Origin and Evolution of Formation Waters in the West-Central Part of the Alberta Basin

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ABSTRACT
This study investigates the origin and evolution of formation waters in the west-central part of the Alberta Basin. Interpreting mainly salinity and Na/Cl distributions throughout the entire stratigraphic succession, formation waters can be divided into four main groups, which probably all started out as seawater: 1) post-Colorado – mainly meteoric water, 2) Colorado (Cardium, Dunvegan, Viking, U. Mannville) – various degrees of dilution with meteoric water, 3) Jurassic-Mississippian (+ L. Mannville) – evaporated seawater, 4) Devonian-Cambrian – evaporated seawater that underwent a high degree of water-rock interaction (albitization). Mixing of these waters is inhibited by the combination of competent shale aquitards of the Colorado Group, Fernie Group and L. Banff-Exshaw formations, and weak flow-driving mechanisms in the deep parts of the stratigraphic succession.

INTRODUCTION
This study investigates the origin and evolution of formation waters in the west-central part of the Alberta Basin (Fig. 1a). The comparison of the major ion chemistry of waters from various aquifers throughout the entire stratigraphic succession is used to identify: a) how deep meteoric water has penetrated into the subsurface and to what extent it has flushed connate formation waters, b) areas of cross-formational flow and mixing, where intervening aquitards are weak or missing, and c) mechanisms that influence and alter formation water chemistry. Elucidation of these issues helps to better understand the interaction of different flow systems in the Alberta Basin and to characterize the evolution of formation waters with respect to the basin history.

HYDROSTRATIGRAPHY
The stratigraphic succession in the study area can be subdivided into three major hydrostratigraphic groups (Bachu, 1995; 1999): 1) Tertiary-Cretaceous, 2) Jurassic- Mississippian, and 3) Devonian-Cambrian, separated from each other by the thick, continuous intervening shale aquitards of the Jurassic Fernie Group and the Mississippian Lower Banff-Exshaw formations, respectively (Fig. 1b).

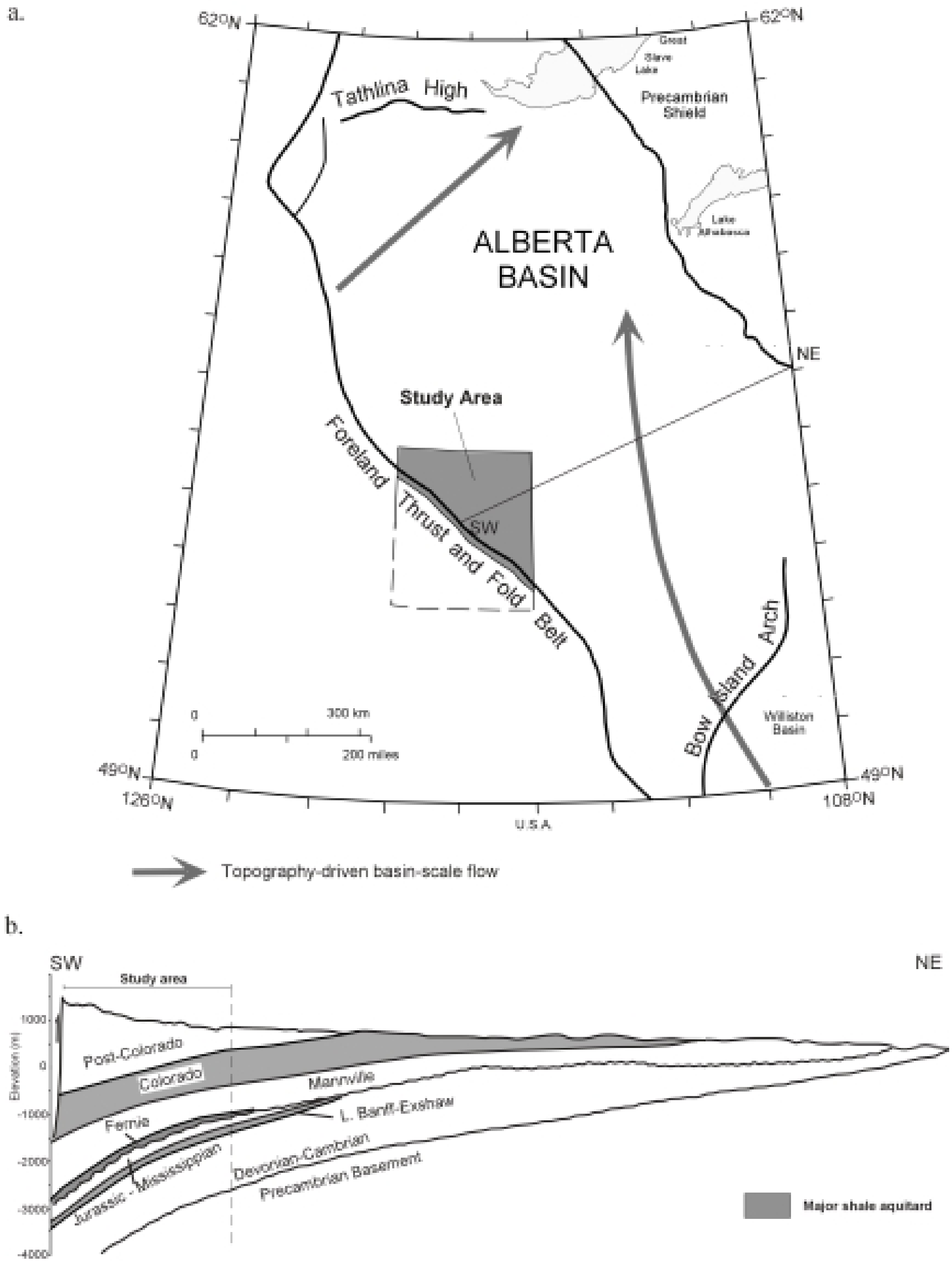

Figure 1: Location of the study area in the Alberta Basin, showing a) generalized basin-scale, topography-driven flow systems (Bachu, 1999), and b) main hydrostratigraphic units in cross sectional view.

The Tertiary-Cretaceous hydrostratigraphic group consists mainly of marine to marginal marine siliciclastics and represents the foreland stage of the Alberta Basin. The succession can be further subdivided into three hydrostratigraphic systems (Fig. 1b): a) the post-Colorado aquifer system, b) the Colorado aquifer-aquitard system and c) the Mannville aquifer system (Michael & Bachu, 2001).

The post-Colorado aquifer system represents a relatively continuous aquifer system from the ground surface to the Lea Park aquitard, and only the Brazeau-Belly River aquifer at the base of this succession is considered in this study. The underlying Colorado aquifer-aquitard system is dominated by the up to 1500 m thick Colorado Gp. shales, which represent a major continuous aquitard system throughout the Alberta Basin (Bachu, 1995; 1999). Three in-bedded sandstone units (Cardium, Dunvegan and Viking) form isolated aquifers. The Viking aquifer is separated from the underlying Mannville aquifer system by the relatively thin Joli Fou aquitard. The Mannville aquifer system is subdivided by the Wilrich aquitard into Upper and Lower Mannville aquifers in the north-western half of the study area.

Large parts of the Triassic-Mississippian strata were eroded in the study area, and the respective formations subcrop below the Jurassic Fernie Group shales. The shales and evaporites in the upper part of the Triassic form an aquitard as a vertically continuation of the Fernie aquitard in the western half of the study area. In the eastern half, sandstones of the lower part of the Triassic and the Permian form a continuous aquifer with the underlying Mississippian carbonates.

The Devonian-Cambrian hydrostratigraphic group, which is confined at its base by the crystalline Precambrian basement, consists mainly of marine carbonates and shales that were deposited during the passive-margin stage of basin evolution. Generally, the platform carbonates and associated reefs from aquifers, whereas the intervening basinal shales act as aquitards.

HYDROCHEMISTRY

This hydrochemical study is based on a total of 1030 water analyses from the post-Jurassic (404), Jurassic-Mississippian (299) and Devonian-Cambrian (327) hydrostratigraphic groups. These data were culled for erroneous analyses and tests according to methods described by Hitchon & Brulotte (1994). Because of their relative conservative chemical behaviour, mainly salinity and sodium/chloride-ratios were used to distinguish between formation waters from the various hydrostratigraphic groups in the study area and to characterize the main chemical processes that affected the water chemistry. The distribution of additional ion concentrations was only used to support or rule out the influence that a single process might have had during the chemical evolution of formation water in any given aquifer.

Most sediments in the entire stratigraphic succession were deposited in a marine to marginal-marine environment and therefore, the respective formation waters probably started out as seawater that was successively altered by water-rock interaction and mixing with meteoric water during sediment burial. Hence, the main water end members are seawater and meteoric water, which have relatively well defined ranges in salinity and [Na]/[Cl]-ratio: Seawater: TDS = 35 g/l, [Na]/[Cl] = 0.85; "Meteoric" water: TDS ~ 0 - 10 g/l, [Na]/[Cl] > 2. The respective formation waters in the three major hydrostratigraphic groups have distinctively different ranges in salinity and [Na]/[Cl]-ratio, and can be grouped accordingly (Fig. 2), confirming the initial hydrostratigraphic delineation based on fluid flow characteristics. Generally, formation waters from the Tertiary-Cretaceous hydrostratigraphic group (except Lower Mannville) have salinities below that of seawater and a relatively wide range in [Na]/[Cl]-ratios (> 1), those from the Jurassic-Mississippian hydrostratigraphic group and the adjacent Lower Mannville have a salinity above that of seawater and a narrow range of [Na]/[Cl]-ratios (< 1), while Devonian waters have very high salinity and low [Na]/[Cl]-ratios (< 0.8).

The main processes that cause an increase/decrease in salinity are evaporation/dilution and dissolution/precipitation. The [Na]/[Cl]-ratio indicates the relative content of the main sodium and chloride minerals, e.g., NaCl, $CaCl_2$, and $NaHCO_3$ dissolved in formation water. Meteoric water and shallow groundwater mainly contain $NaHCO_3$ and almost no chloride, therefore the [Na]/[Cl]-ratio is much larger than 1. Seawater, evaporated seawater, and deep groundwater that contain mainly dissolved halite have a [Na]/[Cl]-ratio around one. Formation waters that contain high concentrations of dissolved $CaCl_2$, hence low [Na]/[Cl]-ratio, are mainly found in aquifers in or in contact with crystalline rocks and are probably formed by the albitization of plagioclas, exchanging Na for Ca.

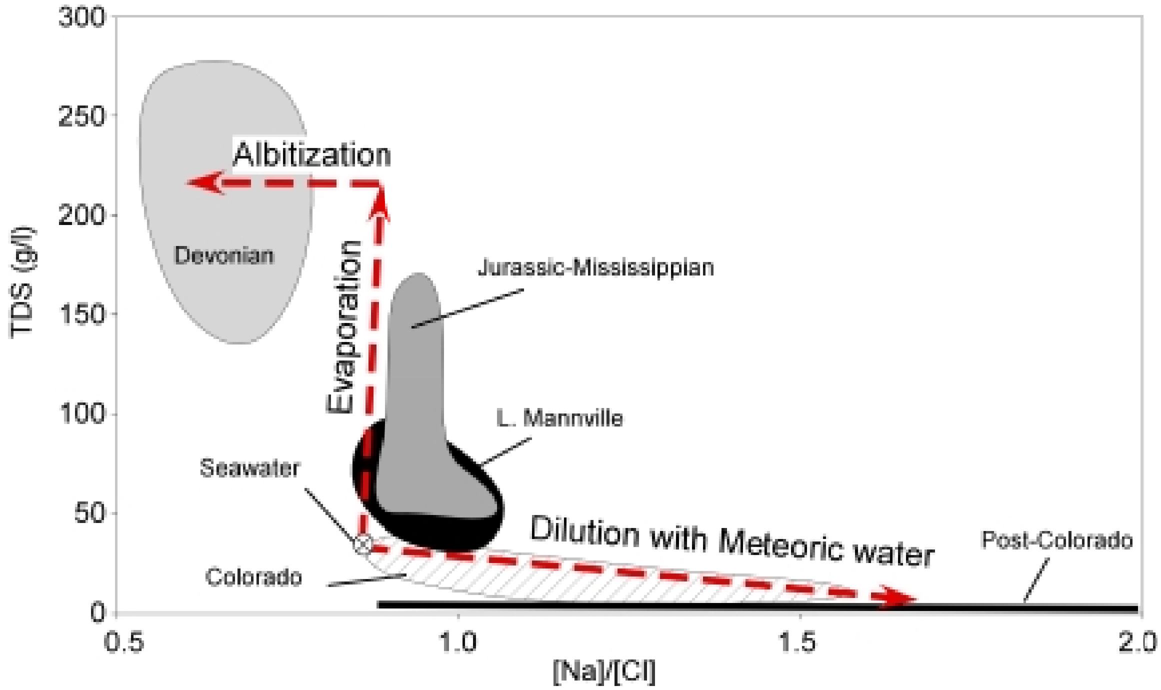

Figure 2: Grouping and schematic evolution of formation waters in west-central Alberta with respect to their variations in salinity and [Na]/[Cl]-ratio.

INTERPRETATION

Starting as seawater, formation waters in the Tertiary-Cretaceous succession (Brazeau-Belly River to Upper Mannville) were successively diluted with fresh, meteoric water. Relatively high salinities, only slightly lower than seawater salinity, in the Upper Mannville to Cardium aquifers indicates that an effective penetration of meteoric waters did not start before the end of deposition of the Colorado shales, which partly isolate(d) these aquifers from the flushing with meteoric water since pre-Laramide time. Only those parts of the Cardium and Dunvegan aquifers that are connected to the ground surface north of the study area, where these formations crop out, contain waters with significantly lower salinity and meteoric Na/Cl-signature. On the other hand, the Brazeau-Belly River aquifer has been effectively diluted by meteoric water, and distributions of hydraulic heads show that a flow system driven by regional-to local-scale topography is presently active in this aquifer.

Also starting as seawater, the Lower Mannville aquifer and aquifers in the Jurassic-Mississippian and Cambrian-Devonian hydrostratigraphic groups probably never were influenced significantly by meteoric water, as indicated by high salinity. The main reason for that could be the lack of a topographic relief during and shortly after deposition of these sediments, that would have induced a deep-penetrating gravity-driven flow system. Halite deposits in the Triassic Charlie Lake Formation indicate that the original seawater, in which the respective sediments were deposited, has evaporated up to the point of halite precipitation. This suggests that formation waters in the

Jurassic-Mississippian succession were mainly formed by the evaporation of seawater. Nevertheless, the distribution of other major ions implies that the composition of these waters was altered further by other processes, such as precipitation of dolomite cements and dissolution of sulphate and halite.

Major salt deposits in the Devonian Elk Point Group northeast of the study area suggest that waters in the Devonian-Cambrian succession have a similar origin and evolution as the Jurassic-Mississippian waters. The much higher salinity of the Devonian formation waters was probably caused by a higher degree of evaporation and an additional dissolution of halite during burial. The shift in the [Na]/[Cl]-ratio towards lower values is most likely due to the albitization of feldspar and suggests that these waters might have re-fluxed through the Precambrian crystalline basement. Hydrothermal convection in this part of the basin was used to explain the massive replacement of Devonian limestones by dolomite (Spencer, 1987). At present, flow in the Devonian aquifers appears to be rather stagnant, because of negative buoyancy effects due to the high density of formation waters and the lack of an active flow-driving mechanism in this part of the Alberta Basin (Michael et al., 2000).

CONCLUSIONS

The observations in this study suggest that an active topography-driven flow system is present only in the uppermost aquifers that overlie the Colorado shales. Thick, continuous shale aquitards in the study area have been preventing the flushing of deeper aquifers with meteoric water, which also implies that there is no significant meteoric recharge from the area of the Rocky Mountains reaching into the undeformed part of the Alberta Basin. Only in the southern part of the study area, Devonian to Jurassic waters get diluted by fresher waters, carried by a large-scale, northward-directed topography-driven flow system (Fig. 1a) originating in recharge areas in Montana (Bachu, 1995, Anfort et al., 2001).

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