Hydrogeology of an Alpine Valley, southeastern British Columbia – Implications for Coalbed Methane Exploration and Development

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PART I – Overview

- Location / Physical Setting
- Stratigraphy / Hydrostratigraphy
- Data Collection
  - Pressure
  - "Transmissivity" (permeability)
  - Water Chemistry
- Sampling Locations / Instrumentation

PART II – GROUNDWATER FLOW

- Flow System
  - Physical Constraints
  - Hydrochemical Constraints
- Numerical Modeling

PART III – Exploration / Production Considerations

- Production – e.g. Well Spacing
- Gas Content / Gas origin
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STUDY LOCATION
COAL FIELDS LOCATION MAP
(general)

LEGEND
- Coalfield
- Highway
- Mine

Alberta – British Columbia border
PHYSICAL SETTING

- ALPINE VALLEY, FRONT RANGES, ROCKY MOUNTAINS
  - ELEVATIONS
    - LOWLAND (VALLEY) - 1550 - 1600 m
    - UPLAND - 2200 - 2800 m

- RUGGED TERRAIN WITH FEW DATA
PHYSICAL / CHEMICAL HYDROGEOLOGY

STRATIGRAPHY DEFINES MAJOR HYDROSTRATIGRAPHIC UNITS:

- CARBONIFEROUS
  - LIMESTONE; SOME DOLMITE AND SANDSTONE

- TRIASSIC
  - SANDSTONE AND SHALE

- JURASSIC
  - SHALE AND SANDSTONE/SILTSTONE

- JURASSIC/CRETACEOUS
  - SANDSTONE, SILTSTONE, SHALES, COAL (Mist Mountain Formation)
  - Coals are sub-bituminous
GEOLOGICAL MAP

- Syncline
- Bourgeau Thrust
- Lewis Thrust
CROSS-SECTION

Syncline:
- Plunges north at shallow angle
- Open to slightly overturned
- Axial plane strikes at \( \approx 160^\circ \); dips westerly
DATA COLLECTION

Groundwater Surface Water Sampling

Samples collected of surface and formation water (groundwater) for chemical analyses from:
• Seeps, streams, open wells, ponds, monitoring wells / piezometers

Hydraulic Data

Hydraulic conductivity and water level data from:
• Open wells, monitoring wells / piezometers

Hydrological Data

• Gauging stations, streams, seeps, ponds
Sample / Monitoring Locations
(Plan View)

- Site 1
- Site 2
- Elk River Valley

- open wells
- streams
- seeps
- ponds
- CBM test
- guaging st.

Sample / Monitoring Locations
(Plan View)
SAMPLING
INSTRUMENTATION SITES 1 and 2
(CROSS-SECTION SITE 1)

VE = .65x
# APPROACH / OUTLINE

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CONCEPTUAL MODEL OF FLOW
PHYSICAL HYDROGEOLOGY

M. King Hubbert (1940)

Classic Model Of Upland To Lowland Flow

Joseph Toth (1963)

Regional Flow Systems
UPLAND – LOWLAND FLOW

Recharge

Discharge

Symmetry Boundary

Impermeable Boundary

gradient
“ALTITUDE EFFECT”

$\delta^{18}O$ and $\delta^2H$ (data from Yonge et al., 1989)

\[
\delta^{18}O = -10.25 - 0.002 \text{ (elev.)} - 0.009 \text{ (dist.)}
\]

\[
\delta^2H = -75.67 - 0.015 \text{ (elev.)} - 0.08 \text{ (dist.)}
\]
Isotopic fractionation

“lighter or depleted” $\delta^{18}O / ^2H$

“heavy” isotopes

“enriched” $\delta^{18}O / ^2H$
HYDROCHEMISTRY

CONSTRAINTS ON FLOW

- APPROXIMATELY 50 SAMPLES COLLECTED FROM:
  - MONITORING WELLS
    - COMPLETED FROM ABOUT 50 TO 200 m DEPTH
  - OPEN WELLS (UP TO 600 m DEPTH)
  - SEEPS
  - PONDS
  - STREAMS
  - ELK RIVER
“ALTITUDE EFFECT” $\delta^{18}$O and $\delta^2$H

- Open wells
- Seeps
- Ponds
- Streams
- MW Site 1
- Coals Site 1
- GMWL
- MW Site 2

$\delta^2$H \% SMOW vs $\delta^{18}$O \% SMOW

Group A
Group B
Mixing
GMWL
LEL
SYNTHESES

GROUP A GROUNDWATER (“fresh”)
- HIGH TRITIUM; ENRICHED $\delta^{18}O/\delta^2H$
- LOW TDS
  - LOW HCO$_3^-$

GROUP B GROUNDWATER (“evolved”)
- LOW OR NO TRITIUM; DEPLETED $\delta^{18}O/\delta^2H$
- HIGH TDS
  - HIGH HCO$_3^-$ ENRICHED IN $\delta^{13}C$

INTERMEDIATE
- TRANSITIONAL / MIXED COMPONENT
HYDROCHEMICAL CONSTRAINTS ON FLOW

Depleted $\delta^{18}O$ and $\delta^2H$
FLOW SYSTEM
MATHEMATICAL REPRESENTATION

- 3-D FINITE ELEMENT – Watflow 3-D (Molson et al.)

- BOUNDARY CONDITIONS
  - Water table is fixed (specified head)
  - Lewis and Bourgeau thrusts assumed impermeable (no flow)

- SOLVE FOR STEADY-STATE FLOW:

\[
\frac{d}{dx} (K_x \frac{dh}{dx}) + \frac{d}{dy} (K_y \frac{dh}{dy}) + \frac{d}{dz} (K_z \frac{dh}{dz}) = 0
\]
NUMERICAL SIMULATION

Model Domain:
Heterogeneous and anisotropic conductivity field with 420,000 elements (3-D domain)

Hydraulic Parameters:
- equiv. porous media
- K values
- porosity values
- anisotropy ratios

Boundary Conditions:
- specified head
- “no flow”
RESULTS - NUMERICAL SIMULATION

STEADY STATE VELOCITY FIELD (m/sec) - SECTION 2

WEST

5.000E-08 m/sec
(4.32E-03 m/day)

SPECIFIED HEAD
(WATER TABLE)

Little Weary Ridge

EAST

IMPERMEABLE BOUNDARY (NO FLOW)

IMPERMEABLE BOUNDARY (NO FLOW)
SO WHAT IS THE APPLICATION!!!!
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CBM PRODUCTION

DECREASE RESERVOIR PRESSURE (for an under-saturated initial condition)

- METHANE DESORBS FROM THE COAL STRUCTURE
- WATER AND GAS FLOW TOWARD THE PRODUCTION WELL

Intersection with adsorption isotherm for 16.5 cm$^3$/g (i.e., critical desorption pressure)

Intersection with adsorption isotherm for 13 cm$^3$/g (i.e., critical desorption pressure)

Reduce pressure (by 170 m)

Reduce pressure (by 320 m)

Initial reservoir condition (ca. 408-525 m, 12-17 cm$^3$/g)

Initial reservoir pressure (470 m)

Pressure, kPa

(0) (1000) (2004) (306) (408) (510) (612)

Measured Gas Content (cm$^3$ / g)
CBM PRODUCTION

DISTANCE FROM THE BOREHOLE

STAGE 1
water flow

STAGE 2
water & dissolved methane

STAGE 3
gas & water flow

original potentiometric surface
drawdown
discharge

PRESSURE

water flowing

water and gas flowing
CBM / WATER PRODUCTION

DEWATERING
STABLE PRODUCTION
DECLINING PRODUCTION

PROD.
WATER
METHANE
TIME
CBM DEVELOPMENT
Depressurization

• How many wells?
• Spacing?
• How much water?
“BULK-ROCK” RESPONSE TO DEPRESSURIZATION

“Real World”

- Borrow methods from the Water Well Industry

Pumping Test: (65 m³/day for 15 days)
  - drawdown is proportional to “Q” (pumping rate)
  - drawdown is inversely proportional to hydraulic conductivity (“K” or “T”)
DRAWDOWN
22,000 minutes (15 days) Q = 65 m³/day

VE = .65x
1. steep and narrow → low perm

2. volume of rock impacted by pressure-pulse is small
CBM EXPLORATION

Detailed view, Figure 4

Elk River

Little Weary Ridge
Zone(s) of most significant over-pressuring?
EFFECTS ON FLOW SYSTEM
e.g. Water Table Flux

Other Data:
- Isotopic data
- Stream flow
- Monitoring well

(a) No production wells
(b) 3 production wells
Gas Origin???
EXPLORATION: Biogenic Processes

HYDROLYTIC FERMENTATIVE

Fatty Acids
Acetate
Hydrogen

CO₂
NH₄⁺
HS⁻

H₂ - REDUCING ACETOGENIC H₂ - UTILIZING

METHANOGENS

Acetate Fermentation

\[ CH₃COO^- + H^- \rightarrow CH₄ + CO₂ \]

Carbonate Reduction

\[ CO₂ + 4H₂ \rightarrow CH₄ + 2H₂O \]
EXPLORATION: Geochemical Markers

- $\delta^{13}C$ – DIC becomes enriched (+35 ‰)
- DIC concentration (mg/L) increases
- Methane concentration (mg/L) increases

Diagram shows as DIC $\uparrow \delta^{13}C_{DIC} \uparrow$ and CH$_4$ $\uparrow$

TYPICAL OF METHANOGENIC ENVIRONMENTS!!
Carbon dioxide is generated through methanogenesis dissociates into the groundwater resulting in high DIC concentrations (1250 + mg/L).
SUMMARY AND CONCLUSIONS

Setting
- Alpine valley southeastern British Columbia
- Relief: 1550 – 2800 m
- Structurally relatively complex

Data
- Collected from wells, seeps, streams, ponds
- Detailed hydraulic, geochemistry and flow
SUMMARY AND CONCLUSIONS
con’t

- **Flow and Flow Modeling**
  - Constrain flow chemically and physically
  - Represent flow mathematically
  - Simulations useful for early stage evaluations of development / exploration scenarios (must understand limitations of models)

- **Gas Origin**
  - Predominantly biogenic (CO₂ reduction)
  - Generated by active groundwater flow
THANK YOU!