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Paleo-hydrogeological evolution of a fractured-rock aquifer since the Champlain Sea incursion in the St. Lawrence Valley (Quebec, Canada)

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At the end of the last glaciation about 13,000 years ago, an oceanic arm named the Champlain Sea occupied southern Quebec, Canada, during about 2,000 years. This marine water invaded the underlying aquifer systems, which is especially apparent in the Montérégie Est area where the regional fractured rock aquifer system contains non-potable brackish water over an area of about 2,000 km^2. Similar marine invasions have left a geochemical imprint on groundwaters in other sites around the globe as well. Yet few studies have tried to reconstruct the paleoconditions under which postglacial marine invasion of aquifers have occurred. The objective of our study was thus to better understand the processes involved in the postglacial invasion of aquifers by marine water under the paleoconditions prevailing in southern Quebec. This work was based on a conceptual model considering the temporal evolution of marine conditions (water level and salinity), the dynamic sedimentation of a clayey aquitard on the sea bottom, and the decrease in hydraulic conductivity with depth in the regional fractured rock aquifer. Processes were studied using numerical models considering increasingly more complex and realistic conditions, over a period of interest extending from the onset of the marine incursion (13 ka BP) to the present day (0 ka BP).

Results first show the major impact of the clay aquitard sedimentation (on the sea bottom) on the invasion process. The formation of the aquitard largely hinders the direct marine invasion of the aquifer to a short period in the order of 200 years. However, the salinity stored in the large volume of water trapped within sediments forming the aquitard is partly expelled in the aquifer by compaction, which effectively prolongs the indirect marine-water invasion of the aquifer. The presence of the aquitard also precludes later leaching of the seawater-derived salinity that was introduced in the rock aquifer, thus allowing extensive preservation of brackish groundwater, as observed today in the study area.

Moreover, results underscore the highly transient nature of the groundwater flow regime through the whole period of interest and beyond. Patterns typical of buoyancy-driven flow are clearly identified in the numerical simulations, including convection cells and fingering, thereby underscoring the key role of spatiotemporal variations of groundwater salinity and hence density on the subsurface flow dynamics. Furthermore, the depth of seawater penetration is found to be strongly limited by the reduction of hydraulic conductivity with depth in the rock aquifer. Owing to the long 11,000 year period following the retreat of the sea, diffusion proved to be a major mechanism contributing to the "mixing" and spreading of salinity originating from marine invasion, in the aquitard as well as the aquifer.

Despite uncertainties about paleoconditions and hydraulic properties, this research provides a plausible explanation for the groundwater salinity presently found in the clay aquitard and rock aquifer. Overall, this study provides a much better understanding of marine water invasion processes under realistic paleoconditions, and proposes a methodology that could be applicable to other regions where postglacial marine invasions have occurred.