Long range regional groundwater flow systems in the Northern Great Plains: (2) Physics of regional groundwater flow in Alberta

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ABSTRACT
A number of prominent papers during the last two decades have proposed that six differing basin-scale groundwater flow systems exist in Alberta, including three different gravitationally-driven systems within the Upper Devonian formation extending from Montana to northern Alberta (Bachu, 1995, 1999; Michael and Bachu, 2002), a groundwater flow system within the Lower Devonian aquifers of southwestern Alberta, driven by 'past tectonic compression' updip to the east (Bachu 1995, 1999), and a system driven by gravitational forces from the Rocky Mountains eastward towards Great Slave Lake (Bachu, 1999; Michael and Bachu, 1999). In actuality, none of the above systems exist as the applied methodologies do not adhere to basic thermodynamic principles, Darcy's law, the equation of continuity, Hubbert's Force Potential, and Groundwater Flow Systems Theory.

RÉSUMÉ
Au cours des deux dernières décennies, plusieurs articles importants ont proposé six (6) différents systèmes d'écoulement des eaux souterraines pour de grand bassins en Alberta, avec trois (3) systèmes d'écoulements gravitaires dans la formation du Dévonien Supérieur s'étendant du Montana jusqu'au nord de l'Alberta (Bachu, 1995, 1999; Michael and Bachu, 2002), un (1) système d'écoulement souterrain vers l'est à l'intérieur des couches aquifères du Dévonien Inférieur du sud-ouest de l'Alberta, généré par les anciennes compressions tectoniques dans le pendage-amont (Bachu 1995, 1999), et un (1) système d'écoulement gravitaire vers l'est provenant des Rocheuses vers le Grand Lac des Esclaves (Bachu, 1999; Michael and Bachu, 1999). En pratique, aucun des systèmes proposés existent puisque la méthodologie n'adhère pas aux principes de base de la thermodynamique, à la loi de Darcy, à l'équation de continuité, aux forces potentielles d'Hubbert, et à la théorie des systèmes d'écoulement des eaux souterraines.

1 INTRODUCTION

A number of practical considerations have put the presumed existence of long range groundwater flow systems into contention in the area of the Northern Great Plains in Canada, such as CO_2 sequestration in Alberta and Saskatchewan, as well as extraction of the Athabasca oil sands and subsurface waste water disposal in Alberta (Athabasca oil sands and Swan Hills). Thus, in this area, regional groundwater flow has moved beyond the realm of academic studies and became an important component of environmental concerns by industry, governments and the public.

Weyer & Ellis (2013, this volume) reported on long range gravitational flow system [i] (Figure 1) which was postulated by Downey et al. (1987), stretching from Montana to Saskatchewan and Manitoba with a length of about 1100 km. This paper deals with a second postulated flow system [ii] (Figure 1), which was introduced by Bachu (1999), and stretches about 1600 km from Montana to northern Alberta. This paper concerns itself with gravitational system [ii] and additional postulated long range and regional-scale groundwater systems with different driving mechanisms in Alberta.

2 LONG RANGE BASIN WIDE AND REGIONAL SCALE FLOW SYSTEMS IN ALBERTA

Since 1995, Bachu (1995, 1999), Anfort, Bachu and Bentley (2001), and Michael and Bachu (2002) postulated six basin-wide long range groundwater flow systems for Alberta and in addition, four regional-scale flow systems, all of them presently and simultaneously active in various layers and parts of the sedimentary basin. Topography, tectonic compression, and erosional rebound were selected as driving forces. For the sake of clarity, we would point out that topographical forces are a misnomer for the gradients of the ubiquitous gravitational force field in the subsurface of the Earth.

Stefan Bachu was involved, as the sole author or coauthor, in all of the postulated basin-scale and regional-scale groundwater flow systems in Alberta under discussion here. In an attempt to help better explain the different proposals, we have subdivided the list below into two sections and show, in each section, the systems according to their first publishing date. That is the reason why long range flow system [ii] of Figure 1 became System [3] in the list below and in the text subsequent to this list.

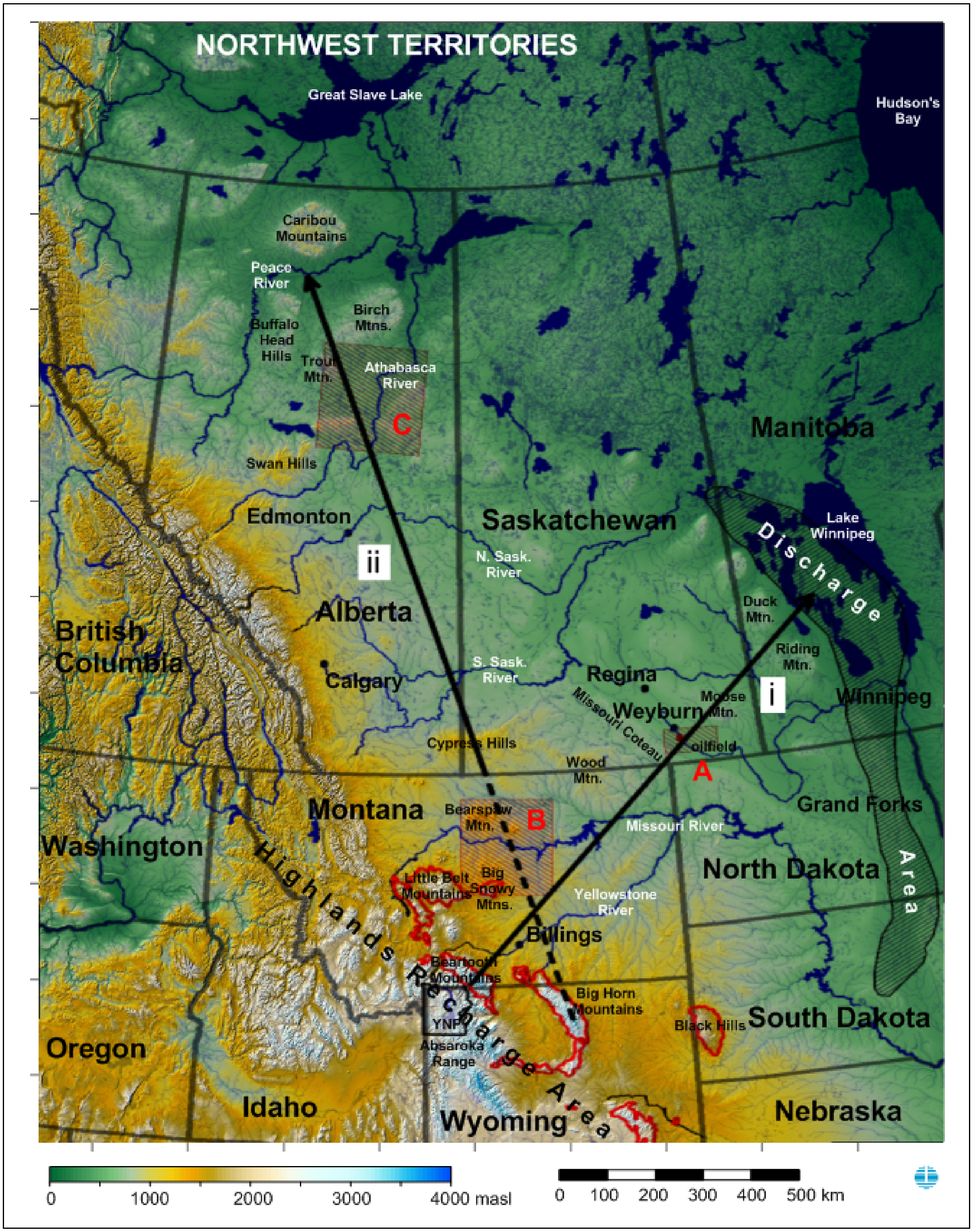

Figure 1. Long range regional groundwater flow systems [i] and [ii] in the prairie provinces and US states proposed by Bachu (1999) and Downey et al. (1987). Mountainous outcrops of aquifer systems (after Downey, 1986, Figure 4) are outlined in red.

A: BASIN-SCALE FLOW SYSTEMS:

- System [1]: "*Basin-scale south-northeastward topography-driven flow*", in "*Pre-Cretaceous hydro-stratigraphic succession*" (Bachu, 1995, Figure 9). [→ Figure 2]
- System [2]: "*Basin-scale flow of probable tectonic origin with strong buoyancy effects*" in "*Pre-Cretaceous hydrostratigraphic succession*" (Bachu, 1995, Figure 9) . A similar system appears in Bachu [1999, Figure 8], where it is described as "*Basin-scale flow driven by past tectonic compression in the Lower Devonian aquifers*". [→ Figure 2, 3]
- System [3]: "*Topography-driven basin-scale flow*" (Bachu, 1999, Figure 8) stretching from the Big Horn Mountains in Montana to the Peace River in northern Alberta; replacing System [1] above. [→ Figure 3]
- System [4]: "*Main basin-scale flow system driven by topography"* (Anfort, Bachu, & Bentley, 2001, Fig. 9). [→ Figure 4]
- System [5]: "*Topography-driven basin-scale flow*" (Michael & Bachu, 2002, Figure 1a) replacing gravitational systems [1] and [3] above. [→ Figure 5]
- System [6]: "*Topography-driven basin-scale flow*", stretching from the Rocky Mountains to Pine Point, Great Slave Lake (Bachu, 1999, Figure 8; Michael and Bachu, 2002, Figure 1a). [→ Figures 3, 5]

B: REGIONAL-SCALE FLOW SYSTEMS:

- System [7]: "*Regional-scale flow driven by erosional rebound*" in "*Post-Jurassic hydrostatic succession*" (Bachu, 1995, Figure 9). In Bachu [1999] a similar system is described as "*Inward flow driven by erosional rebound in the Cretaceous succession*". [→ Figure 2, 3]
- System [8]: "*Updip flow of connate waters*" (Anfort, Bachu, Bentley, 2001, Figure 9). [→ Figure 4]
- System [9]: "*Downdip flow of meteoric water driven by the Grosmont drain*" (Anfort, Bachu, and Bentley, 2001, Figure 9). [→ Figure 4]
- System [10]: "*Regional scale flow driven by past-tectonic compression in the Paleozoic aquifers feeding into the main basin scale systems*" (Michael and Bachu, 2002, Figure 1a). [→ Figure 5]

Within the multitude of basin-wide flow systems, Systems [1], [3], [4], [5], and [6] are long range gravitationally-driven systems supposedly leading from as far as Montana to northern Alberta. Although they all have been postulated by S. Bachu as author or co-author, they show remarkable differences (Figure 6) in origin (location of recharge area), route, and endpoint of flow lines (location of discharge area). It would appear that the postulated flow systems are not based on hard data but are the

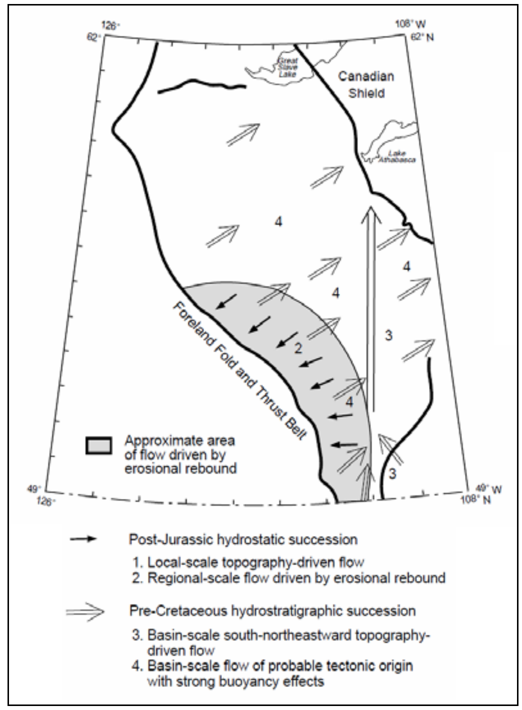

Figure 2. "*Diagrammatic model of the flow of formation waters in the Alberta basin: Plan view*" from Bachu (1995, Figure 9).

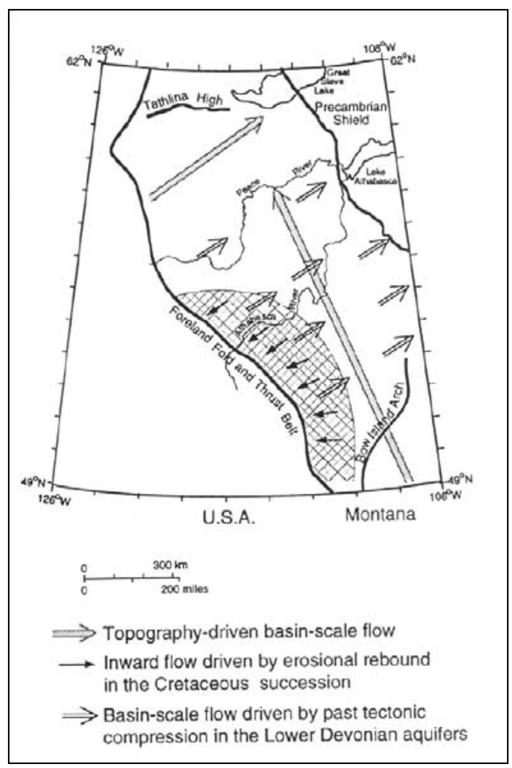

Figure 3. "*Plan-view diagrammatic representation of the flow systems and pattern in the Alberta basin*" from Bachu (1999, Figure 8).

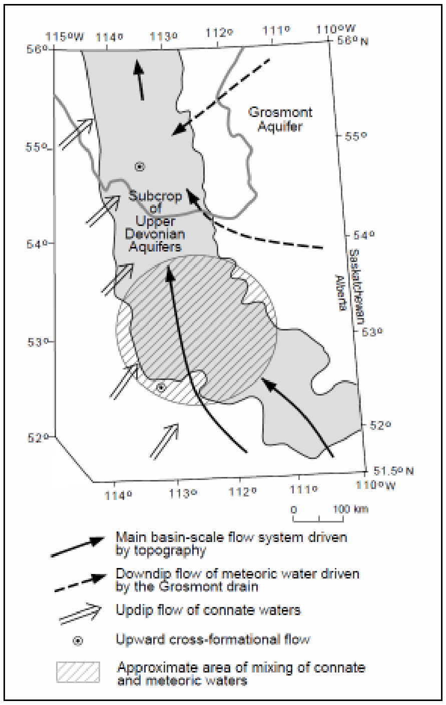

Figure 4. "*Diagrammatic representation of flow of formation waters in the Upper Devonian-Lower Cretaceous strata in the southeastern part of the Alberta basin*" from Anfort, Bachu, and Bentley (2001, Figure 9).

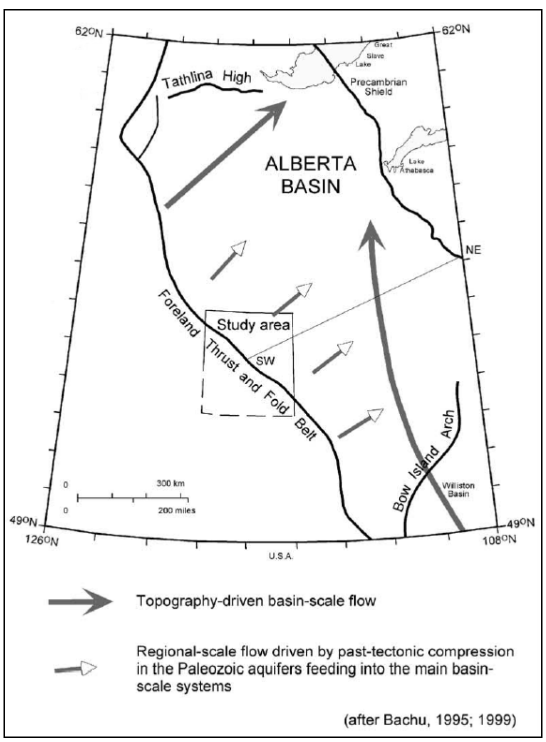

Figure 5. "*Main basin-scale flow systems identified previously* […] *are shown in plan view*" from Michael and Bachu (2002, Figure 1).

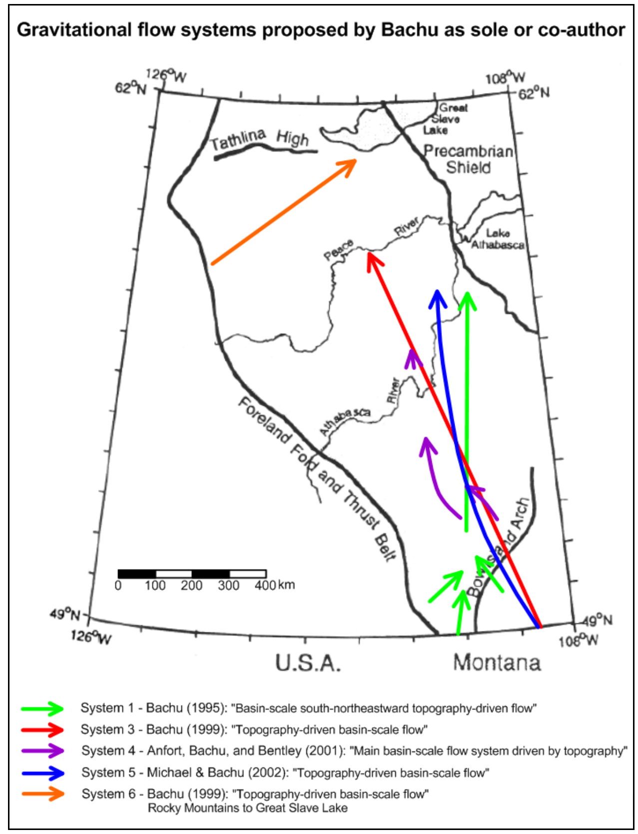

Figure 6. Comparison of various gravitational flow systems by Bachu (1995, 1999), Anfort, Bachu, and Bentley (2001), and Michael and Bachu (2002).

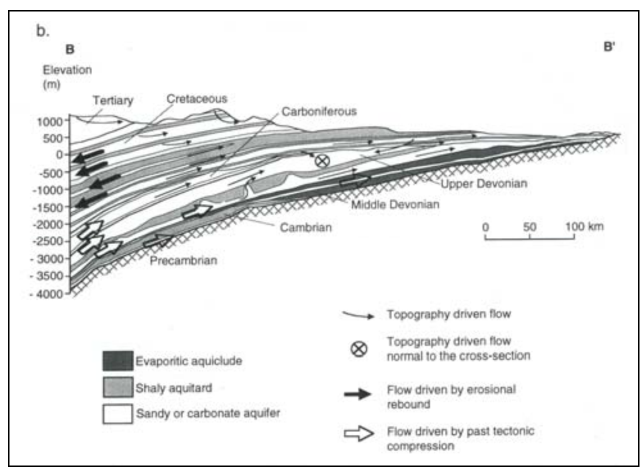

Figure 7. "*Diagrammatic representation of flow systems and flow pattern in the Alberta basin:* […] *9b) in the central-southern part*" (from Bachu, 1999, Figure 9).

outcome of flexible concepts and based upon engineering hydraulics assumptions as outlined by Bear (1972) and de Marsily (1986). Engineering hydraulics is based on false assumptions such as the incompressibility of water, and that buoyancy forces exist as independent forces and are always directed vertically upwards or downwards. These assumptions are without merit in physics (Weyer, 1978, 2009).

Instead, the extent and flow lines of regional groundwater flow systems need to be determined by making use of the rules and physics of groundwater flow systems theory and Hubbert's (1940) force potential. We address this matter in more detail below in Section 3.

Within the oil industry, in particular in the reach of the southwestern part of the Athabasca oil sands (Wabasca oil sands), System [3], with its assumed discharge point at the Peace River is quoted and taken as proof that there is no effect of waste water discharge into the Athabasca River or an effect of substantial water withdrawal on the Athabasca River. In the chain of postulated long range groundwater flow systems, System [3] (Bachu, 1999, discharging into the Peace River) was the second and has been supplanted by System [4] (Michael and Bachu, 2002) discharging into the Athabasca River catchment basin within the area of the Athabasca oil sands (Figure 6). Nevertheless, the opinion that this groundwater discharges into the Peace River has maintained prominence within the oil industry, notwithstanding the later publication by Michael and Bachu (2002).

Understanding the groundwater flow pattern within the karstic Devonian of this area will become significantly more important as the karstic Grosmont formation contains a large amount of bitumen which presently is in its first stages of development. The assumption of long range groundwater flow discharging into the Peace River is presently convenient from an environmental point of view. This unproven concept may, however, become a serious impediment to the practical development of the Grosmont bitumen. The Devonian Grosmont Formation is estimated to contain more bitumen than the Cretaceous layers of the Athabasca oil sands.

Based upon Michael and Bachu (2002), we will have to conclude that, according to the aforementioned authors, waste water injected within the reach of the long range groundwater flow system [4] discharges eventually into the Athabasca River System. We have not yet established, however, whether this long range system from Montana to northern Alberta exists at all. We will address this matter further down in Section 3.

In addition to gravitational forces (in his nomenclature: topographic forces), Bachu (1999) cites tectonic forces and erosional rebound forces as main driving forces. In doing so he assumes that these forces would override the ubiquitous gravitational forces, an assumption with no basis in physics. Figure 7 depicts Bachu's (1999) concept of the occurrence of these different forces in the Cretaceous formation (erosional rebound) and Lower Devonian formation (tectonic forces). Both mechanisms are addressed in more detail in Section 3.2 below.

Anfort, Bachu, and Bentley (2001) also made use of the legacy concepts of 'connate water', updip flow (by buoyancy of light fluid) and downdip flow (by buoyancy of heavy fluid). Connate water in the Devonian would be 360 to 400 million years old, which could not be measured reliably by isotopes or by other means. Therefore the authors must rely on chemistry, possibly ignoring the intricacies of water-rock interactions.

Updip and downdip are terms which cling stubbornly to life in the oil industry. Both should not be used any more in the context of regional flow as the concepts originated in engineering hydraulics and rely heavily on the existence of hydrostatic buoyancy forces. Weyer (1978, 2009) has shown that so-called 'buoyancy forces' are Hubbert's (1940) pressure potential forces which happen to always be directed vertically upwards under hydrostatic conditions and which may, under hydrodynamic conditions, take any direction in space including vertically downwards (Weyer, 1978: buoyancy reversal). Under conditions of buoyancy reversal, lighter fluids move downward faster than heavier fluids.

3 GROUNDWATER DYNAMICS

3.1 Gravitational forces

Deep groundwater flow has been assumed to recharge in Montana as far away as the Big Horn Mountains or Big Snowy Anticlinorium, and to discharge in northern Alberta (Bachu, 1999; Anfort, Bachu, and Bentley, 2001; Michael and Bachu, 2002). A cornerstone of this concept is the belief that significant amounts of groundwater can only flow within aquifers, rather than in aquitards.

According to the concepts adopted, recharge of the aquifer system occurs only at the mountainous outcrop area of these aquifers while discharge is restricted to the 'downstream' outcrop area of the very same aquifer systems. The overlying 'impermeable' aquitard supp-osedly prevents communication between this aquifer system and the overlying groundwater body and groundwater table (Figure 8). About 50 years ago, this concept was surpassed by the work of Freeze and Witherspoon (1967), which recognized aquitards (and caprocks) as an integral part of groundwater flow systems (Figure 9). Artesian conditions (flowing wells) occur in discharge areas. Figure 9 also indicates that, in the configuration shown, twice as much groundwater flows in the overlying aquitard (downwards under recharge areas and upwards under discharge areas) as through the aquifer (laterally only).

In fact, head distributions in aquifers under aquitards directly reflect the topographical oscillation of the groundwater table (Figure 10). Under recharge areas the head in the aquifer is lower than the ground-water table; below discharge areas the head in the aquifer is higher than the groundwater table. These configurations have been confirmed by field measurements at many sites worldwide. Figure 11 shows data from one site, which has been published by Albinet & Cottez (1969).

Bachu's (1995, 1999) application of the erroneous concept of impermeable aquitards (Figure 8) seems to have led to the postulated long range groundwater flow system between the upstream and downstream outcrop areas of the same aquifer system. This is the only 'hydraulic' reason why the long range groundwater flow systems between Montana and northern Alberta should exist as presumed by their supporters. In applying this concept to the Athabasca oil sands, erroneous operational

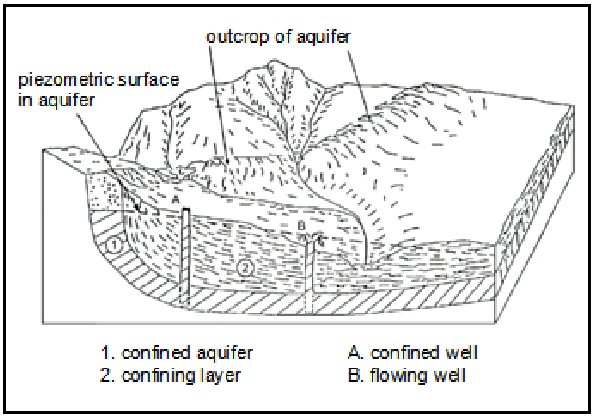

Figure 8. Waltz's (1973, Figure 6.1.3) erroneous concept of regional groundwater flow in artesian aquifers.

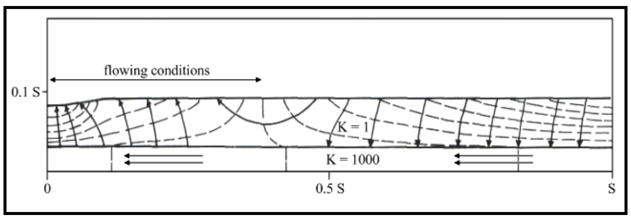

Figure 9. A physics-based concept of regional groundwater flow incorporating aquitards (after Freeze and Witherspoon, 1967, Figure 7[2]).

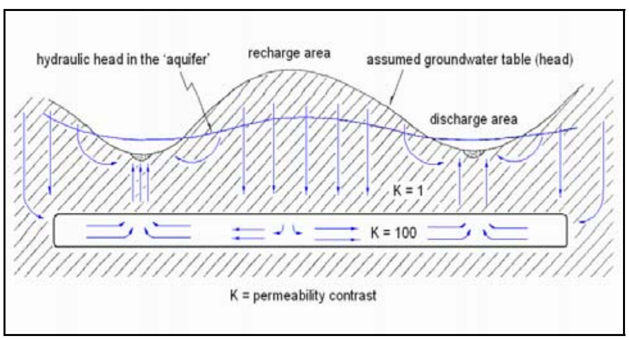

Figure 10. Heads in buried aquifers usually directly reflect the oscillations of the groundwater table (from Weyer, 2006, Figure 10).

recommendations were provided to industry, governments, and the public which need to be revisited and revised.

A major physical inconsistency in Bachu's (1995, 1999) concept of long range groundwater flow in Alberta is the assumption that gravitationally-driven groundwater flow exists in northern Alberta within the Devonian layers from the Rocky Mountains to Great Slave Lake but the same type of flow would not exist in central and southern Alberta (Figures 5 and 6) although the geological and hydrodynamical conditions are similar. Likewise, flow supposedly driven by 'tectonic compression' (Devonian layers) and 'erosional rebound' (Mesozoic layers) supposedly exist in southern and central Alberta but not in

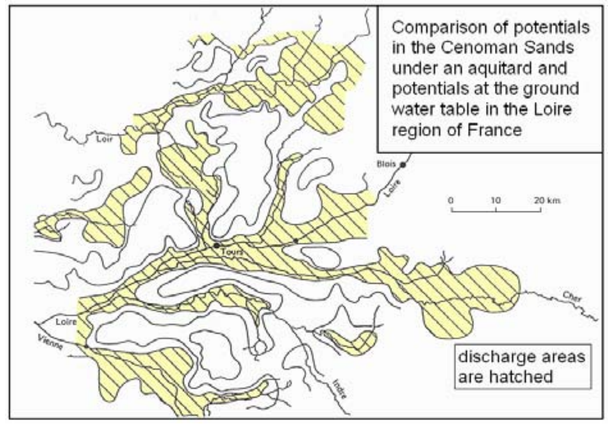

Figure 11. Plan view of groundwater flow systems penetrating an aquitard (after Albinet & Cottez, 1969, Figure 2).

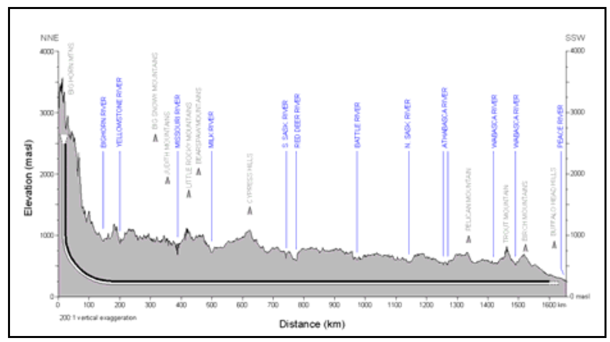

Figure 12. Topographical (groundwater table) cross-section along the postulated long range groundwater flow system [ii] as shown in Figure 1. Grey peaks indicate maximum elevations of nearby mountains. The black and white 'pipe' schematically represents the regional aquifer system (white) overlain by an aquitard (black).

northern Alberta. Adequate technical explanations have not been given.

Hubbert's (1940) force potential and the derived gravitationally-driven regional groundwater flow systems are the basis of physically consistent investigations of regional groundwater flow. Thermodynamically, force fields for subsurface fluid flow are arranged in such a way that the total energy consumption within the field is minimized. Figure 12 shows a greatly-exaggerated (200:1) groundwater table configuration along the postulated groundwater flow system [ii] (Figure 1). Contrary to Bachu's (1999) assumptions, recipients of water from this postulated groundwater flow system (should it exist) would be the Yellowstone and Missouri Rivers and their tributaries in Montana. In Alberta the Oldman and Red Deer Rivers of the South Saskatchewan River system, the North Saskatchewan and Athabasca River (as well as their tributaries) would be the recipients of deep groundwater flow according to the application of Hubbert's force potential and groundwater flow systems theory.

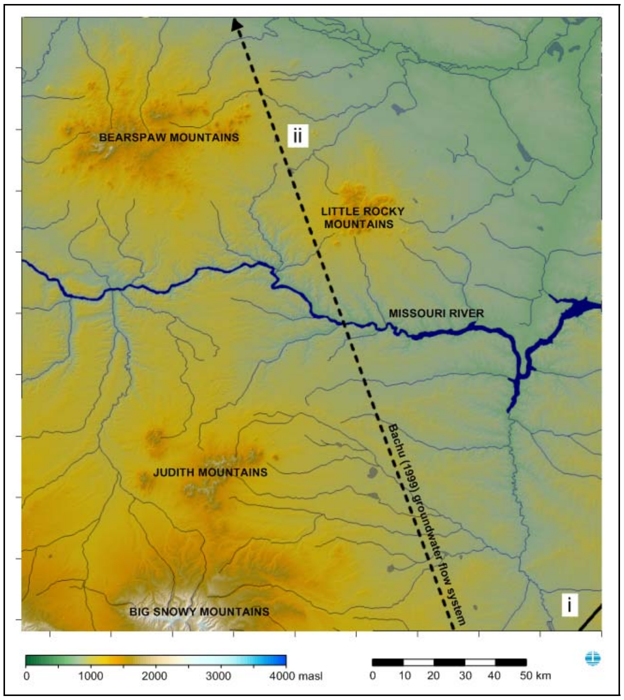

Figure 13. Disconnect between Bachu's (1999) postulated groundwater flow system in Paleozoic layers and groundwater table mounts of the Big Snowy, Judith, Little Rocky, and Bearspaw Mountains in Montana. Location of map indicated as area "B" in Figure 1.

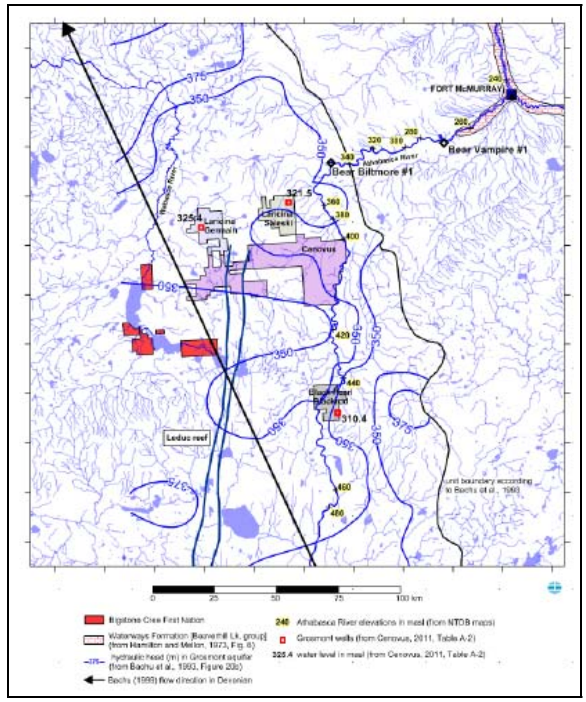

Figure 14. Hydraulic heads in Devonian layers (blue lines) reported by Bachu et al. (1993, Figure 20 b))

Figure 13 represents the area "B" in Figure 1. The flow system [ii] proposed by Bachu (1995, 1999) would underflow or bypass the Big Snowy, Judith, Little Rocky, and Bearspaw Mountains, as well as the Missouri River, without any hydrodynamic effect whatsoever. It would also underflow the Cypress Hills in Canada (Figure 1). This scenario is not sustainable from a hydrodynamic point of view (Figure 9) according to Freeze and Witherspoon (1967). Moreover, the Paleozoic aquifer systems outcrop at the Big Snowy Mountains and other mountains to the west of the area considered. Flow from these outcrops towards the east would interfere with the systems proposed by Bachu (1999).

3.2 Tectonic and erosional rebound forces

Flow by tectonic and erosional rebound forces have been proposed by Bachu (1995, 1999) as a mechanism for present day fluid flow within aquifers. This was in response to compressional tectonic forces associated with Cretaceous mountain building and possibly ongoing differential movement within plates or at their boundaries, and in response to widening pore space due to erosional unloading. While these forces would have an effect, lag times do not depend on core permeabilities or permeabilities determined by pump and drill-stem tests [DST] but on the regional bulk permeabilities (including secondary permeabilities of fractures and fault zones).

These regional permeabilities may be several orders of magnitude higher than permeabilities determined from cores or DST tests, as described for limestone by Kiraly (1975). The response by groundwater flow to the slowly changing forces of compression or erosional rebound is, in geological terms, practically instantaneous except in conditions of hydraulically "tight" rocks (Neuzil and Pollock, 1983). In general, the calculations applied are often based on the methodologies of engineering hydraulics using hydrostatic conditions, with stress and pressure as the parameters affecting fluid flow (Parks and Tóth, 1995; Neuzil and Pollock, 1983).

The lag times involved in tectonic compression may be practically examined by considering the effect of the strong 1964 Alaska earthquake on water levels in wells in Alberta. The seismic compressional waves caused significant water level rises within a large number of automatically observed observation wells (often installed in confined aquifers) which receded within hours or days (Gabert, 1965) as observation wells are often installed in confined aquifers. The response time depends directly and linearly on the permeability of layers present (Bredehoeft and Hanshaw, 1968). As Bachu (1995, 1999) positioned the tectonically-driven flow within aquifers, time lags of days and possibly years or hundreds of years cannot maintain tectonically-driven flow within aquifer systems as shown in Figures 2, 3, and 7.

When searching for the "*Possible effects of erosional changes of the topographic relief on pore pressures at depth*" in the Red Earth Creek area of Alberta, Tóth and Millar (1983) assumed hydraulic conductivity values between 10^{-7} and 10^{-12} cm/sec for the aquitards 'Cretaceous AB' and 'Devonian AB'. The prequel paper (Tóth, 1978, Table 3) indicates that all of the hydraulic conductivity values for aquitards are from core analyses and selected DST tests only. The reported hydraulic conductivity values (between $4*10^{-6}$ and $8*10^{-7}$ cm/s for the Devonian aquitard and 10^{-5} cm/s for the Cretaceous aquitard) are considerably higher than those used by Tóth and Millar (1983) for the calculation of hydraulic time lags for pressure propagation from the surface to the top of the Precambrian. Considering the hydraulic conductivity values from Tóth (1978, Table 3) and the effect of secondary permeability on regional bulk hydraulic conductivities, the adjustment time for head changes at the top of the Precambrian would then be in the 400 year range or significantly shorter. Such short time lags for head adjustments in shale would be instantaneous in a geological time context.

Parks and Tóth (1995, p. 291) "*have shown that amongst six alternative mechanisms to explain the hydraulic gradients observed in the Upper Cretaceous and Tertiary strata of our study area, only rock-pore dilation due to erosional rebound is supported by field evidence. The effect appears vertically concentrated in the shaley Bearpaw Formation and Edmonton Group strata*". The underpressurization effect coincides with shaley layers, as does buoyancy reversal (Weyer, 1978, 2009) which exists in areas of strong downward flow through shaley layers. It causes a significant pressure reduction (underpressure) as side effects. Parks and Tóth (1995) did not consider buoyancy reversal as a mechanism causing 'underpressure' under recharge areas such as their field site.

Bekele et al. (2003, p.143) point out that, in the Alberta basin, "*processes that contribute to the formation of large underpressures remain equivocal. Previous studies have largely neglected the influence of glacial unloading and focused primarily on erosion; however, the amount of underpressuring simulated by basin models that incorporate long-term erosion is insufficient*".

We submit that a re-examination of all available data with a strict application of the physically based methodology of Hubbert's (1940) force potential, including buoyancy reversal (Weyer, 1978) as well as groundwater flow systems theory (Freeze and Witherspoon, 1967) and consideration of possible man-made influences will lead to hydrodynamically-based explanations of the so-called 'underpressures' encountered within the Alberta basin. Thereby, the need to involve 'tectonic compression' or 'erosional rebound' forces within regional groundwater flow systems may become superfluous.

3.3 Field evidence of flow opposing proposed basin-scale flow system [3]

Bachu et al, (1993) published interpreted head data (Figure 14) which, in the area of the Athabasca oil sands (Figure 1; area [C]), indicated groundwater flow directions within the Devonian layers which directly contradict the postulated flow directions of system [3]. Therefore the Birch Mountains are not underflown towards the Peace River as shown in Figure 15 (E-D). Instead the Bachu et al. (1993) equipotential lines (heads) show the flow in the Devonian layers to target the Athabasca River (Figure 16) under pre-production conditions. The complexity of the groundwater dynamic conditions between the Wabasca and Athabasca Rivers is such that we argue that eventually a 3D regional mathematical model (from the groundwater table to the Precambrian) will be necessary to optimize groundwater water pumping, SAGD operations (within the Cretaceous layers and the Devonian Grosmont formation) as well as waste water disposal in this area. This model should be developed and operated in cooperation by the industry and the stakeholders involved.

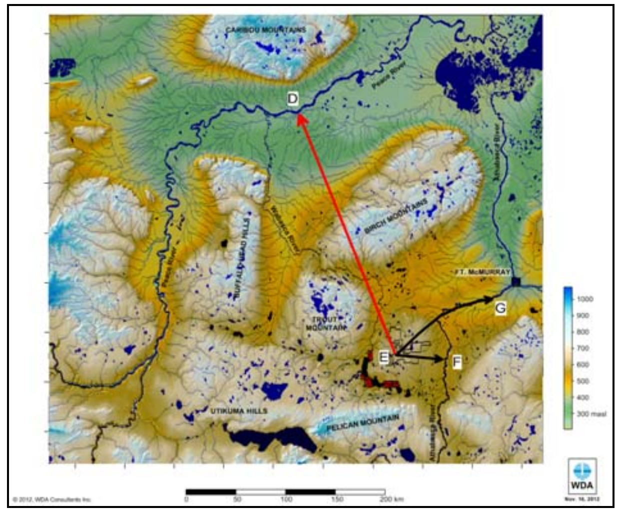

Figure 15. E-D: Part of Bachu's (1995, 1999) postulated groundwater flow system [3]; E-G topographical cross-section for groundwater flow into the Athabasca River.

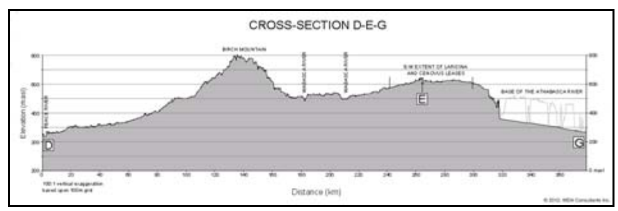

Figure 16. Topographical and groundwater table cross-section D-E-G in Figure 15.

4 CONCLUSIONS

Thermodynamic reasoning and published field data, show that all of the long range and regional groundwater flow systems listed above do not exist as postulated, neither those supposedly driven by gravitational forces nor those supposedly generated by tectonic compression or by erosional rebound. Instead there exist a number of shorter gravitationally-driven groundwater flow systems of possibly about 100-200 km length. They need to be investigated in the wake of the planned CO_2 sequestration and the development of the Wabasca Oil Sands.

Any interpretation of regional groundwater flow systems needs to be cross-checked against the unforgiving yardstick of physical causation. All the postulated long range and regional groundwater flow systems failed that test.

As a conclusion of a general nature, it became clear that physically-consistent studies of regional groundwater flow systems need to be based upon Hubbert's force potential and groundwater flow systems theory and not on the methodology of engineering hydraulics. There is an immediate need to conduct these kind of studies with an concerted effort in order to accommodate planned CO_2 sequestration in Alberta and to sustainably manage water production, SAGD operations and waste water disposal in the area of the Wabasca oil sands and beyond.

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