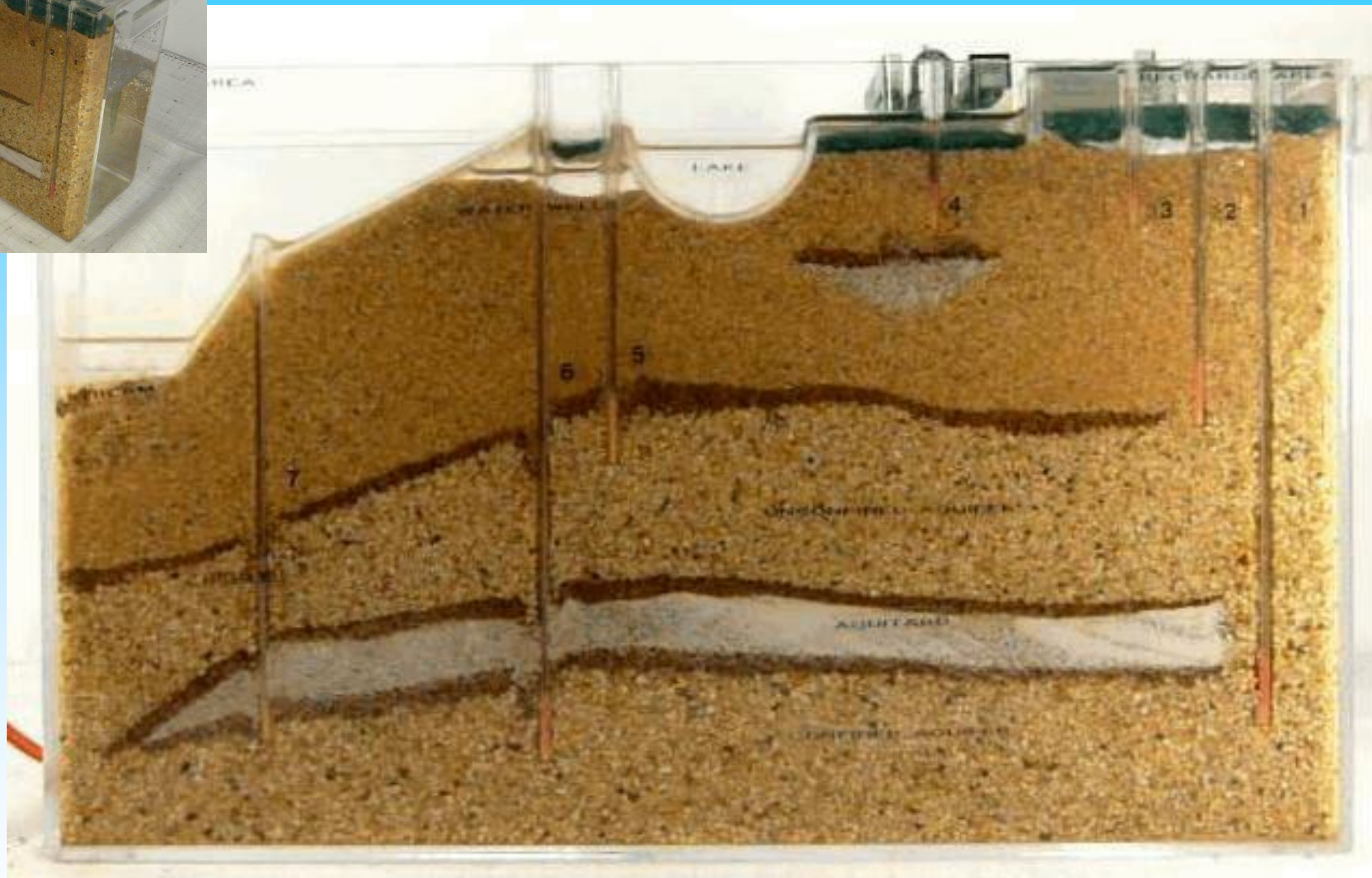
Athabasca Oil Sands: free convection or groundwater flow systems and variable density flow?

by

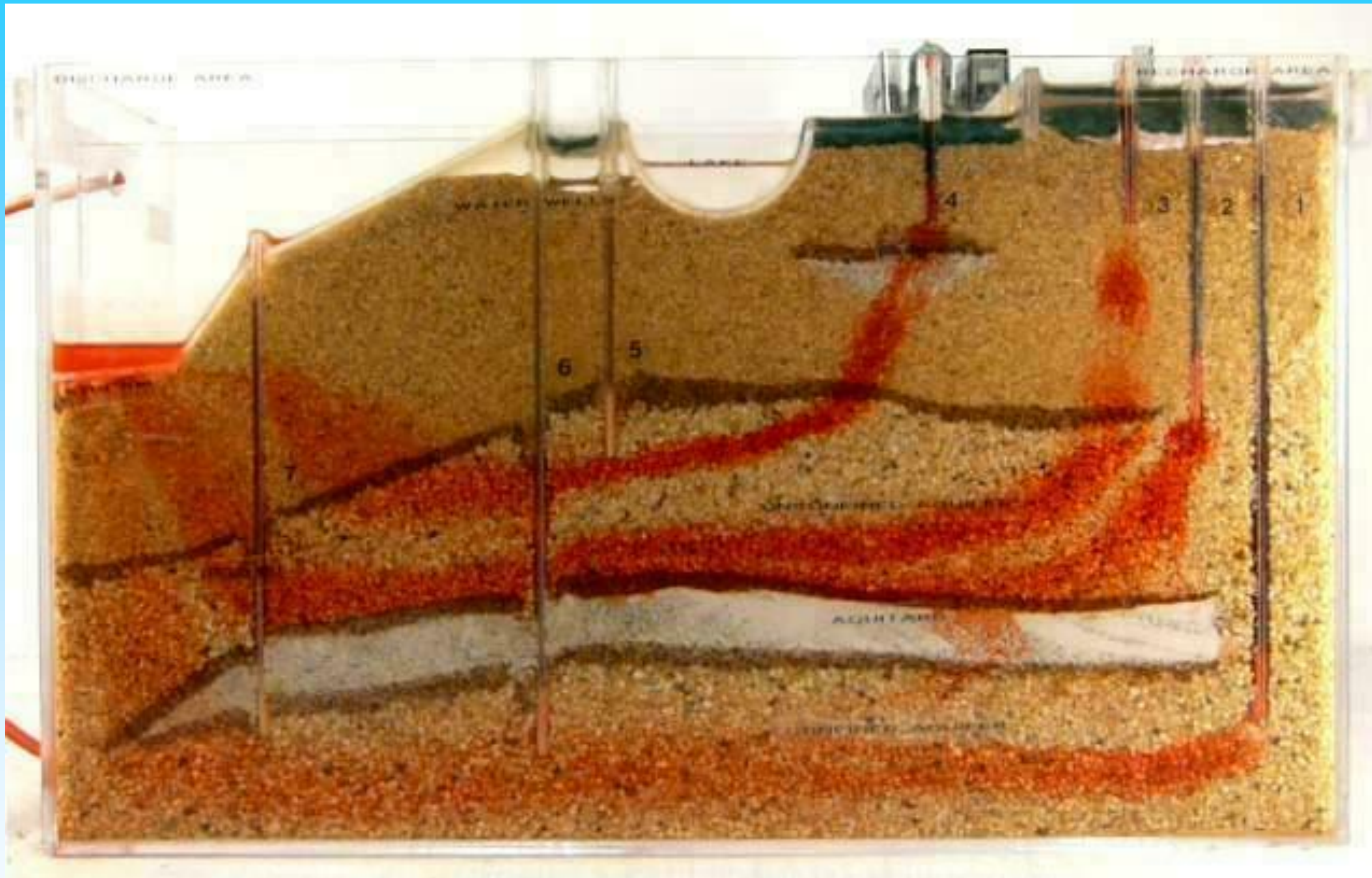
K. Udo Weyer and J.C. Ellis
WDA Consultants Inc. Calgary
weyer@wda-consultants.com

April 20, 2015. ESAA Watertech 2015, Banff, AB

The driving force is Gravitation !!



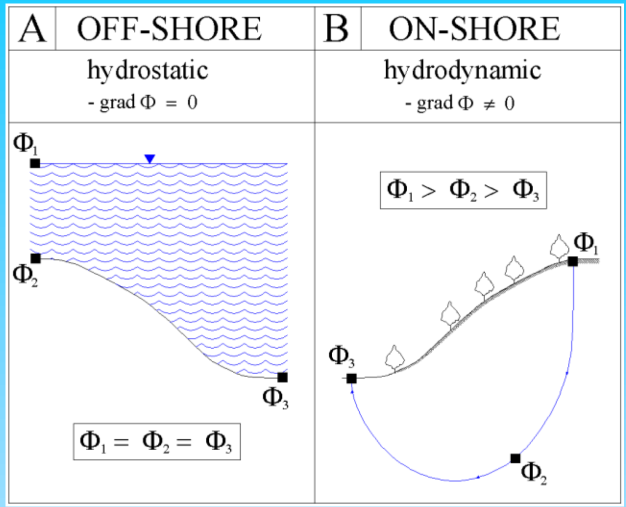
Pressure gradients are not the motor for motion of fluids in the subsurface. Upward flow maintained by unused gravitational energy. The stored energy stems from gravitational energy not needed to overcome resistance during downward flow



Demonstration of groundwater flow entering a surface water body from beneath.

Hydrostatic versus Hydrodynamic flow conditions

[1] [2]



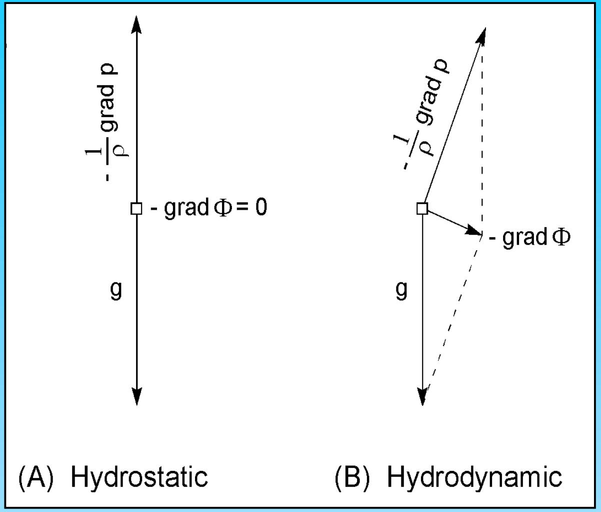
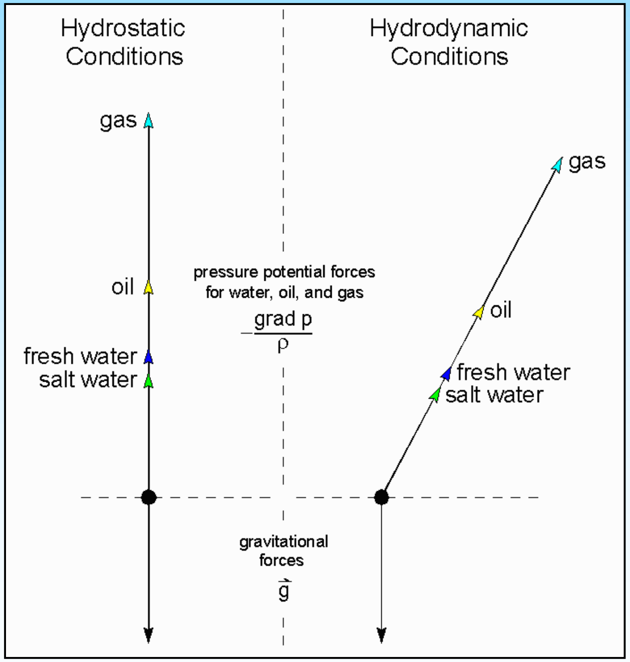


Figure 1 (left): Comparison of hydrostatic and hydrodynamic conditions in subsurface fluid flow (from Weyer, 2010. [Φ: hydraulic potential; grad Φ : hydraulic force]

Figure 2 (right): Hydrostatic forces versus hydrodynamic forces (after Hubbert, 1953).



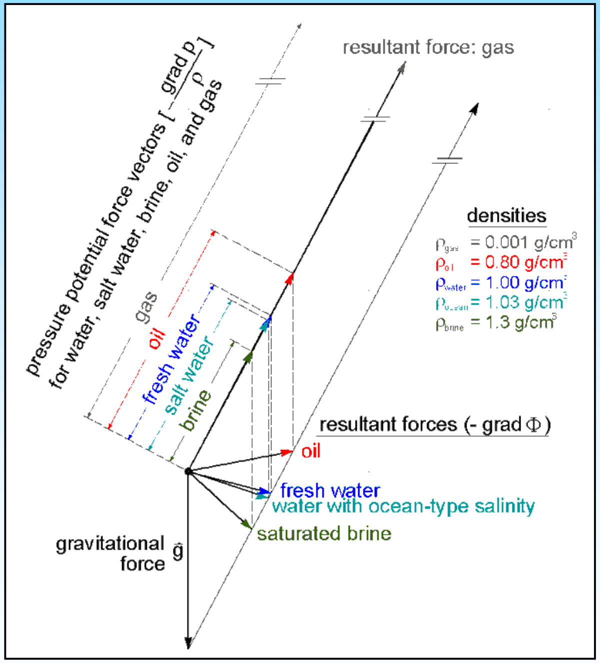
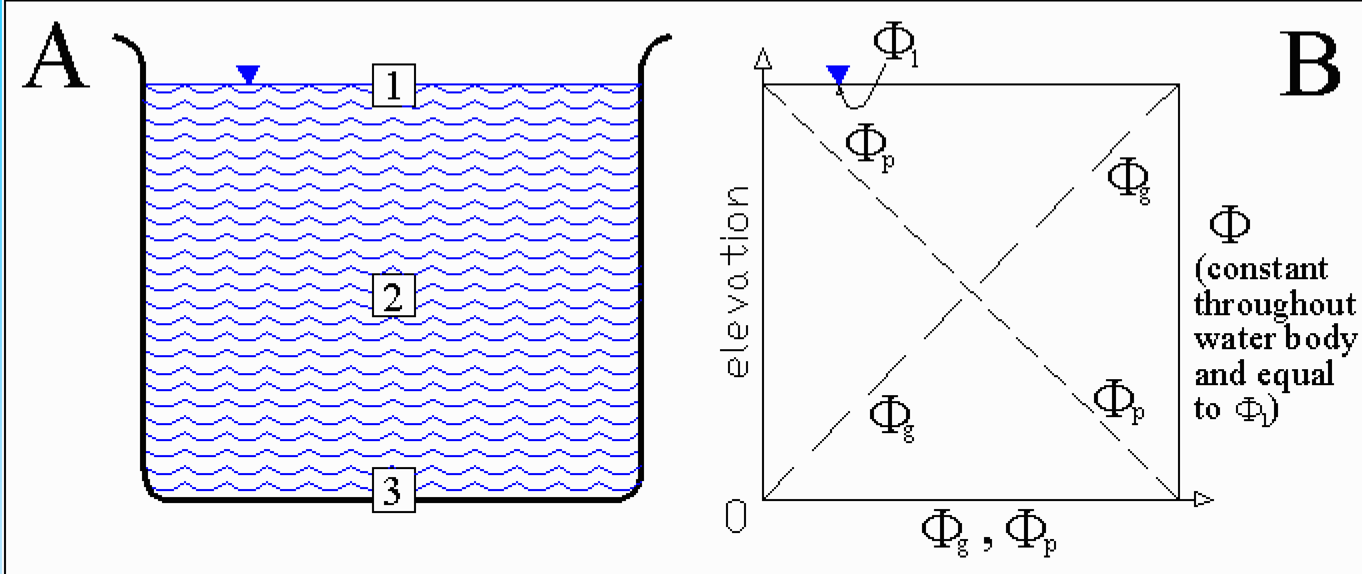


Figure 3 (left): Comparison of forces under hydrostatic and hydrodynamic conditions (from Weyer, 2010)

Figure 4 (right): Resultant calculation of flow directions for fluids of different density within the fresh water force field. From Weyer (2010)

[3] [4]



1 $\Phi_1 = \Phi_{g1} + \Phi_{p1}$
$= \Phi_{g1}$

$\Phi_{g1} > \Phi_{g2} > \Phi_{g3}$

2 $\Phi_2 = \Phi_{g2} + \Phi_{p2}$

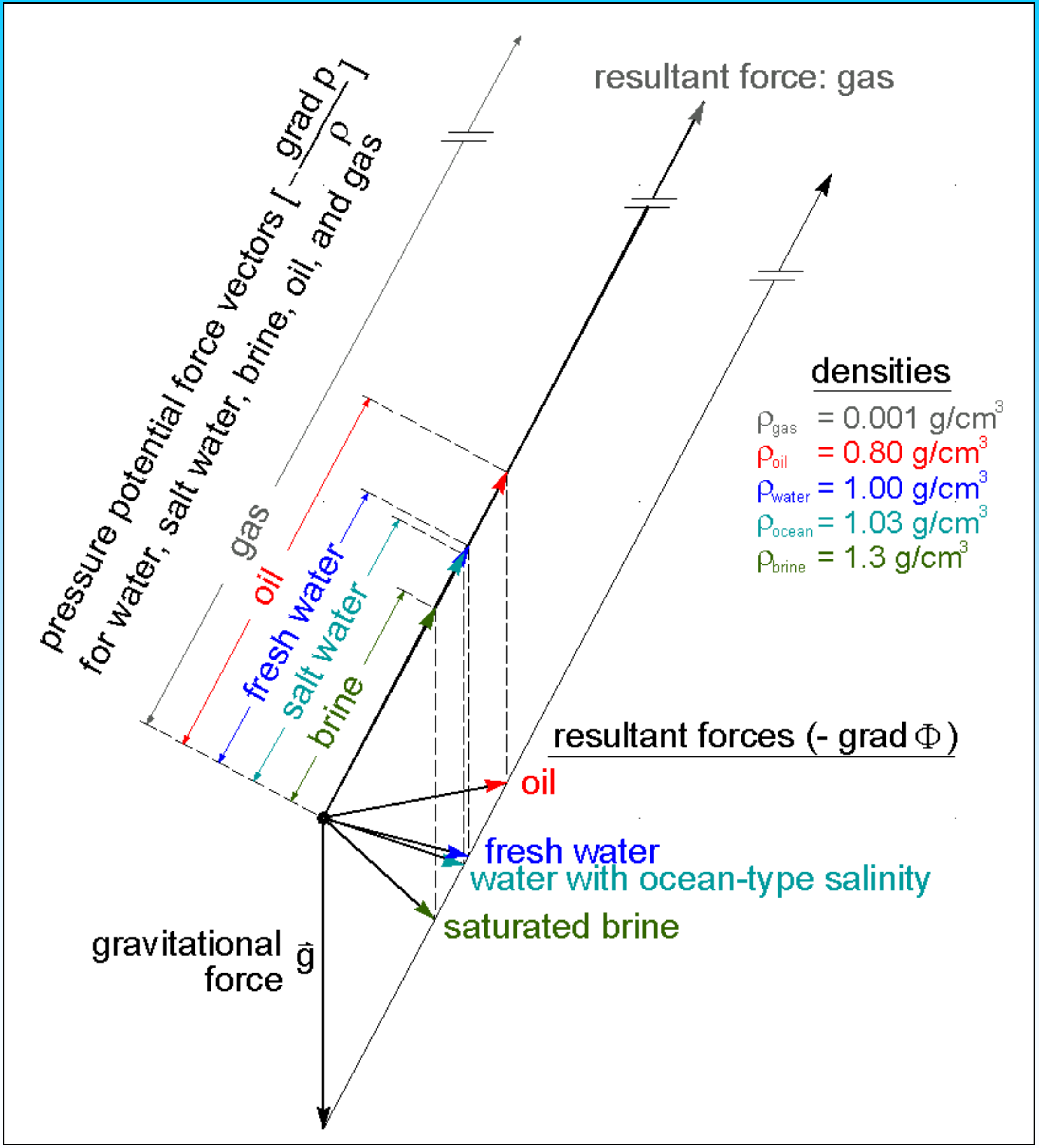
$\Phi_{p1} < \Phi_{p2} < \Phi_{p3}$

3 $\Phi_3 = \Phi_{g3} + \Phi_{p3}$
$= \Phi_{p3}$

$\Phi_1 = \Phi_2 = \Phi_3$ (grad $\Phi = 0$)

hydrostatic case = gravitational flow systems do not exist

Weyer, 2010



Resultant force directions for fluids with various densities within the fresh water force field.

Variable density flow

Variable density

Variable density implies that the density varies in space.

Forced and Free convection (Bear, 1972, p. 642)

Convection imposed by internal means is known as forced convection, while fluid motion caused by density differences due to temperature variations in the field of flow is called free, or natural convection.

The density differences could also be caused by chemical constituents.

What we address:

- Bachu and Underschultz’s (1993) buoyancy forces do not exist.
- Free convection does not exist under on-shore hydrodynamic conditions.
- In groundwater discharge areas saturated brine can flow to the surface.
- Variable density flow transports ocean-type salt water to a small river and was successfully calculated in a numerical model of a groundwater flow system using a density ρ=1 g/cm^3, so can be water of a temperature of 100°C.
- Buoyancy reversal takes on an important role in the groundwater dynamics of the Athabasca oil sands, so does Hitchon’s (1969) low fluid potential drain.
- The above mechanisms and insights are of significance for an optimal and successful practical operation of bitumen production from the Athabasca oil sands.

The big difference between assumptions and physical reality – or – where the handling of variable density flow usually goes astray

Referring to Bear (1972, p. 654), Bachu et al. (1993, p. 7) and Bachu and Underschultz (1993, p.1754) both considered two types of driving forces for variable density groundwater flow in northeast Alberta, "*a* ***potential force resulting from piezometric head differences****, and a* ***buoyancy force*** *resulting from density differences (Hubbert, 1940; Bear, 1972)*".

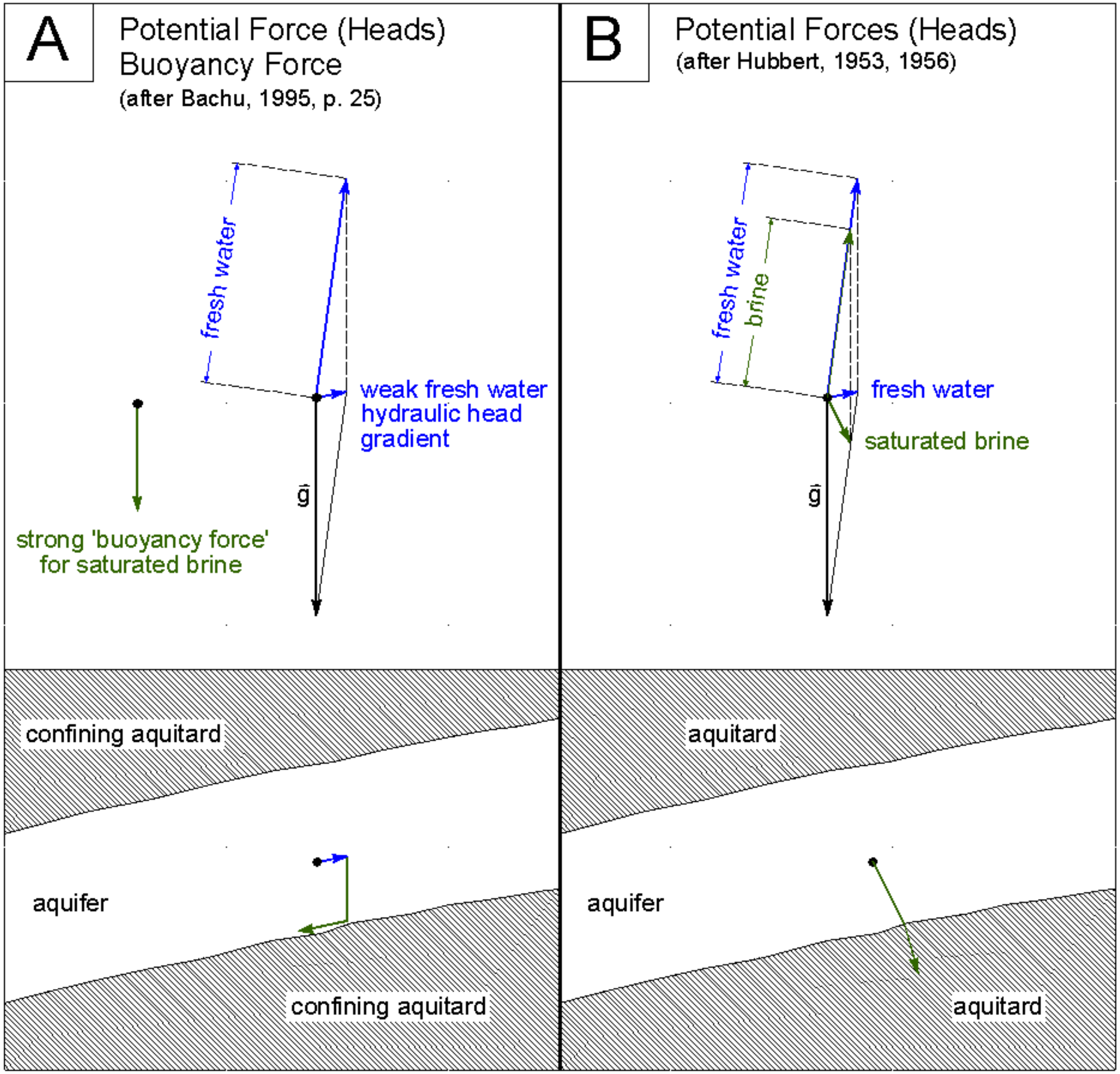
First a corrective note:

The above reference to Hubbert's (1940) treatise on the physics of groundwater flow is incorrect. Hubbert (1940) never mentioned 'buoyancy' or 'buoyancy forces' and, as a matter of fact, Hubbert deals with variable density flow only in 1953 (Hubbert, 1953, 1956) and there in a manner diametrically different from that of Bear (1972), Bachu et al. (1993), Bachu and Underschultz (1993), and Bachu (1995).

Bachu, S., J.R. Underschultz, B. Hitchon, and D. Cotterill, 1993. Regional-Scale Subsurface Hydrogeology in Northeast Alberta. Alberta Research Council, Bulletin No. 61, 44 p.

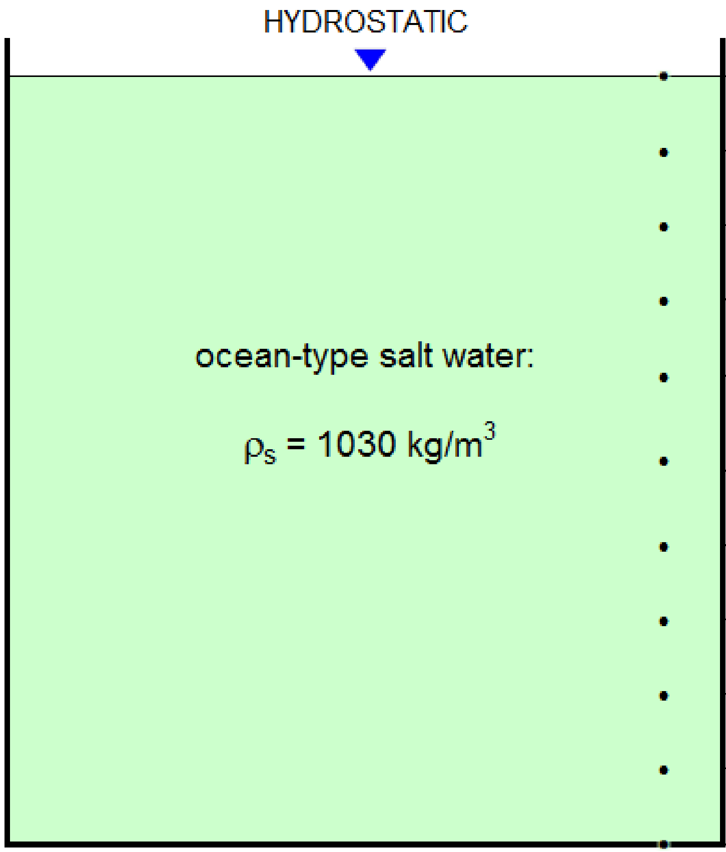
Bachu S., and J.R. Underschultz, 1993. Hydrogeology of formation waters, northeastern Alberta basin. AAPG Bulletin, vol. 77, issue 10, p. 1745-1768.

Bachu, S., 1995. Flow of variable-density formation water in deep sloping aquifers: review of methods of representation with case studies. Journal of Hydrology, vol. 164, p. 19-38.



Schematic comparison of hydraulic forces by Bachu (1995) and Hubbert (1953, 1956).

Bachu (1995) clearly lays out the conditions for buoyancy forces that had already been described in Bachu et al. (1993) and Bachu and Underschultz (1993).



Elevation z [m]	Pressure P [Pa]	Equiv. Fresh Water Head $H_f = z + P/\rho_o g$ [m]	Total Force Potential (energy/mass) Φ [m^2/s^2]	Total Head H_t [m]
10	0	10	98.1	10
9	10104.3	10.03	98.1	10
8	20208.6	10.06	98.1	10
7	30312.9	10.09	98.1	10
6	40417.2	10.12	98.1	10
5	50521.5	10.15	98.1	10
4	60625.8	10.18	98.1	10
3	70730.1	10.21	98.1	10
2	80834.4	10.24	98.1	10
1	90938.7	10.27	98.1	10
0	101043	10.3	98.1	10

Bear (1972), Bachu et al (1993), Bachu and Underschultz (1993), Bachu (1995) and many others are in error when claiming that variable density flow needs to be dealt with by applying two force systems that of piezometric head forces and that of buoyancy forces.

The action of buoyancy is physically incorporated within the vectorial calculation of potential (energy/mass) forces as shown in slides 8 and 12.

FREE CONVECTION

Hydrostatic Boundary Conditions

Off-Shore and laboratory experiments

Hydrothermal Convection

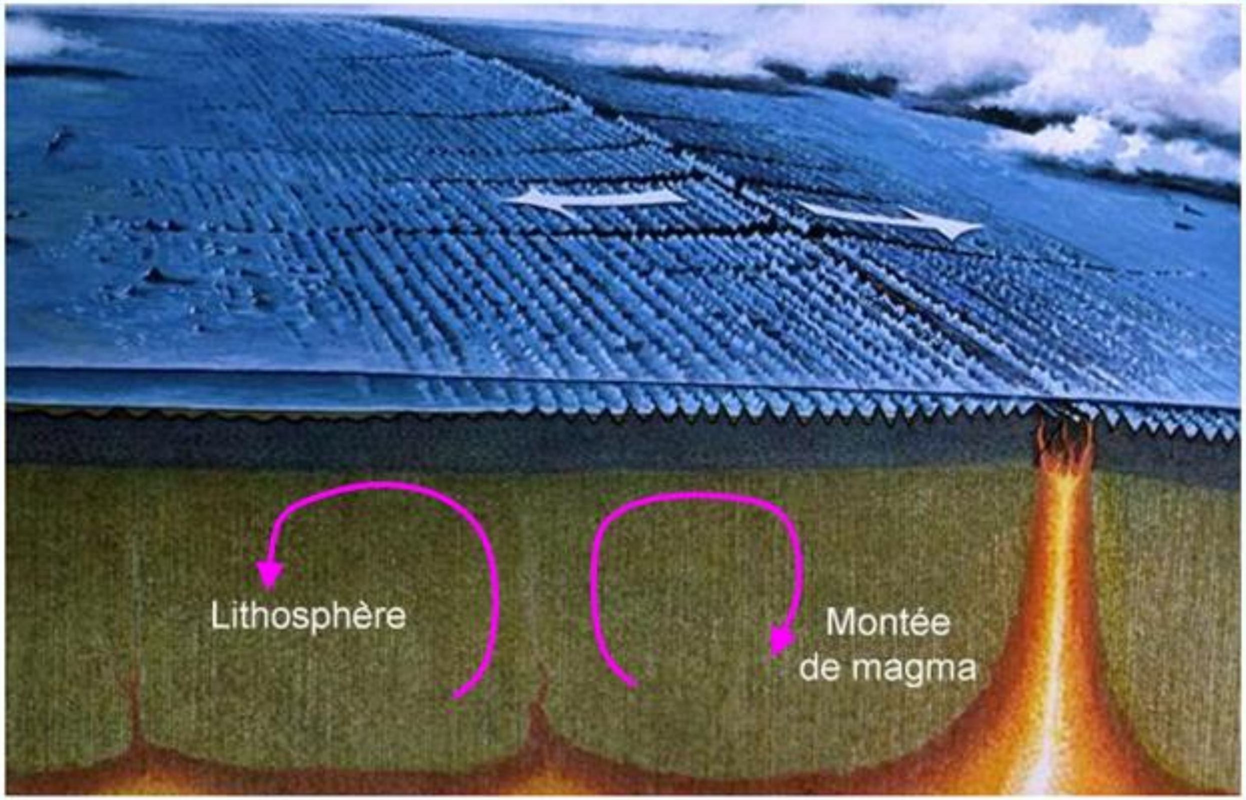
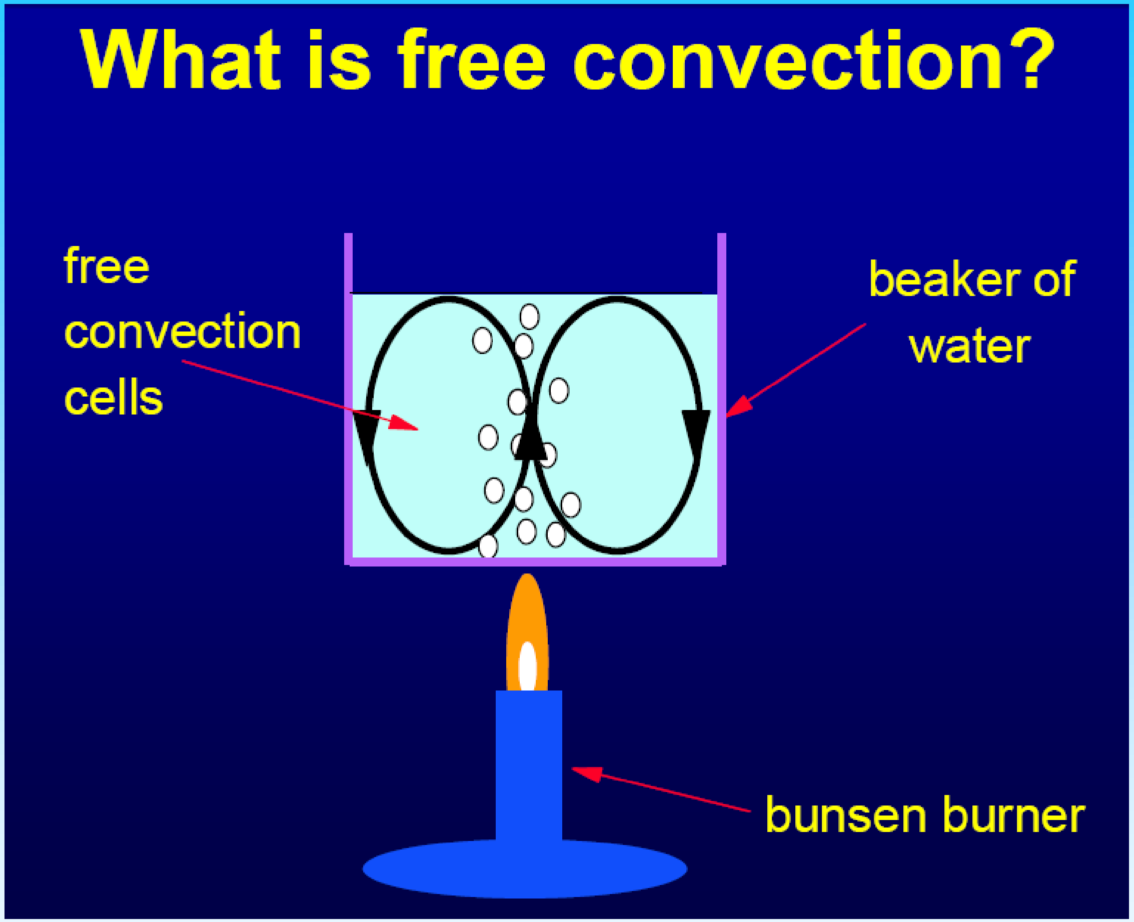


Figure 12.4b - Topographie du fond de l'océan Atlantique, illustrant la ride médio-océanique

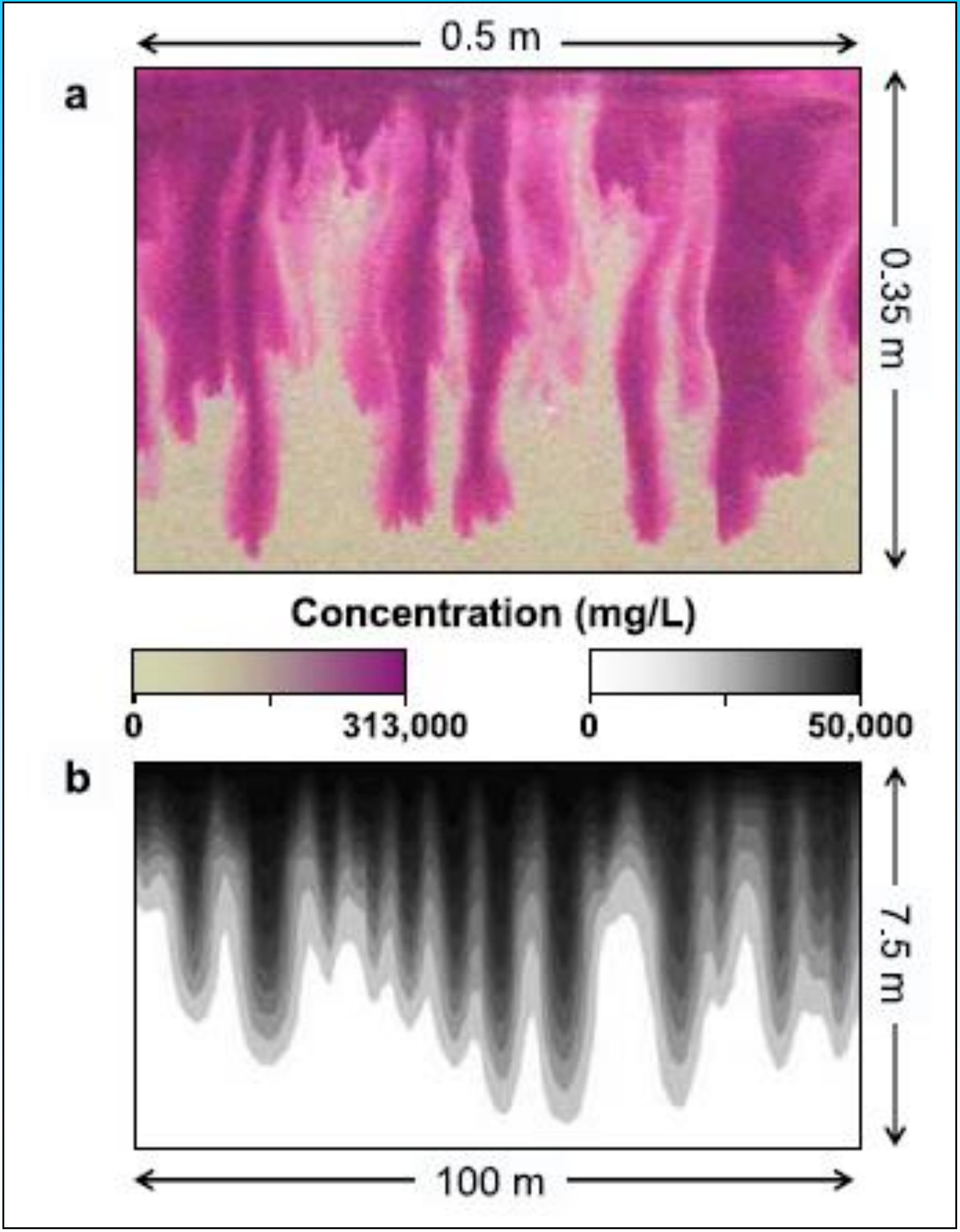
Black Smokers – slide by John Molson, Laval University



Simmons, 2011, Variable Density Groundwater Flow: From current challenges to future possibilities. Presentation at the 2nd International HydroGeoSphere User Conference, April 11-13, 2011, Hannover, Germany.

Cases of free convection in a laboratory setting which can also be numerically modelled:

1. Heat source underneath a hydrostatic system
2. Heavier fluid on top of a hydrostatic water body

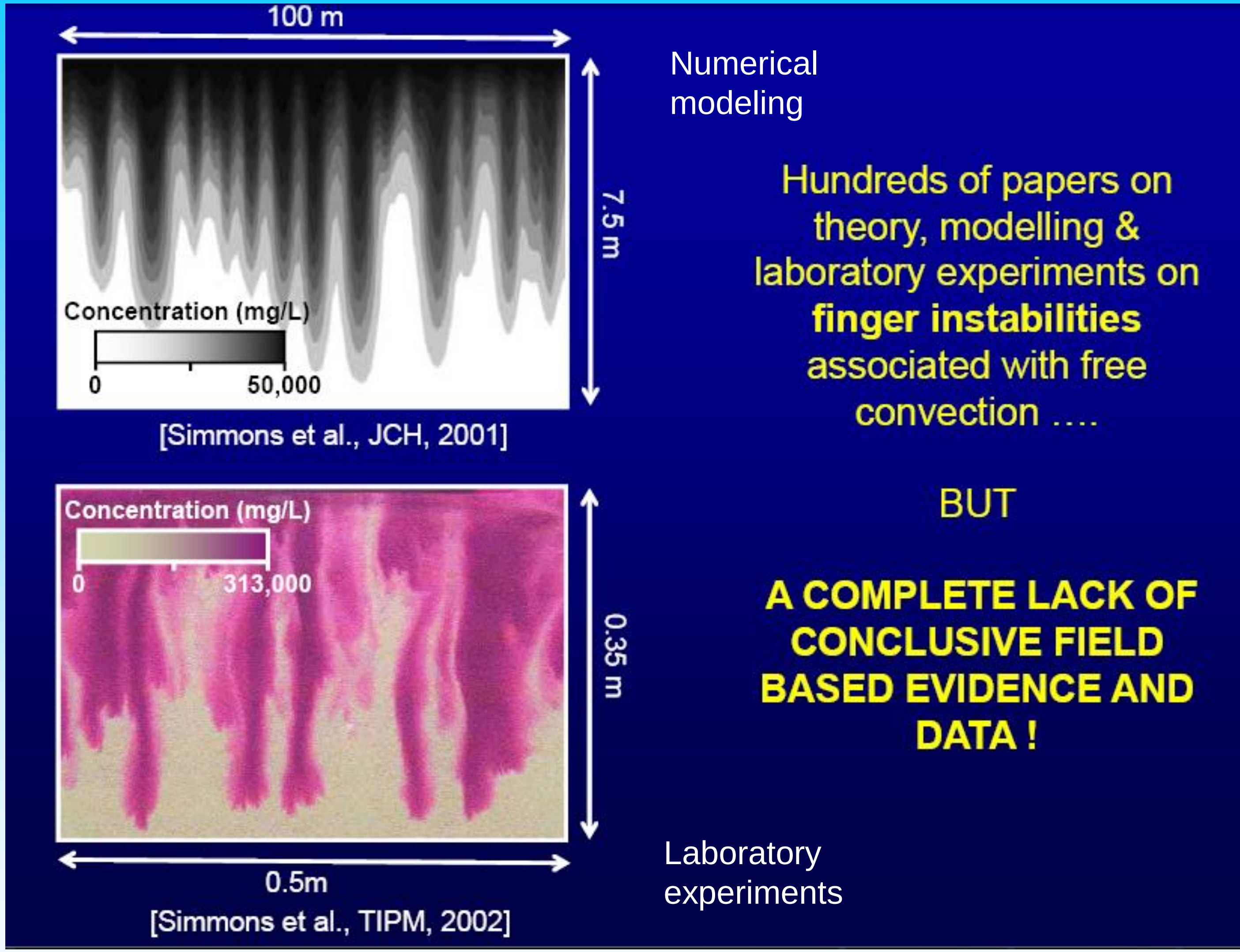


"Representative examples of fingering associated with unstable free convection in groundwater from (a) laboratory experiments and (b) numerical modeling."

In the experiment a heavier saline fluid is positioned upon the less saline water under hydrostatic conditions. The numerical calculation relies upon similar conditions.

Van Dam, R. L., C.T. Simmons, D.W. Hyndman, and W.W. Wood, 2009. Natural free convection in porous media: First field documentation in groundwater. Geophysical Research Letters, vol. 36, issue 11, Fig. 1.

[Refers to Abu Dhabi.]



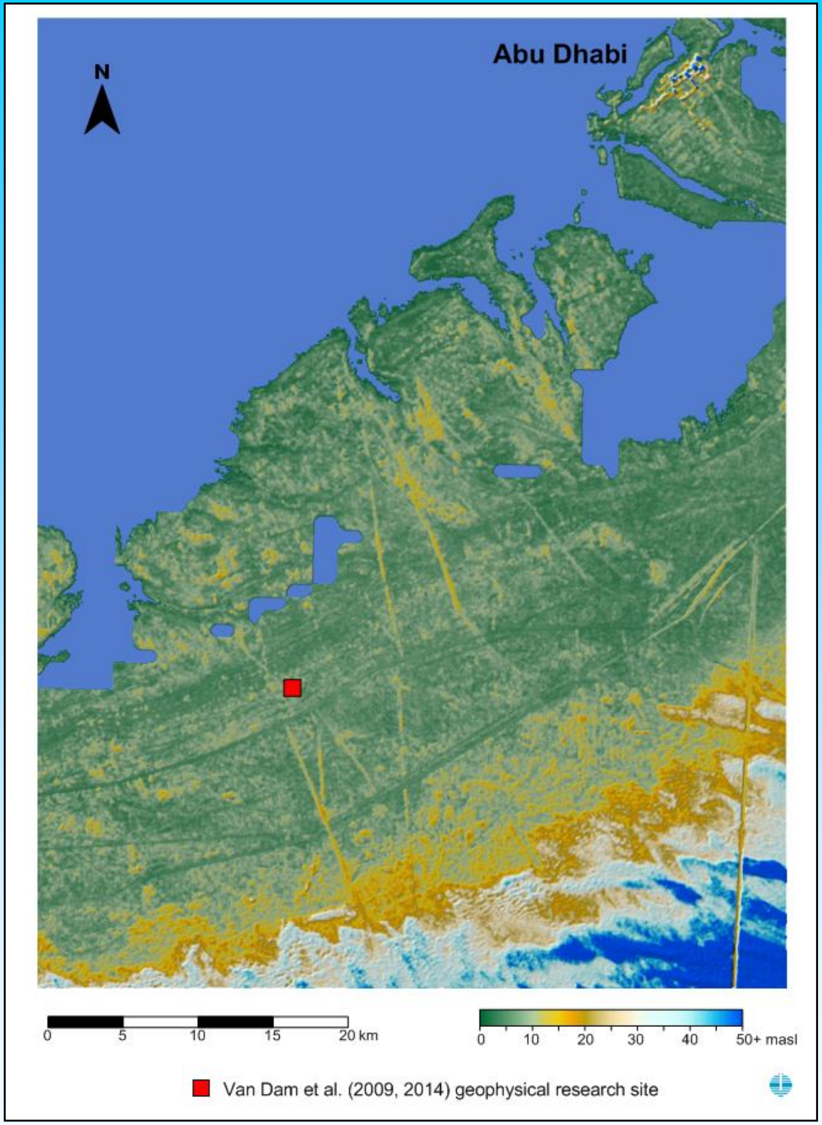
Simmons, 2011, Variable Density Groundwater Flow: From current challenges to future possibilities. Presentation at the 2nd Int'l HydroGeoSphere User Conference, April 11-13, 2011, Hannover, Germany.

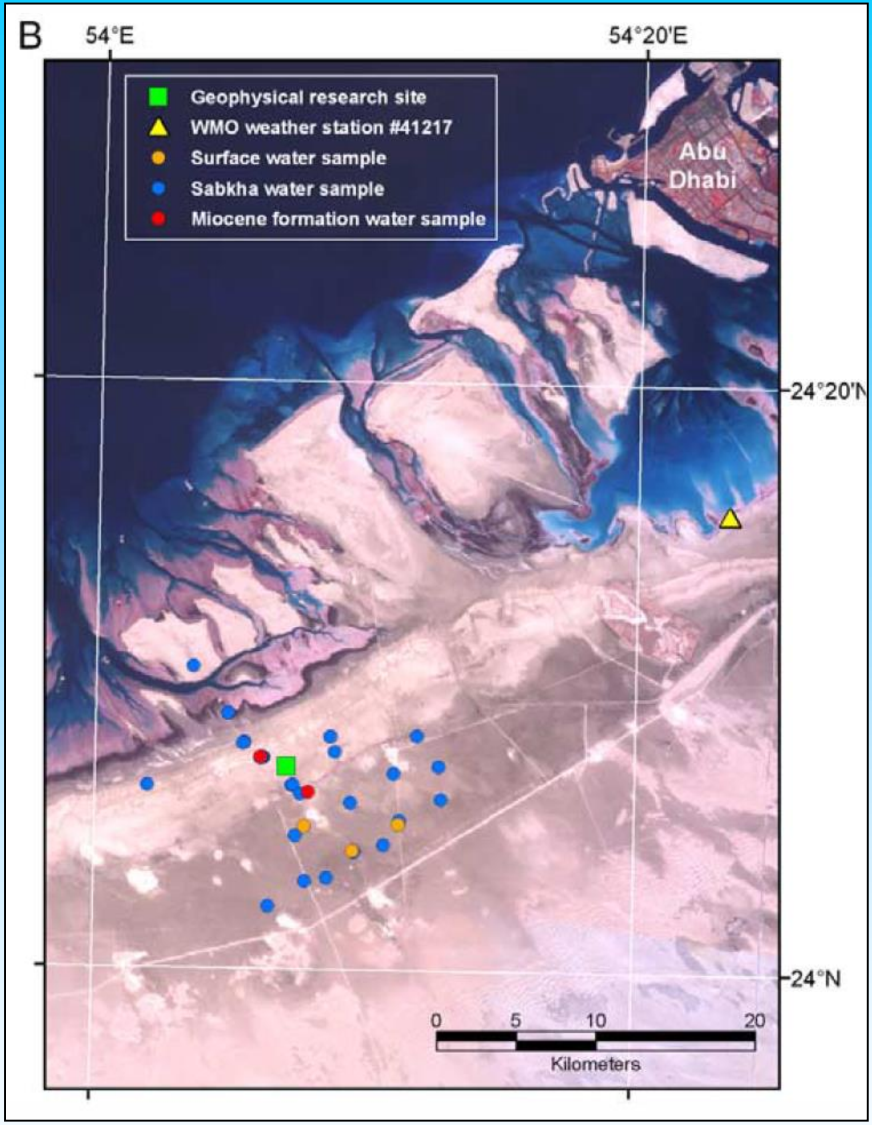
Downloaded on August 31, 2013 from http://www.hgs-conference2011.uni-hannover.de/fileadmin/hgs_2011/pdf/Simmons_HGS_Workshop_2011.pdf

Abu Dhabi, UAE
Naturally occurring free convection?

after CIA, 1995

Overview of the United Arab Emirates. Red square: Field site.





Van Dam et al., 2009, Fig. 2c

The geophysical research site lies within a hummocky area of the sabkha, indicating the presence of strong local flow systems after rain events.

History

2008 first electrical resistivity measurements in Abu Dhabi Sabkha

2009 paper in AGU's Geophysical Research Letters: "*Natural free convection in porous media: First field documentation in groundwater*"; believe they found fingering; co-author Craig T. Simmons

2009 second electrical resistivity measurements in Abu Dhabi Sabkha. No fingering found

2011 Hannover and Feflow presentations by Craig T. Simmons:

"*Hundreds of papers on theory, modelling & laboratory experiments on* ***finger instabilities*** *associated with free convection … BUT* ***A COMPLETE LACK OF CONCLUSIVE FIELD BASED EVIDENCE AND DATA !****"*

2014 paper in AGU's Water Resources Research "Electrical imaging and fluid modelling of convective fingering in a shallow water-table aquifer," co-author Craig T. Simmons. The paper deals with the 2008 and 2009 field measurements of electrical resistivity. Surprisingly the conclusion is now that free convection exists in the Sabkhat al Salamiyah of Abu Dhabi.

Continued on next slide

In addition to previous electrical resistivity work an additional hydrological numerical model was calculated with the boundary conditions as shown below:

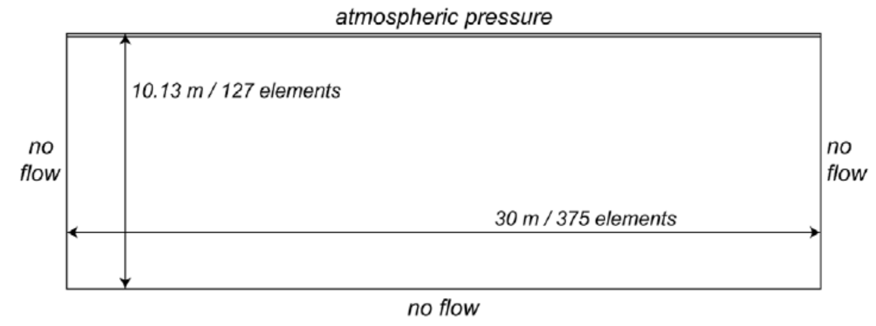


Figure 6. Geometry and boundary conditions for the simulation. Parameter values are listed in Table 3.

Van Dam et al., 2014

$$u = -\frac{\kappa}{\mu}(\nabla p + \rho g \nabla z),$$

Van Dam et al., 2014, Equation (3)

A velocity potential version of Darcy's equation was used.

The model domain is essentially a closed box of about 30 m length and 10 m height. It is essentially hydrostatic although a groundwater table gradient of 0.0002 m has been measured in the field and supposedly superimposed as a hydraulic gradient. However, the gradient of the groundwater table is nearly never the actual hydraulic gradient causing groundwater flow. The authors did not take the actual gradients and flow direction into account. They ignored the actual local and regional groundwater flow pattern in the area of their investigation.

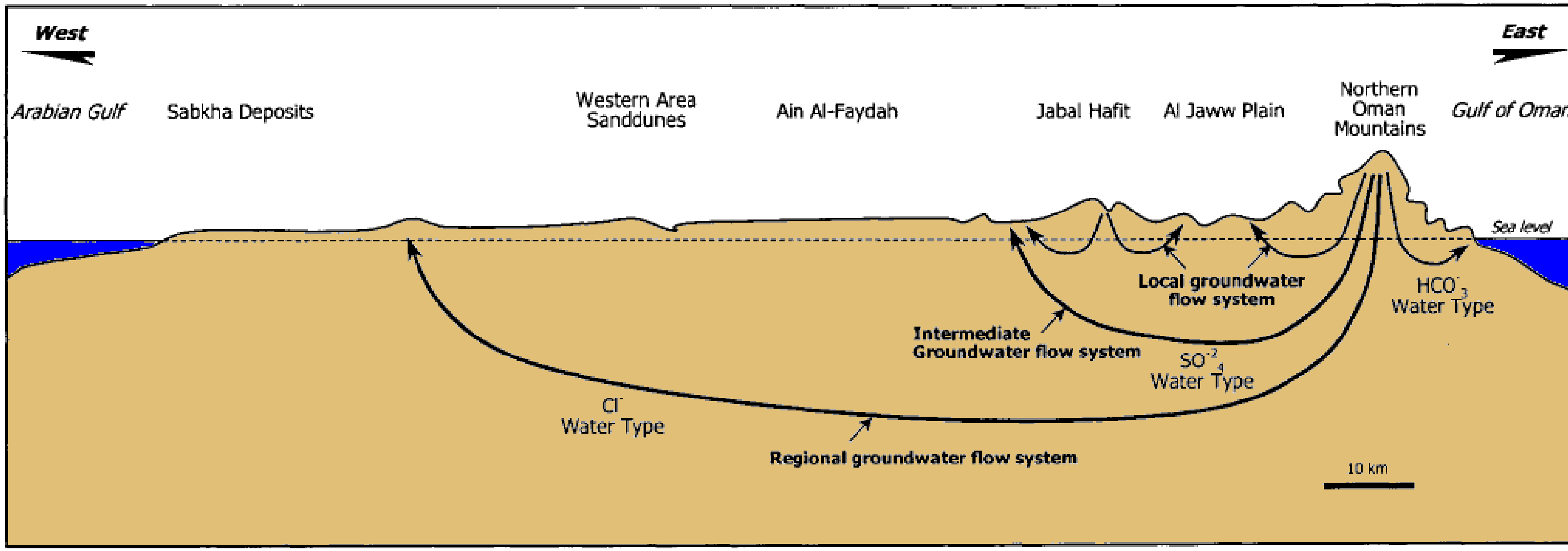
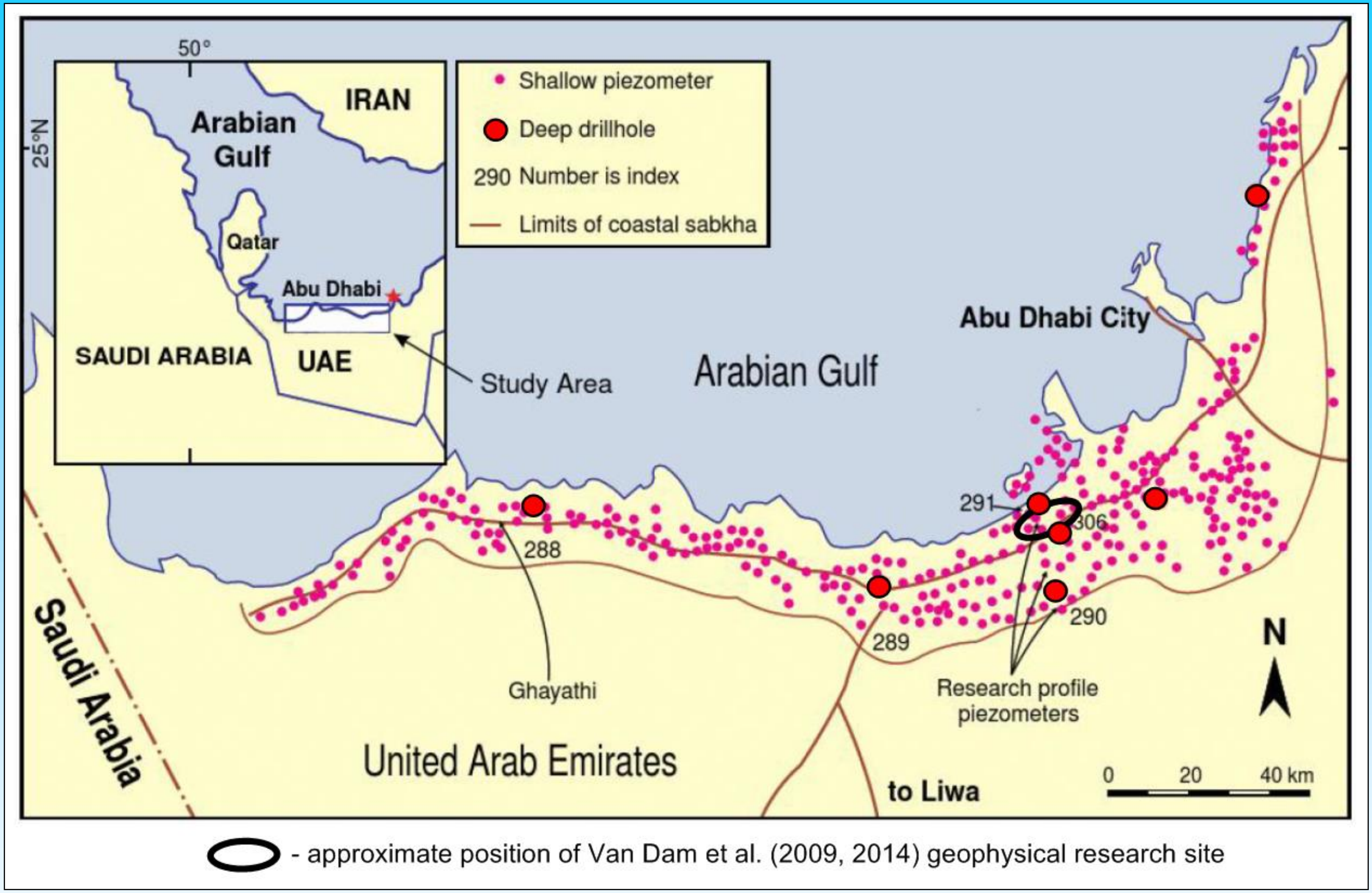


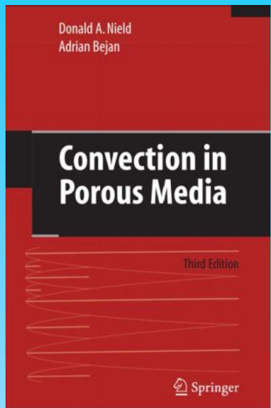
Fig. 8.55. Schematic diagram illustrating different flow systems in the United Arab Emirates, based on hydrological, hydrochemical and isotopic characteristics of groundwater (modified from Rizk and El-Etr, 1994).

After Alsharhan et al., 2001

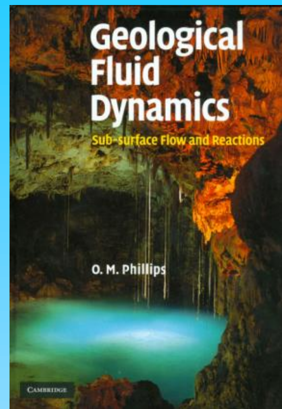
Schematic diagram of regional and intermediate groundwater flow system. The regional systems deliver Cl^- water to the regional Sabkhat discharge areas



Map showing the location of shallow, intermediate, and deep piezometers on the coastal sabkha of Abu Dhabi. Modified from Wood (2011), after Wood et al. (2002).



2006



2009

Free convection: a regress in hydraulic knowledge?

Both of these textbooks are from authors who are proponents of ‘free convection’ based on the application of an invalid form of Darcy’s equation (using pressure gradients as driving forces) and the assumption of hydrostatic conditions to prevail in an hydrodynamic environment.

The answer to the above question is:

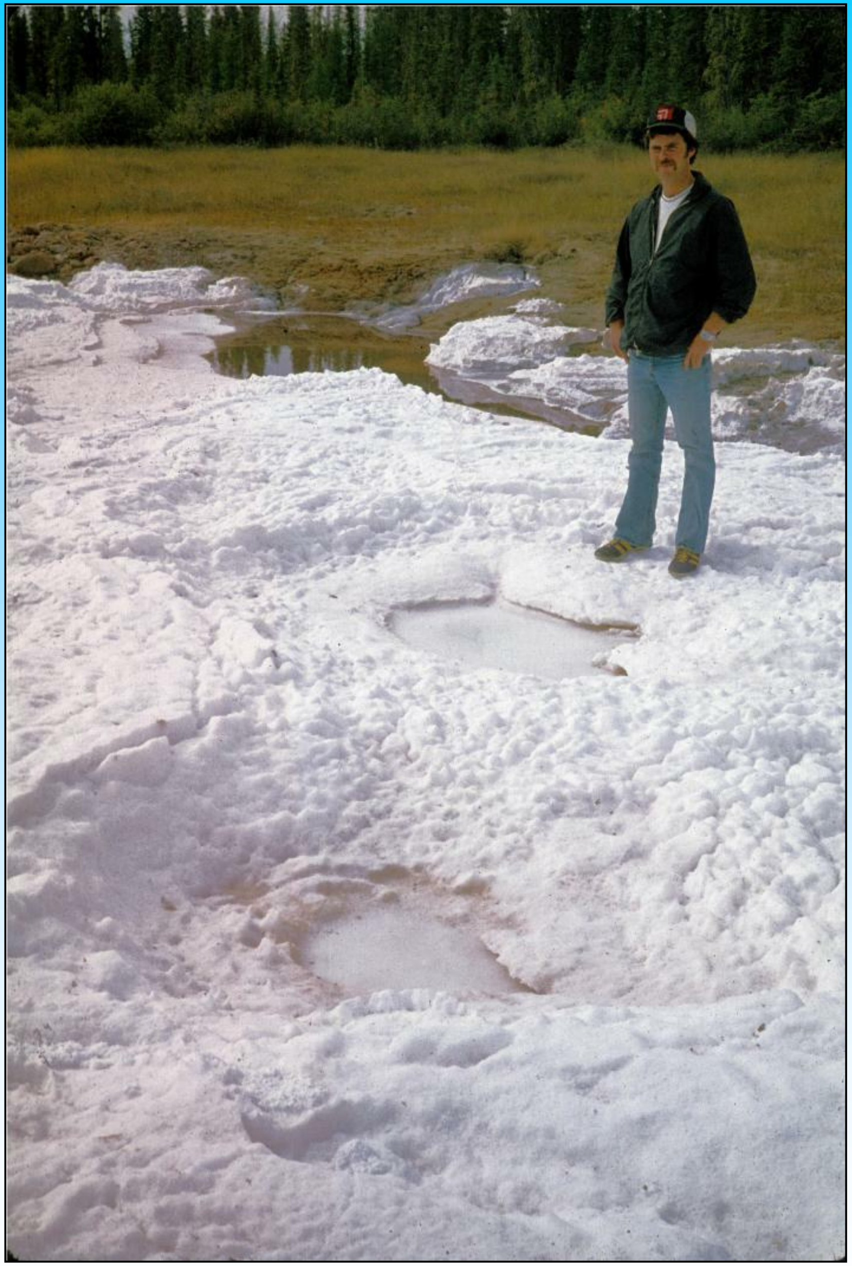
Definitely YES

Density changes along flow lines within real-world groundwater flow systems

A. Field example Salt River Basin, NWT, Canada:
Upward discharge of **saturated brine**.

Saturated brine (ρ ~1.3 g/cm^3) flows upwards to the surface?

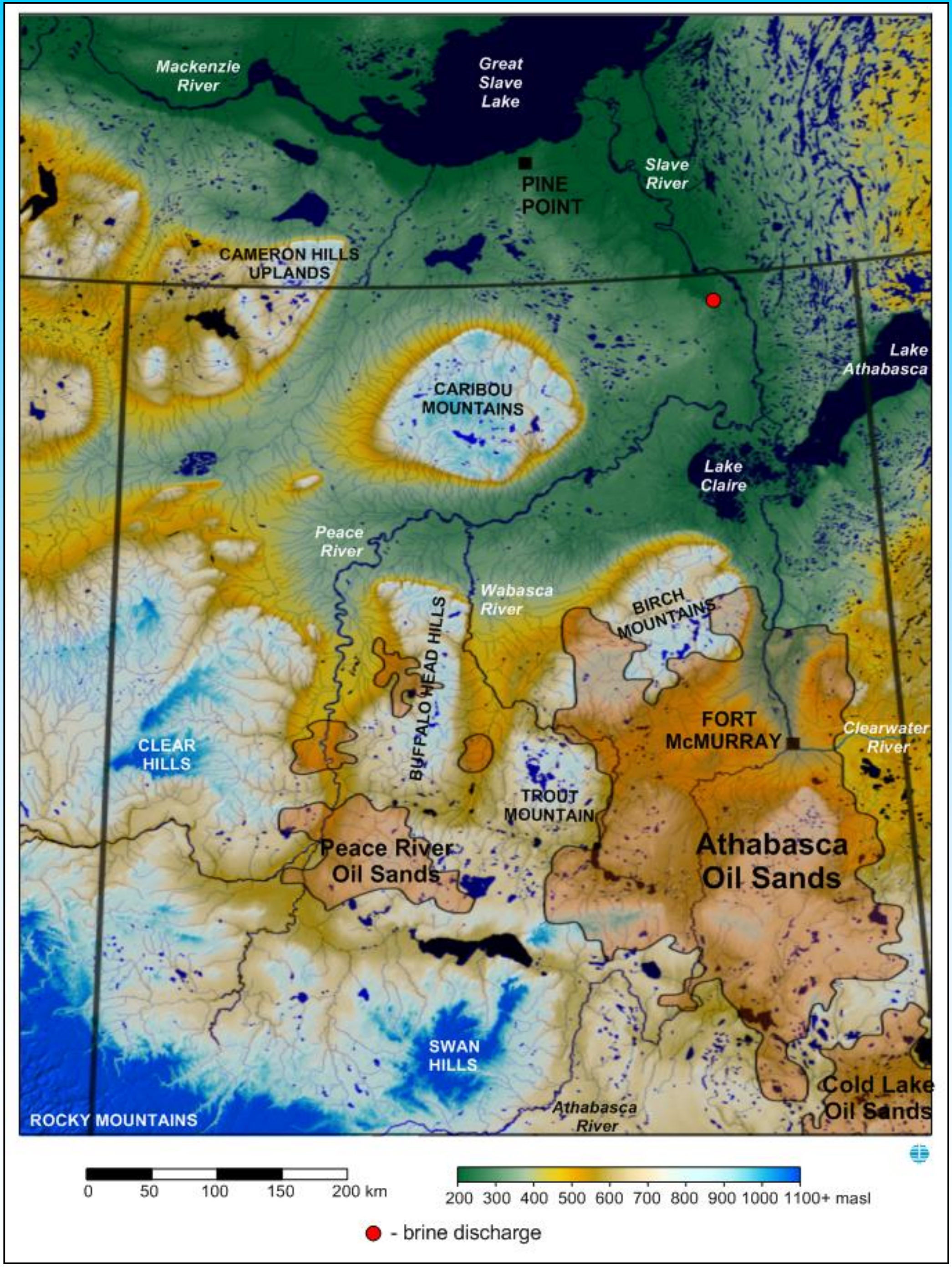
Many scientists and practitioners in Alberta and worldwide claim that buoyancy forces (in this case directed downwards) would prevent this from happening.



Field example in Salt River catchment basin, NWT, Canada

- Saturated [~350 g/l; density ~1.3 g/cm^3] brine discharging upwards beside a creek
- Salt deposit is caused by precipitation of salt not by evaporation of brine.

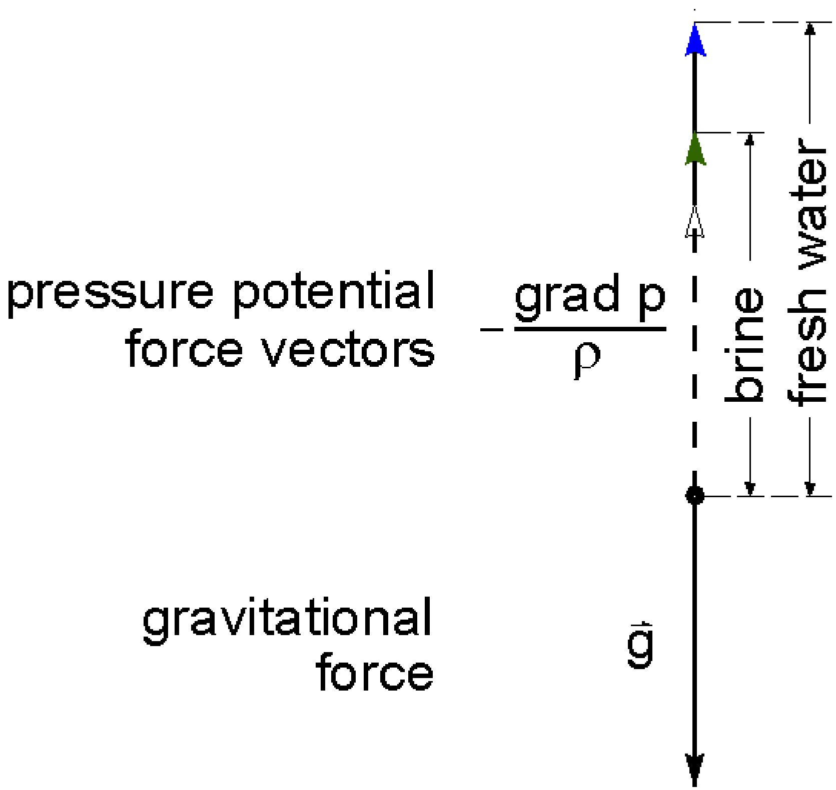
picture: K.U.Weyer, 1977

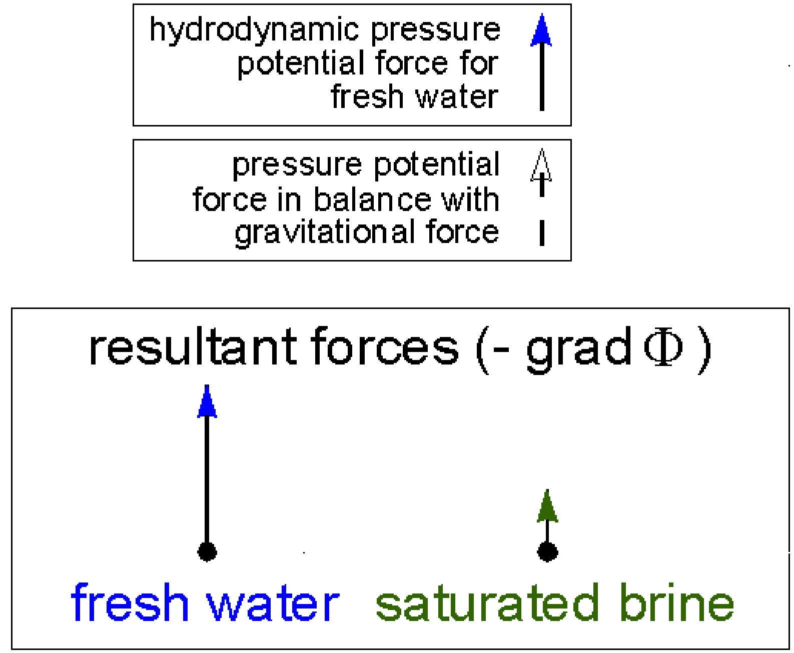


Upward discharge of saturated brine to the surface in the head waters of the Salt River

Extent of oil sands taken from Einstein, 2006

Explanation why saturated brine did flow upwards to the surface, passing through a very low-permeable layer

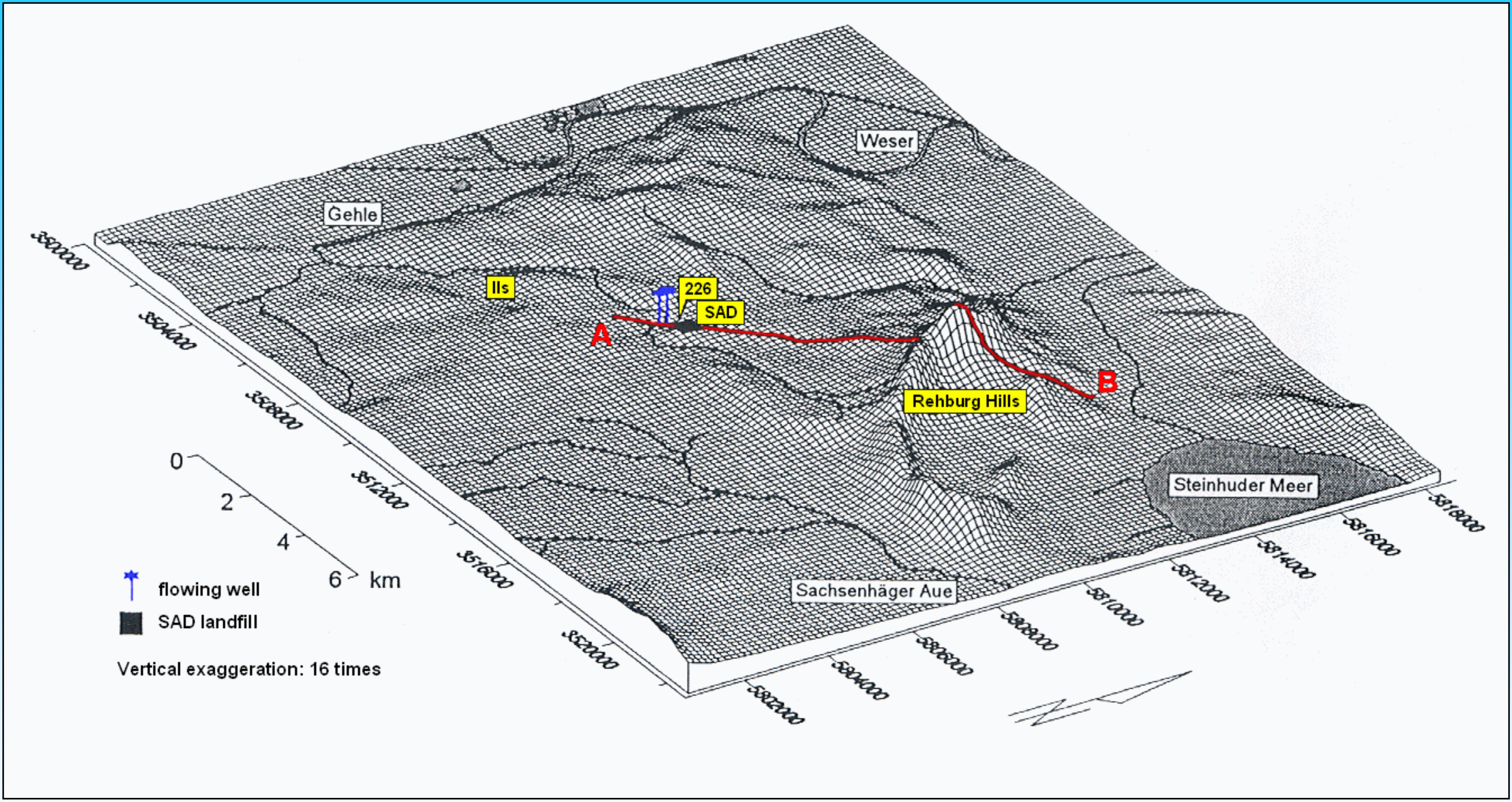




(in both cases, the upwards-directed pressure potential force exceeds the downward-directed gravitational force, resulting in upwards-directed gradients of the fluid potentials)

Density changes along flow lines within real-world groundwater flow systems

B. Field example and mathematical model: Upward discharge from a depth of 1000 m of **ocean-type saline water** in a deep groundwater flow system at Münchehagen, Germany



Weyer, K.U., 1996. Physics of groundwater flow and its application to the migration of dissolved contaminants. Final Research report to the Federal Environmental Office of the German Government, April 1996 [in German], 204 p

2D-vertical model of groundwater flow directions at the Münchehagen landfill area

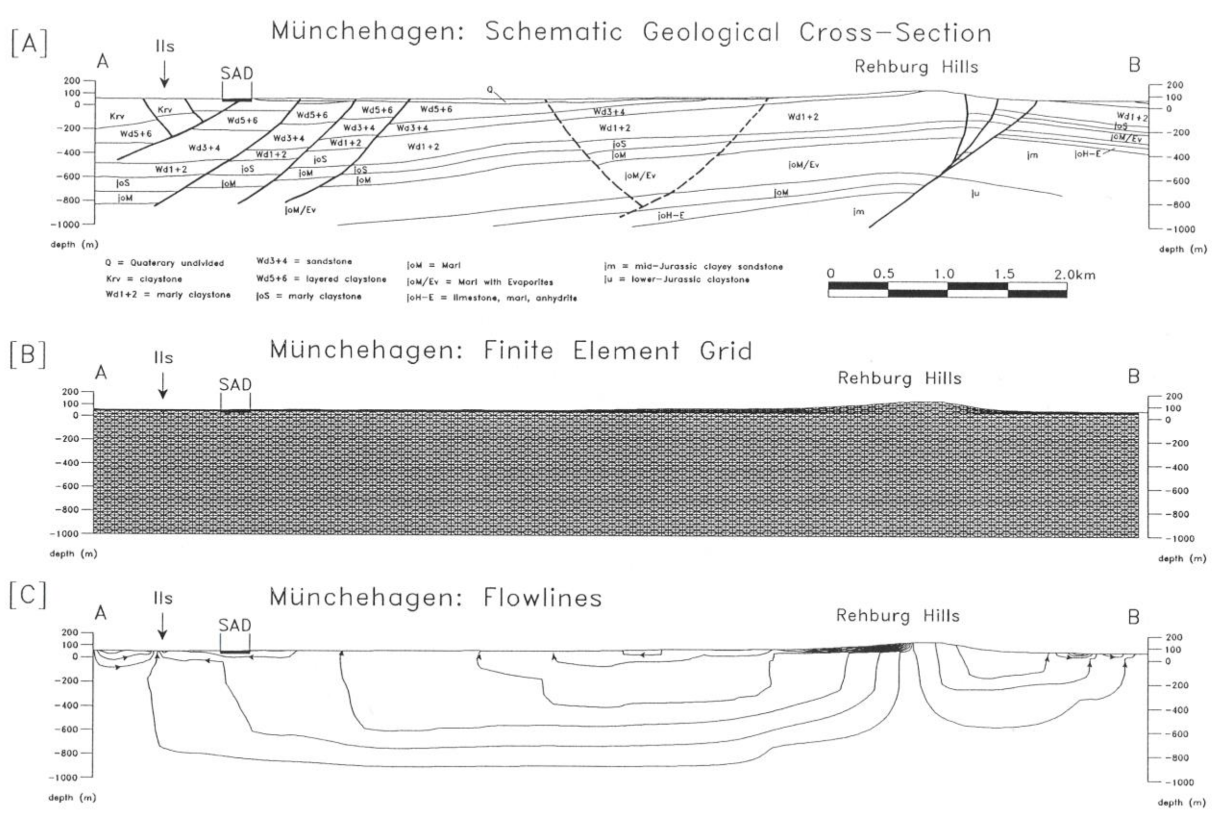
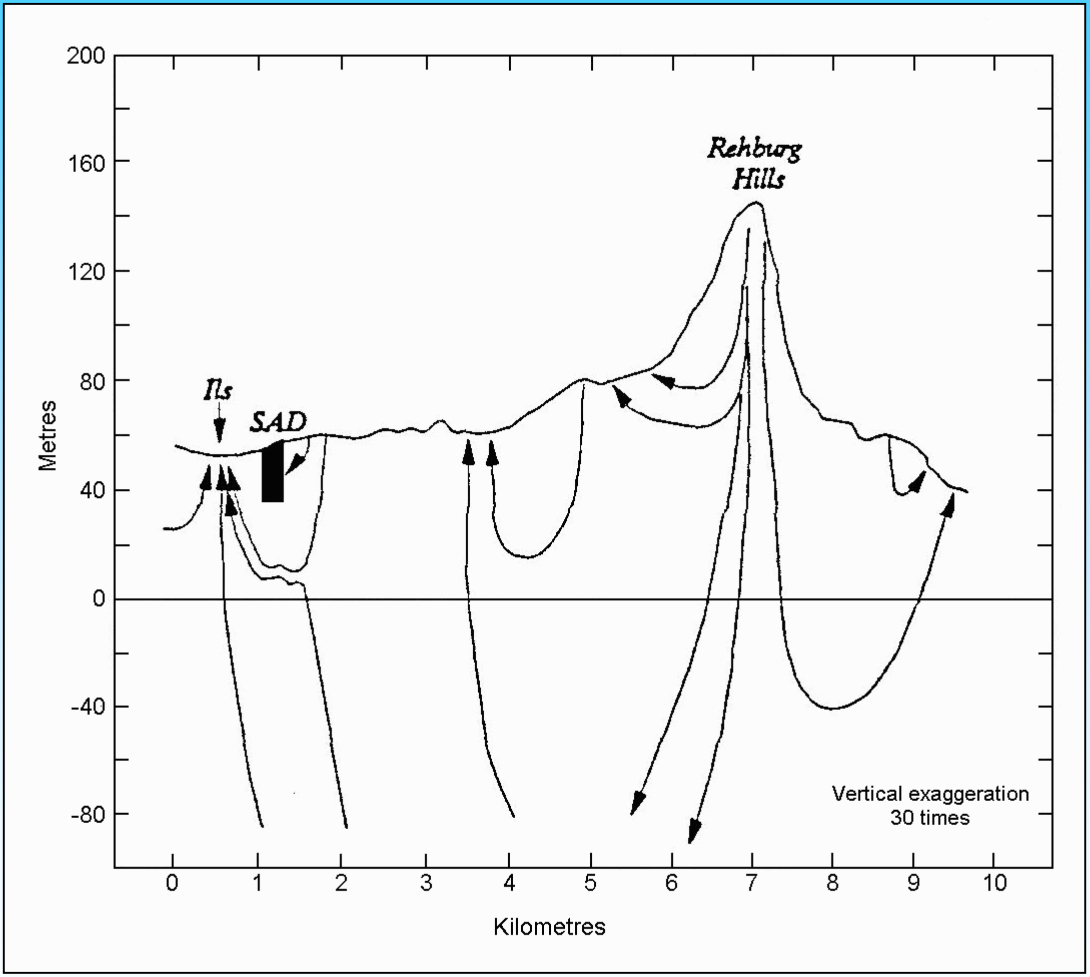


Fig. 3 A: Geological cross-section A-B (see Fig. 1). The geological profile was composed based on data from Jordan (1975) and Rohde (1992). B: Finite element grid for geological cross-section A-B. C: Vertical groundwater flow model Münchehagen: Flow lines in geological cross-section A-B. Vertical exaggeration is 1:1.

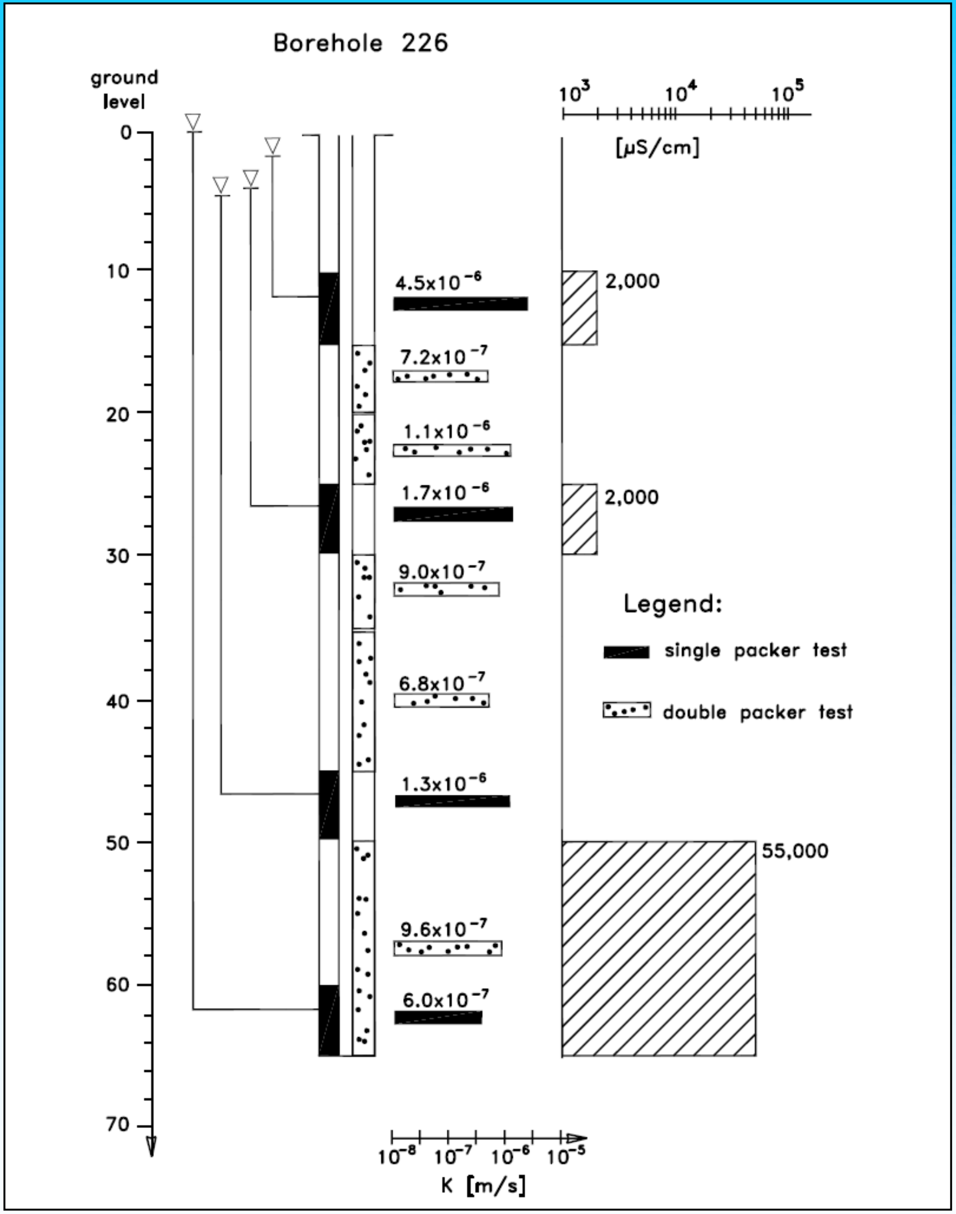
Geologic cross-section taken from 1:25,000 geologic maps. Calculated groundwater flow directions based on groundwater table (following topography) and estimated permeability contrasts

Cross-section A-B showing flow lines calculated by 2D-vertical mathematical model



Weyer, 1996

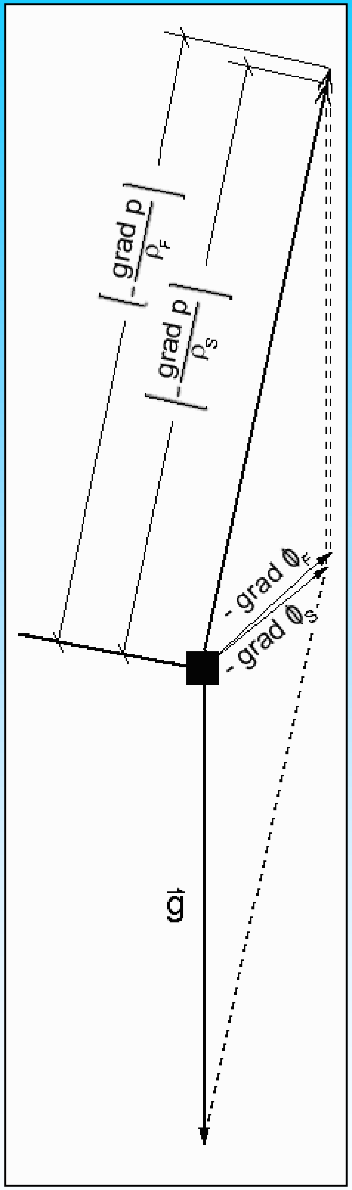
- SAD = landfill Münchehagen
- Laterally-compressed flow lines as returned by model calculation; vertical exaggeration 30:1
- Upward flow line of saline water occurs at 50 m depth below ground
- Due to higher permeable layer, lateral flow of shallow and deep flow lines converge towards river Ils



Gronemeier et al., 1990, Fig.7

Occurrence of saline water in borehole 226 at a depth of about 50 m below ground.

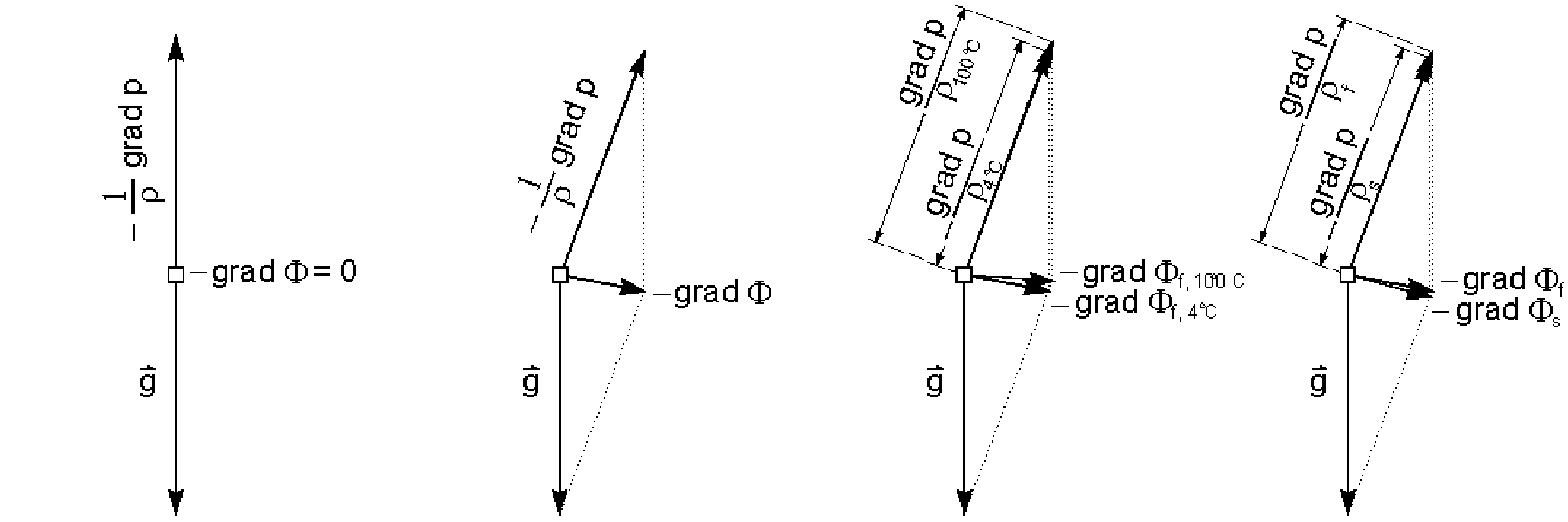
- Conductivity and salinity of the saline water is about that of ocean water.
- Upward flow of saline water to about 50 m depth due to higher permeable layer above that depth (see permeability distribution in diagram).
- Due to that higher-permeable layer, lateral flow of shallow and deep flow lines converge towards river Ils.
- Water levels in diagram indicate downward flow in local flow system and upward flow in the regional saline flow system.
- The occurrence of salt water is coincidental. The same flow pattern would emerge with freshwater.



Weyer, 1996

Why is fresh water modeling suited to determine the flow lines of saline seawater?

- Freshwater determines the field of the potential in the subsurface.
- With a density of 1.03 g/cm^3 the vectoral pressure potential force for this seawater-type saline water is very similar in magnitude and direction to that of fresh groundwater with a density of 1.00 g/cm^3.
- Thus the flow directions are very similar for ocean-type saline groundwater and fresh groundwater [see adjacent figure].
- This has been verified by the occurrence of saline water at a depth of about 50 m below ground in borehole 226 and in the model results.



(A) Hydrostatic

(B) Hydrodynamic

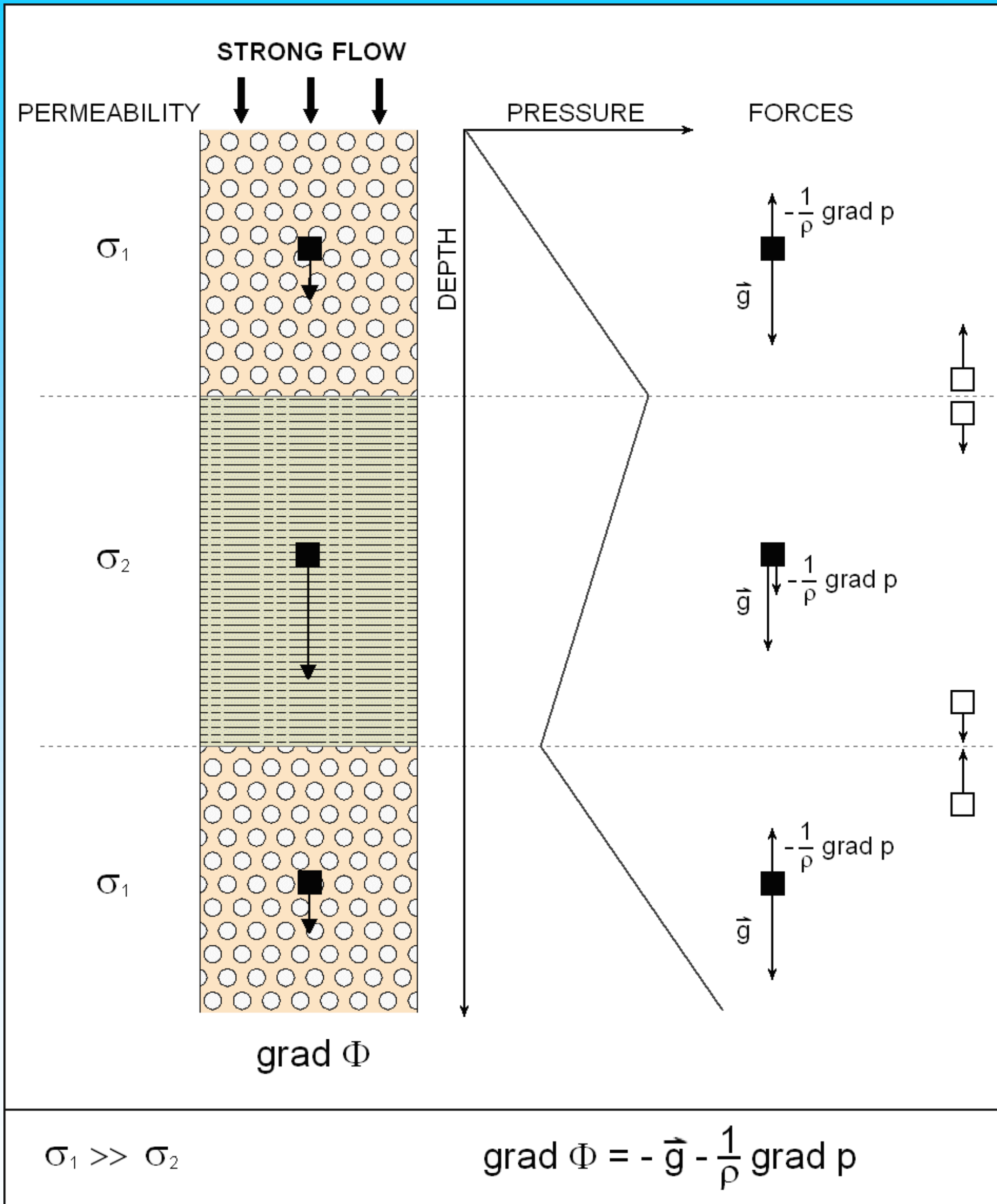
(C) Effect of temperature (4°C vs. 100°C)

(D) Effect of salinity (ocean-type) (ρ = 1.03 g/cm³)

Explanation of Symbols

- (grad p) / ρ	= pressure potential force	p	= pressure
$\vec{g}$	= gravitational force	ρ	= density
- grad Φ	= resultant hydraulic force	f	= fresh water
		s	= ocean-type saline water

Downward-Directed Pressure Potential Forces: ‘Buoyancy Reversal’



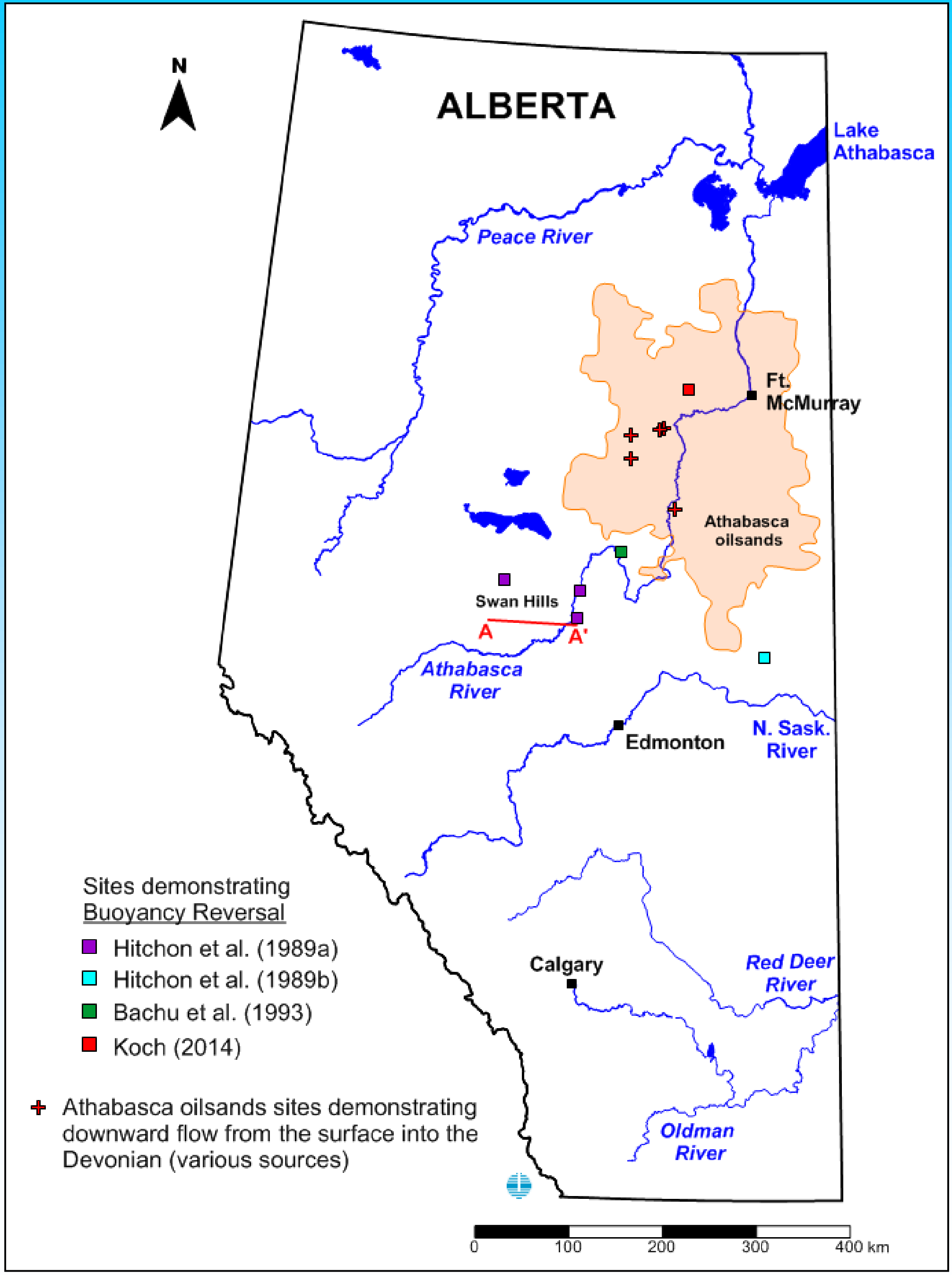
Directions of gravitational and pressure potential forces at ‘Buoyancy Reversal’

$$\text{grad } \Phi = \text{hydraulic force}$$

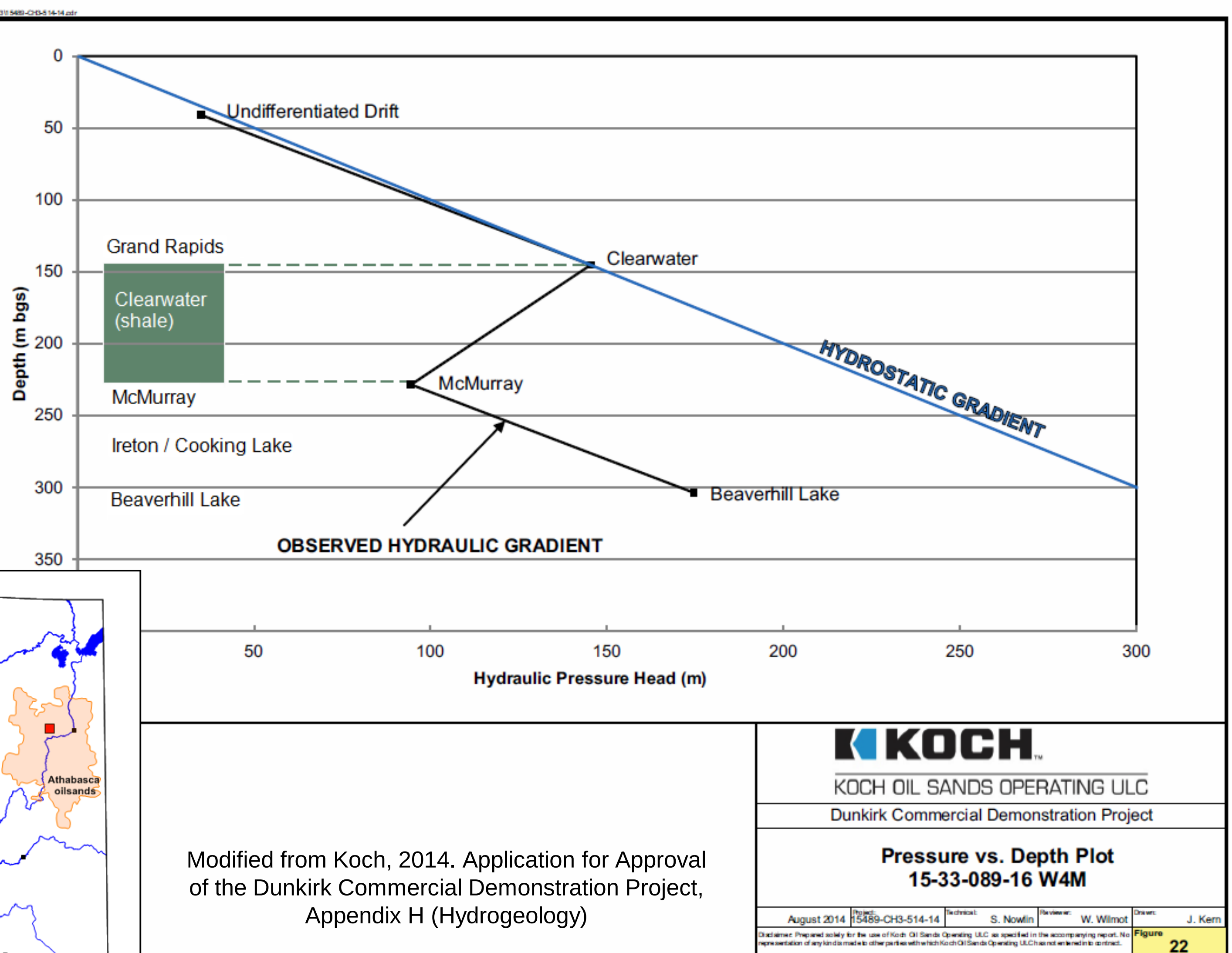
$$-\vec{g} = \text{gravitational force}$$

$$-\frac{1}{\rho}\text{grad } p = \text{pressure potential force}$$

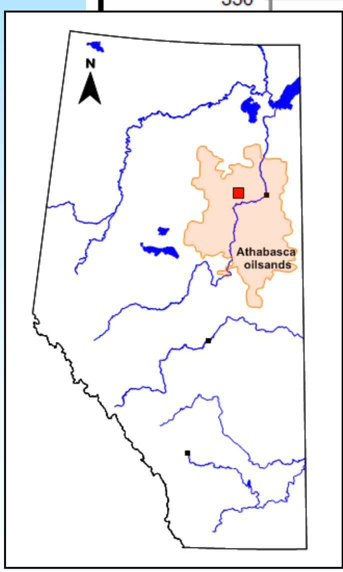
Modified after Weyer, 1978



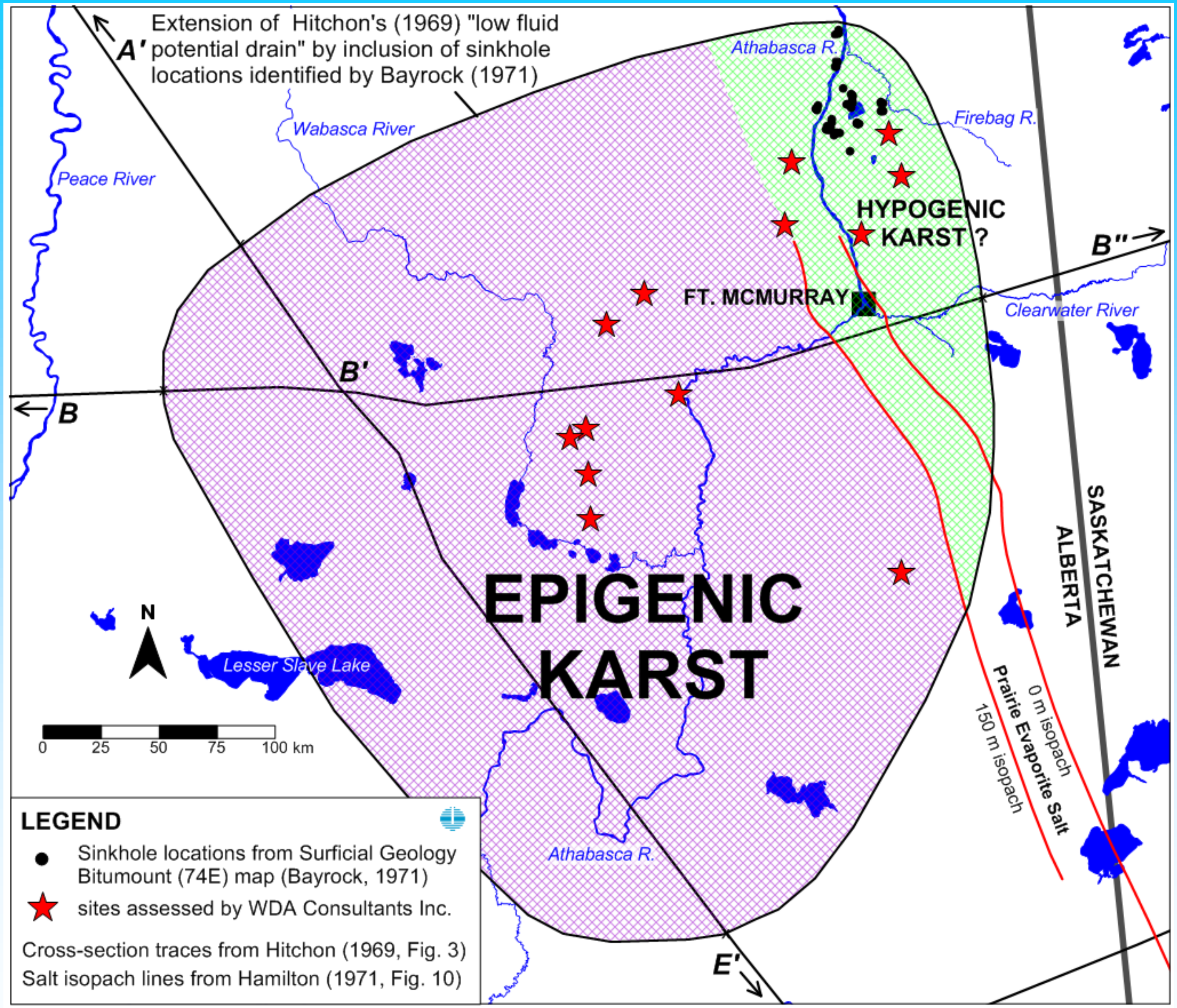
Documented Occurrences of Buoyancy Reversal in Alberta



Modified from Koch, 2014. Application for Approval of the Dunkirk Commercial Demonstration Project, Appendix H (Hydrogeology)



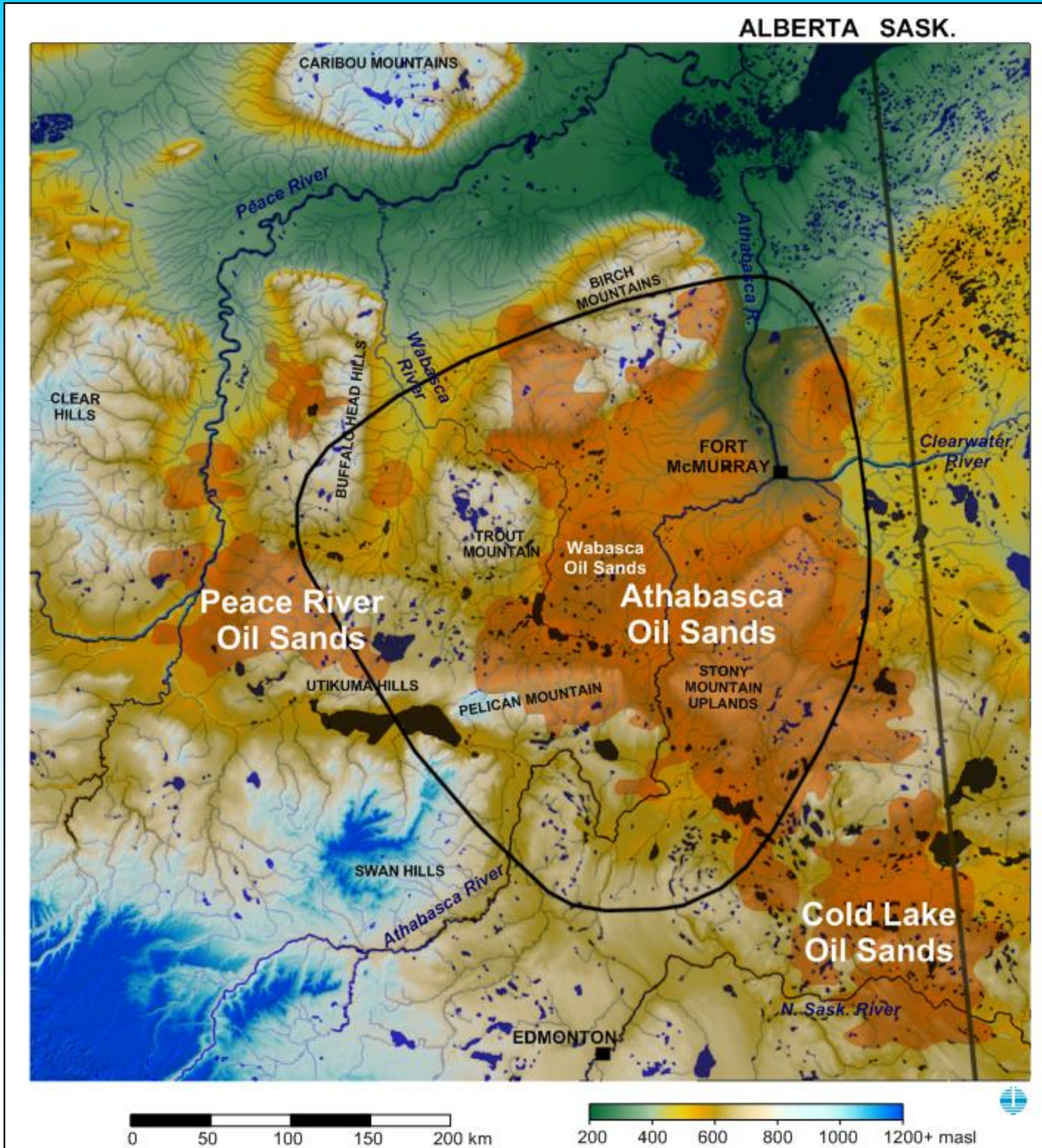
Occurrence of Buoyancy Reversal caused by downward flow through the Cretaceous Clearwater aquitard into the Devonian.



Karst and salt dissolution

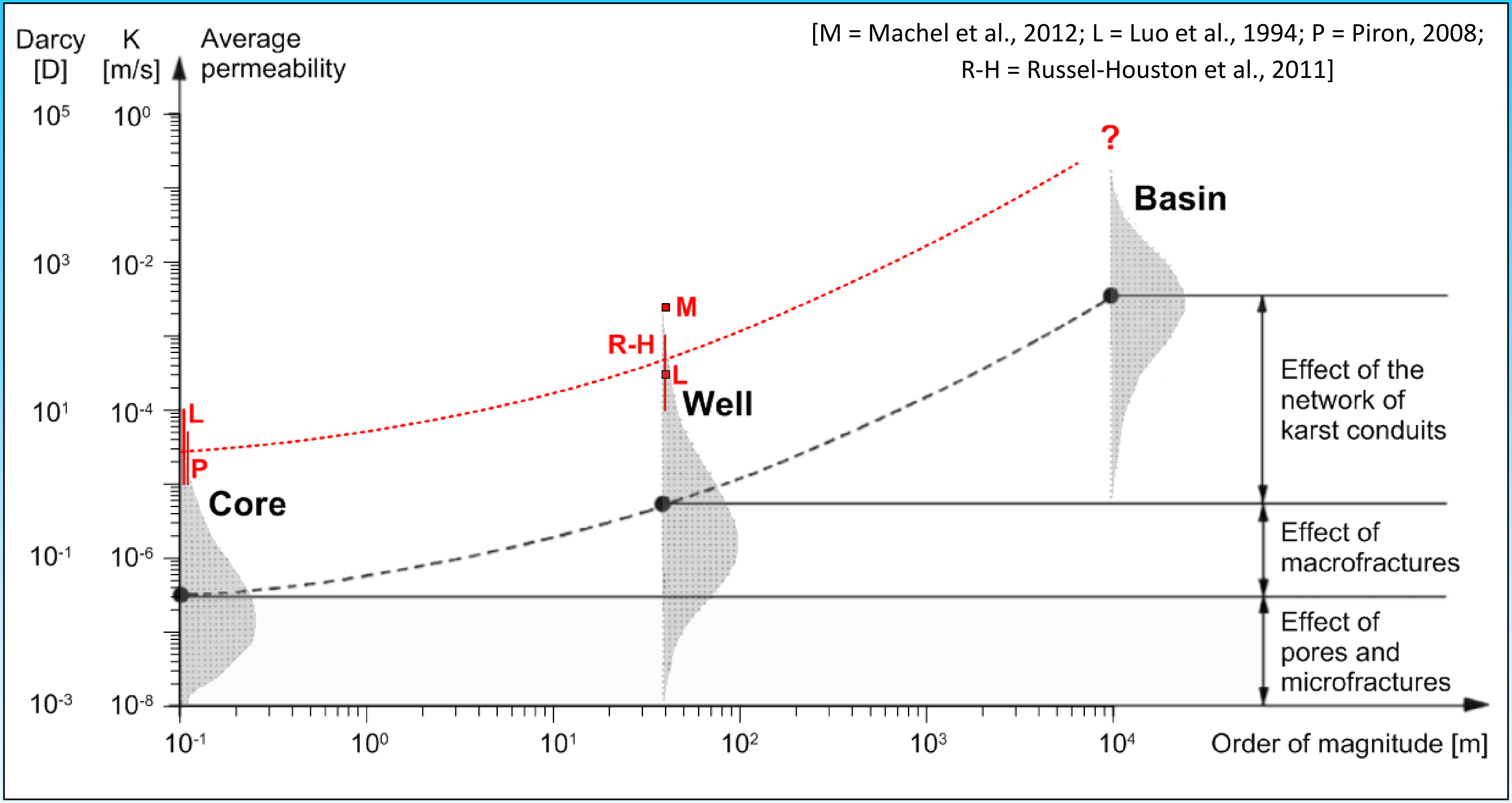
Epigenic karst: formed close to surface in recharge areas

Hypogenic karst: formed at depth and in regional discharge areas



Schematically-estimated extent of Hitchon's (1969) "low fluid potential drain" in the area of the Athabasca oil sands

Extent of oil sands taken from Einstein, 2006

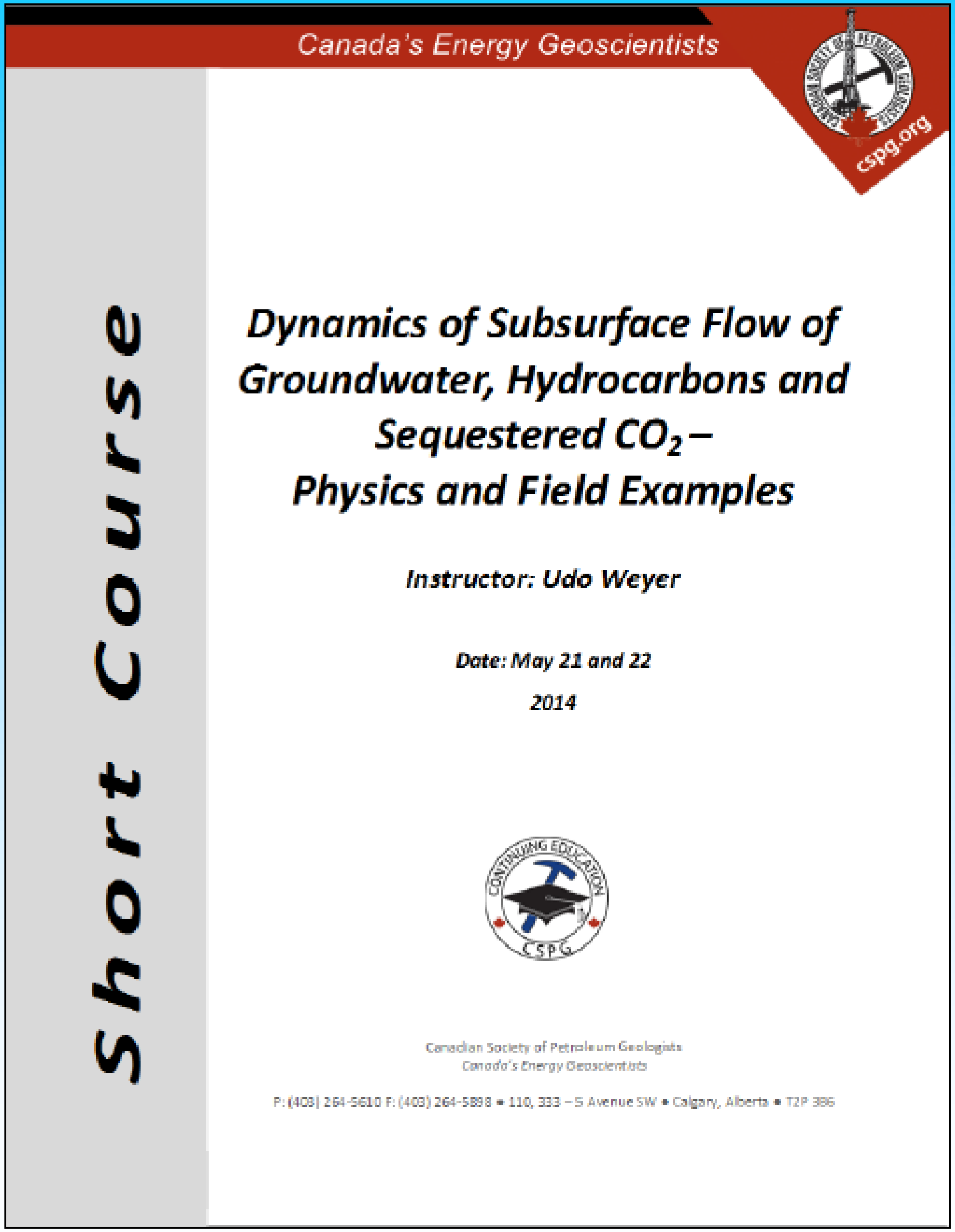


(after Kiraly, 1975, Fig 19)

Effect of scale on permeability in karst. Literature data for the Grosmont reservoir added. Hundreds of Darcies occur at the well scale. Speculation of possibly thousands of Darcies in a basin-scale network of karst conduits.

Synopsis

- Free convection can only exists in nature under hydrostatic boundary conditions.
- Under hydrodynamic conditions saturated brine may flow upwards to the surface if the hydraulic and geologic conditions are right.
- When dealing with on-shore conditions the application of physically-consistent force potentials and groundwater flow systems are the methods of choice at the Athabasca oil sands.



Canada's Energy Geoscientists

cspg.org

Short Course

Dynamics of Subsurface Flow of Groundwater, Hydrocarbons and Sequestered CO_2 – Physics and Field Examples

Instructor: Udo Weyer

Date: May 21 and 22

2014

Canadian Society of Petroleum Geologists
Canada's Energy Geoscientists

P: (403) 264-5610 F: (403) 264-5898 • 110, 333 – 5 Avenue SW • Calgary, Alberta • T2P 3B6

Any questions on the physics of groundwater dynamics and its field documentations in the Athabasca oil sands?

References [38 entries]

Alsharhan, A. S., Z.A. Rizk, A.E.M. Nairn, D.W. Bakhit, and S.A. Alhajari (eds.), 2001. Hydrogeology of an Arid Region: The Arabian Gulf and Adjoining Areas: The Arabian Gulf and Adjoining Areas. Elsevier, 366 p., ISBN: 978-0444539489

Bachu, S., 1995. Flow of variable-density formation water in deep sloping aquifers: review of methods of representation with case studies. Journal of Hydrology, vol. 164, p. 19-38.

Bachu, S., 1999. Flow systems in the Alberta basin: Patterns, types and driving mechanisms, Bulletin of Canadian Petroleum Geology, vol. 47, no. 4, p. 455-474.

Bachu S., and J.R. Underschultz, 1993. Hydrogeology of formation waters, northeastern Alberta basin. AAPG Bulletin, vol. 77, issue 10, p. 1745-1768.

Bachu, S., J.R. Underschultz, B. Hitchon, and D. Cotterill, 1993. Regional-Scale Subsurface Hydrogeology in Northeast Alberta. Alberta Research Council, Bulletin No. 61, 44 p.

Bayrock, L.A., 1971. Surficial Geology Bitumount (NTS 74E). Alberta Research Council, Alberta Geological Survey, Map 140, scale 1:250 000.

Bear, J., 1972. Dynamics of Fluids in Porous Media. American Elsevier Publishing Company, Inc., New York, NY, USA, 764 p., ISBN: 978-0444001146

Central Intelligence Agency (CIA), 1995. Shaded Relief map of the United Arab Emirates. Downloaded from http://en.wikipedia.org/wiki/ File:United_arab_emirates_rel95.jpg on February 13th, 2014.

Cowie, B.R., B. James, and B. Mayer, 2015. Distribution of total dissolved solids in McMurray Formation water in the Athabasca oil sands region, Alberta, Canada: Implications for regional hydrogeology and resource development. AAPG Bulletin, vol. 99, issue 1, p. 77-90.

Einstein, N., 2006. Athabasca Oil Sands map. Downloaded from http://en.wikipedia.org/wiki/File:Athabasca_Oil_Sands_map.png on March 28, 2014

Frind, E. O., and J.W. Molson, 2010. Review of “Physical Processes in Carbon Storage” by Udo Weyer, January 11, 2010. Outside review, 16 pages. Available from http://www.wda-consultants.com/papers.htm.

References, ctd.

Gronemeier, K., H. Hammer, and J. Maier, 1990. Hydraulische und hydrodynamische Felduntersuchungen in klüftigen Sandsteinen für die geplante Sicherung einer Sonderabfalldeponie [Hydraulic and hydrodynamic field studies in fractured sandstone for safe disposal of special industrial waste]. Zeitschr. dt. geol. Ges., vol.141, p.281-293

Hamilton. W.N., 1971. Salt in East-Central Alberta. ARC Bulletin No. 29.

Hitchon, B., 1969. Fluid flow in the Western Canada sedimentary basin: 1. effect of topography. Water Resources Research, vol. 5, issue 1, p. 186-195, DOI: 10.1029/WR005i001p00186

Hitchon, B, C.M. Sauveplane, S. Bachu, E.H. Koster, and A.T. Lytviak, 1989a. Hydrogeology of the Swan Hills Area, Alberta: Evaluation for deep waste injection. ARC Bulletin No. 58.

Hitchon, B, S. Bachu, C.M. Sauveplane, A. Ing, A.T. Lytviak, and J.R. Underschultz, 1989b. Hydrogeological and geothermal regimes in the Phanerozoic succession, Cold Lake area, Alberta and Saskatchewan. ARC Bulletin No. 59

Hubbert, M.K., 1940. The theory of groundwater motion. Journal of Geology, vol. 48, no. 8, p. 785-944. Available from http://www.jstor.org/stable/30057101.

Hubbert, M.K., 1953. Entrapment of petroleum under hydrodynamic conditions. The Bulletin of the American Association of Petroleum Geologists (AAPG), vol. 37, no. 8, p. 1954-2026. Available from http://archives.datapages.com/data/bulletns/1953-56/data/pg/0037/0008/1950/1954.htm

Hubbert, M.K., 1956. Darcy's Law and the Field Equations of the Flow of Underground Fluids. Petroleum Transactions, AIME, Vol. 207: 222-239. Also published in 1957 in Hydrological Sciences Journal 2(1), p. 23-59 (the volume covering the 1956 Centennial Darcy Symposium). Available from https://www.onepetro.org/general/SPE-749-G

Kiràly, L., 1975. Rapport sur l'état actuel des connaissances dans le domaine des caractères physiques des roches karstiques. In: Hydrogeology of Karstic Terrains, International Union of Geological Sciences, Series B, Nr.3, p.53-67

Koch Exploration Canada L.P., 2014. Application for Scheme Approval of Koch Oil Sands Operating ULC Dunkirk Commercial Demonstration Project, Appendix H – Hydrogeology Assessment, Nov. 2014, 280 p.

Luo, P., H. G. Machel, and J. Shaw, 1994, Petrophysical properties of matrix blocks of a heterogeneous dolostone reservoir - the Upper Devonian Grosmont Formation, Alberta, Canada. Bulletin of Canadian Petroleum Geology, v. 42, no. 4, p. 465-481.

References, ctd.

Machel, H.G., M.L. Borrero, E. Dembicki, H. Huebscher, L. Ping, and Y. Zhao, 2012. The Grosmont: the world's largest unconventional oil reservoir hosted in carbonate rocks, appendix in J. Garland, J.E. Neilson, S.E. Laubach, and K.J. Whidden, eds., Advances in Carbonate Exploration and Reservoir Analysis: the Geological Society, London, Special Publications, 370, p. 49-81, DOI: 10.1144/SP370.11.

Ministrone, 2007. Germany map blank. Downloaded from http://commons.wikimedia.org/wiki/File:Germany_map_blank.png on April 17, 2014.

Nield, D.A., and A. Bejan, 2006. Convection in Porous Media, Third Edition. Springer, New York, 640 p., ISBN: 978-3540463849

Phillips, O. M., 2009. Geological Fluid Dynamics: Sub-surface Flow and Reactions. Cambridge University Press, 298 p., ISBN: 978-0521865555

Piron, E, 2008, Reservoir Characterization of the Grosmont Formation at Saleski, NE AB: A Multi-Disciplinary Data Integration Exercise in Progress: Back to Exploration - 2008 Canadian Society of Petroleum Geologists, Can. Soc. of Exploration Geophysicists, Canadian Well-Logging Society Convention Core Conference, abstract, p. 224-225.

Rizk, Z.S., and H.A. El-Etr, 1997. Hydrogeology and hydrogeochemistry of some springs in the United Arab Emirates. Arabian Journal for Science and Engineering, v. 22, p. 95-111.

Russel-Houston, J., K.Gray and P. Pulnam, 2011, Enhanced porosity and paleokarst in the Grosmont Formation, a Giant Bitumen reservoir in Northern Alberta: IAS Meeting of Sedimentology 2011, Zaragoza, Spain, abstract, p.538.

Simmons, C.T., 2011. Variable Density Groundwater Flow: From current challenges to future possibilities. Powerpoint presentation at the 2nd International HydroGeoSphere User Conference, April 11-13, 2011, Hannover, Germany. Downloaded from http://www.hgs-conference2011.uni-hannover.de/fileadmin/hgs_2011/pdf/Simmons_HGS_Workshop_2011.pdf on August 31st, 2013

Van Dam, R. L., C.T. Simmons, D.W. Hyndman, and W.W. Wood, 2009. Natural free convection in porous media: First field documentation in groundwater. Geophysical Research Letters, vol. 36, issue 11, DOI: 10.1029/2008GL036906.

Van Dam, R. L., B.P. Eustice, D.W. Hyndman, W.W. Wood, and C.T. Simmons, 2014. Electrical imaging and fluid modeling of convective fingering in a shallow water-table aquifer. Water Resources Research, vol. 50, no. 2, p. 954-968, DOI: 10.1002/2013WR013673.

References, ctd.

Weyer, K.U., 1978. Hydraulic forces in permeable media. Mémoires du B.R.G.M., vol. 91, p. 285 -297, Orléans, France. Available online at http://www.wda-consultants.com/papers.htm.

Weyer, K.U., 1996. Physics of groundwater flow and its application to the migration of dissolved contaminants. [Darlegung und Anwendung der Dynamik von Grundwasserfließsystemen auf die Migration von gelösten Schadstoffen im Grundwasser]. Final Research report to the Federal Environmental Office of the German Government, April 1996 [in German], 204 p. Available from http://www.wda-consultants.com/berlin.htm

Weyer, K.U., 2010. Physical Processes in Geological Carbon Storage: An Introduction with Four Basic Posters. Internet publication, March 2010, 47 p. Available from http://www.wda-consultants.com/papers.htm.

Weyer, K.U. and J.C. Ellis, 2015. Where does free convection (buoyancy and density driven) flow occur? Extended abstract, CSPG GeoConvention 2015, Calgary, Alberta, Canada, May 2015.

Wood, W. W., 2011. An historical odyssey: the origin of solutes in the coastal sabkha of Abu Dhabi, United Arab Emirates. In: Alsharhan, A.S., and Kendall, C.G. (eds), Quaternary Carbonate and Evaporite Sedimentary Facies and Their Ancient Analogues : A Tribute to Douglas James Shearma. Hoboken, NJ, USA: Wiley-Blackwell, 2011, p. 243-254.

Wood, W. W., W. E. Sanford, and A. R. S. Al Habshi, 2002. Source of solutes to the coastal sabkha of Abu Dhabi. Geological Society of America Bulletin, 114(3), 259-268.