CO_2 DISPOSAL INTO ALBERTA BASIN AQUIFERS

Hydrogeological and Numerical Analysis of CO_2-Disposal in Deep Siliciclastic and Carbonate Aquifers in the Lake Wabamun Area

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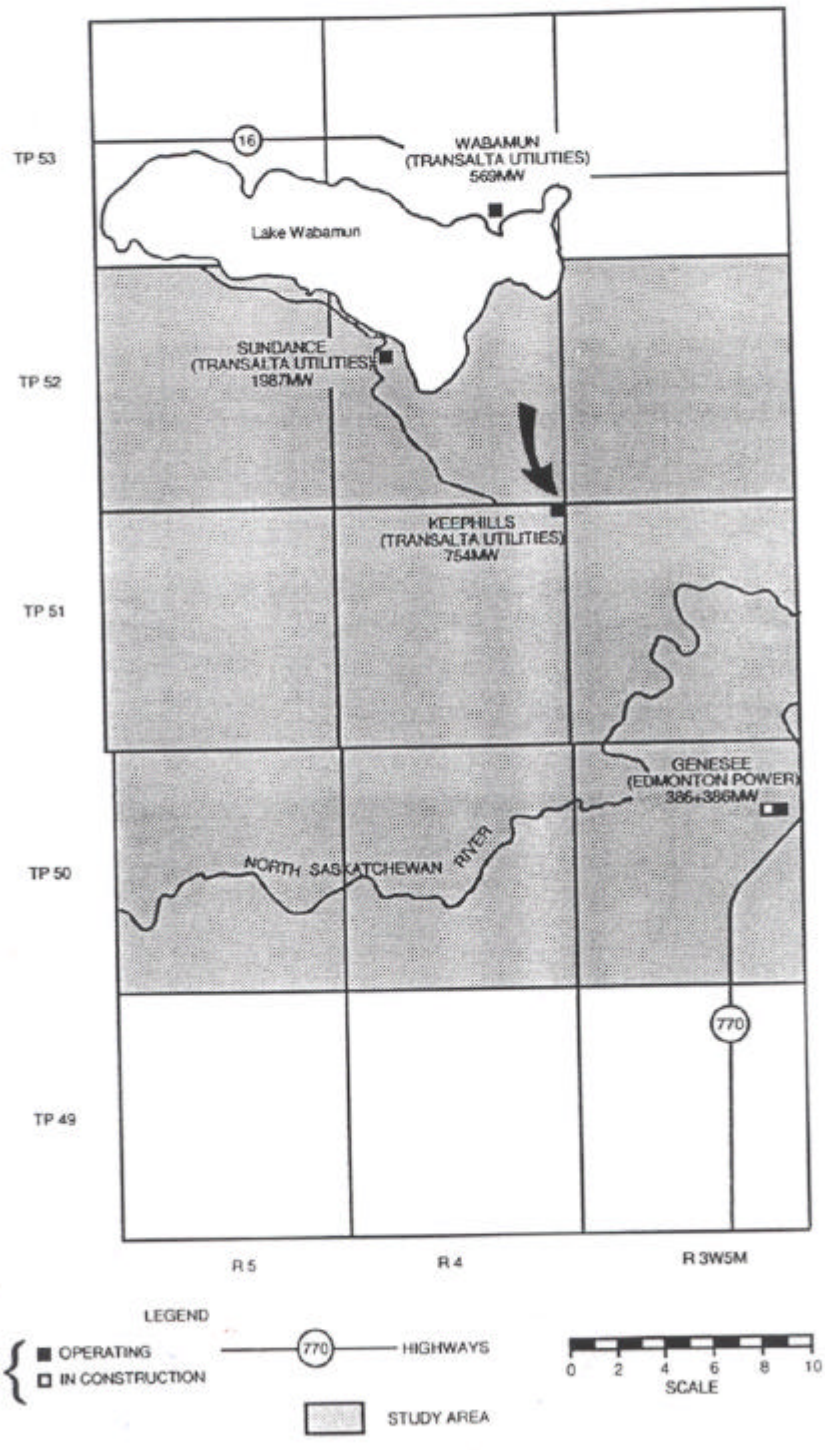
Selection of First Disposal Site



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Stratigraphy, Dominant Lithology and Hydrostratigraphy in Lake Wabamun Area

PERIOD	STRATIGRAPHY		DOMINANT LITHOLOGY	HYDROSTRATIGRAPHY
Quaternary				
Tertiary				
Cretaceous				
	Colorado Group		Shale	Aquitard
	Mannville Group		Sandstone (Shale)	Aquifer
Jurassic	Nordegg Member		Carbonate	Aquifer
Mississippian	Banff Fm.		Carbonate (Shale)	Aquifer
	Exshaw Fm.		Shale	Aquitard
Devonian	Wabamun Group		Limestone	Aquifer
	Winterburn Group	Graminia Fm.	Dolomite	Aquifer
		Blue Ridge Fm.		
		Calmar Fm.	Shale	Aquitard
		Nisku Fm.	Dolomite	Aquifer
	Woodbend Group	Ireton Fm.	Shale	Aquitard
		Cooking Lake Fm.	Carbonate	Aquifer
Cambrian				
Precambrian				

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Glauconitic Sandstone Aquifer Characteristics

Depth:	**1480 m**
Thickness:	**13 m**
Slope (dip to southwest):	**0.005 m/m**
Porosity:	**6% - 12%**
Absolute Permeability:	
horizontal:	**6.2 - 100 md**
vertical:	**30% of horizontal permeability**
Temperature:	**50°C**
Pressure at top of aquifer:	**12.446 MPa**

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Fluid Properties at 50°C

Aqueous Phase

Salinity:	**4wt% (40,000 mg/l)**
Density:	**1030 kg/m^3**
Viscosity:	**0.617 mPa-s**

Carbon Dioxide Phase

Density:	**696 kg/m^3 @12.446 MPa**
Compressibility:	**1.22×10^{-5} /kPa**
Viscosity:	**0.068 mPa-s**
Dispersion coefficient in water:	**3.074×10^{-4} m^2/day**

CO_2-water equilibrium constant:

$$\log K = -2.15 + 0.9930 \log P \quad \text{where P in MPa}$$

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Injection Strategies

Single Injection Well

Well Radius:	3"
Well Completion:	13 m

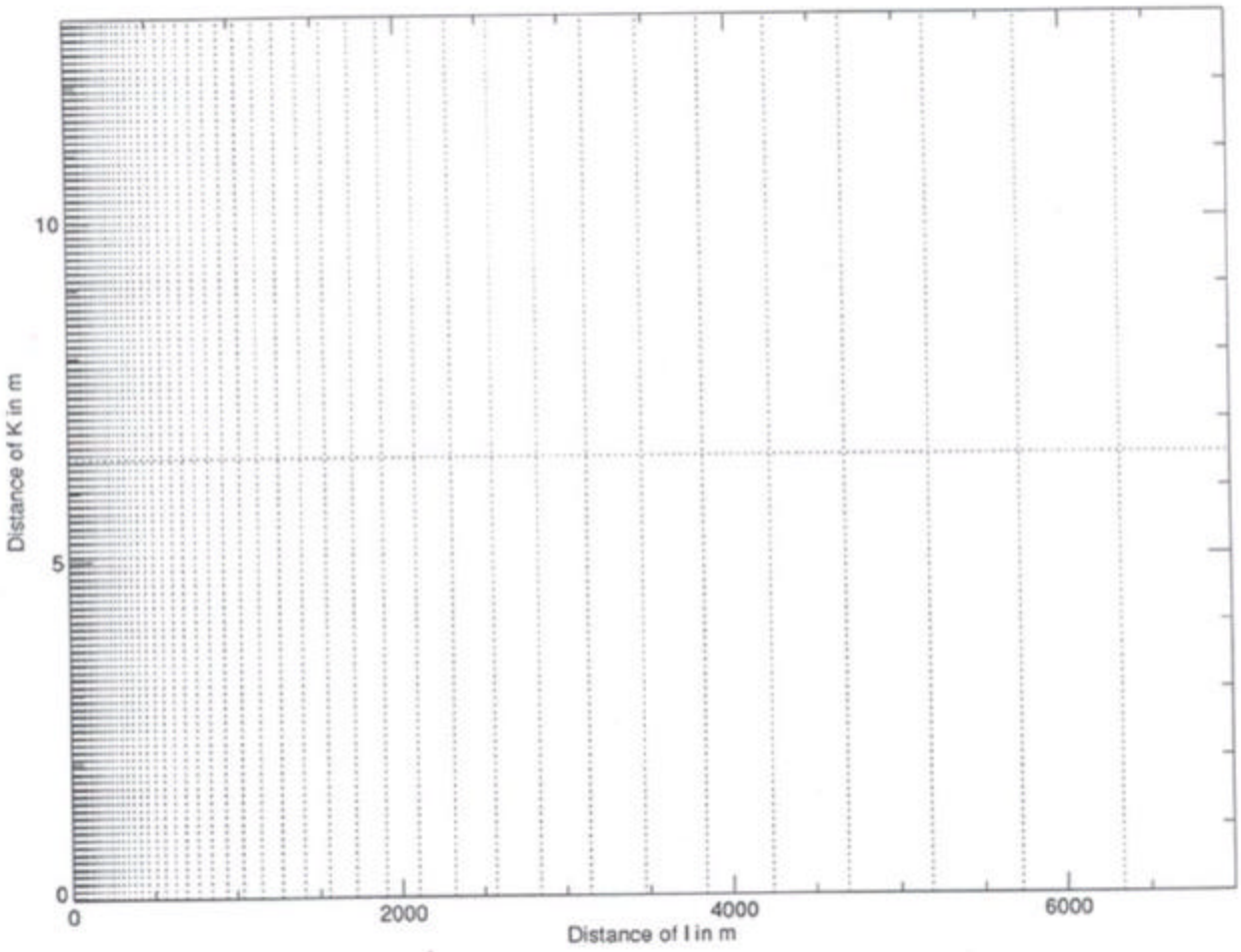
Operating Conditions

Constant Injection Pressure:	30.12 MPa (90% of estimated fracture pressure)
	25.15 MPa (200% of aquifer pressure)

Numerical Study

Effect of Porosity:	6% and 12%
Effect of Permeability:	6.2, 30 and 100 md (horizontal direction)
Effect of Aquifer Heterogeneity:	100 md near well 6.2 or 30 md far from well

2-D Radial Grid Pattern
$(66 \times 1 \times 2)$



Exponential stretch in radial direction:

$$R_i = 9.503\ (e^{0.10005\,i} - 1) \qquad i = 1 \longrightarrow 67$$

where:

$$R_1 = 1\ \text{m} \quad \text{and} \quad R_{67} = 7\ \text{km}$$

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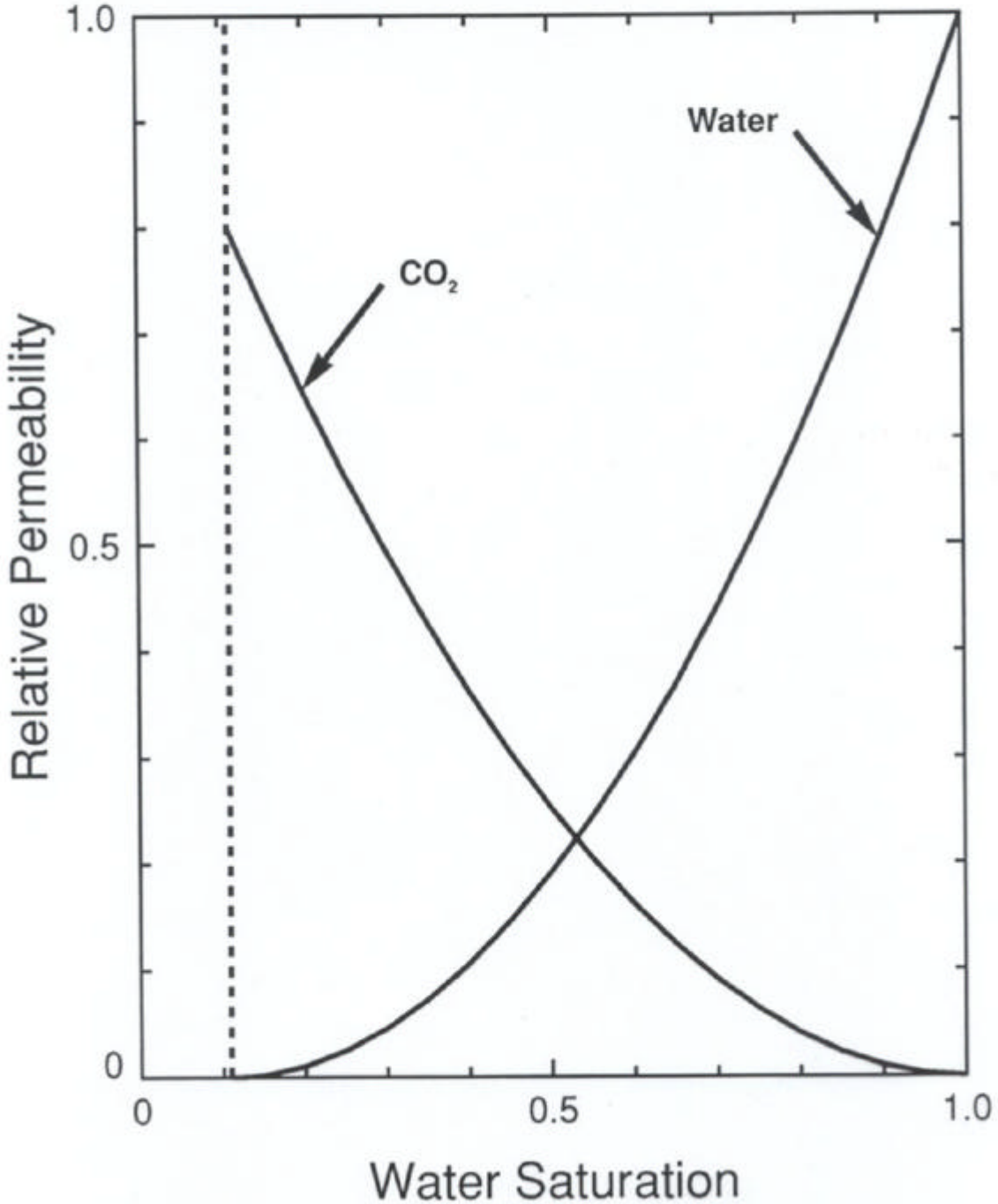
RELATIVE PERMEABILITY CURVES FOR CO_2-WATER SYSTEM

End Point for CO_2 Relative Permeability Curve = 0.8

End Point for Water Relative Permeability Curve = 1.0

Residual CO_2 Saturation = 0

Irreducible Water Saturation = 0.11



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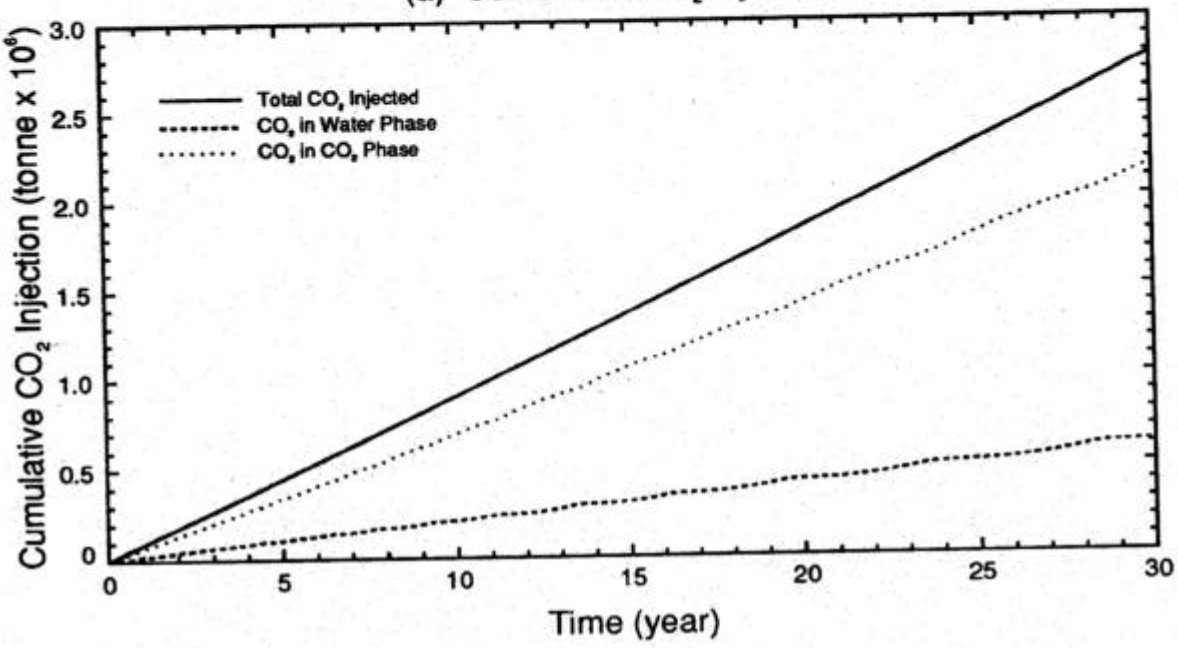
NUMERICAL RUN (CO2_71)

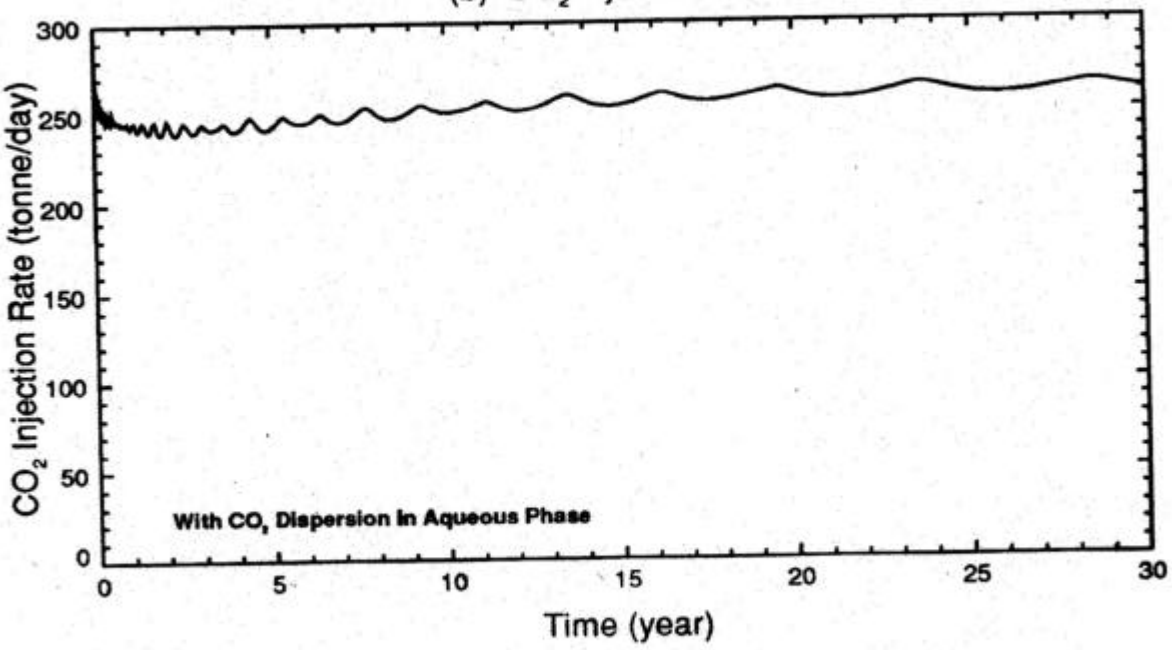
Aquifer Porosity = 0.12 Aquifer Permeability = 6.2 md (horizontal)

Injection Pressure = 30.12 MPa

(a) Cumulative CO_2 Injection



(b) CO_2 Injection Rate



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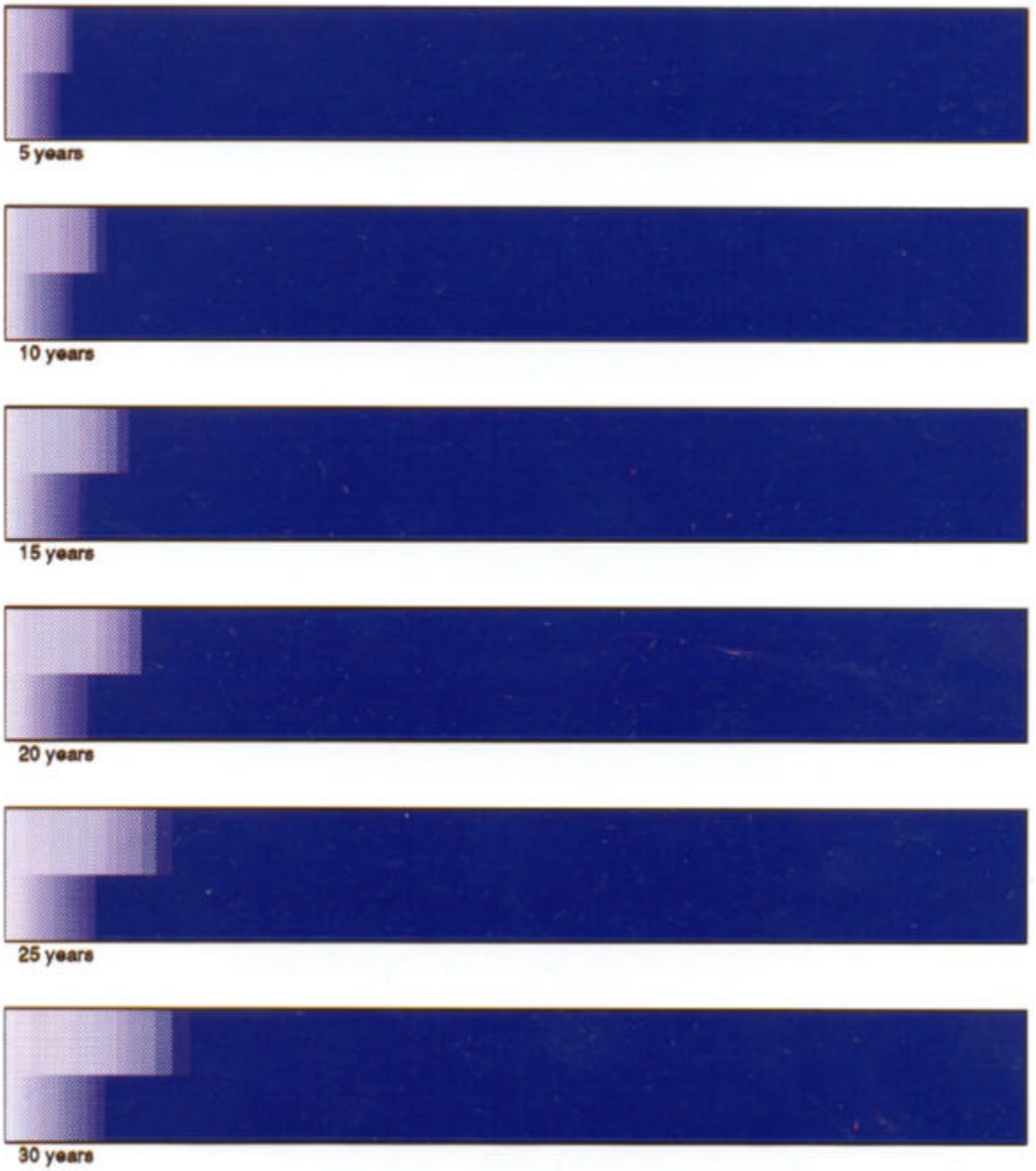
Carbon Dioxide Saturation (Run CO2_71)



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Field dimensions: 6999. (horiz.), 13.00 (vert.)

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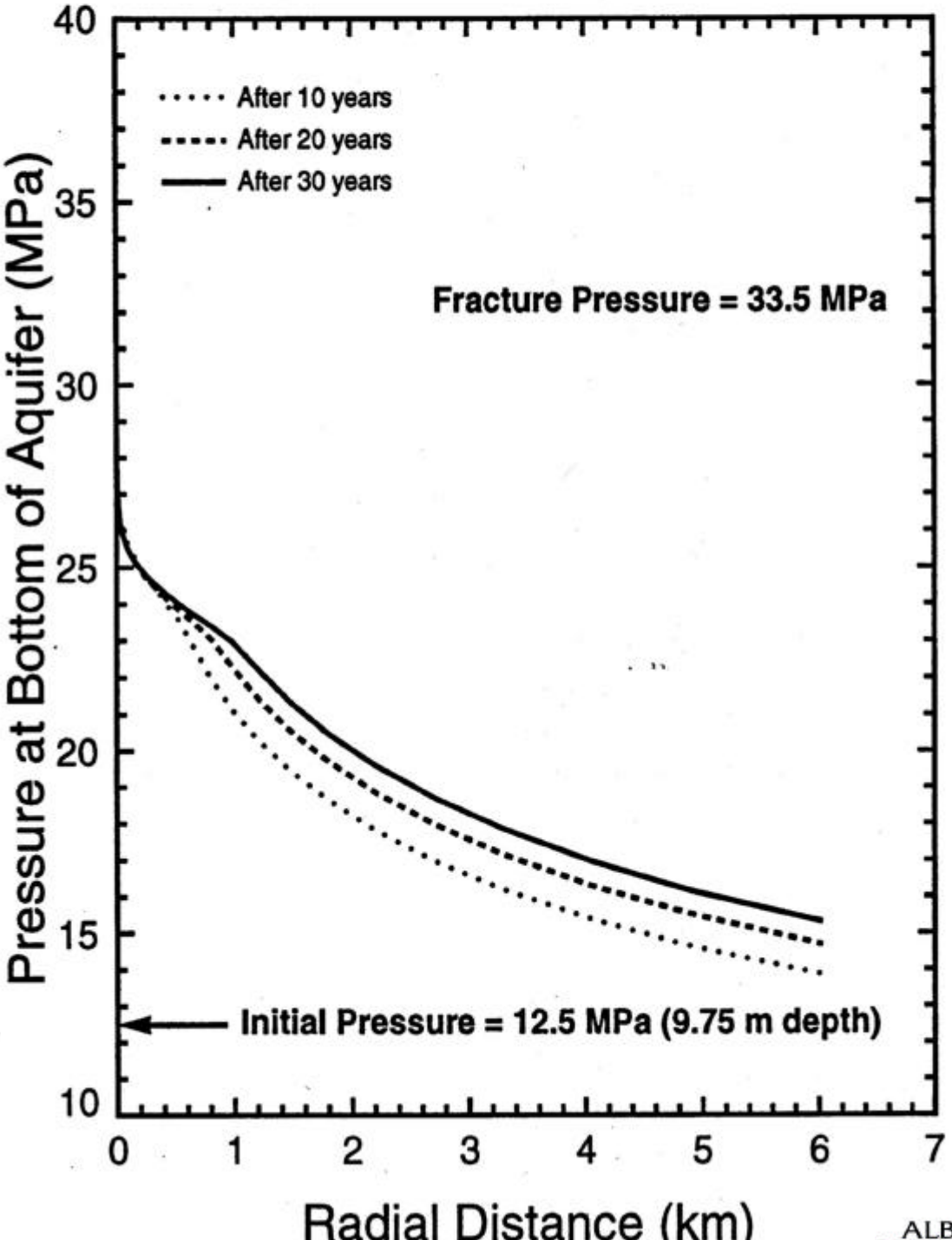
Glauconitic Sandstone Aquifer

NUMERICAL RUN (CO2_71)

Aquifer Porosity = 0.12 Aquifer Permeability = 6.2 md (horizontal)
Injection Pressure = 30.12 MPa

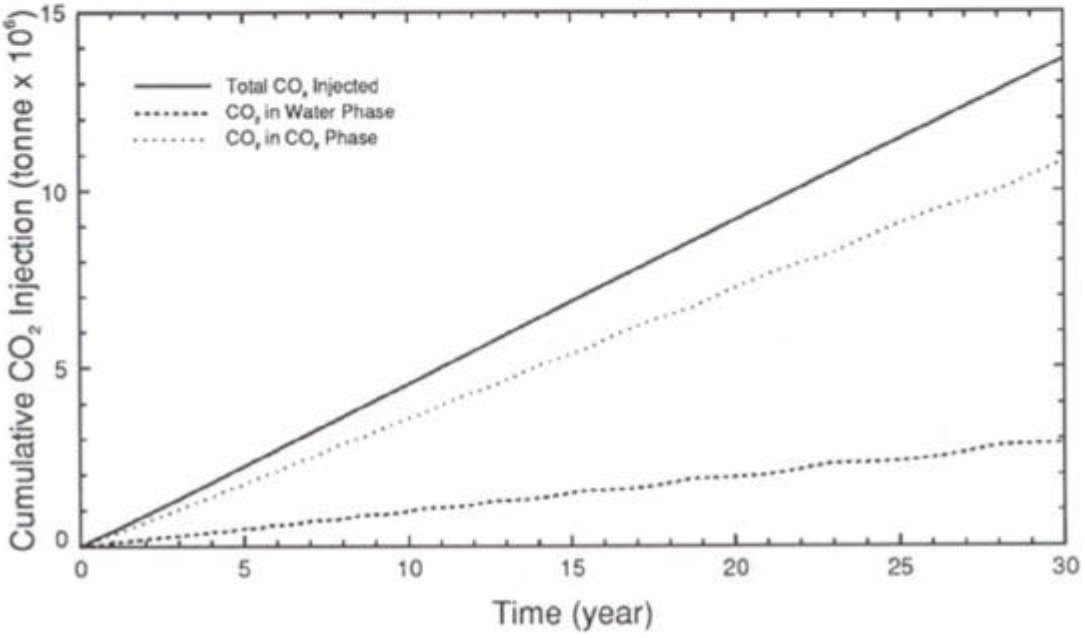


NUMERICAL RUN (CO2_72)

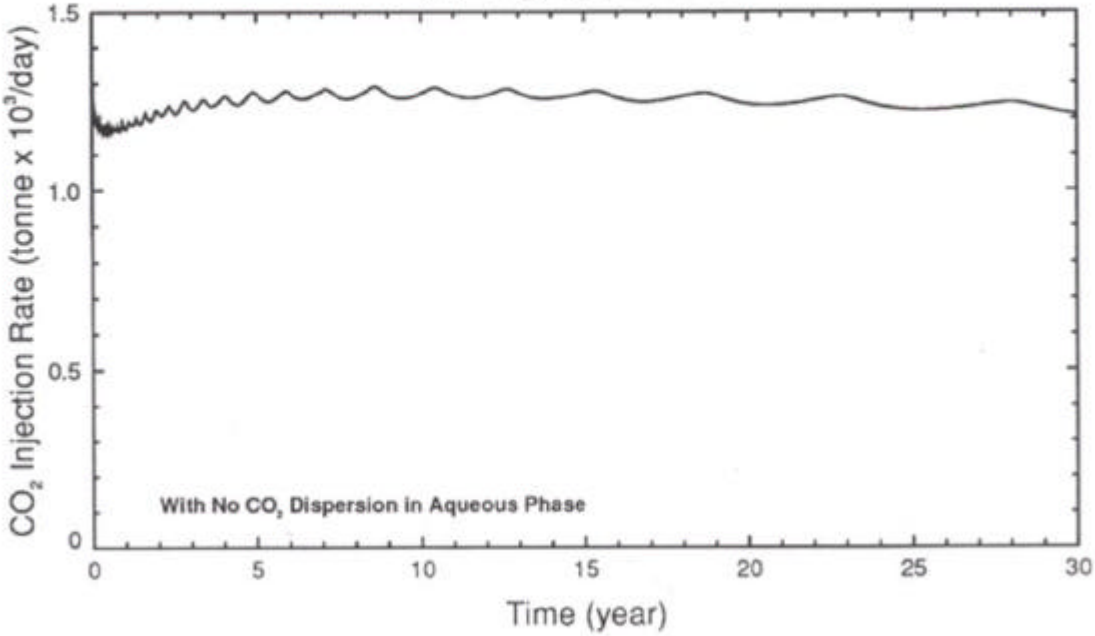
Aquifer Porosity = 0.12 Aquifer Permeability = 30 md (horizontal)

Injection Pressure = 30.12 MPa

(a) Cumulative CO_2 Injection



(b) CO_2 Injection Rate



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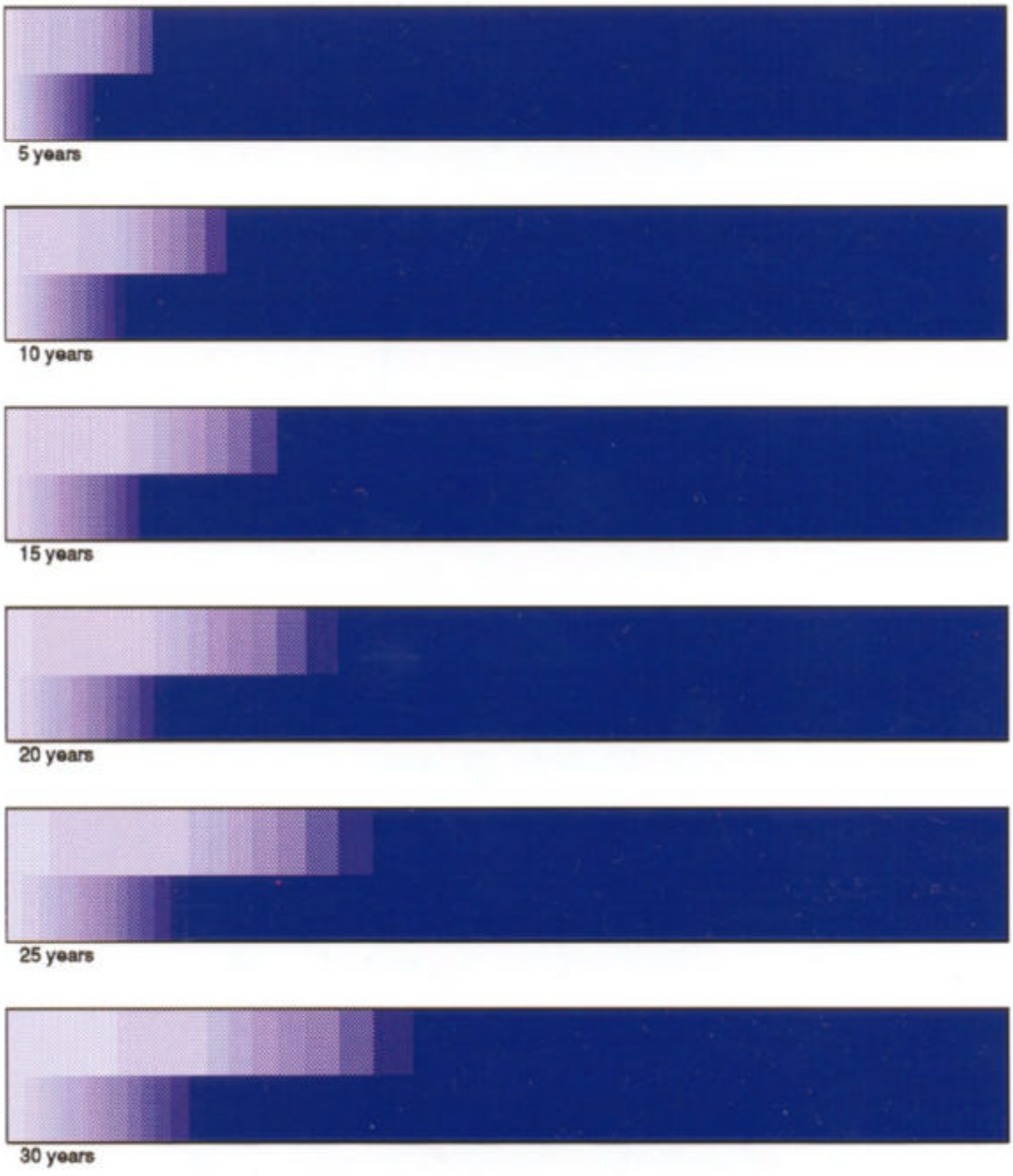
Carbon Dioxide Saturation (Run CO2_72)



Vertical scale factor = 70.000
Field dimensions: 6999. (horiz.), 13.00 (vert.)

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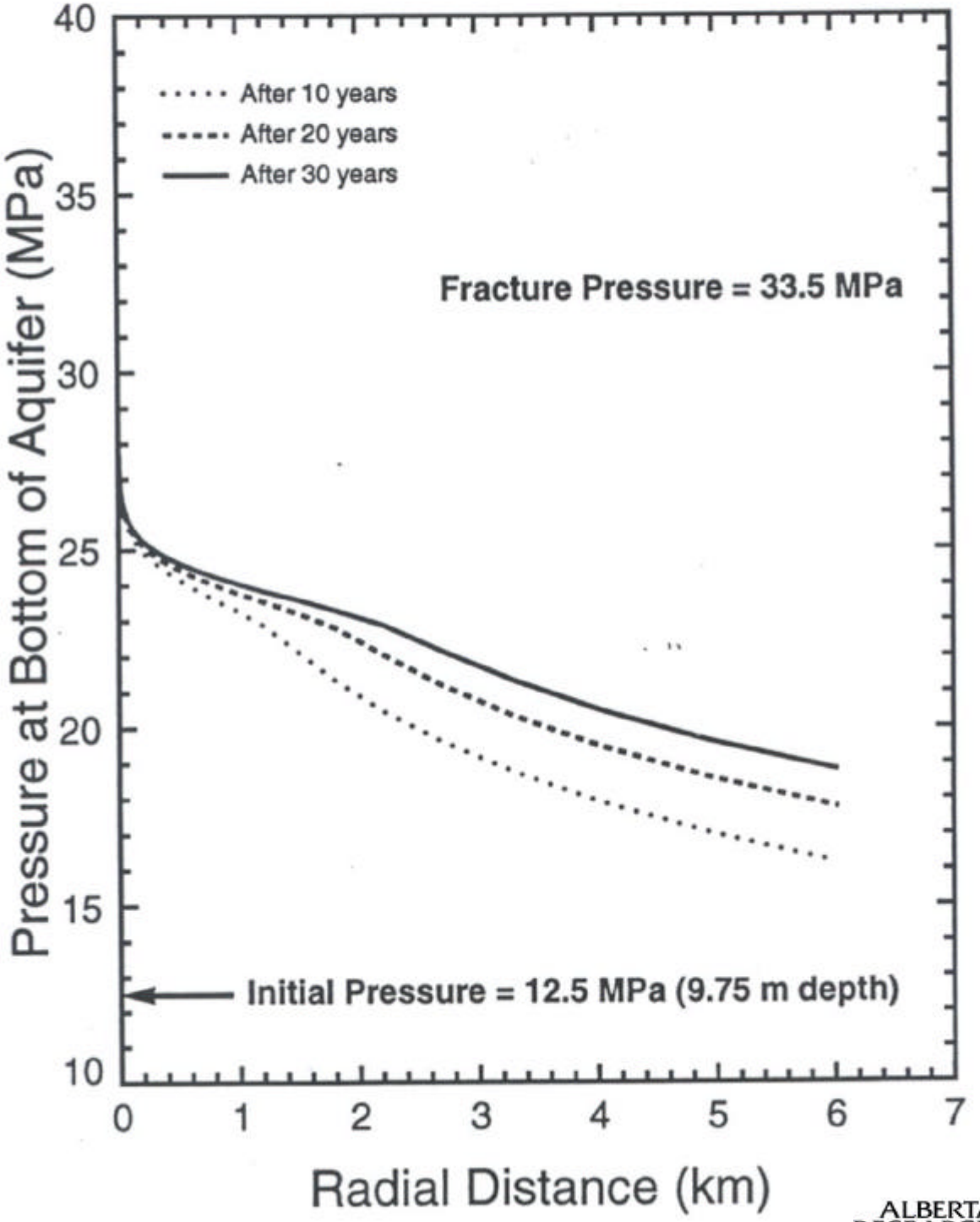
Glauconitic Sandstone Aquifer

NUMERICAL RUN (CO2_72)

Aquifer Porosity = 0.12 Aquifer Permeability = 30 md (horizontal)
Injection Pressure = 30.12 MPa



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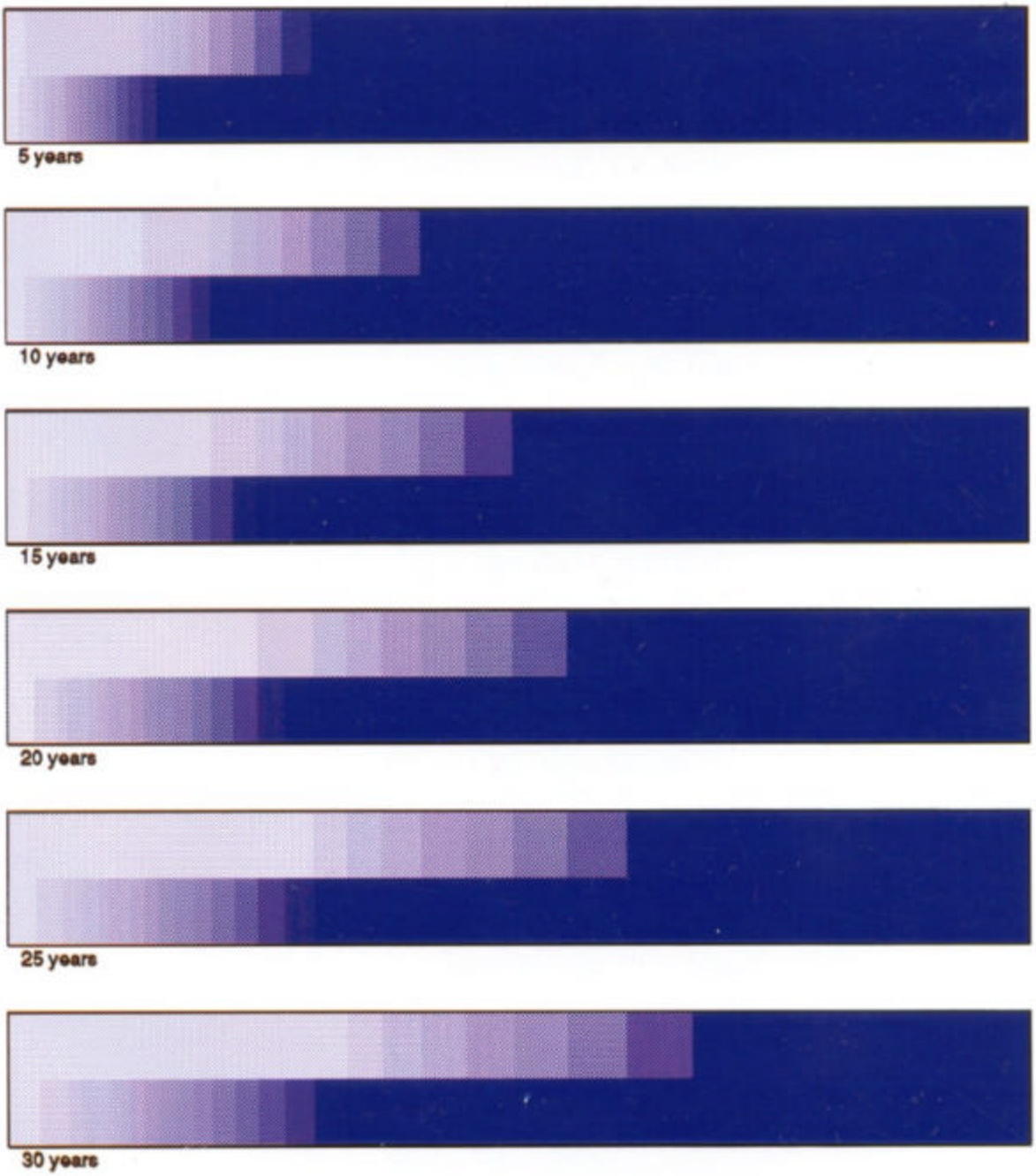
Carbon Dioxide Saturation (Run CO2_73)



Vertical scale factor = 70.000
Field dimensions: 6999. (horiz.), 13.00 (vert.)

0.0000E+00 1.000

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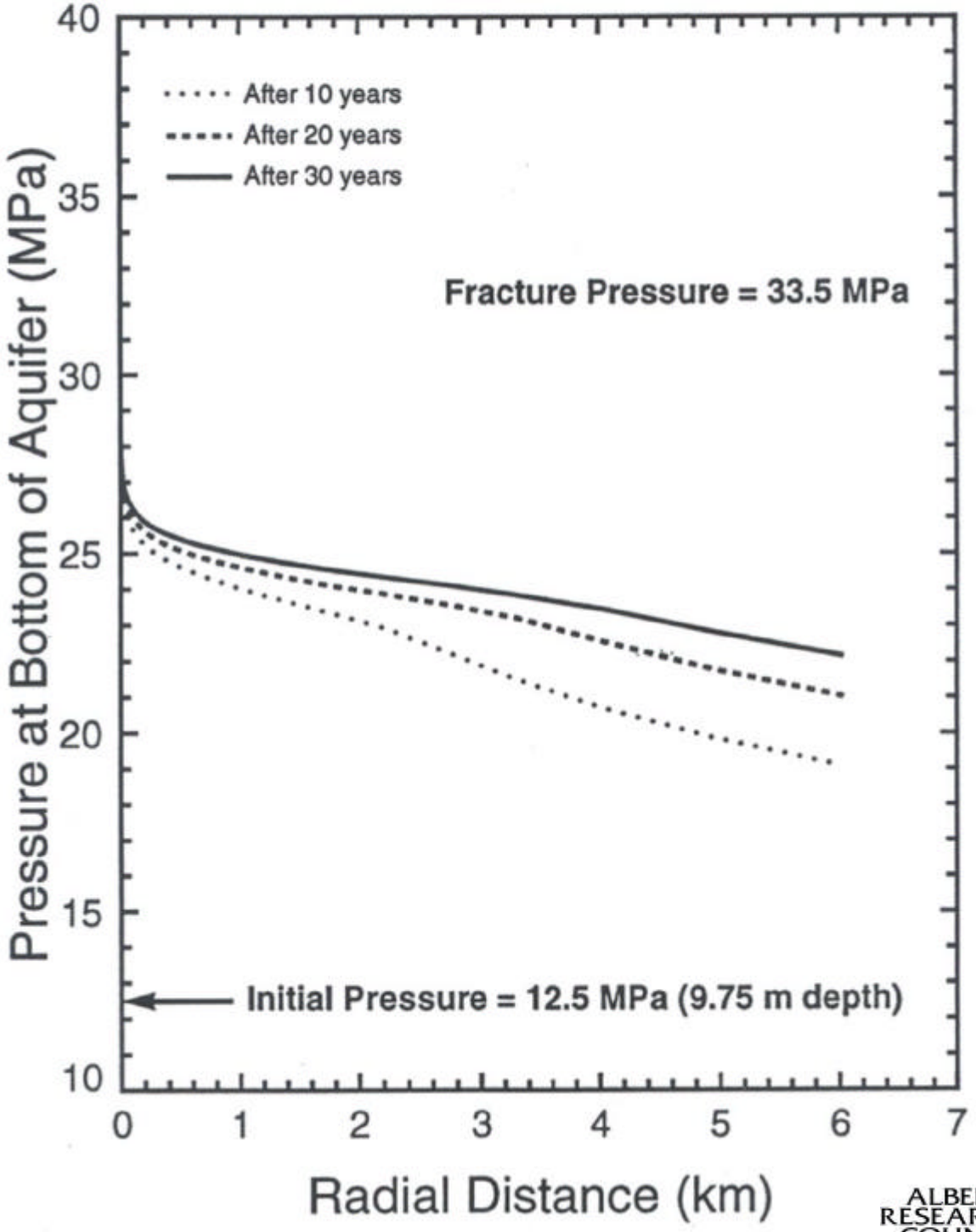
Glauconitic Sandstone Aquifer

NUMERICAL RUN (CO2_73)

Aquifer Porosity = 0.12 Aquifer Permeability = 100 md (horizontal)
Injection Pressure = 30.12 MPa



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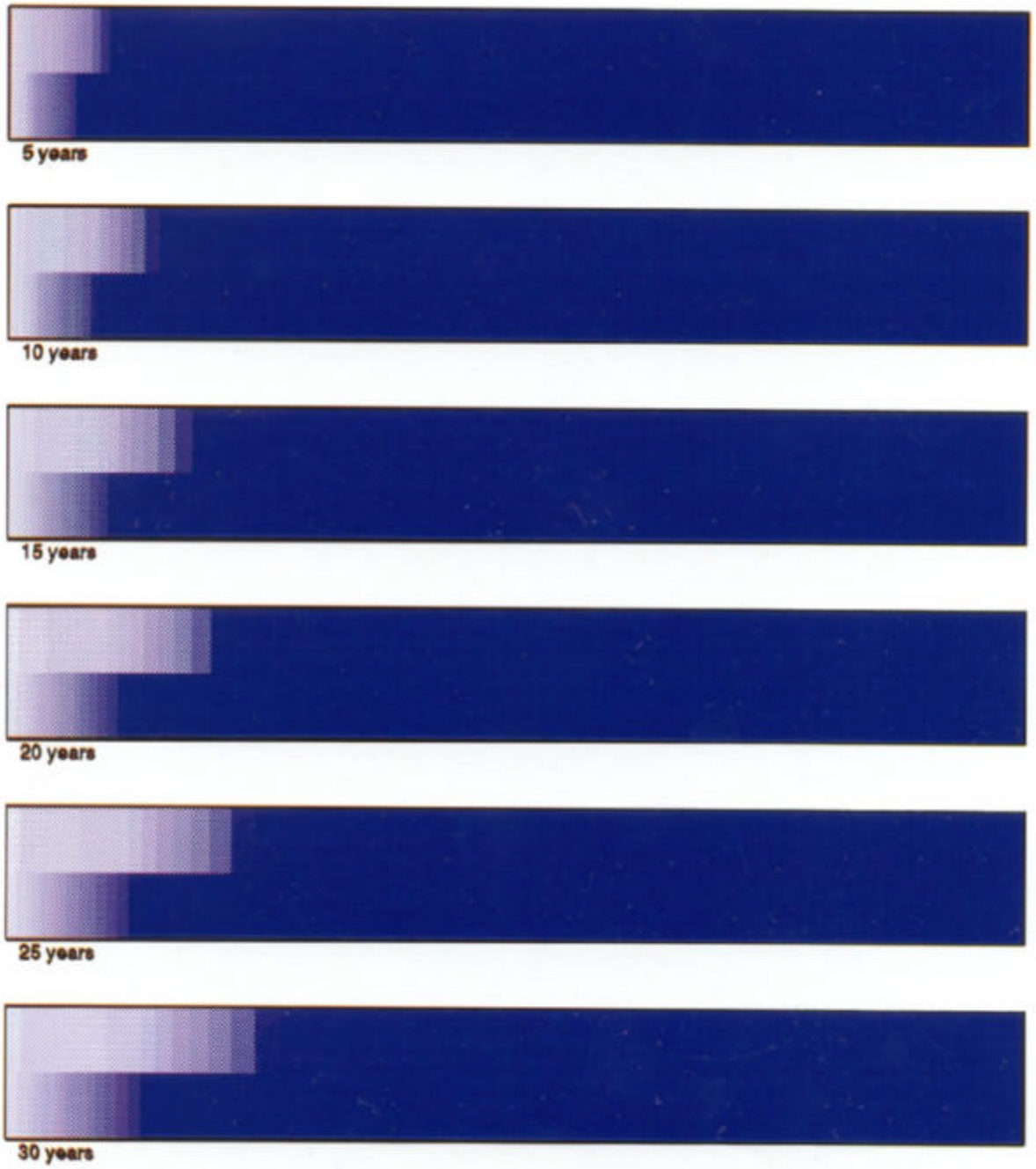
Carbon Dioxide Saturation (Run CO2_74)



Vertical scale factor = 70.000
Field dimensions: 6999. (horiz.), 13.00 (vert.)

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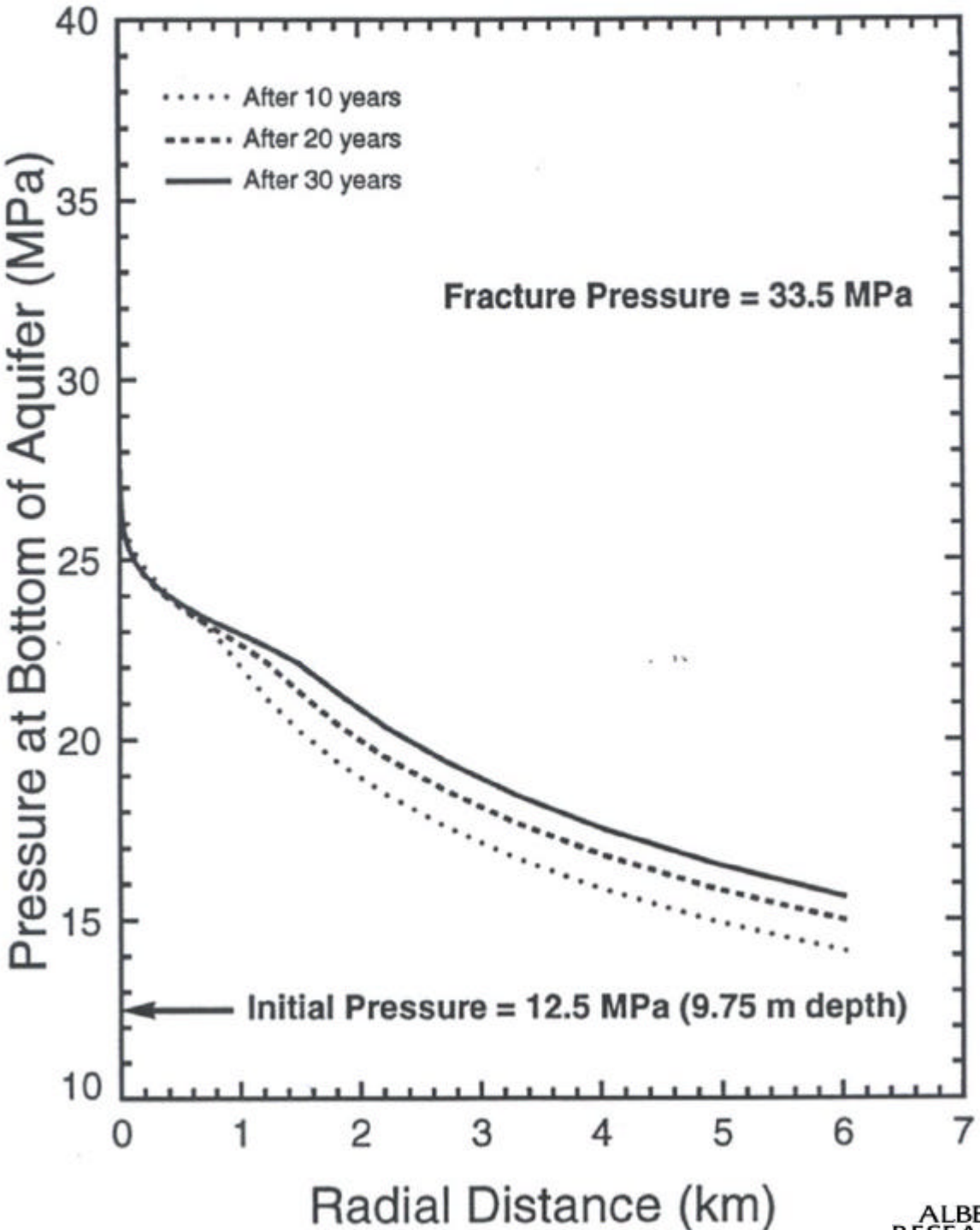
Glauconitic Sandstone Aquifer

NUMERICAL RUN (CO2_74)

Aquifer Porosity = 0.06 Aquifer Permeability = 6.2 md (horizontal)
Injection Pressure = 30.12 MPa



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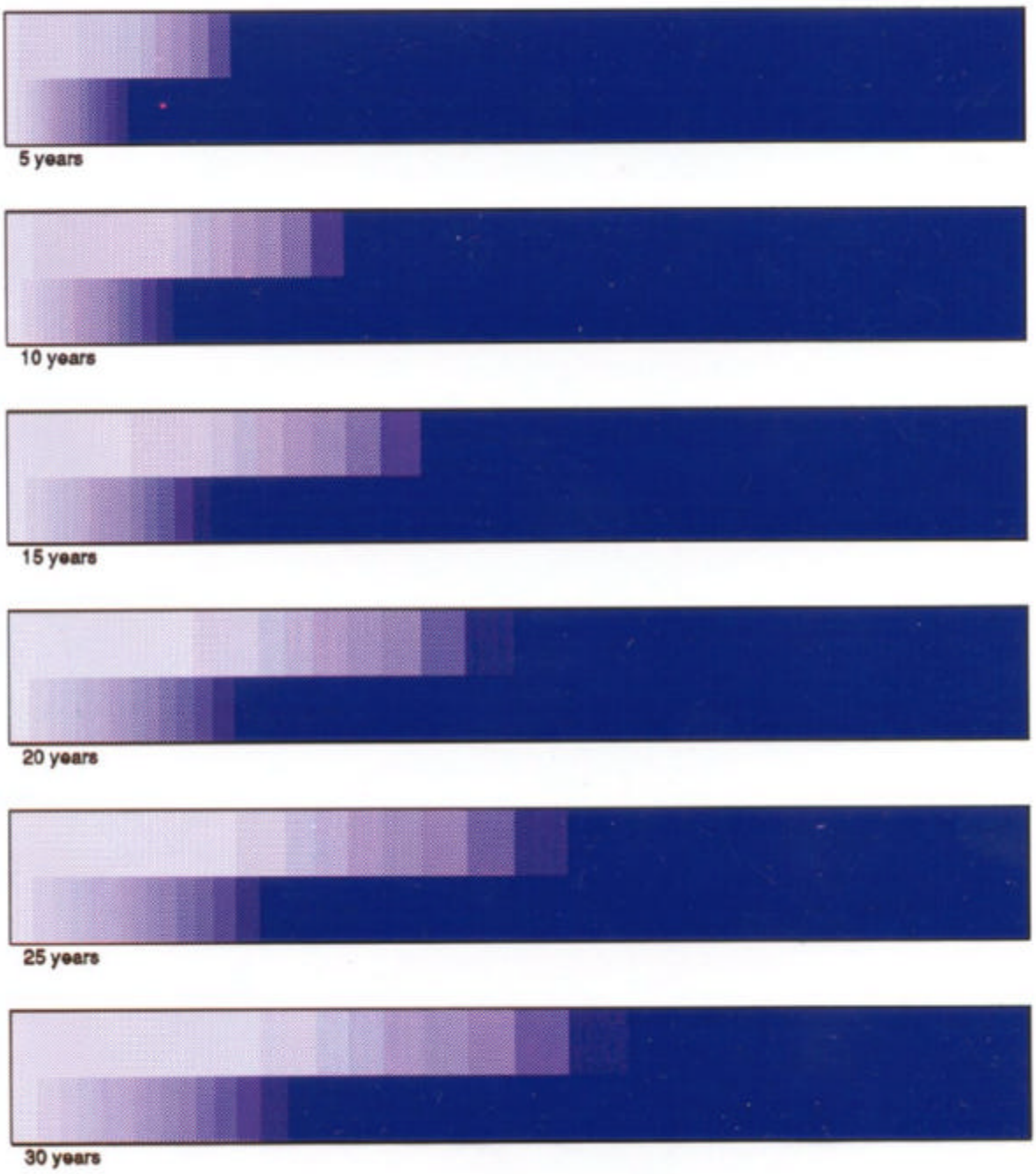
Carbon Dioxide Saturation (Run CO2_75)



Vertical scale factor = 70.000
Field dimensions: 6999. (horiz.), 13.00 (vert.)

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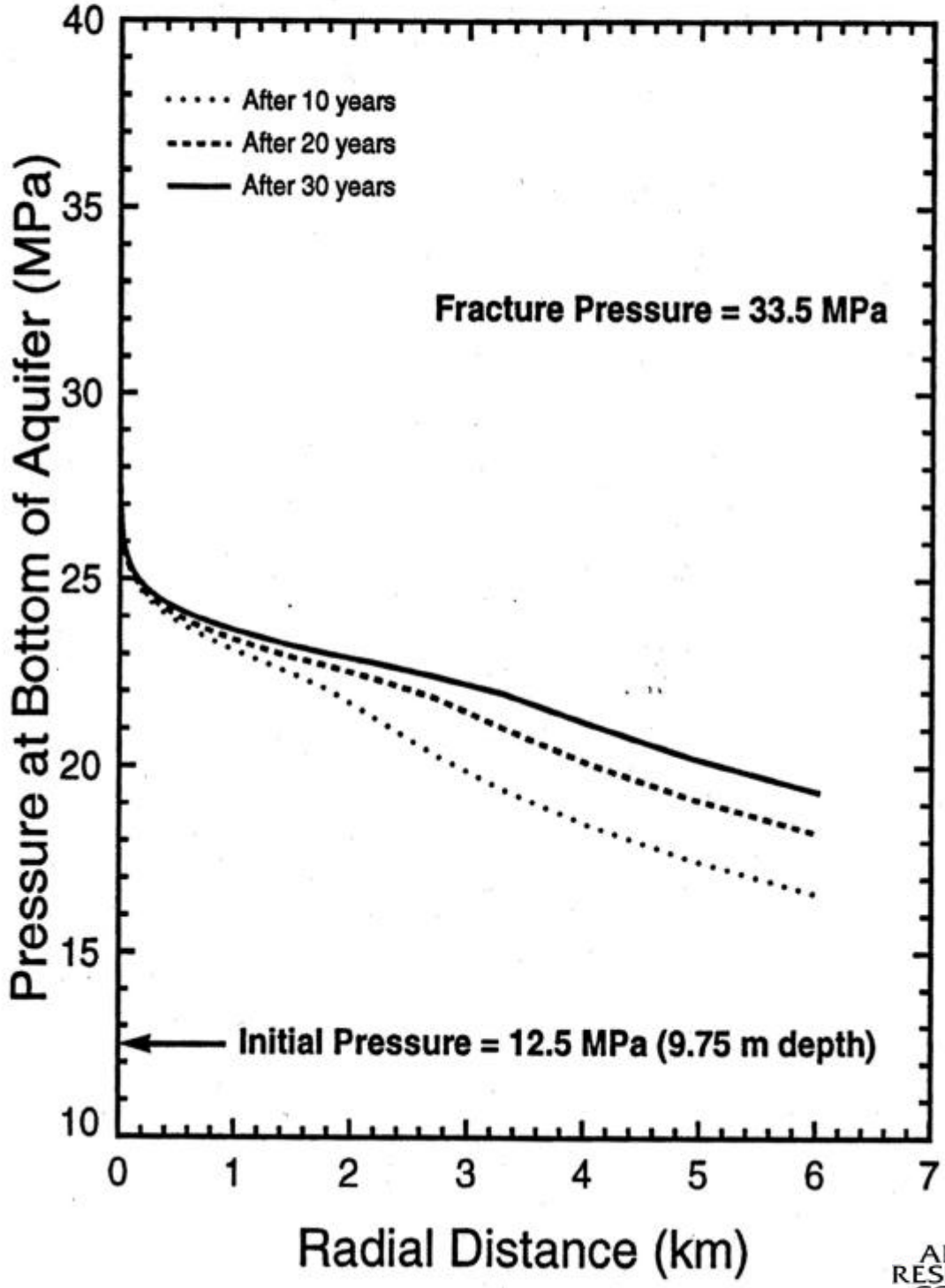
Glauconitic Sandstone Aquifer

NUMERICAL RUN (CO2_75)

Aquifer Porosity = 0.06 Aquifer Permeability = 30 md (horizontal)
Injection Pressure = 30.12 MPa



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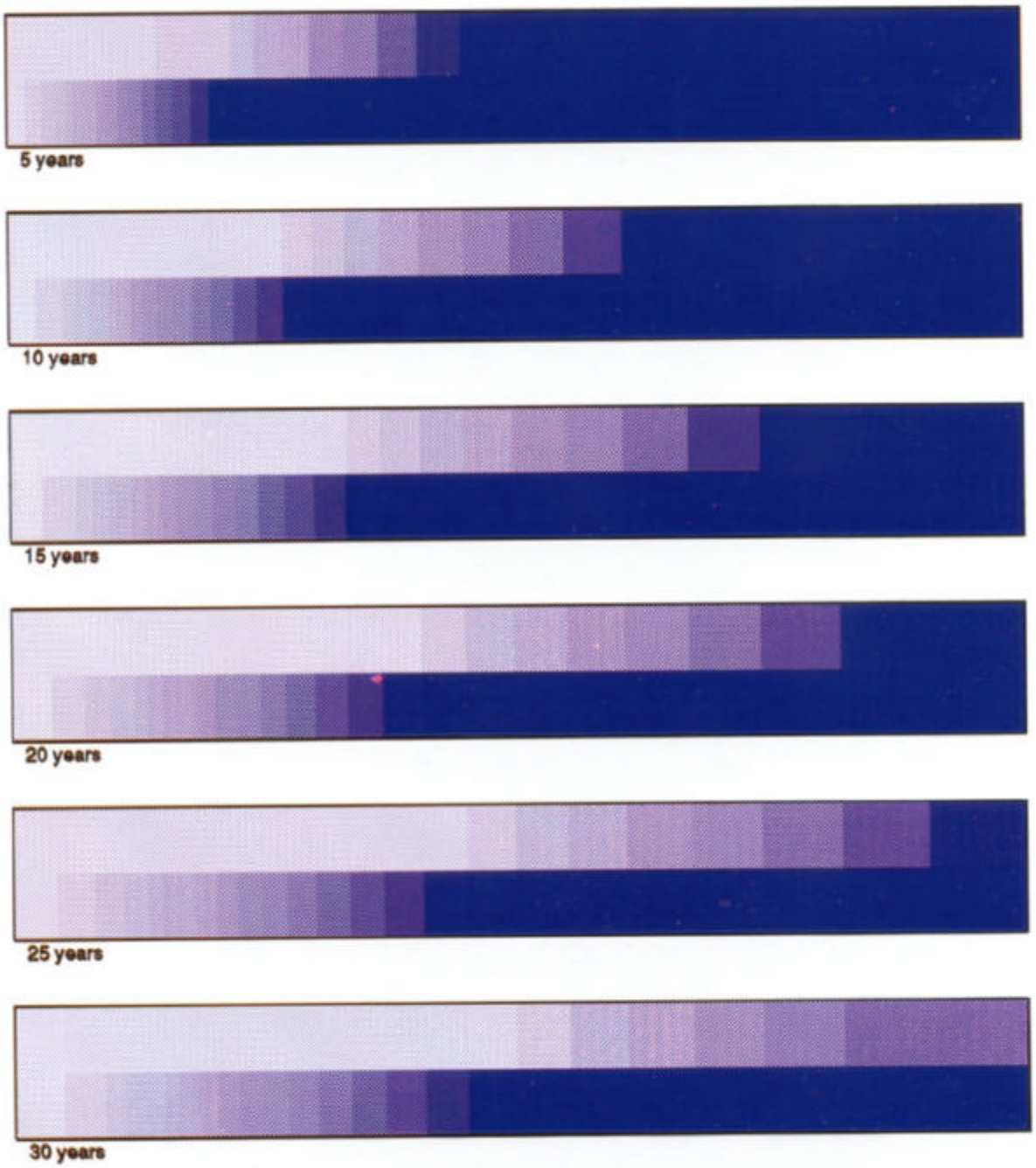
Carbon Dioxide Saturation (Run CO2_76)



Vertical scale factor = 70.000
Field dimensions: 6999. (horiz.), 13.00 (vert.)

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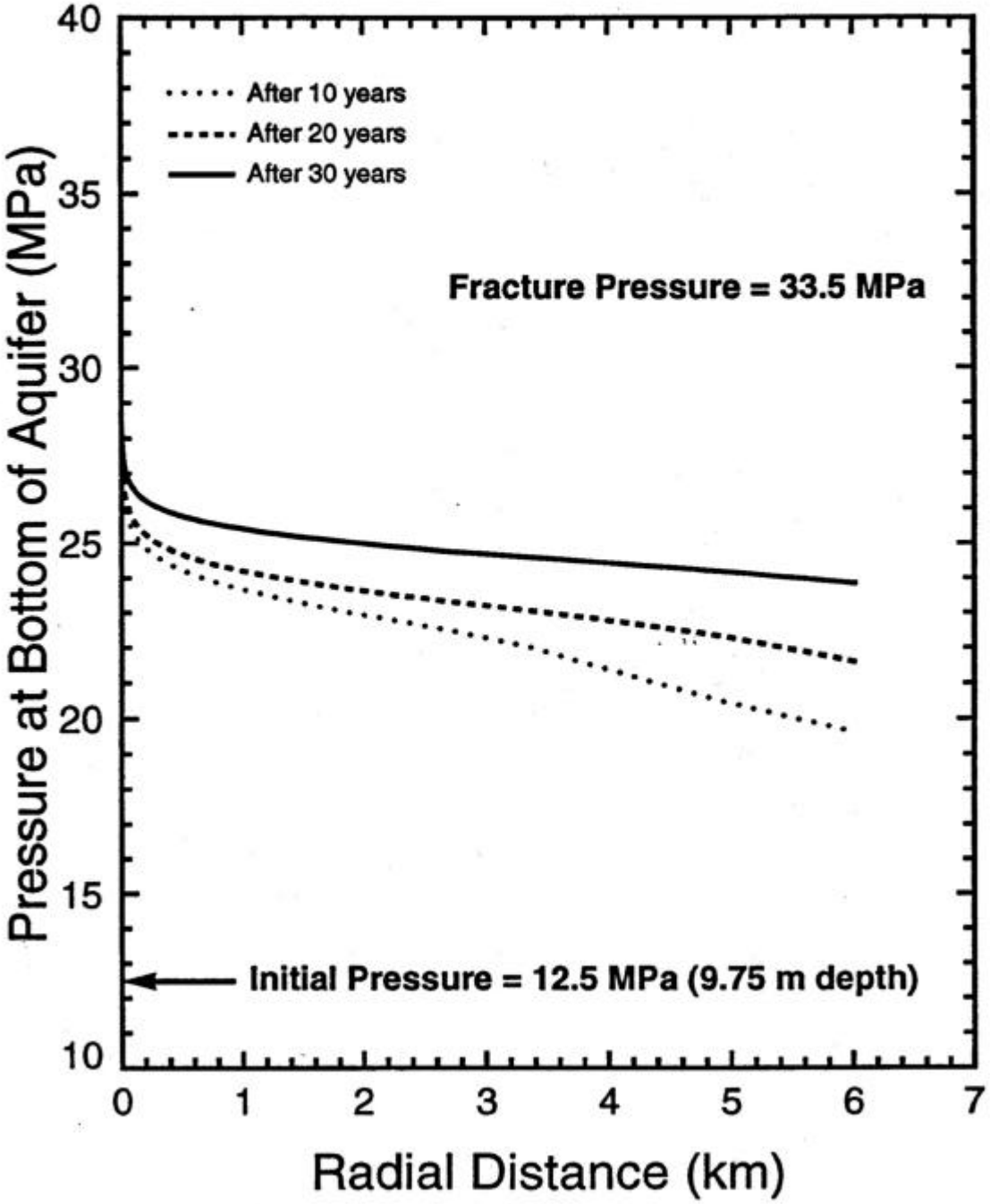
Glauconitic Sandstone Aquifer

NUMERICAL RUN (CO2_76)

Aquifer Porosity = 0.06 Aquifer Permeability = 100 md (horizontal)
Injection Pressure = 30.12 MPa



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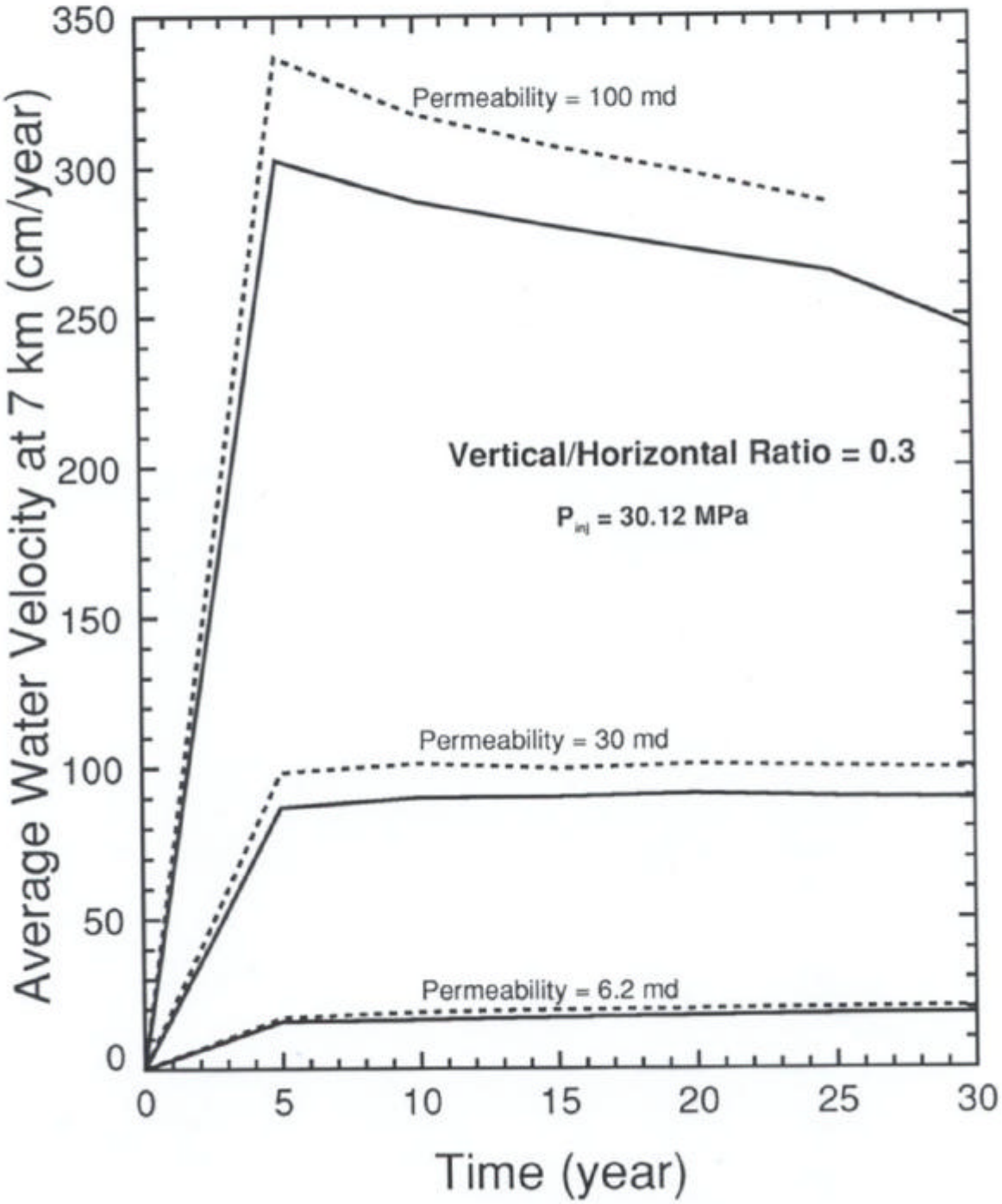
EFFECT OF PERMEABILITY AND POROSITY ON AVERAGE WATER VELOCITY AT OUTFLOW BOUNDARY



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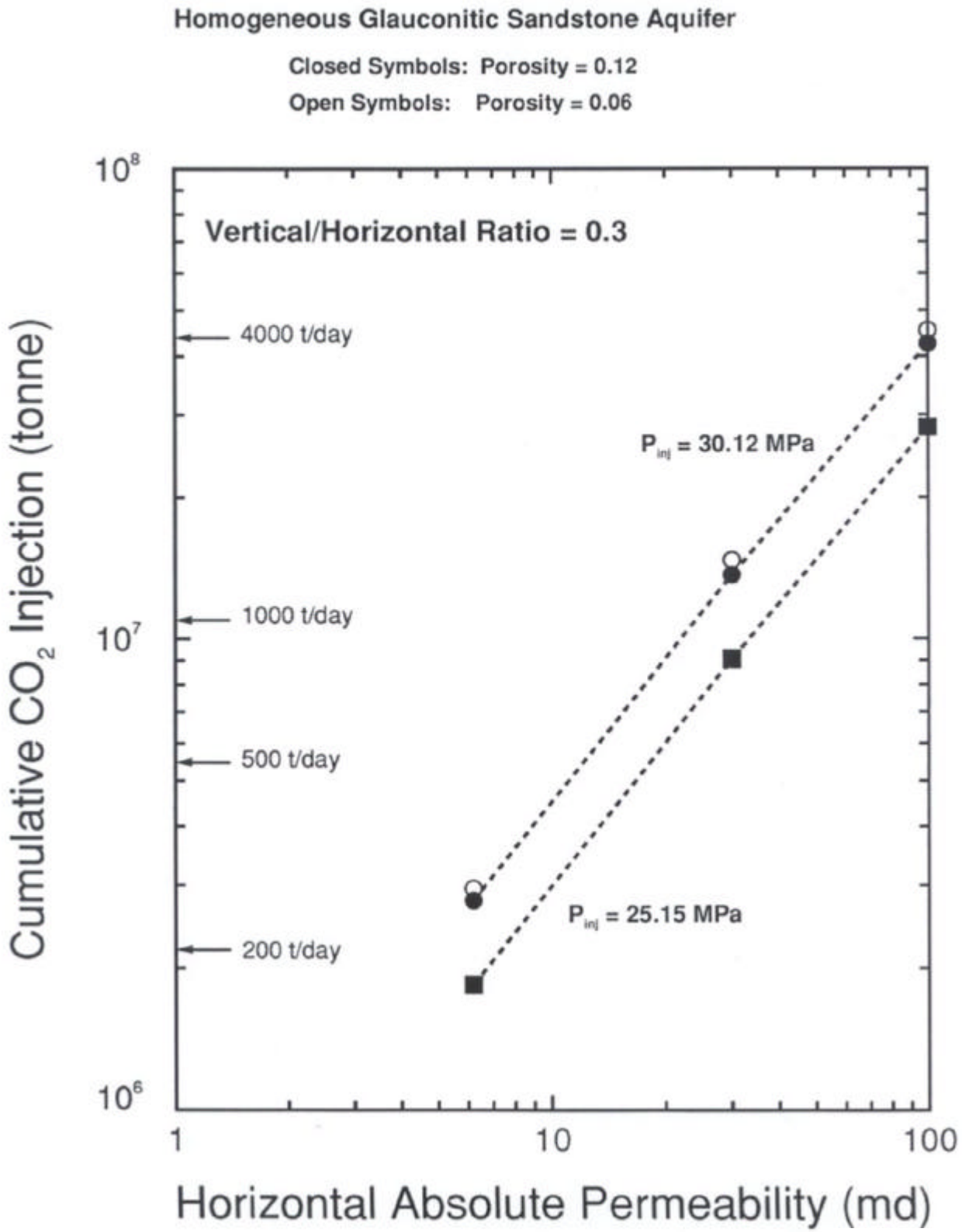
EFFECT OF ABSOLUTE PERMEABILITY ON CO_2 INJECTION AFTER 30 YEARS



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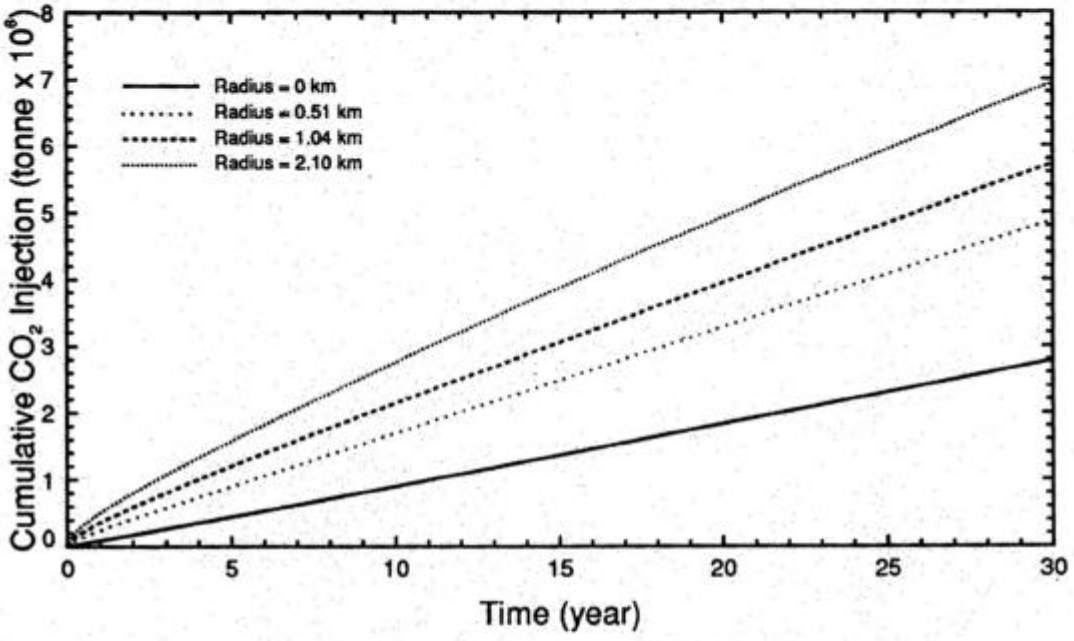
EFFECT OF 100 md ZONE RADIUS

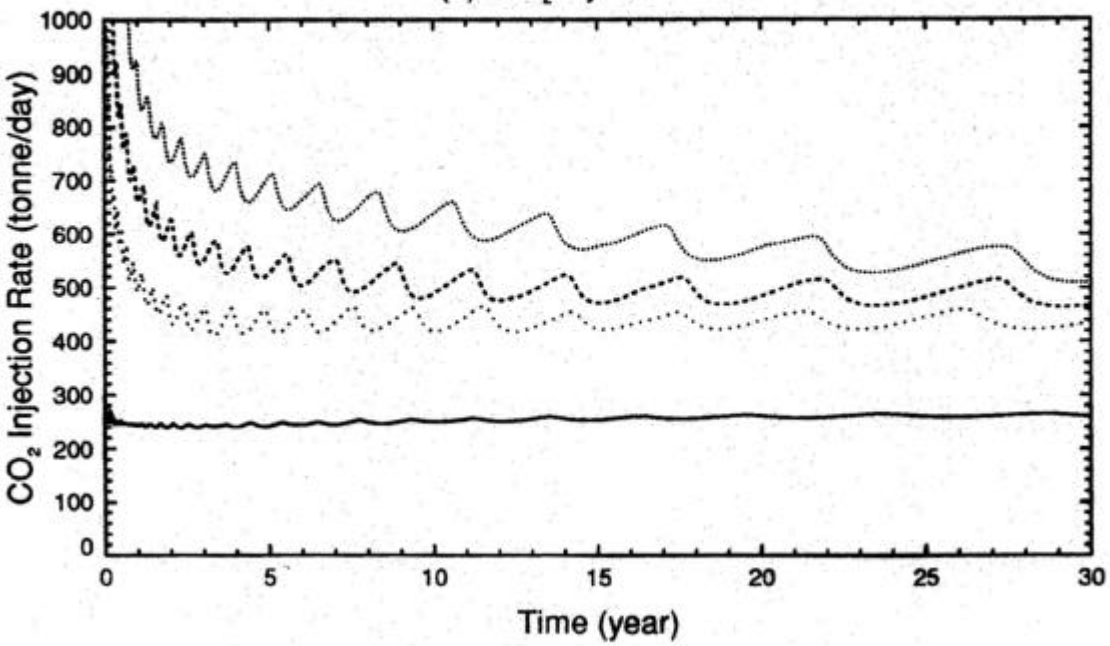
Aquifer Porosity = 0.12 Aquifer Permeability = 6.2 md (horizontal)

Injection Pressure = 30.12 MPa

(a) Cumulative CO_2 Injection



(b) CO_2 Injection Rate



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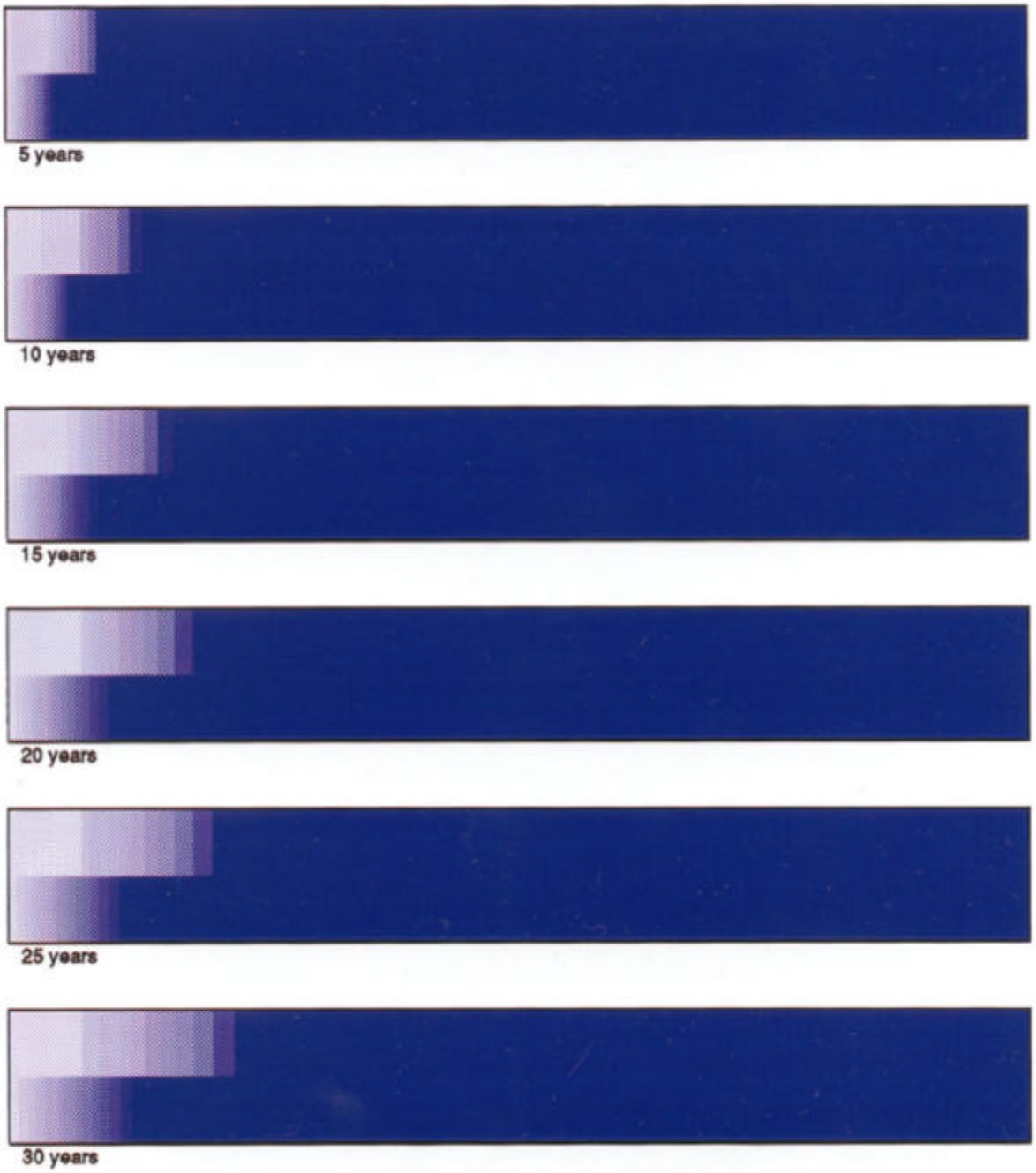
Carbon Dioxide Saturation (Run CO2_80)



Vertical scale factor = 70.000
Field dimensions: 6999. (horiz.), 13.00 (vert.)

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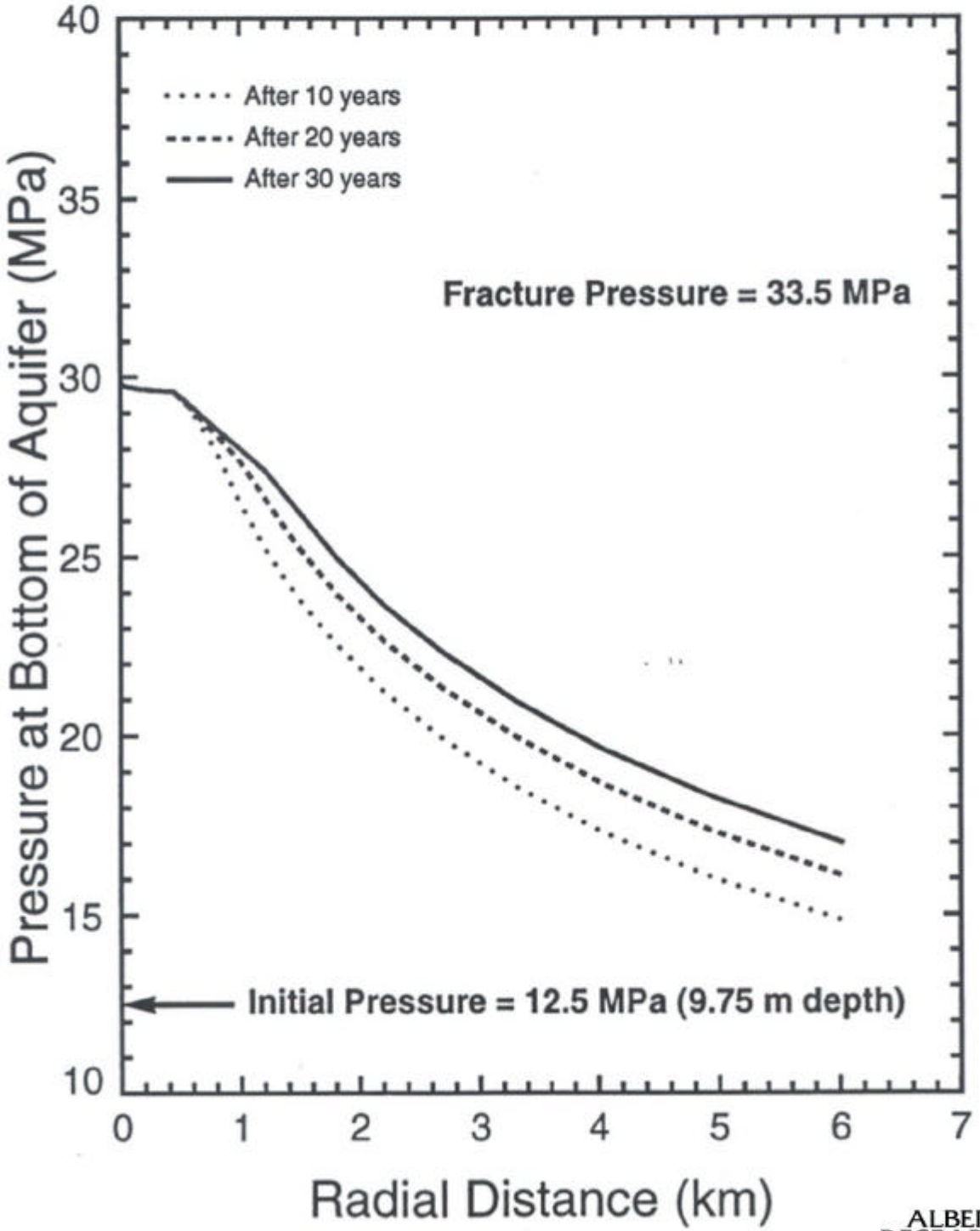
Glauconitic Sandstone Aquifer

NUMERICAL RUN (CO2_80)

Aquifer Porosity = 0.12 Aquifer Permeability = 100/6.2 md (horizontal)
Injection Pressure = 30.12 MPa Radius of 100 md zone = 0.51 km



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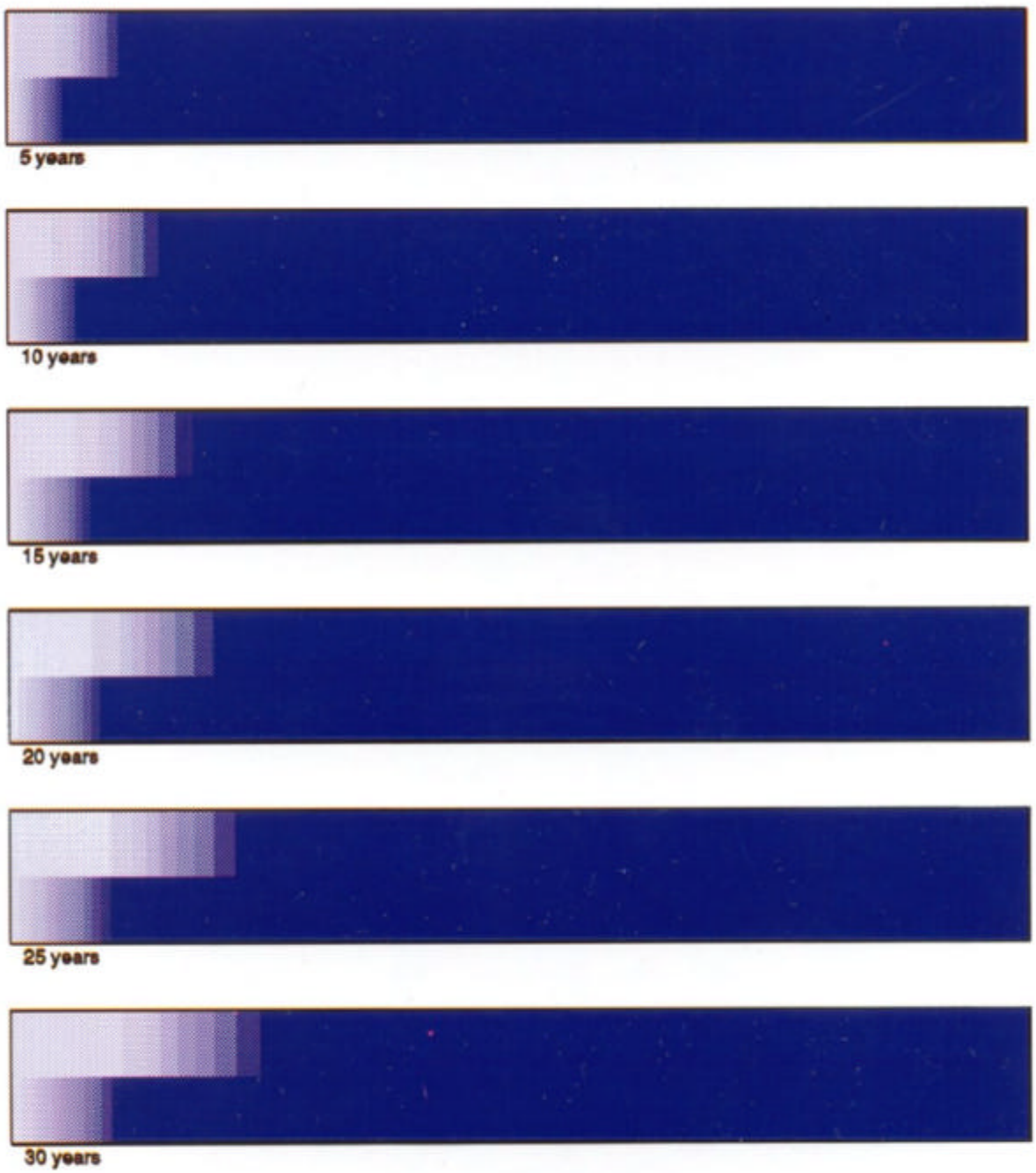
Carbon Dioxide Saturation (Run CO2_81)



Vertical scale factor = 70.000
Field dimensions: 6999. (horiz.), 13.00 (vert.)

0.0000E+00 1.000

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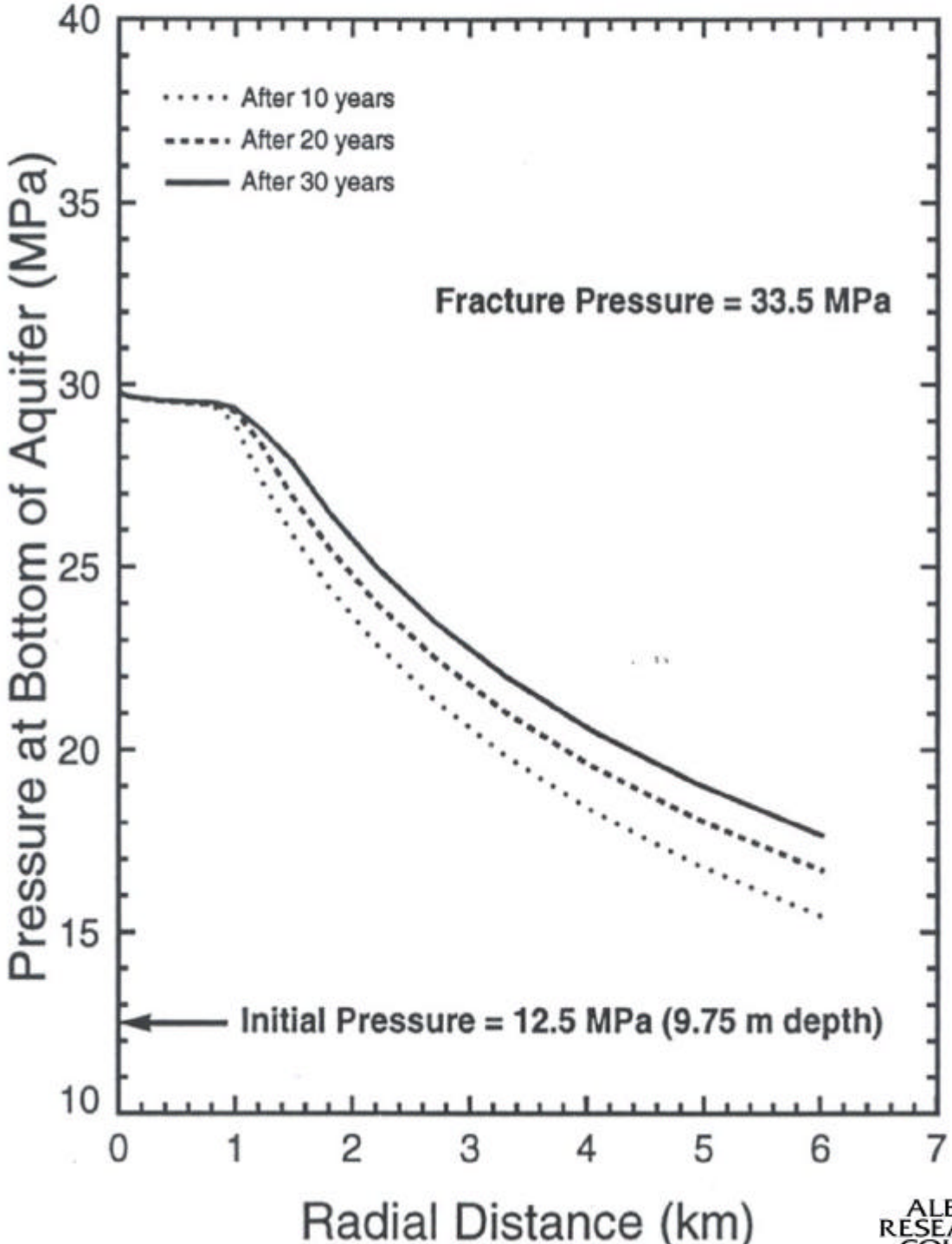
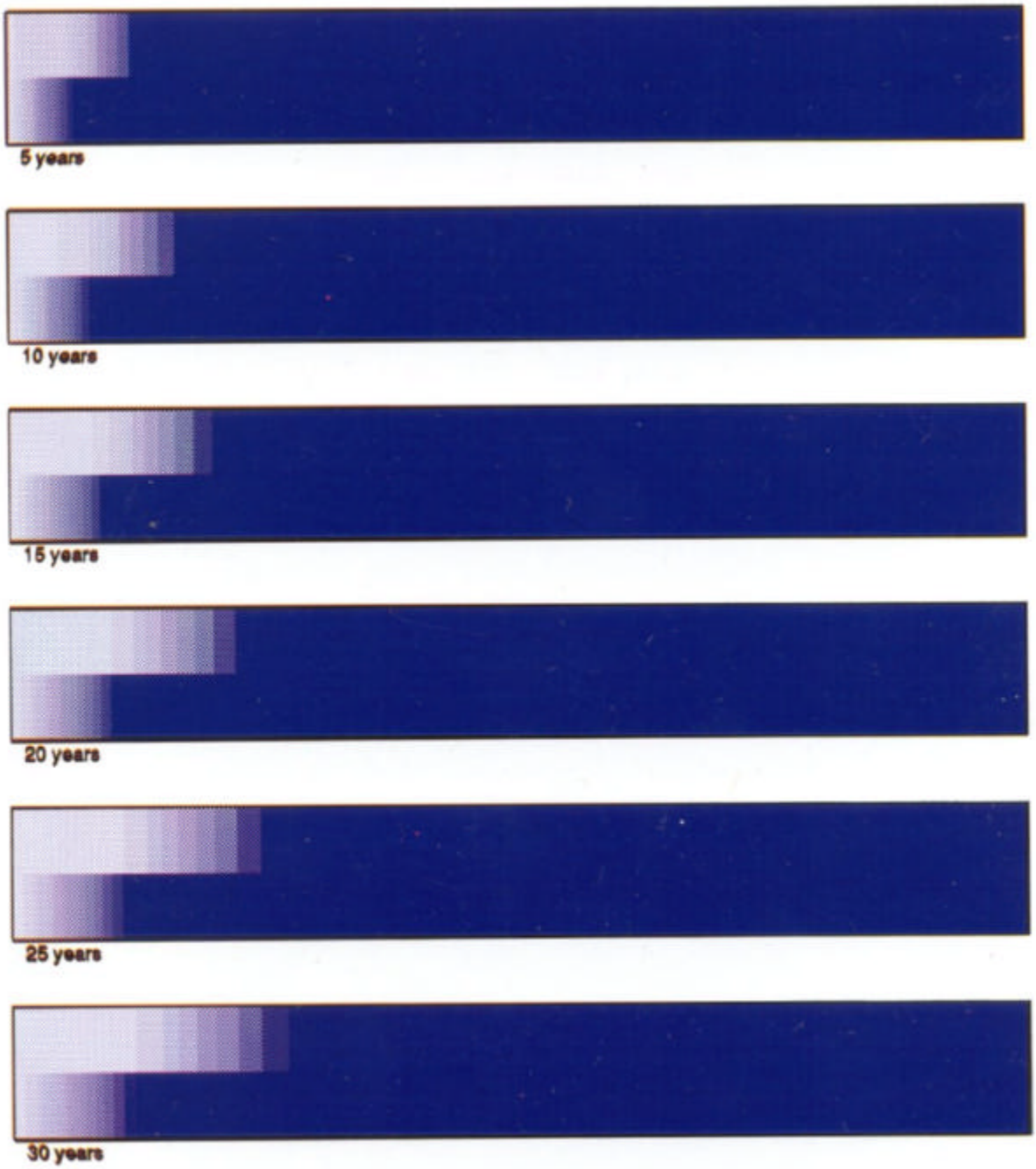
Glauconitic Sandstone Aquifer

NUMERICAL RUN (CO2_81)

Aquifer Porosity = 0.12 Aquifer Permeability = 100/6.2 md (horizontal)
Injection Pressure = 30.12 MPa Radius of 100 md zone = 1.04 km



Carbon Dioxide Saturation (Run CO2_82)



Vertical scale factor = 70.000
Field dimensions: 6999. (horiz.), 13.00 (vert.)

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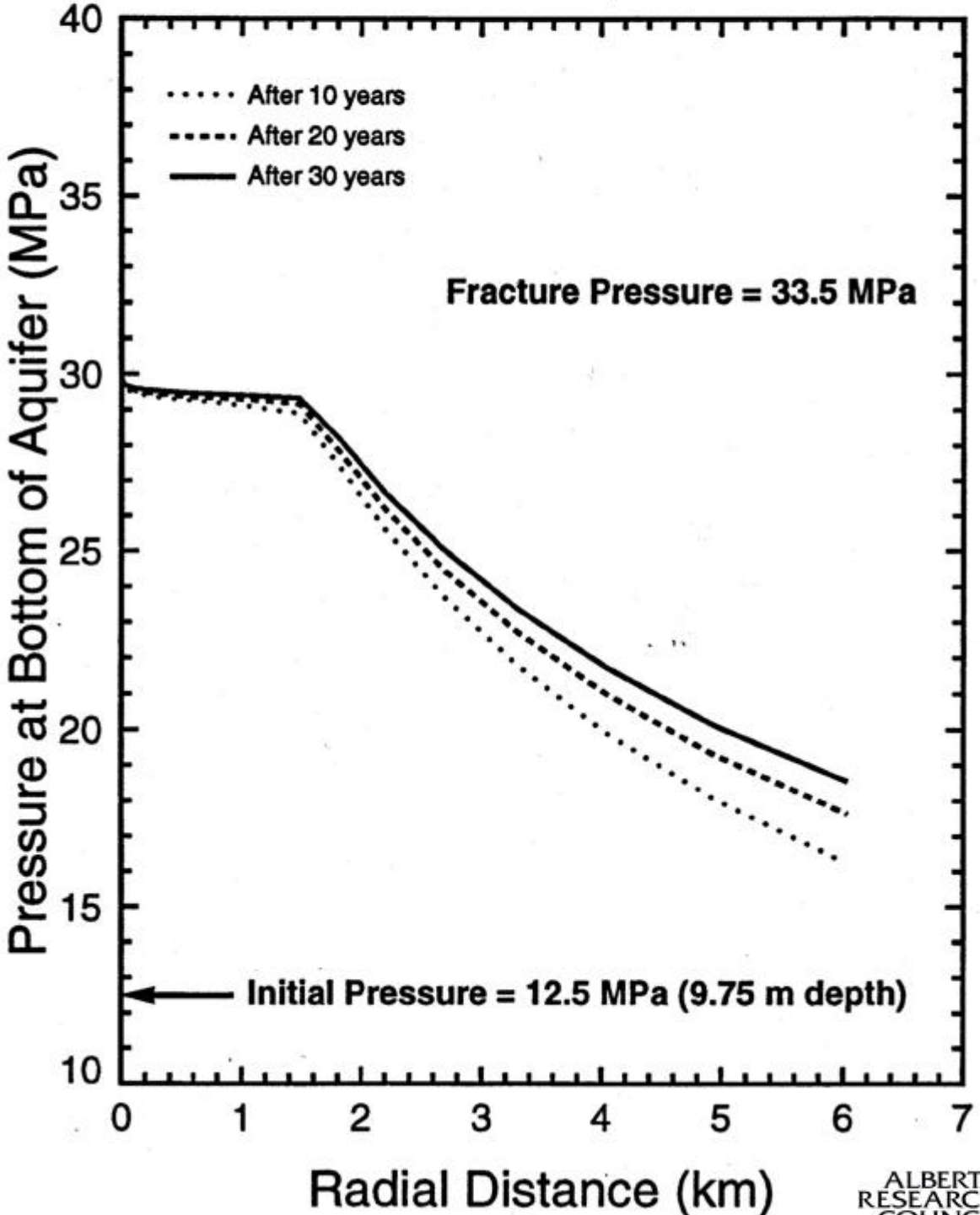
Glauconitic Sandstone Aquifer

NUMERICAL RUN (CO2_82)

Aquifer Porosity = 0.12 Aquifer Permeability = 100/6.2 md (horizontal)
Injection Pressure = 30.12 MPa Radius of 100 md zone = 2.10 km



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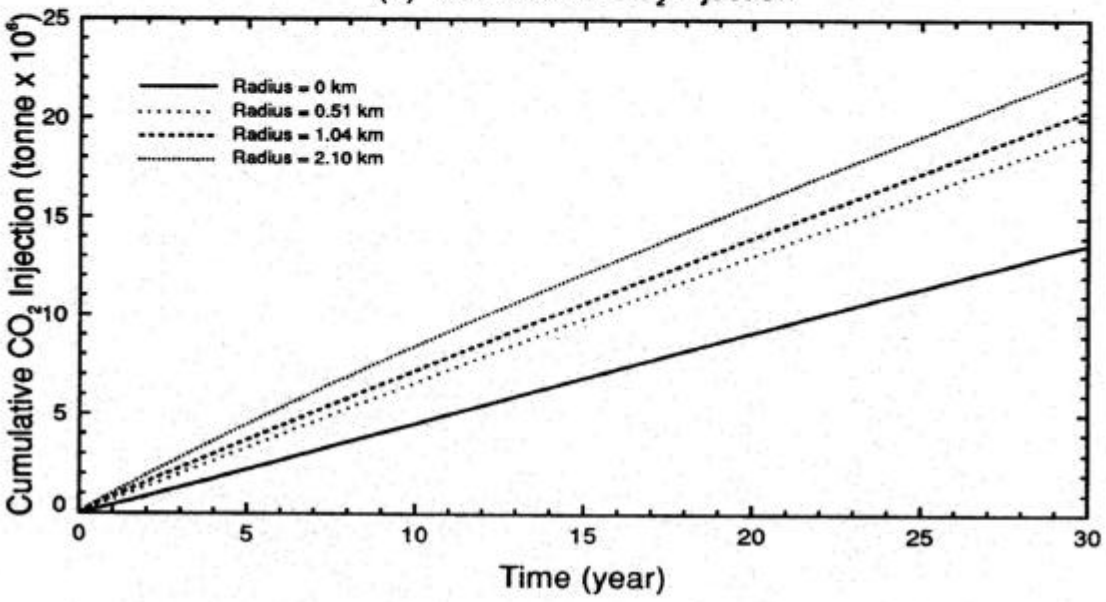
EFFECT OF 100 md ZONE RADIUS

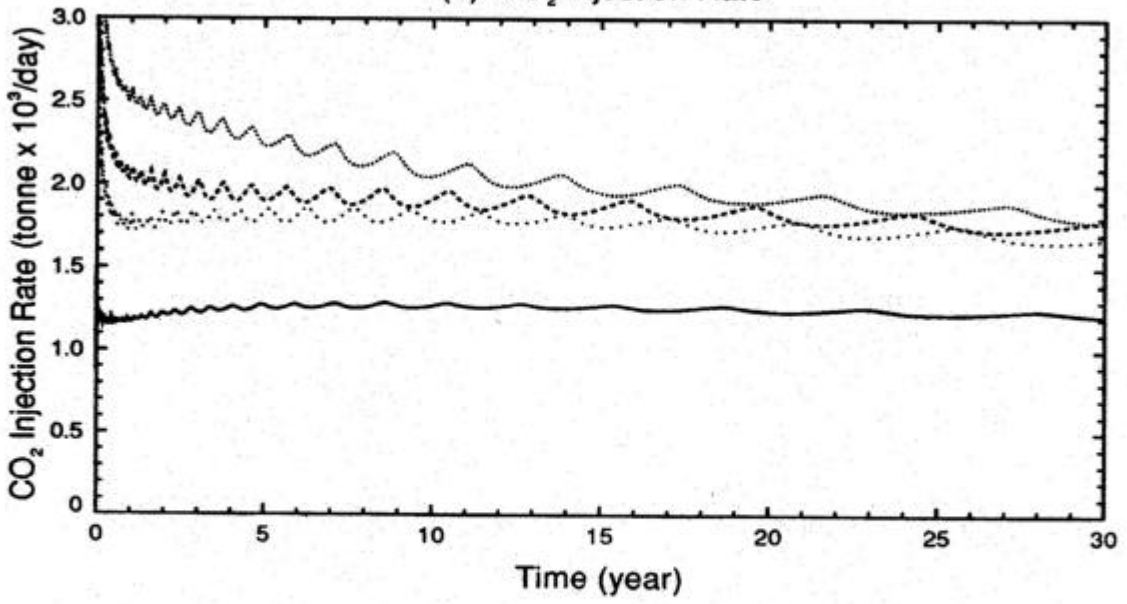
Aquifer Porosity = 0.12 Aquifer Permeability = 30 md (horizontal)

Injection Pressure = 30.12 MPa

(a) Cumulative CO_2 Injection



(b) CO_2 Injection Rate



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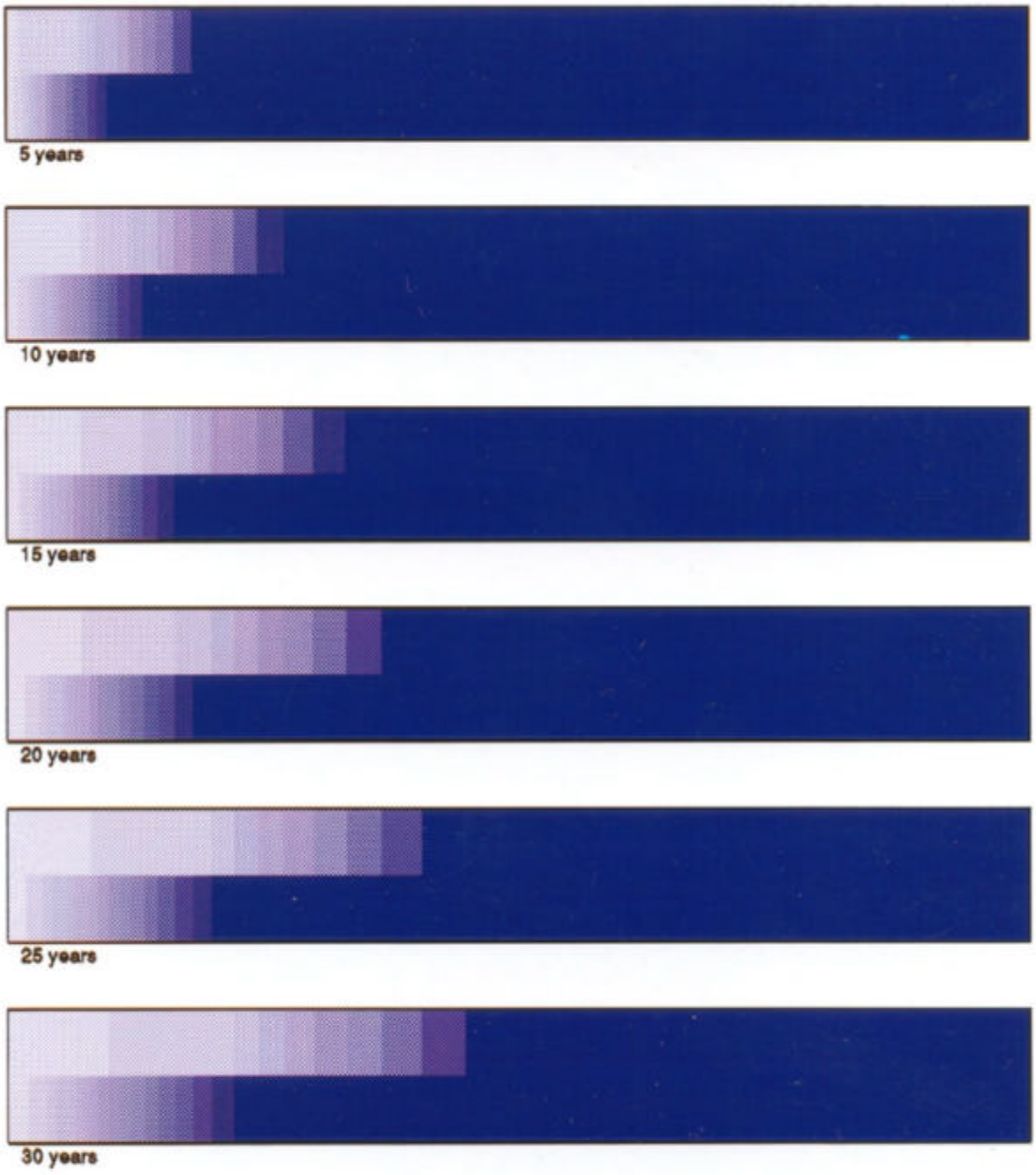
Carbon Dioxide Saturation (Run CO2_83)



Vertical scale factor = 70.000
Field dimensions: 6999. (horiz.), 13.00 (vert.)

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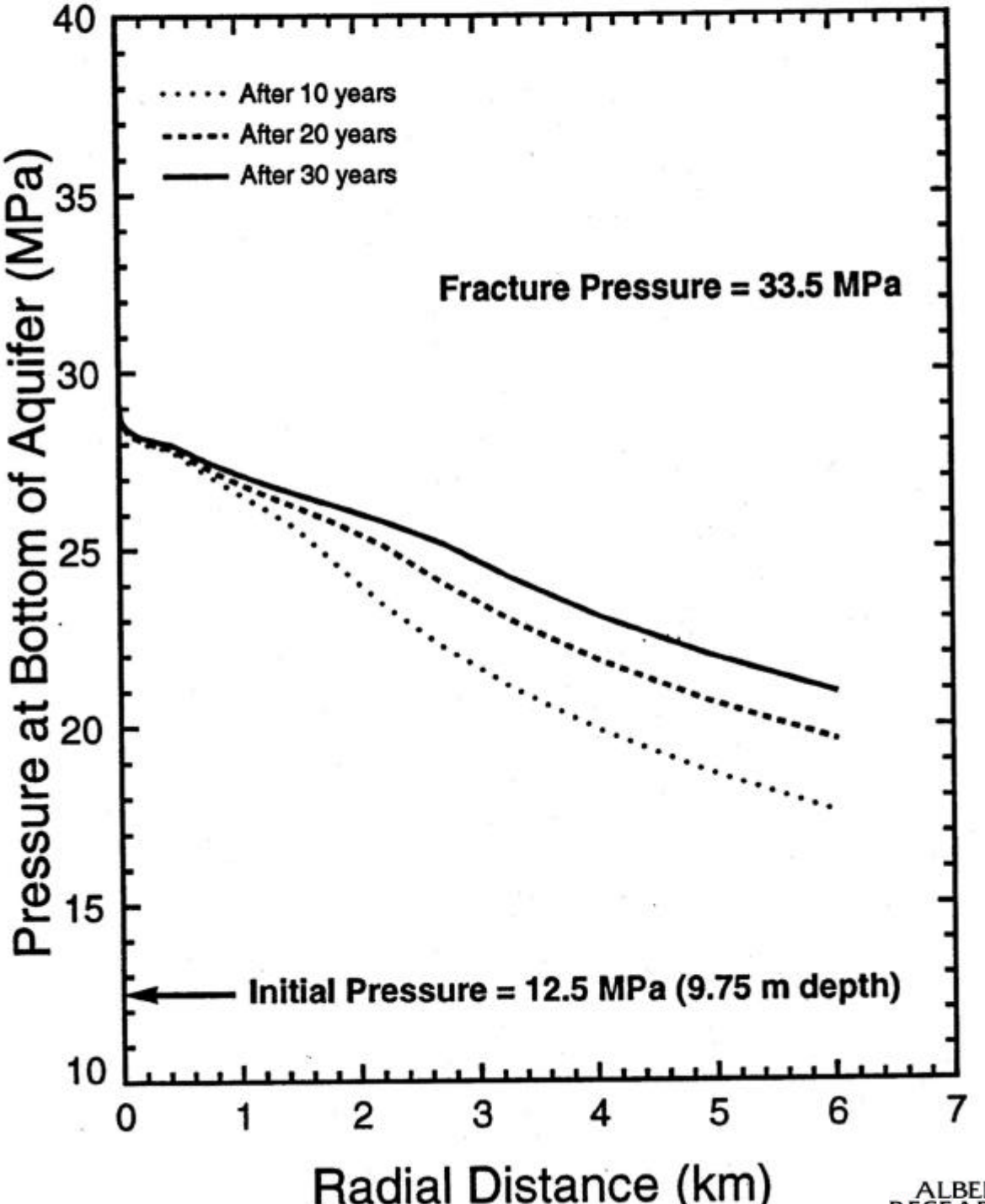
Glauconitic Sandstone Aquifer

NUMERICAL RUN (CO2_83)

Aquifer Porosity = 0.12 Aquifer Permeability = 100/30 md (horizontal)
Injection Pressure = 30.12 MPa Radius of 100 md zone = 0.51 km



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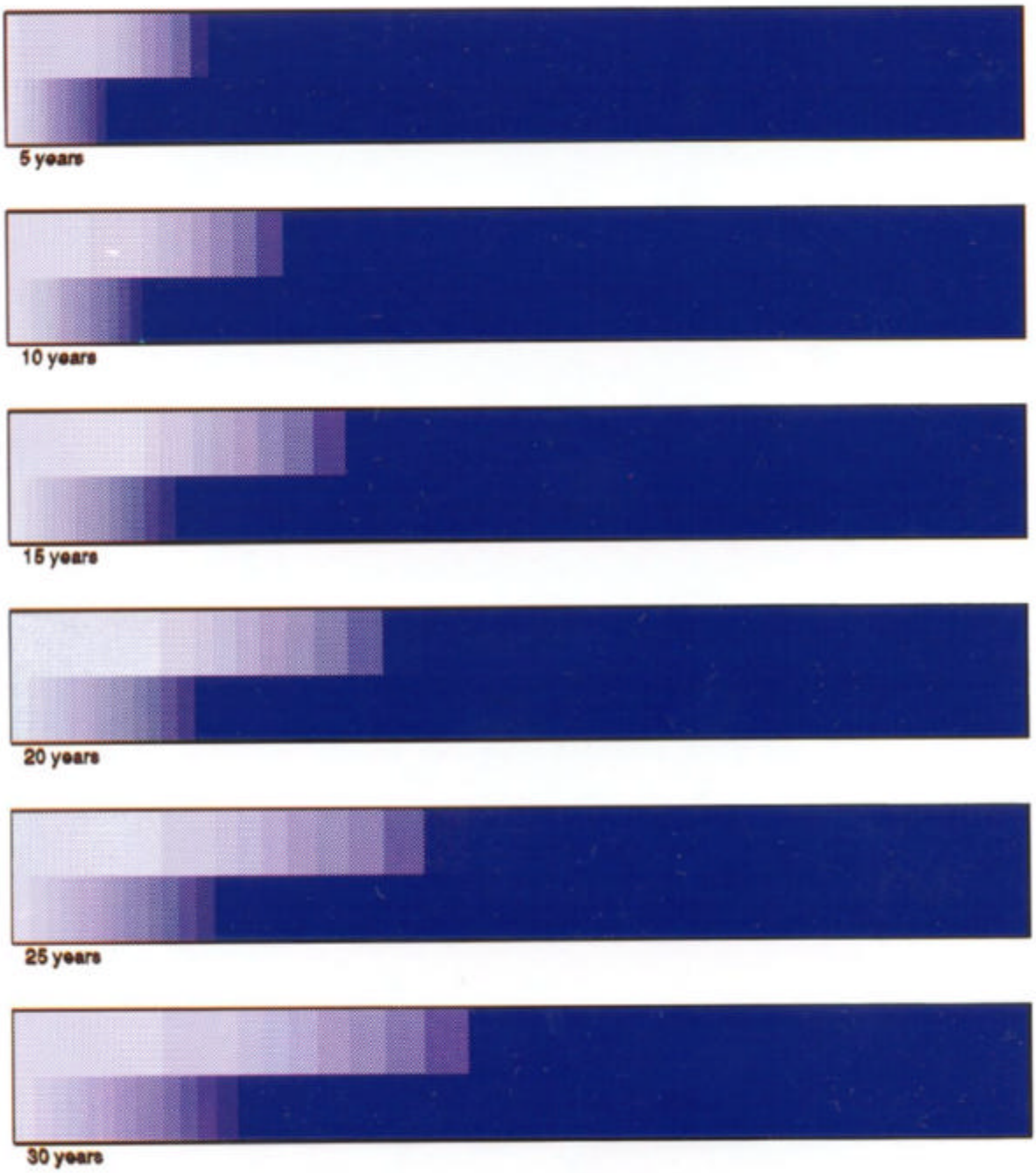
Carbon Dioxide Saturation (Run CO2_84)



Vertical scale factor = 70.000
Field dimensions: 6999. (horiz.), 13.00 (vert.)

0.0000E+00 1.000

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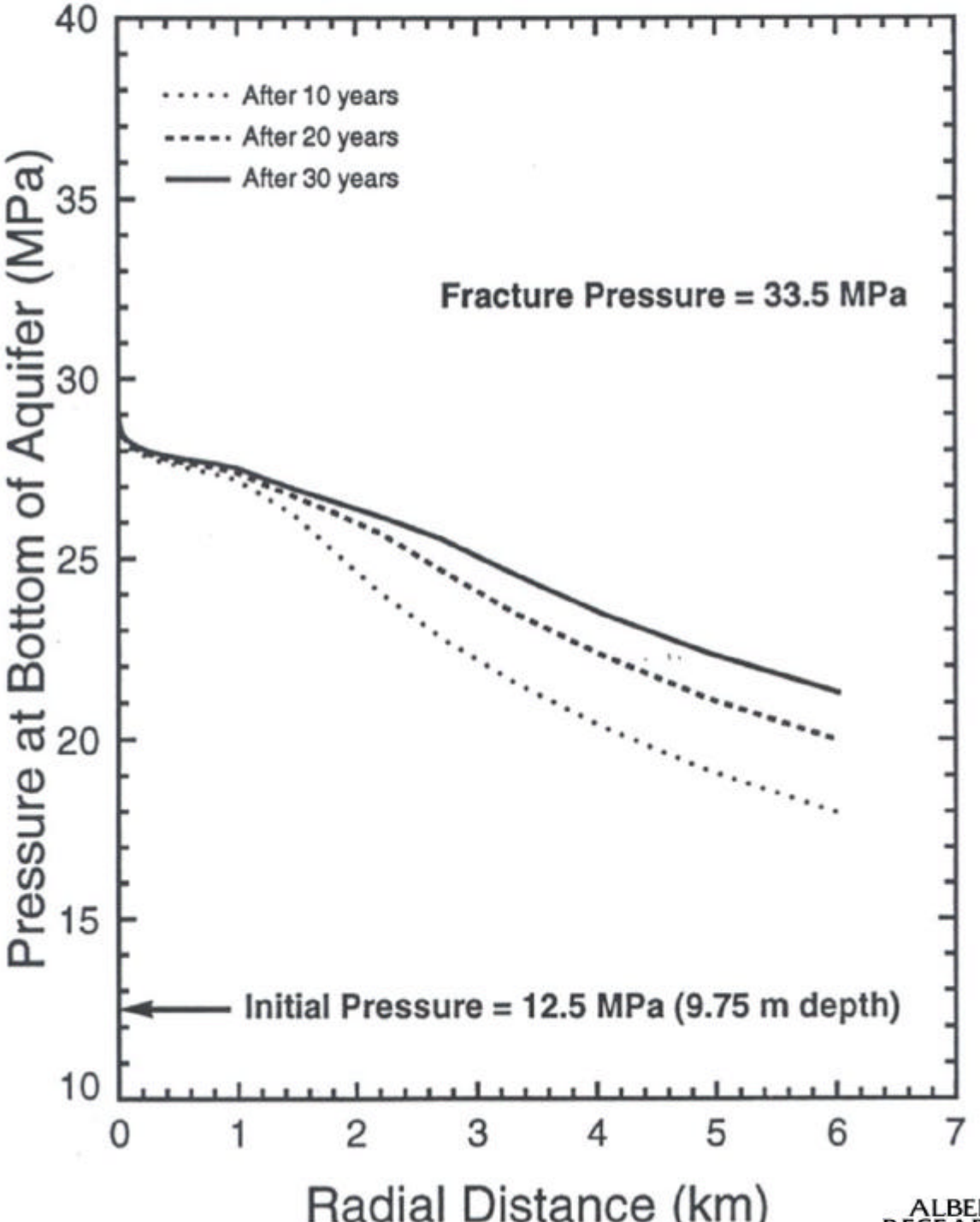
Glauconitic Sandstone Aquifer

NUMERICAL RUN (CO2_84)

Aquifer Porosity = 0.12 Aquifer Permeability = 100/30 md (horizontal)
Injection Pressure = 30.12 MPa Radius of 100 md zone = 1.04 km



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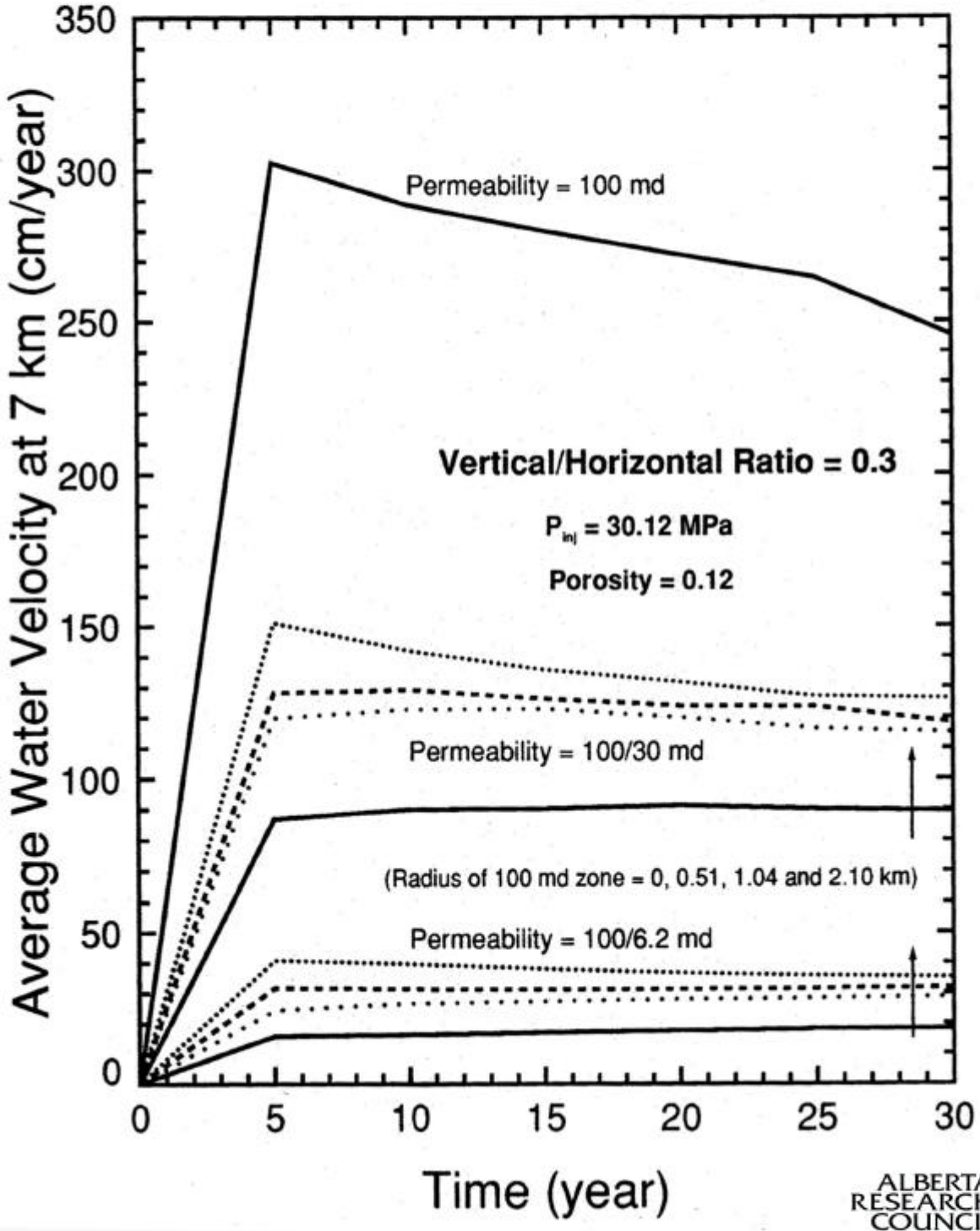
EFFECT OF PERMEABILITY DISTRIBUTION ON AVERAGE WATER VELOCITY AT OUTFLOW BOUNDARY

Heterogenous Glauconitic Sandstone Aquifer

Solid Lines: homogeneous aquifer

Dashed and Dotted Lines: aquifer with 100 md zone



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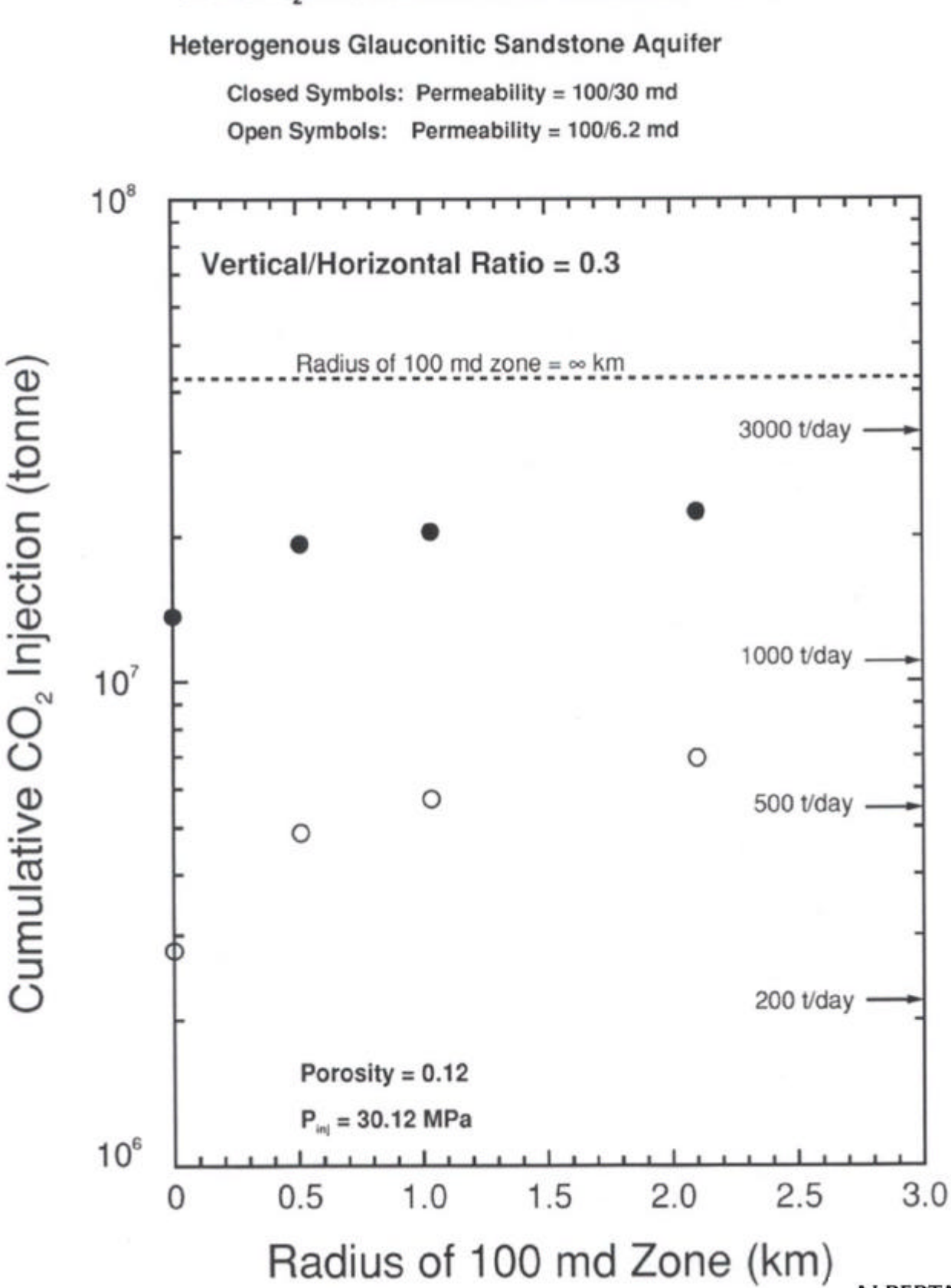
EFFECT OF PERMEABILITY DISTRIBUTION ON CO_2 INJECTION AFTER 30 YEARS



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Aquifer Characteristics

	Glauconitic Sandstone	Nisku
Depth at Injection Site:	1480 m	1860 m
Average Thickness:	13 m	60 m
Slope (dip to southwest):	5 m/km	8.9 m/km
Porosity:	6 - 12%	6 - 12 %
Absolute Permeability:		
Horizontal:	6.2 - 100 md	6.2 - 400 md
Vertical Anisotropy:	0.3	0.27
Average Temperature:	50°C	60°C
Pressure at Top of Aquifer:	12.4 MPa	16.0 MPa
Fracture Pressure:	33.5 MPa	42.1 MPa

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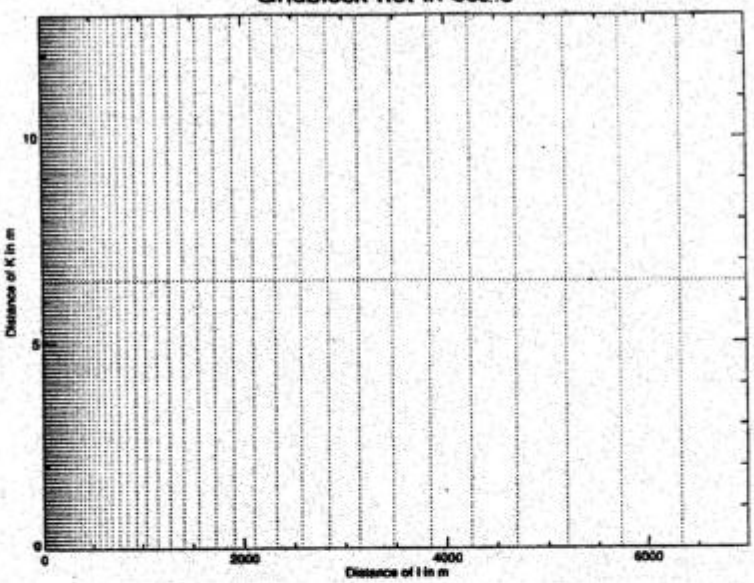
Fluid Properties

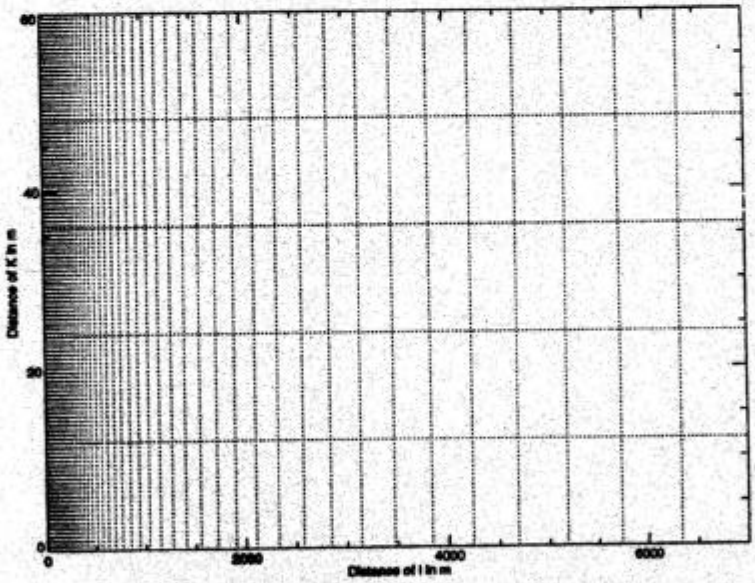
	Glauconitic Sandstone	Nisku
Average Temperature:	50°C	60°C
Aqueous Phase		
Salinity:	40,000 mg/l	190,000 mg/l
Density:	1030 kg/m^3	1155.5 kg/m^3
Viscosity:	0.617 mPa-s	0.840 mPa-s
Carbon Dioxide Phase		
Density:	696 kg/m^3 @12.446 MPa	713 kg/m^3 @ 16 MPa
Compressibility:	1.22×10^{-5} /kPa	8.92×10^{-6} /kPa
Viscosity:	0.068 mPa-s @ 20 MPa	0.081 mPa-s @ 30 MPa
CO_2-Water Dispersion Coeff.:	3.074×10^{-4} m^2/d	3.707×10^{-4} m^2/d
CO_2-Water K-Value:	0.0603 @ 20 MPa	0.0760 @ 30 MPa

2-D Radial Grid Pattern

Gridblock not in scale



(a) Glauconitic Sandstone aquifer (66 × 1 × 2)



(b) Nisku Carbonate aquifer (66 × 1 × 5)

Exponential stretch in radial direction:

$$R_i = 9.503\ (e^{0.10005\ i} - 1) \qquad i = 1 \rightarrow 67$$

where: $R_1 = 1$ m and $R_{67} = 7$ km

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Injection Strategies

	Glauconitic Sandstone	Nisku
Single Injection Well		
Well Radius:	3"	3"
Well Completion:	13 m	60 m
Operating Conditions		
Constant Injection Pressure:		
90% Fracture Pressure:	30.12 MPa	37.86 MPa
200% Aquifer pressure:	25.15 MPa	

Numerical Study

	Glauconitic Sandstone	Nisku
Effect of Porosity:	6 and 12%	6 and 12 %
Effect of Permeability:		
Horizontal Direction:	6.2, 30 and 100 md	6.2, 30, 100 and 400 md
Vertical Anisotropy:	0.3	0.27
Effect of Aquifer Heterogeneity:		
Near Well:	100 md	100 and 400 md
Far from Well:	6.2 and 30 md	6.2 and 30 md

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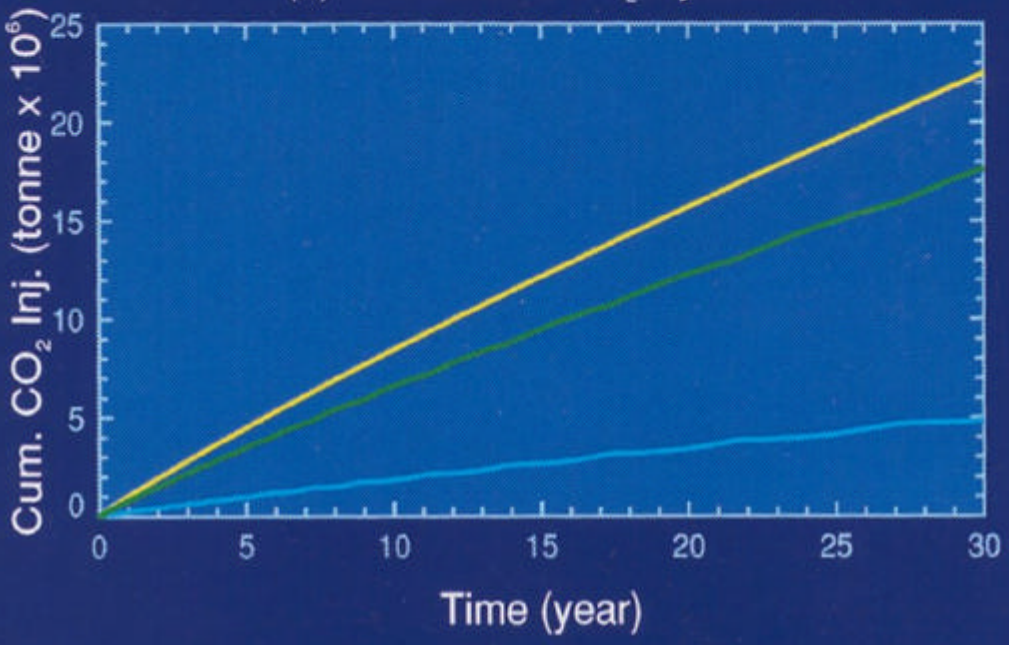
GLAUCONITIC SANDSTONE AQUIFER

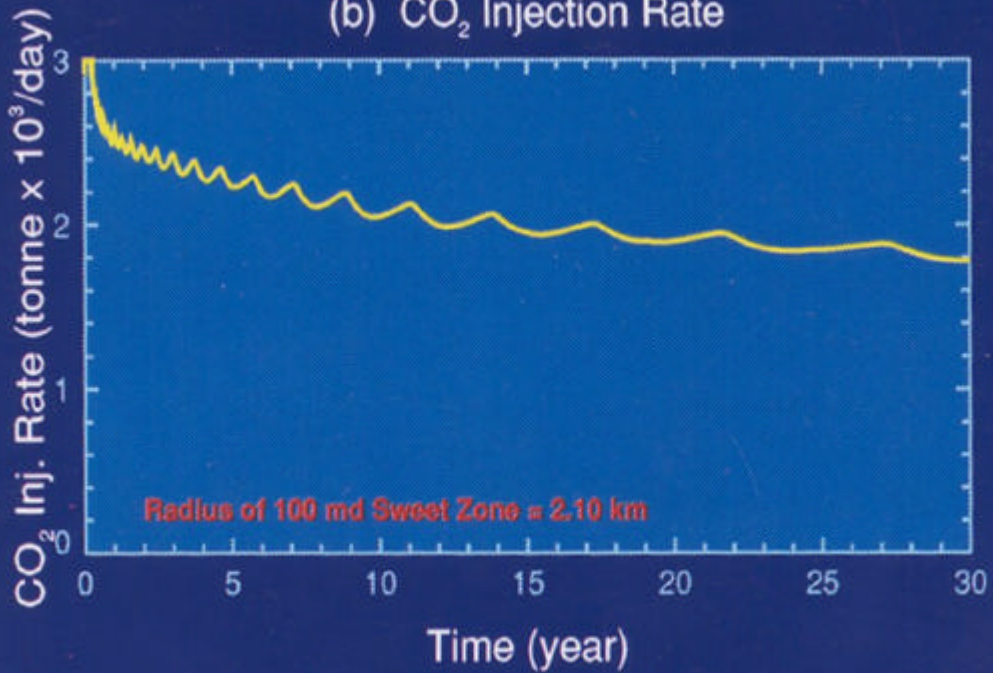
NUMERICAL RUN (CO2_85)

$\phi = 0.12$, $k_h = 100/30$ md, $P_{inj} = 30.12$ MPa

(a) Cumulative CO_2 Injection



(b) CO_2 Injection Rate



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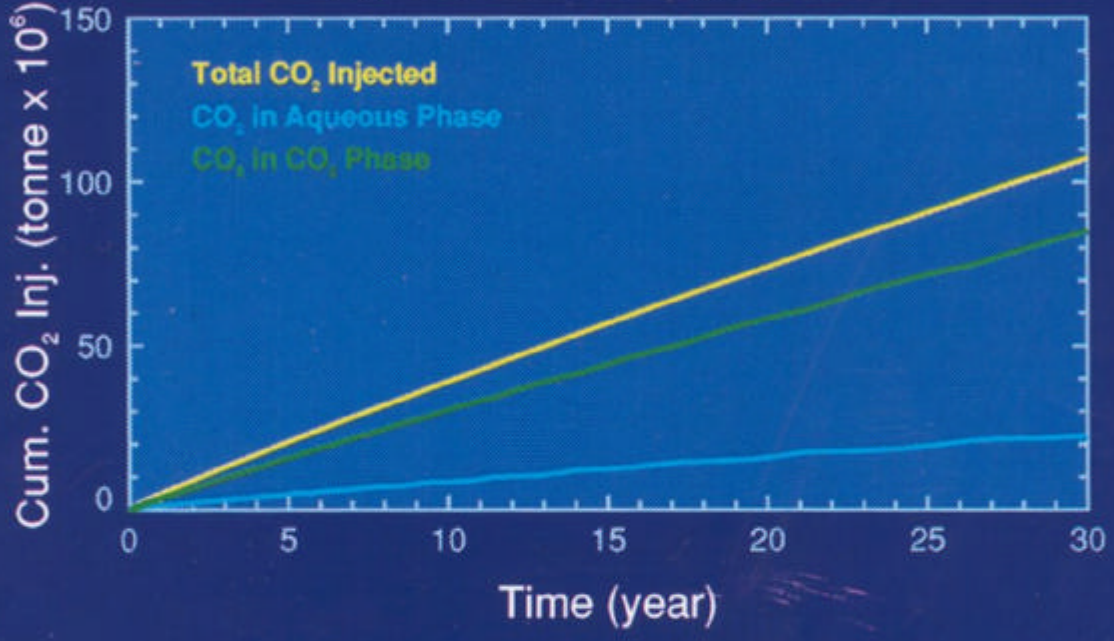
NISKU CARBONATE AQUIFER

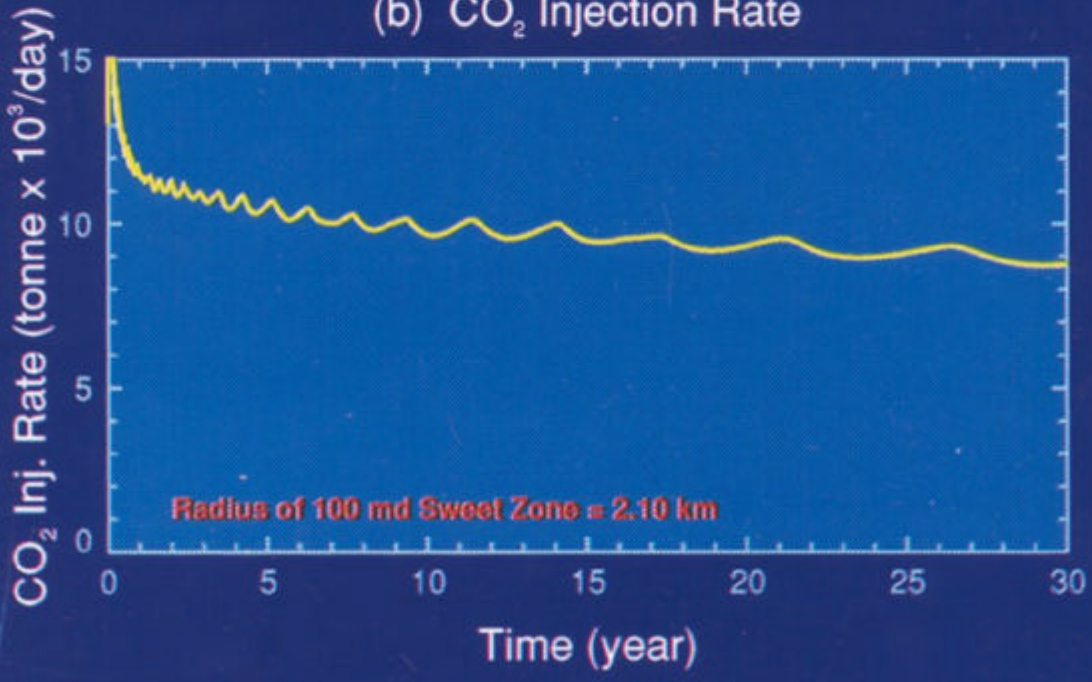
NUMERICAL RUN (CO2_115)

$\phi = 0.12$, $k_h = 100/30$ md, $P_{inj} = 37.86$ MPa

(a) Cumulative CO_2 Injection



(b) CO_2 Injection Rate



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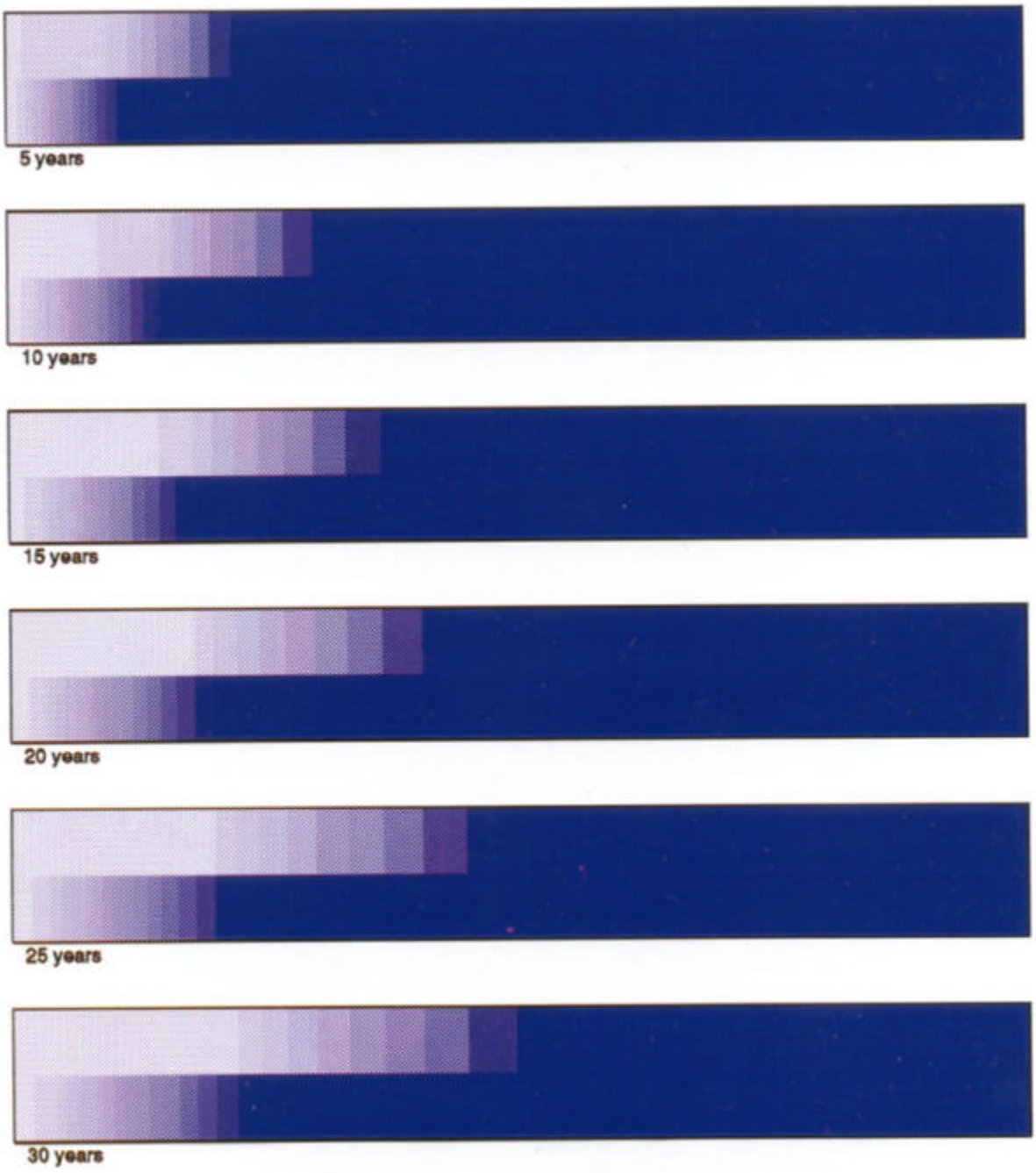
Carbon Dioxide Saturation (Run CO2_85)



Vertical scale factor = 70.000
Field dimensions: 6999. (horiz.), 13.00 (vert.)

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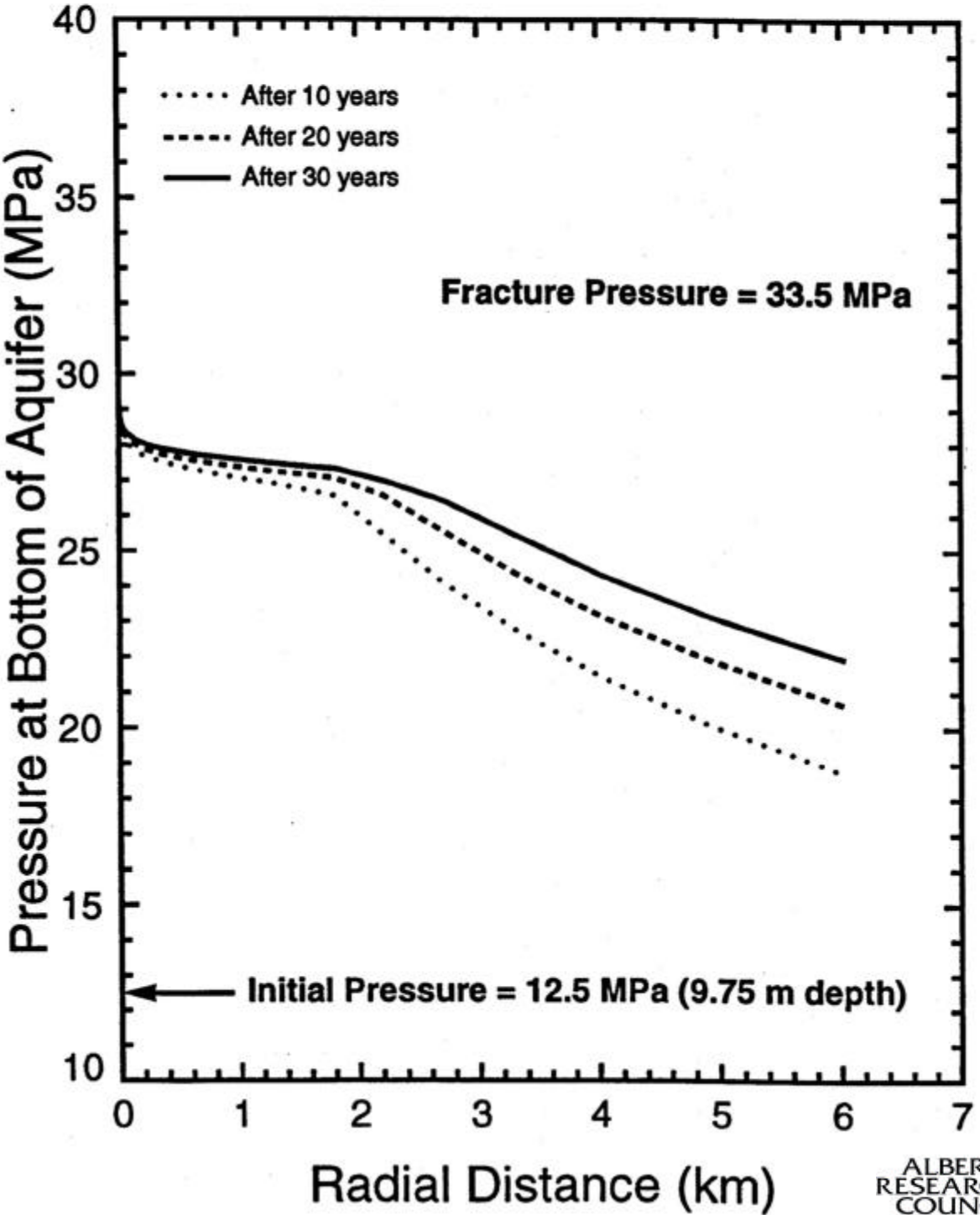
Glauconitic Sandstone Aquifer

NUMERICAL RUN (CO2_85)

Aquifer Porosity = 0.12 Aquifer Permeability = 100/30 md (horizontal)
Injection Pressure = 30.12 MPa Radius of 100 md zone = 2.10 km



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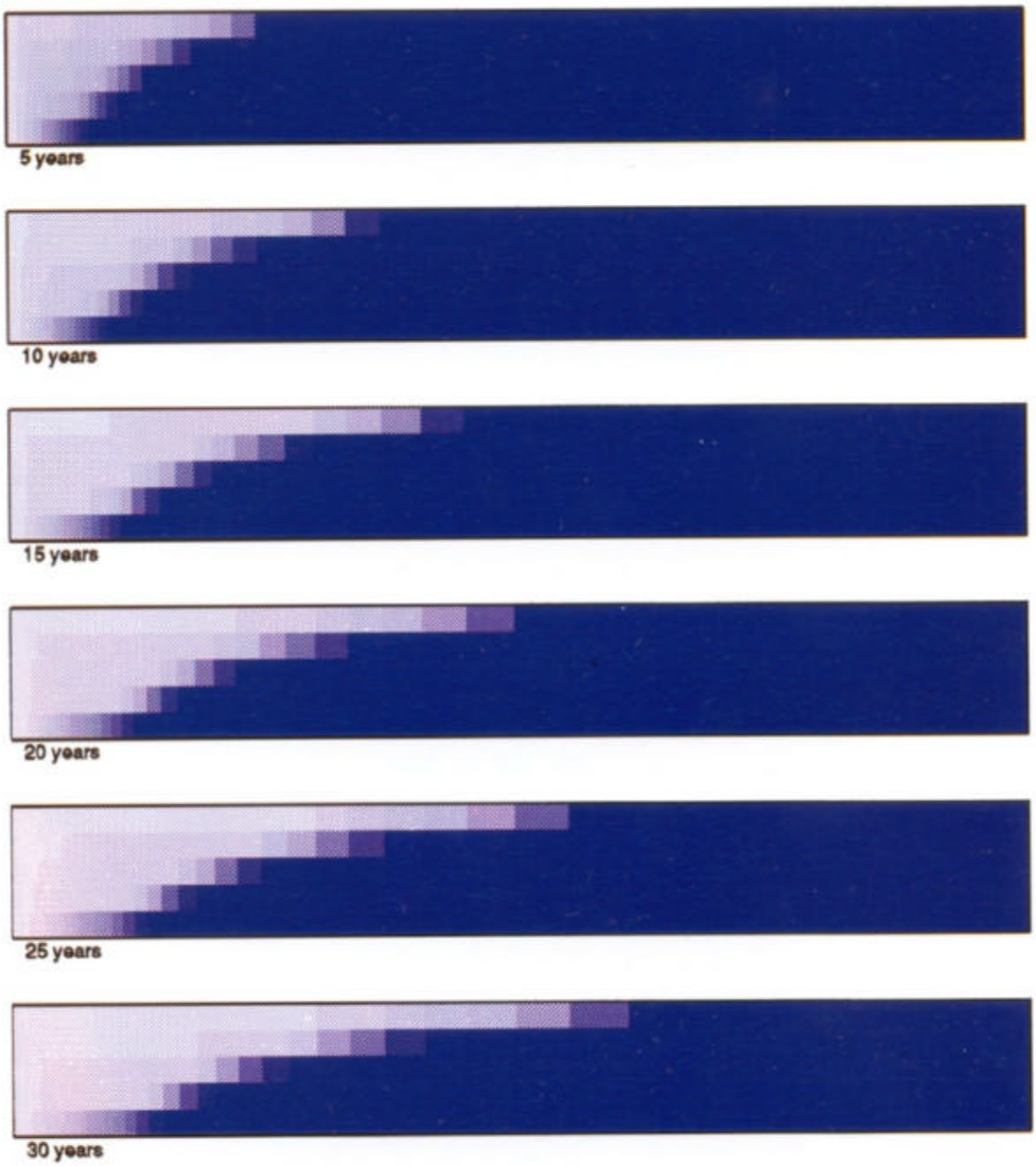
Carbon Dioxide Saturation (Run CO2_115)



Vertical scale factor = 15.000
Field dimensions: 6999. (horiz.), 60.00 (vert.)

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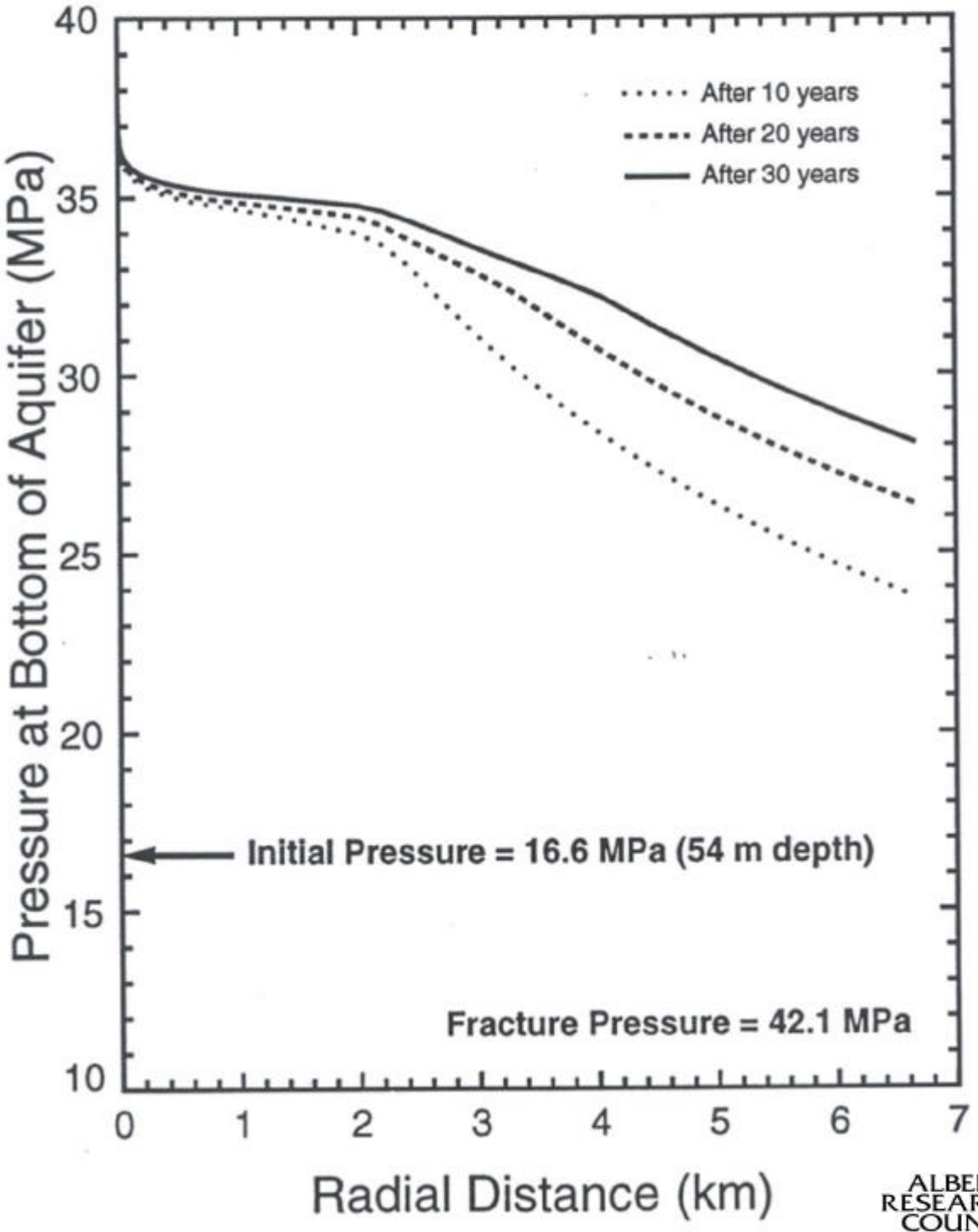
Nisku Carbonate Aquifer

NUMERICAL RUN (CO2_115)

Aquifer Porosity = 0.12 Aquifer Permeability = 100/30 md (horizontal)
Injection Pressure = 37.86 MPa Radius of 100 md zone = 2.10 km



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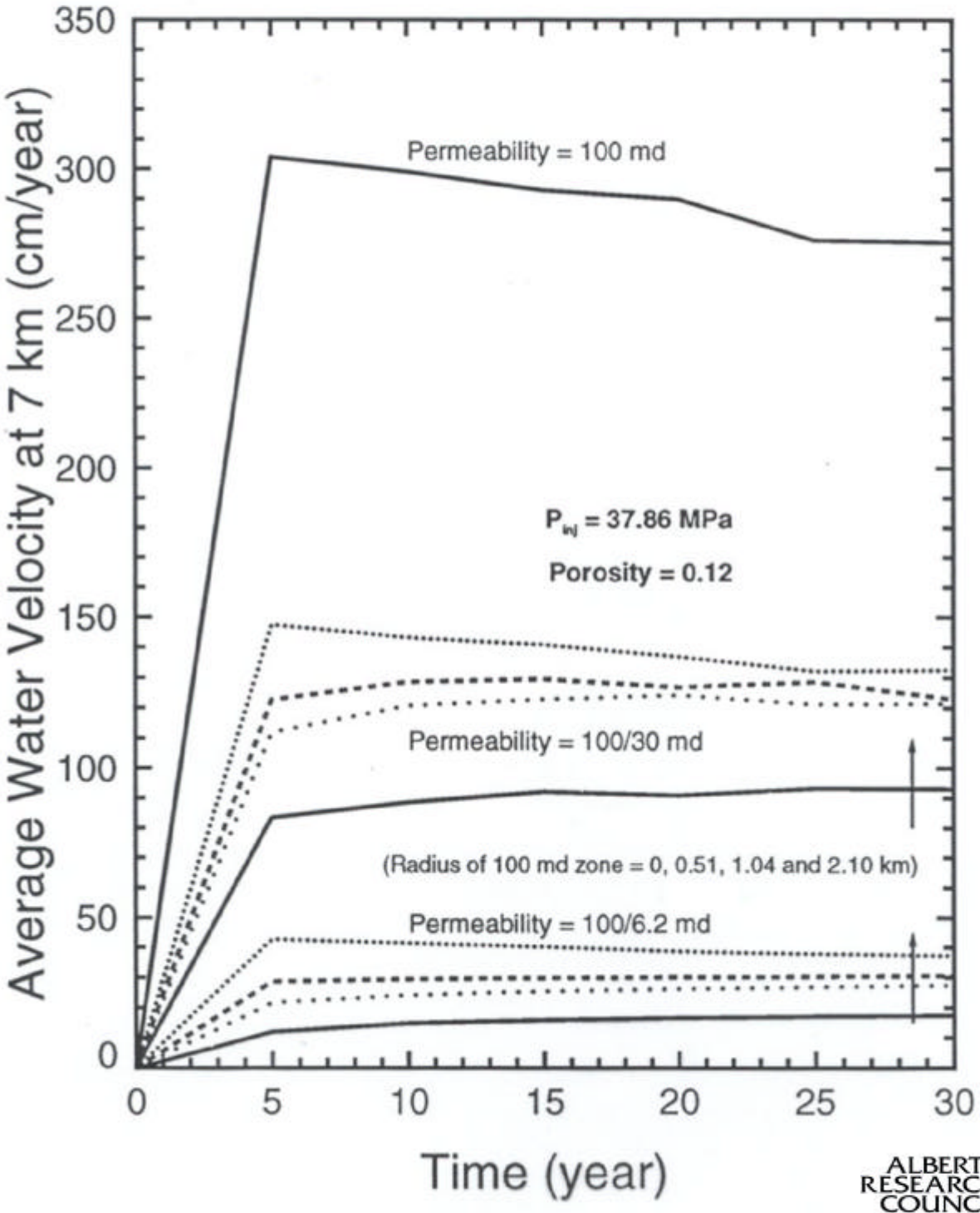
Nisku Carbonate Aquifer

EFFECT OF PERMEABILITY DISTRIBUTION

Solid Lines: homogeneous aquifer

Dashed and Dotted Lines: aquifer with 100 md zone



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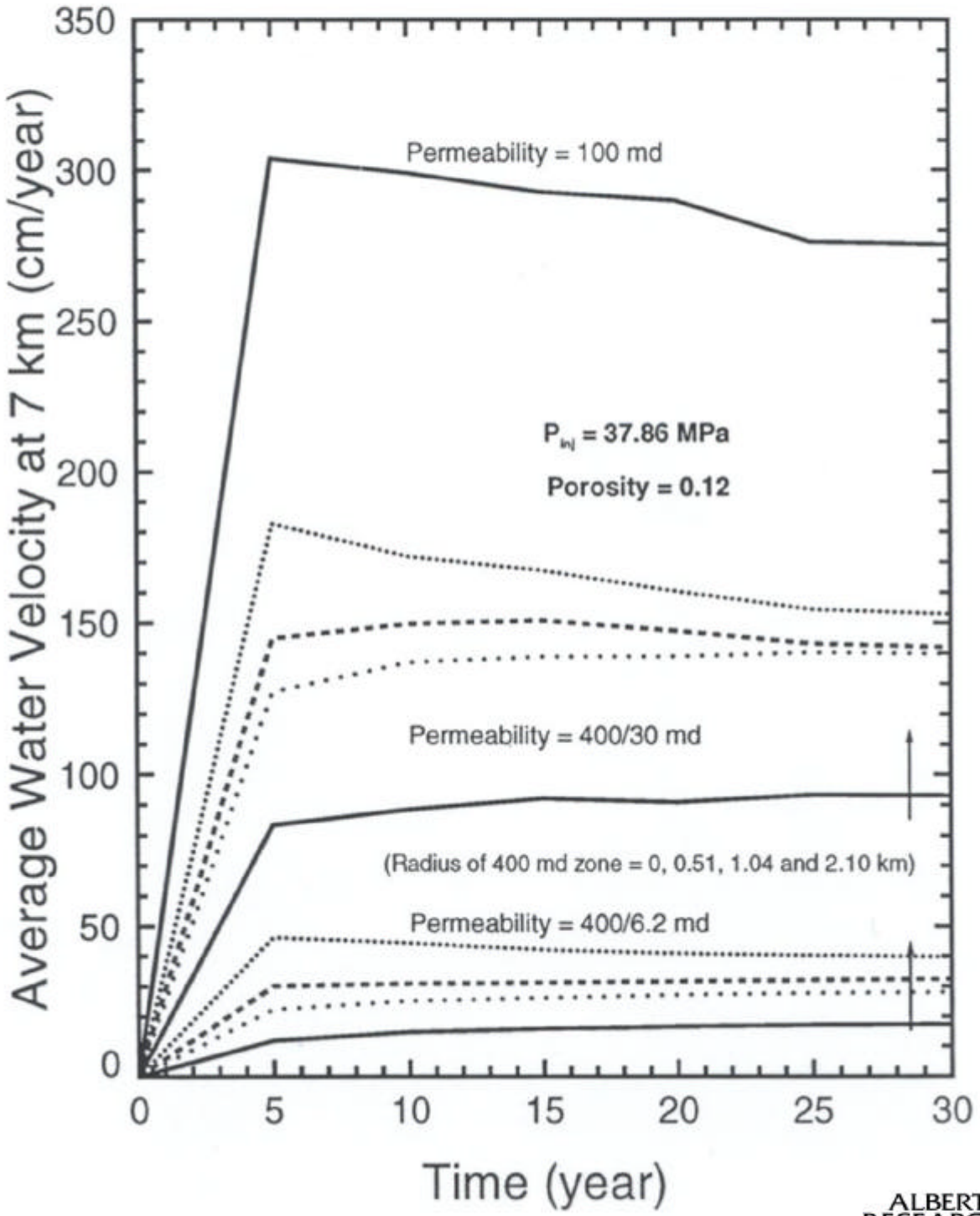
Nisku Carbonate Aquifer

EFFECT OF PERMEABILITY DISTRIBUTION

Solid Lines: homogeneous aquifer

Dashed and Dotted Lines: aquifer with 400 md zone



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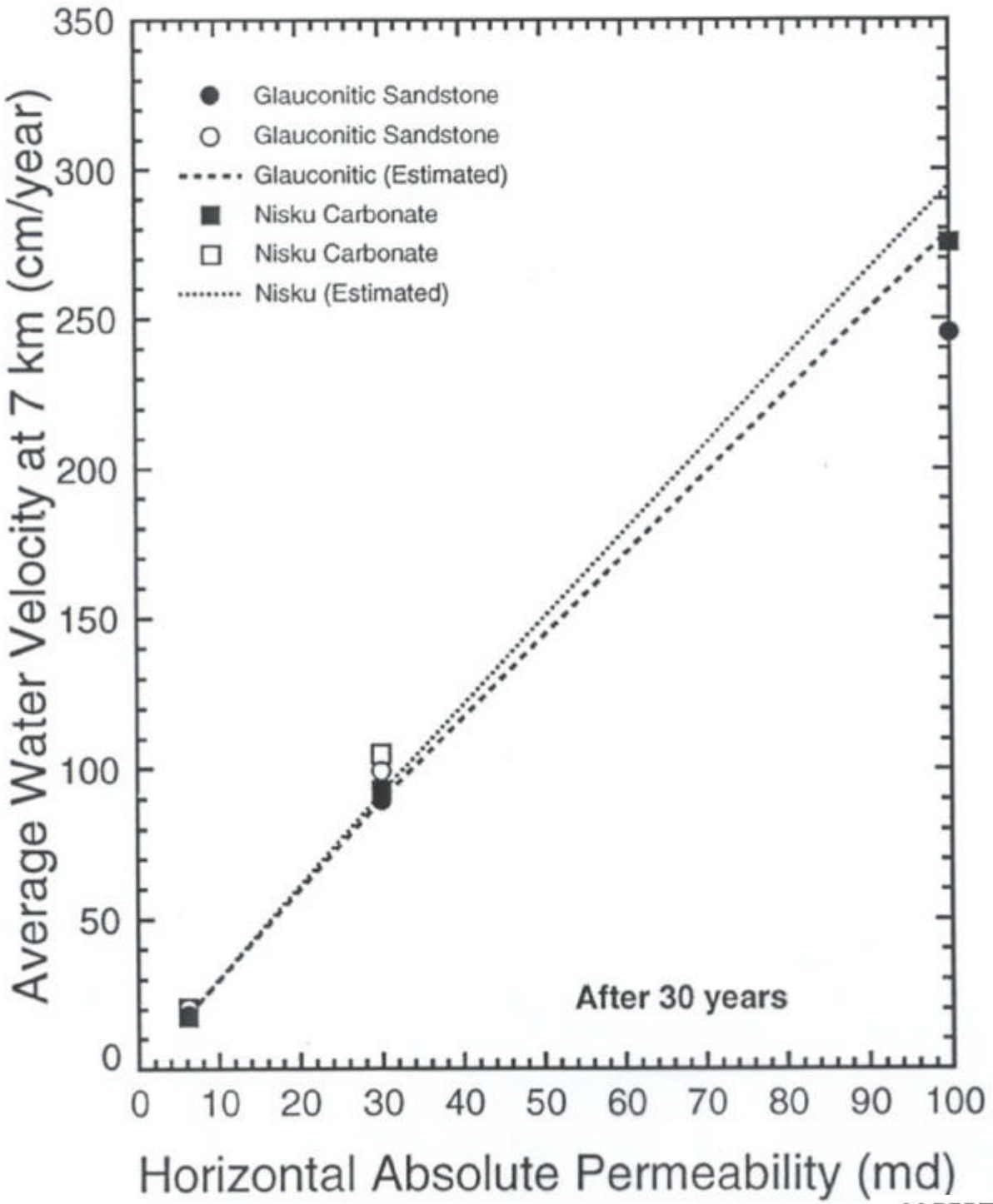
Aquifers in the Alberta Sedimentary Basin



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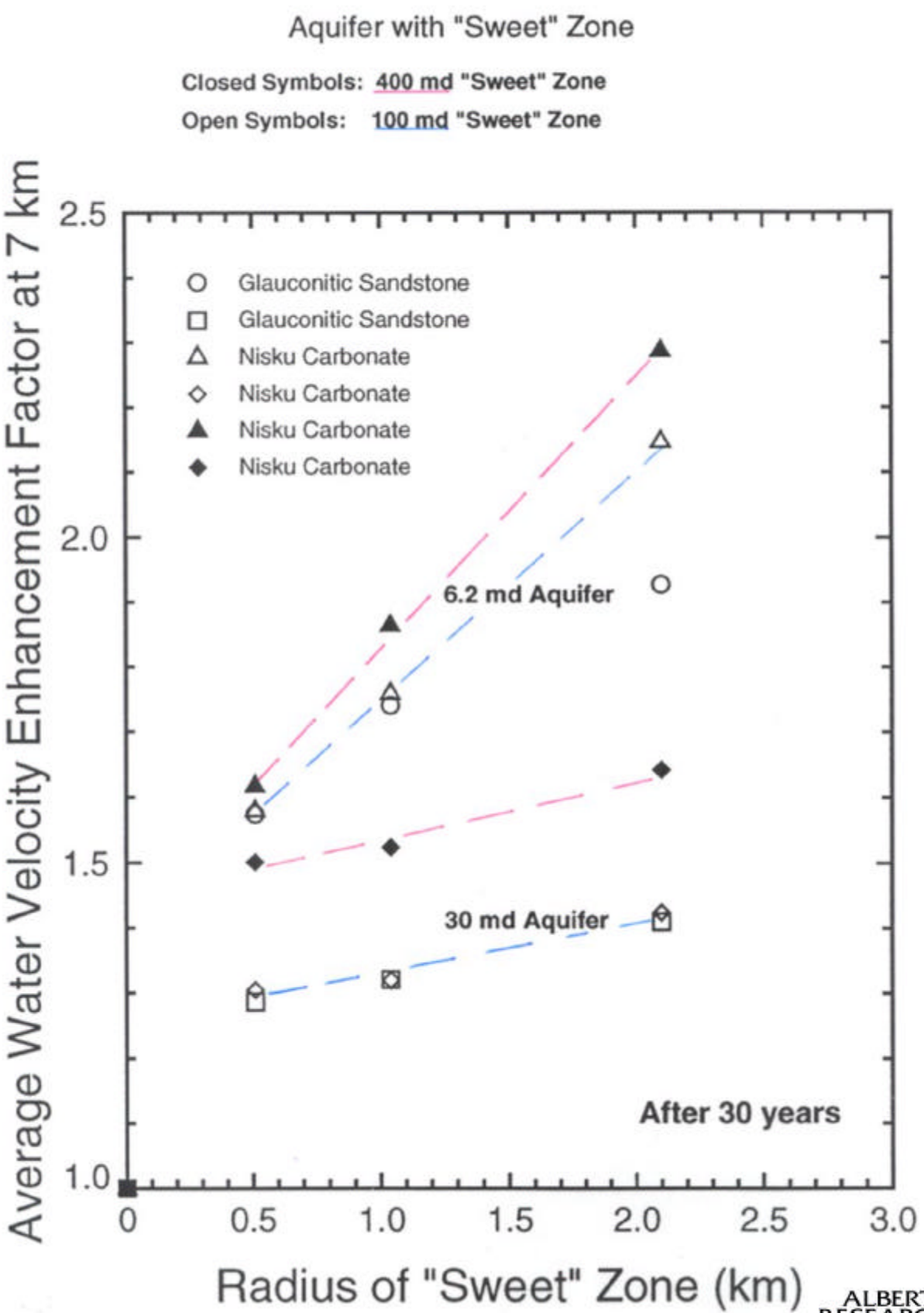
Aquifers in the Alberta Sedimentary Basin



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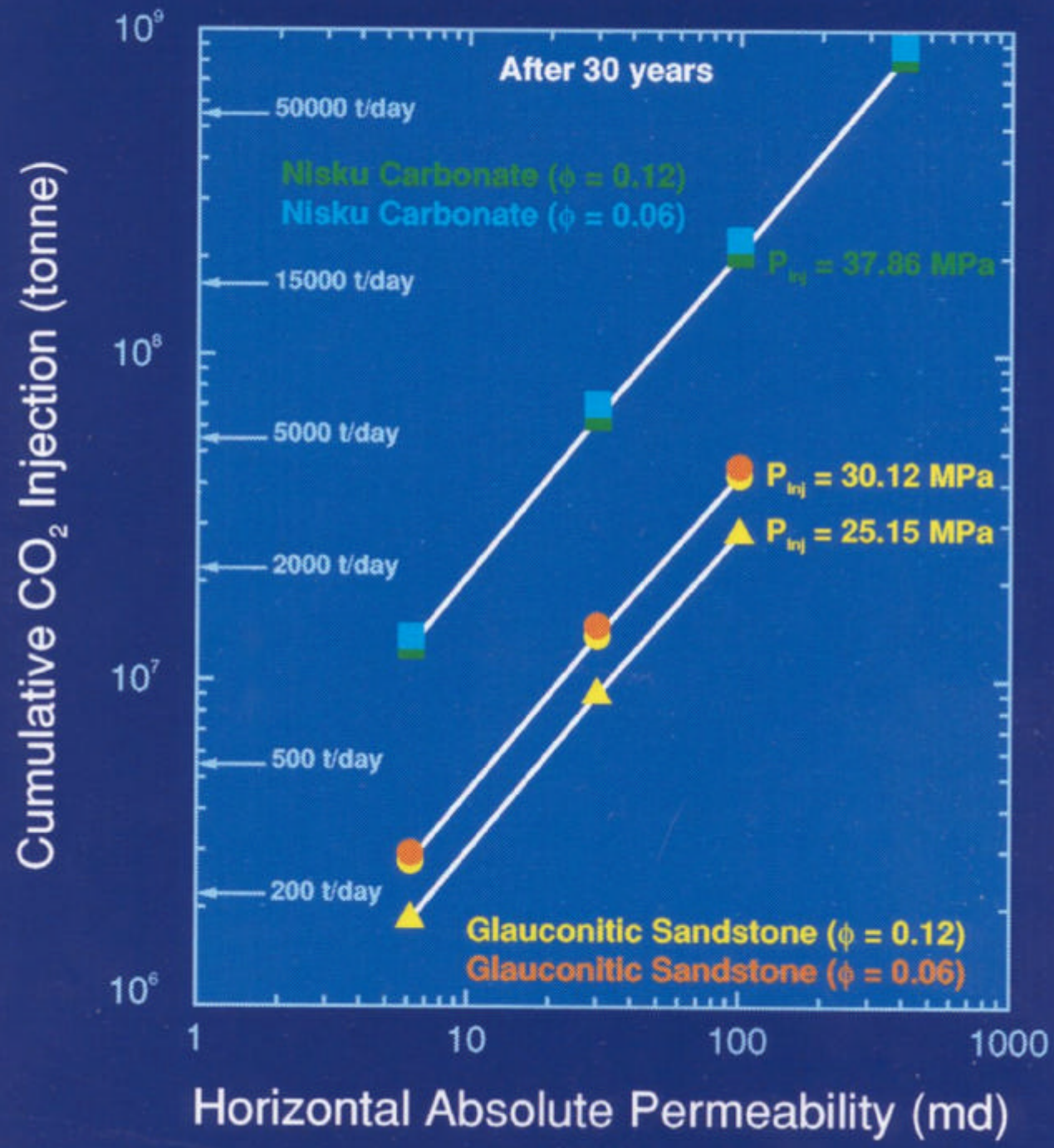
Aquifers in the Alberta Sedimentary Basin

EFFECT OF PERMEABILITY (HOMOGENEOUS AQUIFERS)



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Radial Flow Well Model

Simple steady state, radial outflow well model:

$$q_{co2} = I \times \rho_{co2} \times (P_{inj} - P_{aq})$$

The injectivity well index is: $I = (k_r / \mu_{co2}) \times I'$, where

$$I' = 2 \pi h (k_h \times k_v)^{0.5} f / \ln (r_e / r_w)$$

f :	injector completion factor
h :	thickness of aquifer, [m]
k_h :	absolute permeability in horizontal direction around injector, [m^2]
k_v :	absolute permeability in vertical direction around injector, [m^2]
k_r :	relative permeability of CO_2 ($k_r = 1$ for 100% CO_2 injection)
P_{aq} :	initial aquifer pressure at average depth, [kg / m-s^2]
P_{inj} :	injection pressure, [kg / m-s^2]
q_{co2} :	average mass injection rate of CO_2, [kg / s]
r_e :	distance from centre of wellbore at P_{inj} to point where regional aquifer pressure of P_{aq} is reached, [m]
r_w :	injector radius, [m]
ρ_{co2} :	density of CO_2, [kg / m^3]
μ_{co2} :	viscosity of CO_2, [kg / m-s]

CO_2 Injectivity

Rearranging well equation and choosing $f = 1$:

$$q_{co2} / [\, h \times (P_{inj} - P_{aq}) \,] = C_1 \times [\, (k_h \times k_v)^{0.5}\ k_r \ / \ \mu_{co2} \,]$$

and $C_1 = 5.358 \times 10^{-4}\ \rho_{co2} \ / \ \ln (r_e / r_w)$

where units length, permeability, pressure, injection rate, density and viscosity have been converted to [m], [MPa], [tonne/day], [kg/m^3] and [mPa-s], respectively.

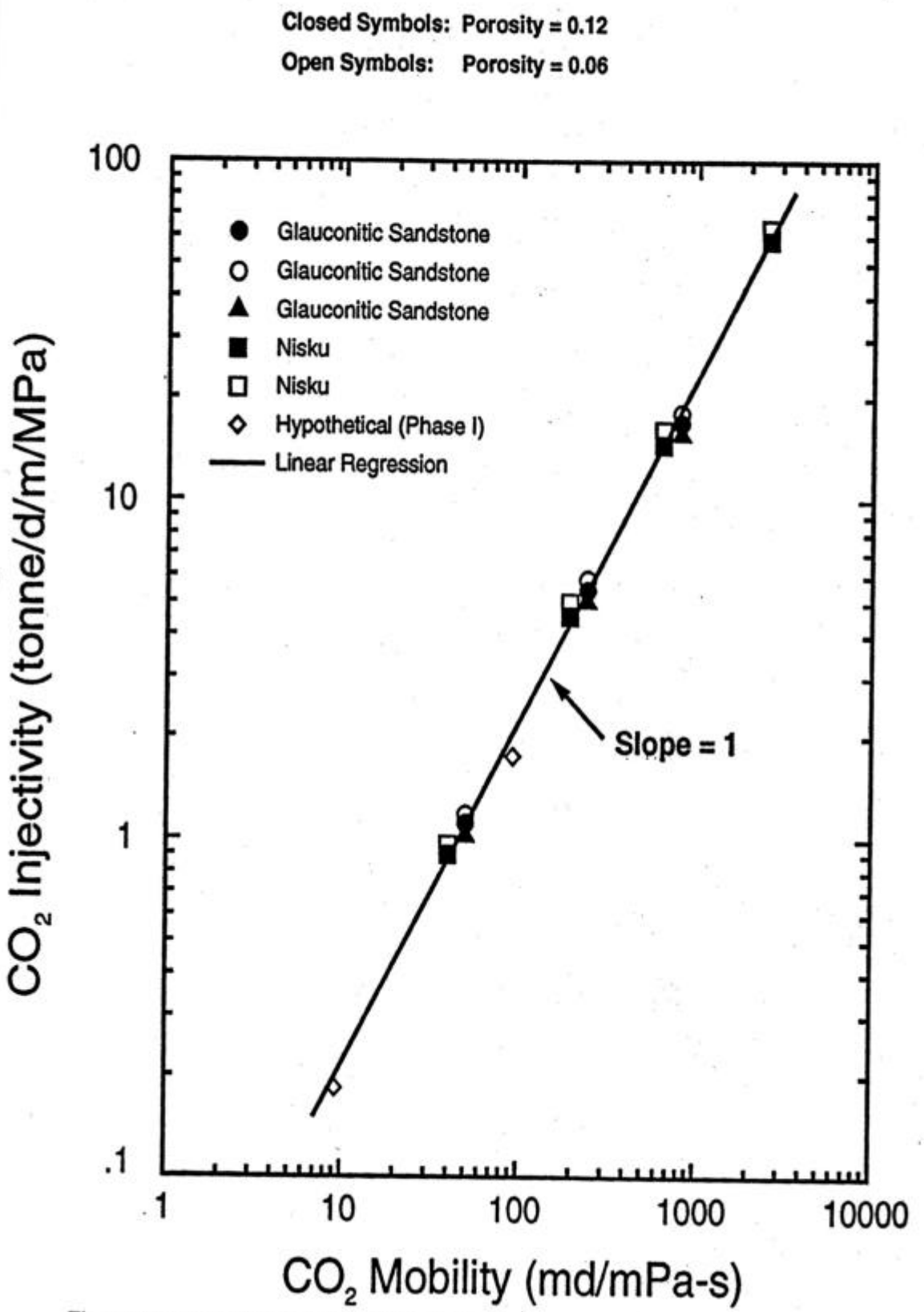
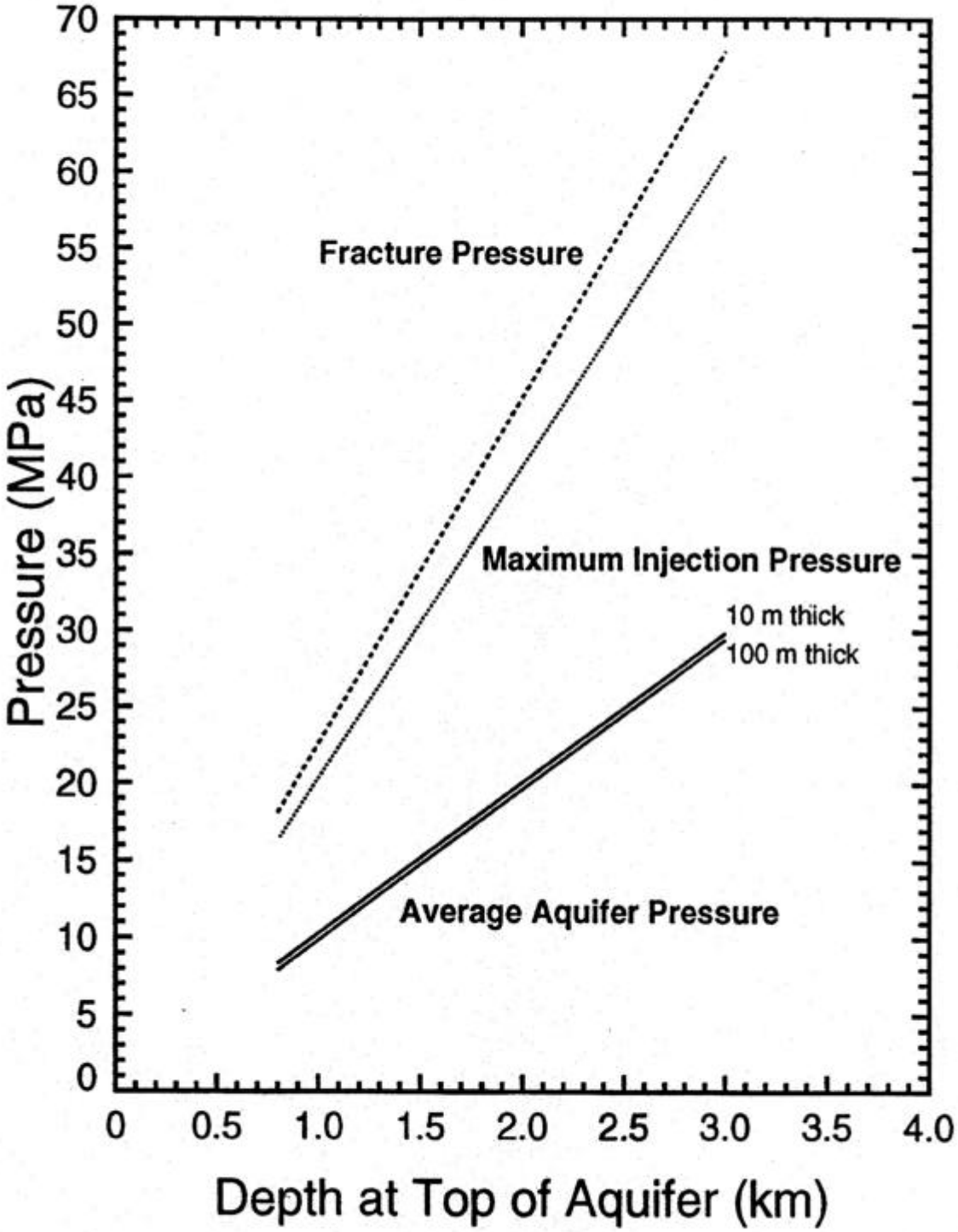


Figure 45: Correlation for CO_2 injectivity for homogeneous aquifers in the Alberta

Estimated CO_2 Injectivity

- Aquifer Depth
- Aquifer Thickness
- Aquifer Absolute Permeabilities
- Aquifer Temperature
  - geothermal gradient
- Initial Aquifer Pressure
  - hydraulic gradient
- Maximum Injection Pressure
  - 90% of fracture pressure
- Viscosity of CO_2



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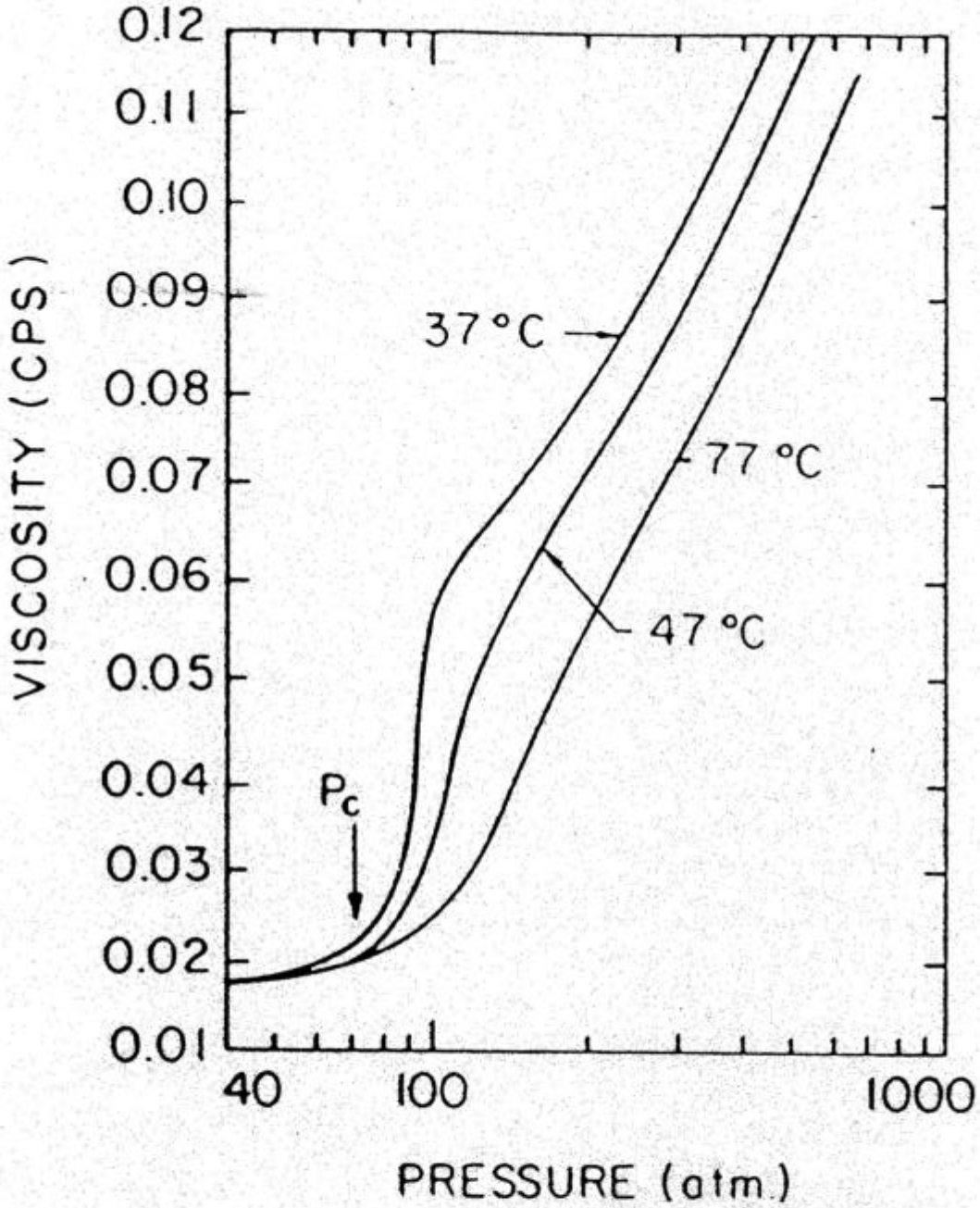

100 atm = 10.13 MPa
1 cp = 1 mPa-s

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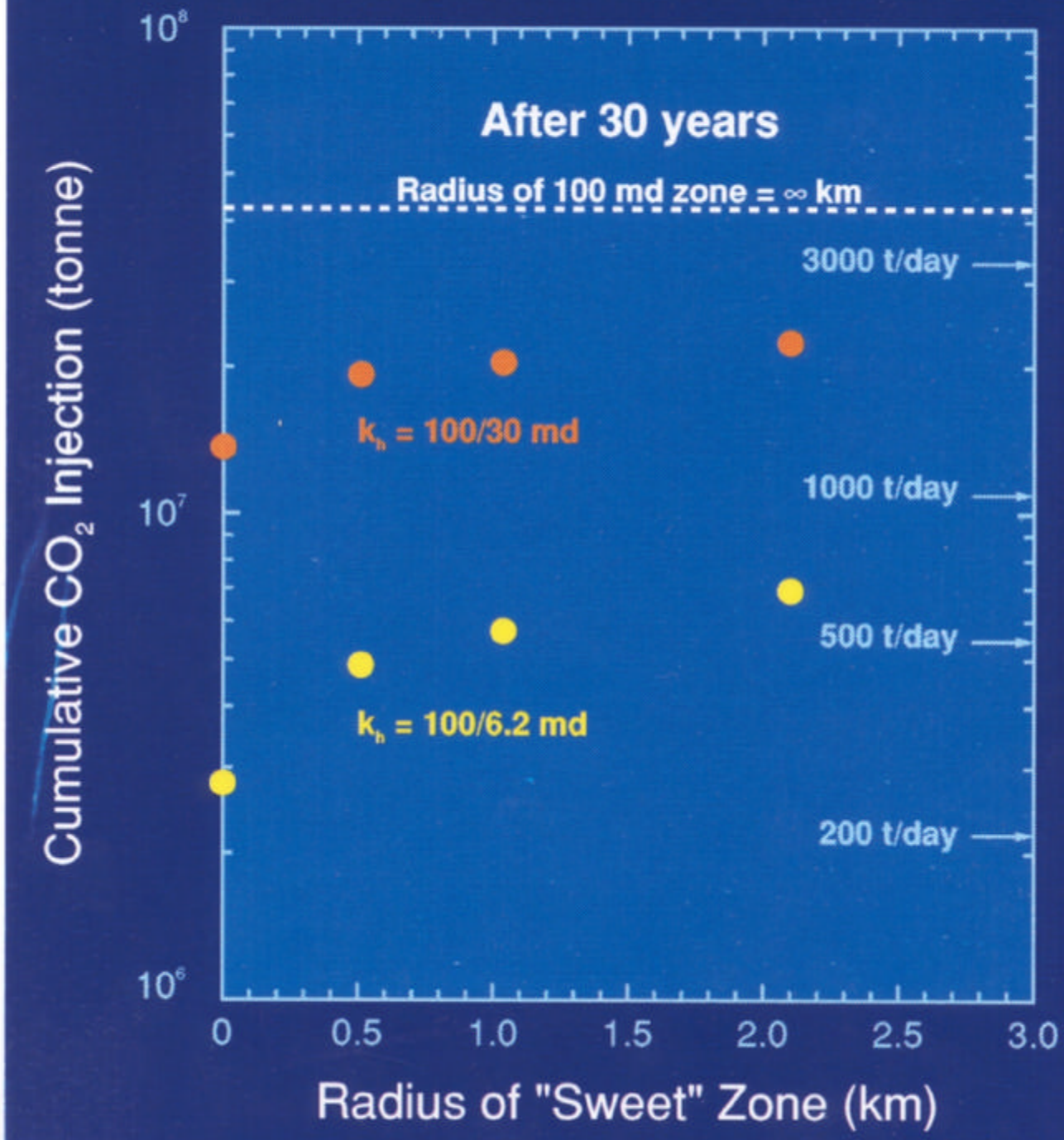
GLAUCONITIC SANDSTONE AQUIFER

AQUIFERS WITH 100 md "SWEET" ZONES

$\phi = 0.12$, $P_{inj} = 30.12$ MPa



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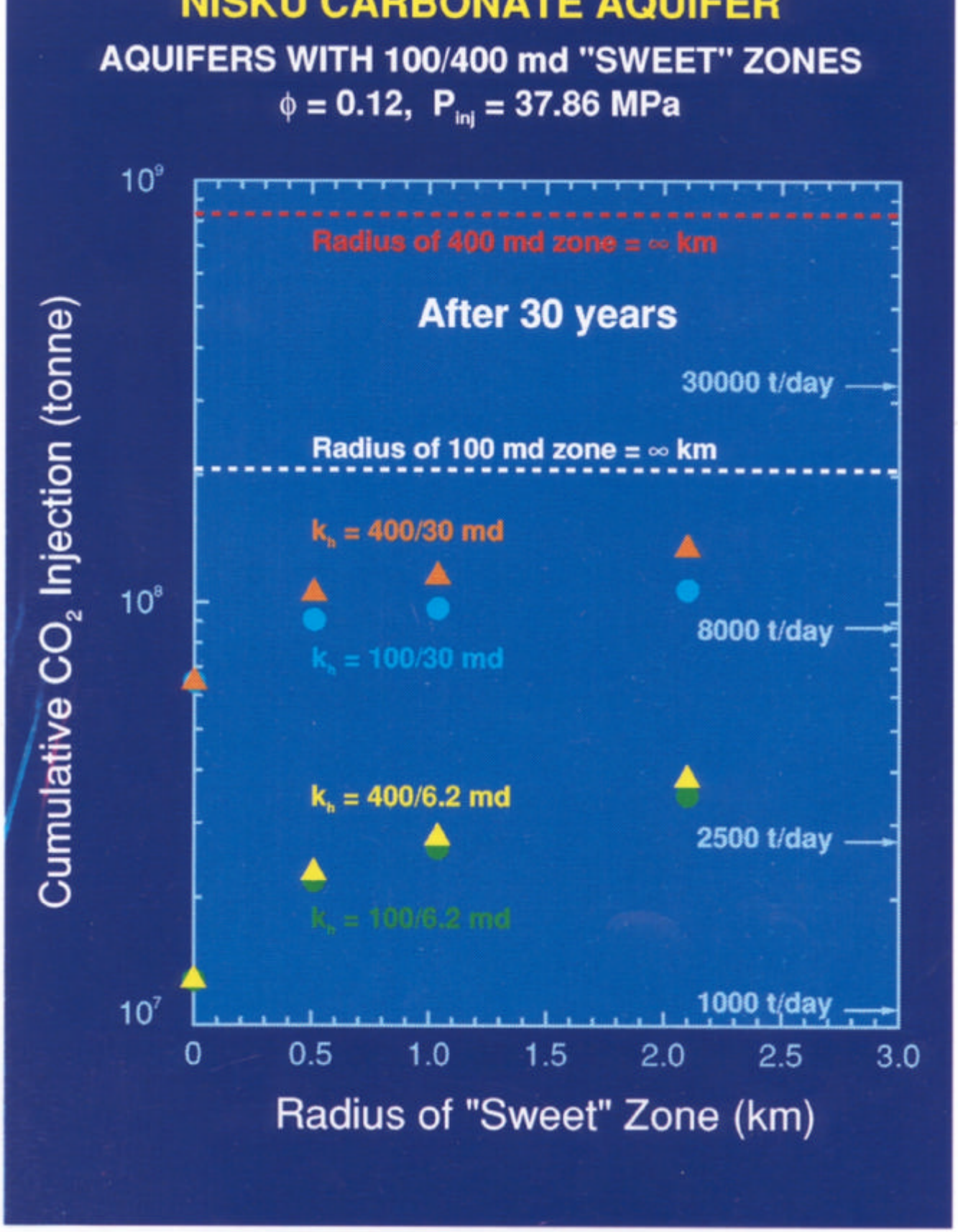

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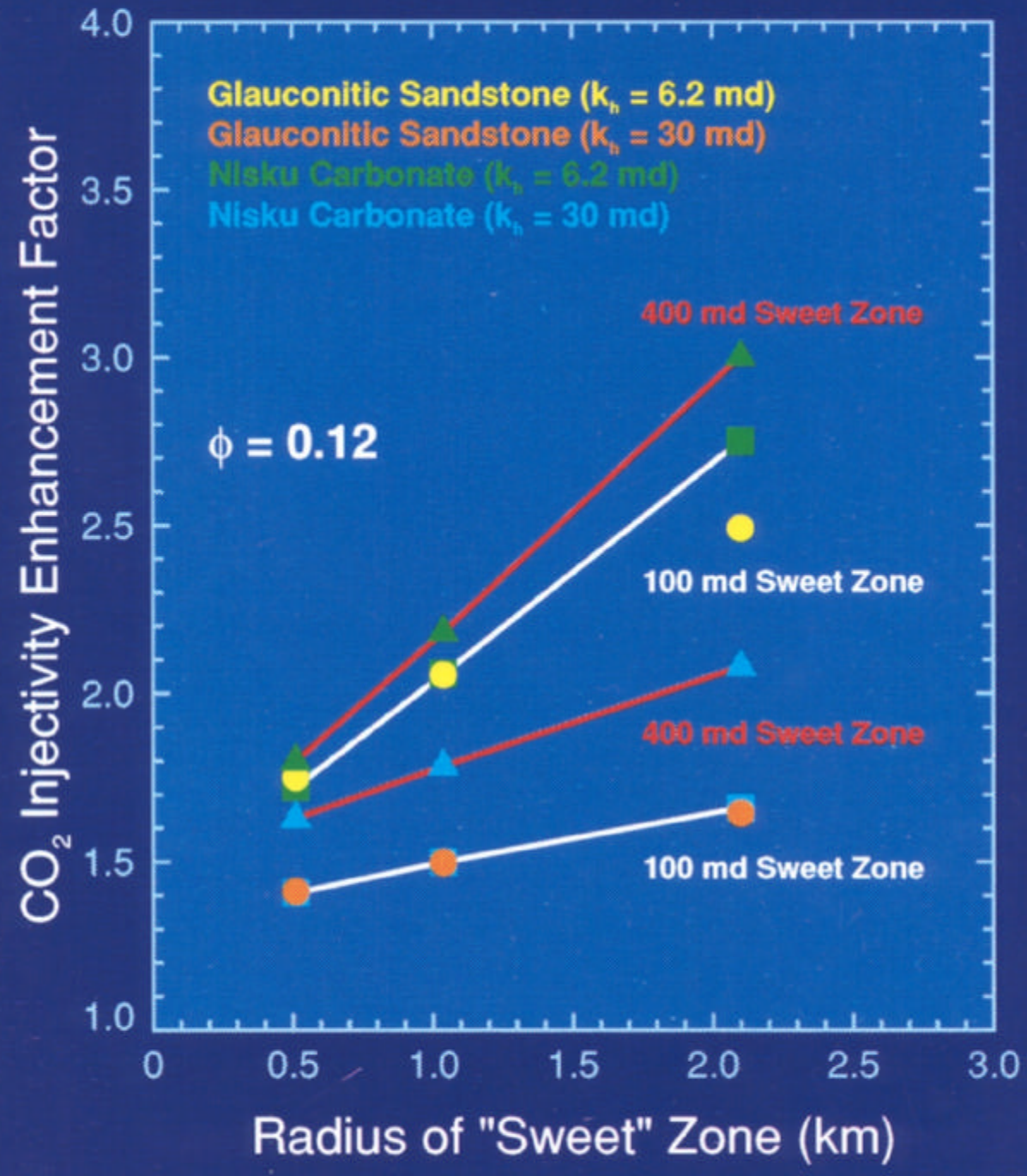
Aquifers in the Alberta Sedimentary Basin

AQUIFER WITH "SWEET" ZONE



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Conclusions

- The most suitable CO_2 disposal aquifers in the Alberta Sedimentary Basin were located at Lake Wabamun, from the point of view of both CO_2 source and aquifer depth. The best disposal aquifers were the relatively thin siliciclastic Glauconitic Sandstone aquifer and the thicker and deeper Nisku carbonate aquifer.

- The site chosen for CO_2 disposal in the Lake Wabamun area was near the southeast corner of Tp. 52, R4 W5 Mer. This is the site of a "sweet" or high permeability zone of 100 md in the Glauconitic Sandstone aquifer.

- The injection strategy is to use one well to access both the Glauconitic Sandstone and the Nisku aquifers.

- For the thin (average 13 m) Glauconitic Sandstone aquifer, CO_2 disposal of 128 to 2,009 t/d/well can be achieved realistically. For the relatively thick (average 60 m) Nisku aquifer, CO_2 disposal of 1,163 to 11,872 t/d/well can be achieved realistically.

- In general, CO_2 will propagate less than 5 km away from the injector after an injection period of 30 years in both the Glauconitic Sandstone and the Nisku aquifers.

- A correlation for the prediction of CO_2 injectivity has been established for homogeneous aquifers, which take into account the aquifer thickness, depth, permeability anisotropy and CO_2 properties at injection conditions.

- A generalized chart can be used to predict the CO_2 injectivity enhancement factor due to the existence of a "sweet" zone in the aquifer. This chart takes into account the regional aquifer permeability and the size and permeability of the "sweet" zone. The existence of this "sweet" zone will allow CO_2 injectivity to improve by a factor of 1.4 to 3.