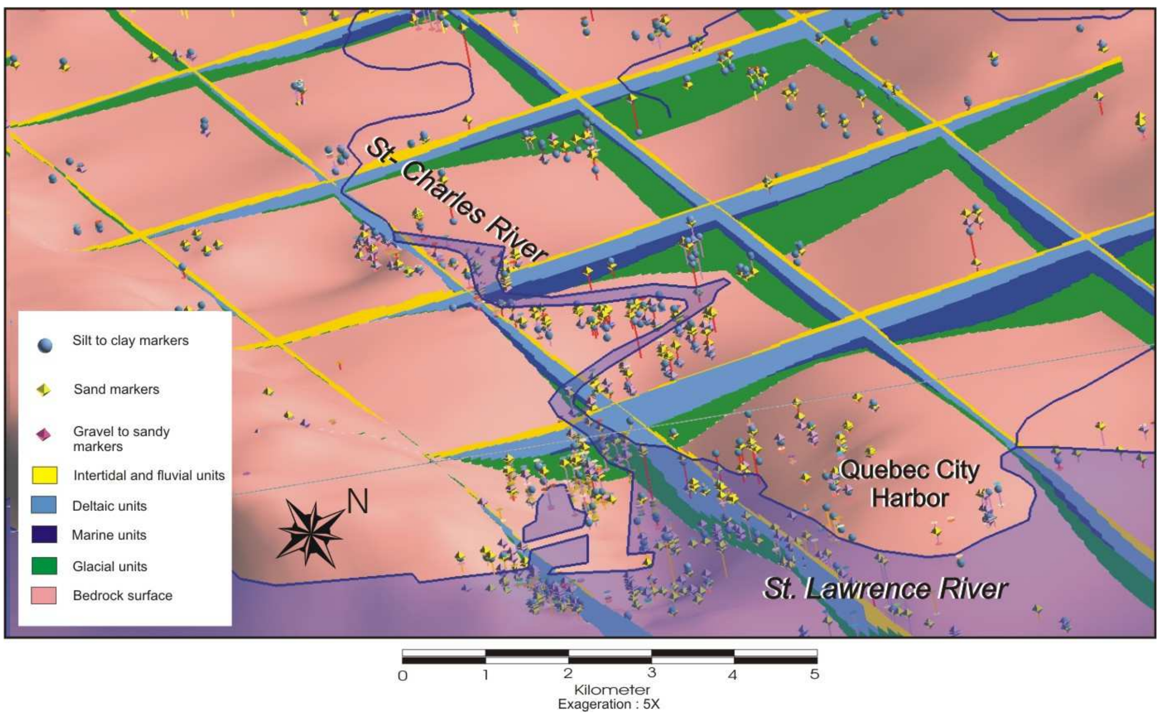

Figure 4. Preliminary 3D model of the south branch of the buried valley in Quebec City. The pink surface corresponds to bedrock. The green surface in cross-section represents till and the blue one is the delta. Yellow diamonds are sand borehole markers, purple diamonds are gravel to sandy borehole markers and blue spheres are silt to clay borehole markers.

(MacPherson, 1967) may suggest a more complex sea level history, particularly in view of high water discharge events from glacial Lake Agassiz (Teller, 1988). However correlations between these discharge events and deposition of the Quebec City delta are not attempted at this point, largely because of the difficulties of connecting terrestrial and marine ^{14}C chronologies. The heterogeneity in the Québec City delta provides clues for the interpretation of sea level fluctuation in the early deglaciation phase.

Late Holocene RSL fluctuations are the result of the combined effects of climate-driven eustatic effects and residual glacioisostatic effects. Major RSL fluctuations were observed in

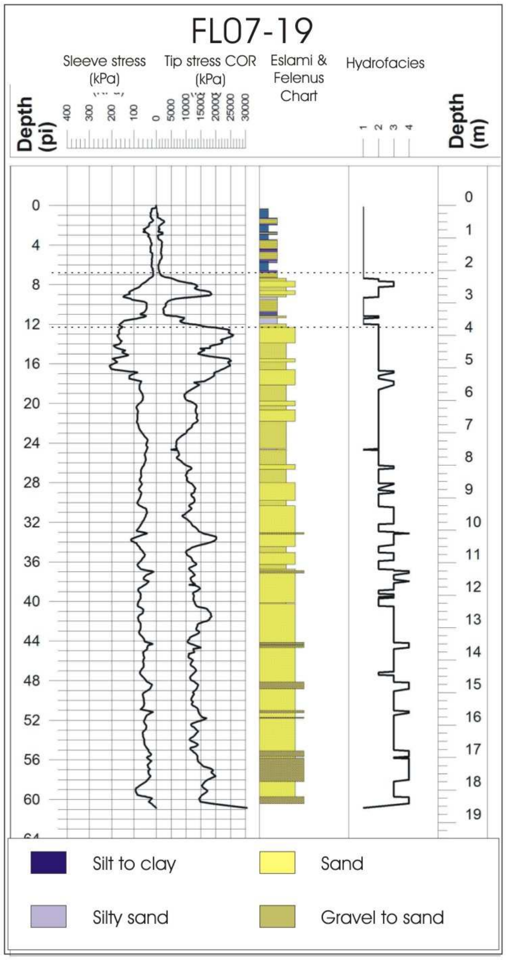

Figure 5. Stratigraphic and hydrofacies interpretation from the CPT borehole based on Eslami and Fellenius chart. (Width of Stratigraphic column is proportional to grain size)

the St. Lawrence estuary by Dionne (2001: Figure 7). In the study area, his Laurentian transgression (around 5 500 years ago) phase led to deposition of the intertidal silts, which cover older sediments in the abandoned early channel of the St. Lawrence River, including the buried delta or bedrock platforms. The subsequent transgression/regression cycles were of lower amplitude, but still had an impact on the heterogeneity of the intertidal silts and on the younger fluvial terraces along Saint-Charles River.

5.2 Hydrofacies distribution

At this point, our knowledge of the depositional environment constitutes the basis of a plausible 3D hydrofacies model distribution. The grain size distribution of the different units is directly related to their depositional environment (Reading, 1996). Those conditions evolved with time as a result of rapidly changing hydrodynamic conditions. Changes in the marine environment (level, waves, currents, and tidal range) or in the fluvial environment (discharge, currents, sediment supply) have an important impact on hydrostratigraphic architecture. The pre-existing configuration of the valley floor also had an impact on erosion and sedimentation patterns.

In the Quebec City region, the nature of Late Quaternary paleogeographic events constrains the assignment of hydrofacies to only a few hydrostratigraphic units. Hence hydrofacies 5 is observed in the till unit underlying the delta. Hydrofacies 2 to 4 mostly lie within the main body of the delta. Hydrofacies 1 represents an aquitard at the top (intertidal silt) and locally at the bottom (marine clay) of the delta. An interbedded unit also occurs locally between the intertidal silt and the deltaic sand. The interpolation of the hydrofacies in the delta body and the processing of borehole logs of the area are under way. The small number of hydrostratigraphic data available in the Quebec City delta doesn't allow us to construct a realistic 3D hydrofacies distribution based on simple interpolation. Different methods of interpolation will be tested to determine which can provide a representative hydrofacies distribution (Kolterman and Gorelick 1996).

5.3 Uncertainty

Uncertainties accumulate during each phase of the preparation of a 3D model. The quality of the model is first controlled by the source of information and its density in the area of interest. (Kaufmann *et al.*, 2008) Standardization and data quality classification provide safeguards against the use of erroneous data in the interpretation of stratigraphic surfaces (Ross et al., 2004). A multi-source database was used to construct the Quebec City model with borehole information coming from Environment Québec, Transport Québec, Hydro-Québec, and engineering reports. Only high quality data were incorporated into the model.

In places where stratigraphic data is sparse or uncertain, interpretation is clearly needed. Hypotheses based on the knowledge of paleoenvironmental conditions provide constraints to avoid incongruities of the geological model. Cross constraints based on hydraulic testing or geophysical data add other perspectives to the 3D model. The use of several lines of evidence provides a good opportunity to test the robustness of the different geological interpretations that are embodied in the model.

Figure 6. Stratigraphic and hydrofacies of the Quebec City delta based on CPT and borehole interpretation. (Stratigraphiy column width is proportional to grain size, see Figure 4 legend)

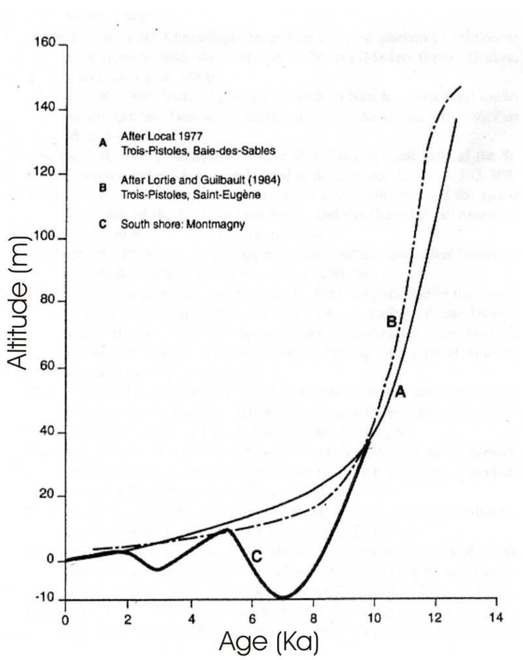

Figure 7. Holocene sea level fluctuation in the St. Lawrence estuary. (after Dionne, 2001).

6 CONCLUSION

Quaternary sediments in the vicinity of Quebec City are the result of a complex erosional and depositional system. The recent discovery of a deltaic aquifer system overlain by intertidal silts (aquitard) in a buried channel of the Proto St. Lawrence illustrates the importance of integrating subsurface data and understanding the rapid paleoenvironmental changes that characterized many Late Quaternary settings. In Québec City, these had a direct impact on deltaic sediment architecture and on the distribution of hydraulic properties in the buried valley aquifer. The 3D geological model delineates the subsurface distribution of hydrostratigraphic units and allows the interpolation of hydraulic properties in a regional framework incorporating observed hydrofacies distribution. The geological interpretation that arises from the integration of old and new data in a 3D model corroborates the complex architecture of Quaternary sediments in the buried valley as well as in adjacent terrains. Available hydrogeological data will also be integrated, although their number, spatial distribution and quality are generally not sufficient to fully characterize the site. To overcome this and to provide a better insight into the distribution of the hydraulic properties, the Quebec City area is compared to a nearby site, where deltaic depositional environments were quite similar, and for which extensive characterization has been carried out (Lefebvre et al. 2004). Future work will involve testing different types of interpolation methods in order to produce a representative 3D distribution of hydrofacies. Fuller characterisation of the Quebec City aquifer is required to understand its dynamics and guide its future sustainable exploitation, whether for water supply or geothermal energy production from this urban groundwater resource.

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