ITG

Institute of Theoretical Geophysics

University of Cambridge

Clean Power 2010

Friday, June 25 2010

C C S Research

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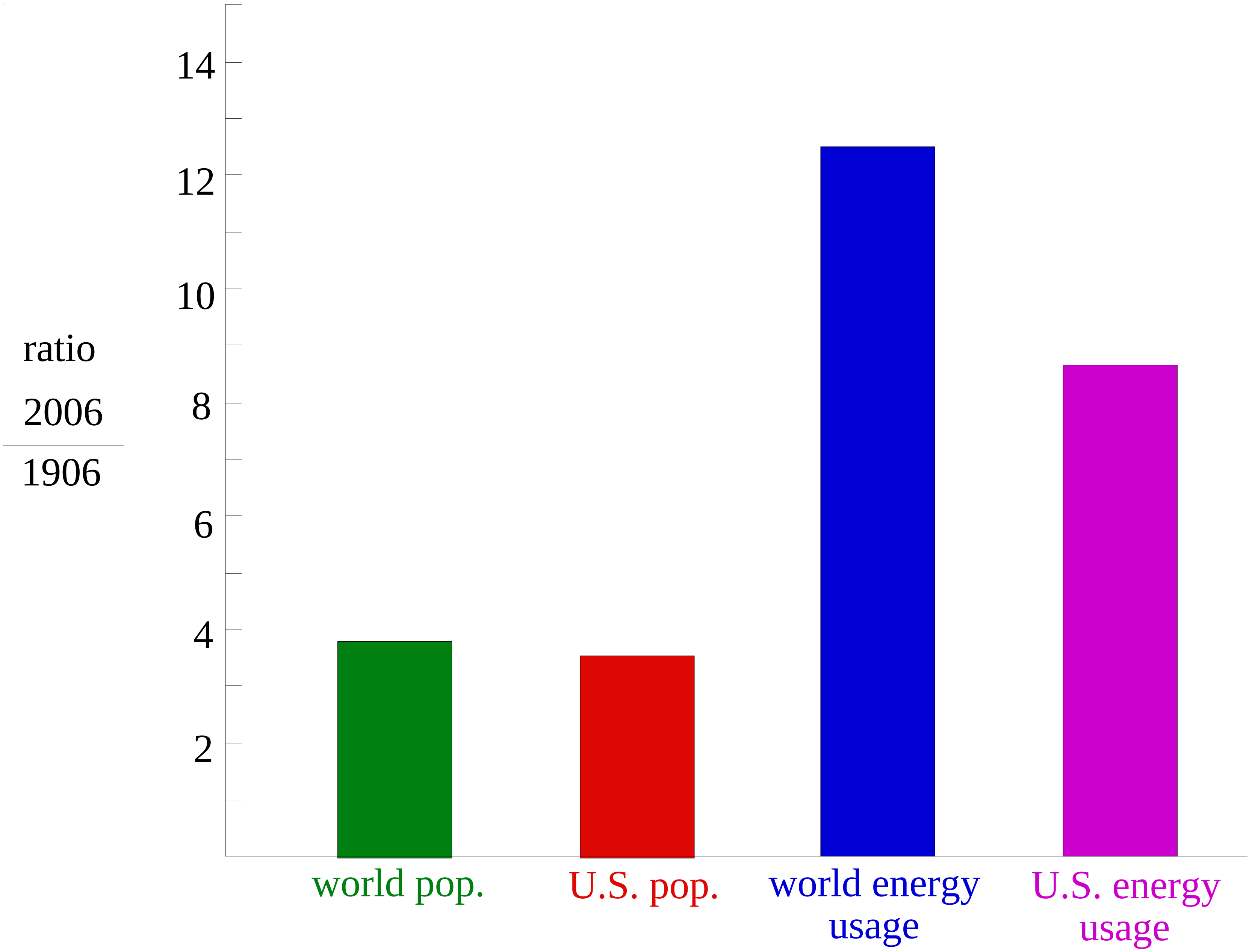
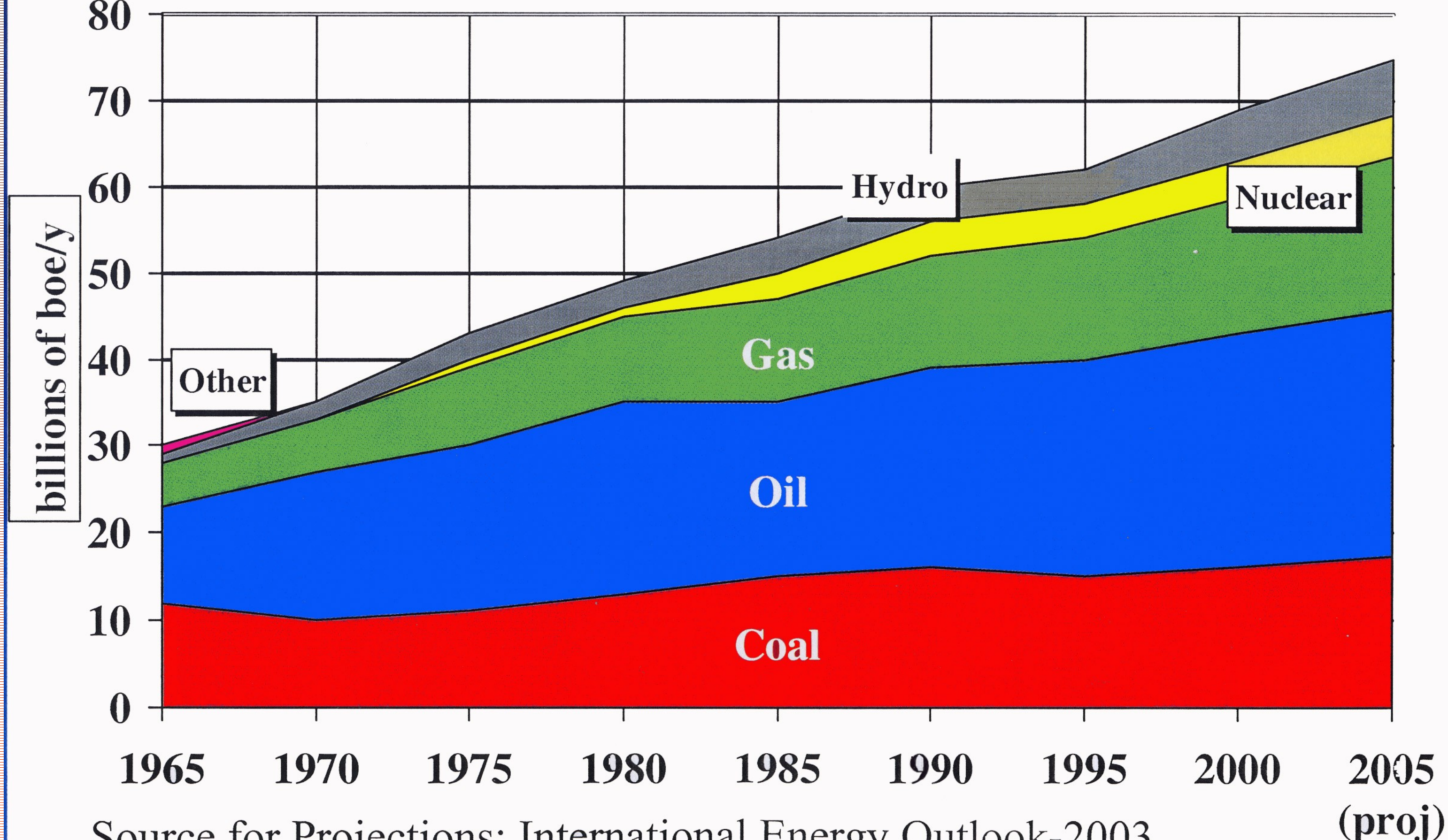
1 Background The current World



ratio
2006
1906
14
12
10
8
6
4
2
world pop.
U.S. pop.
world energy usage
U.S. energy usage

Fossil Fuels Still Account for Over 85% of the Primary Energy Consumed in the World



Source for Projections: International Energy Outlook-2003

- Anthropogenic CO_2 output ~ 28 Gt/yr (USA ~ 6, UK ~ 0.6, Australia ~ 0.3)

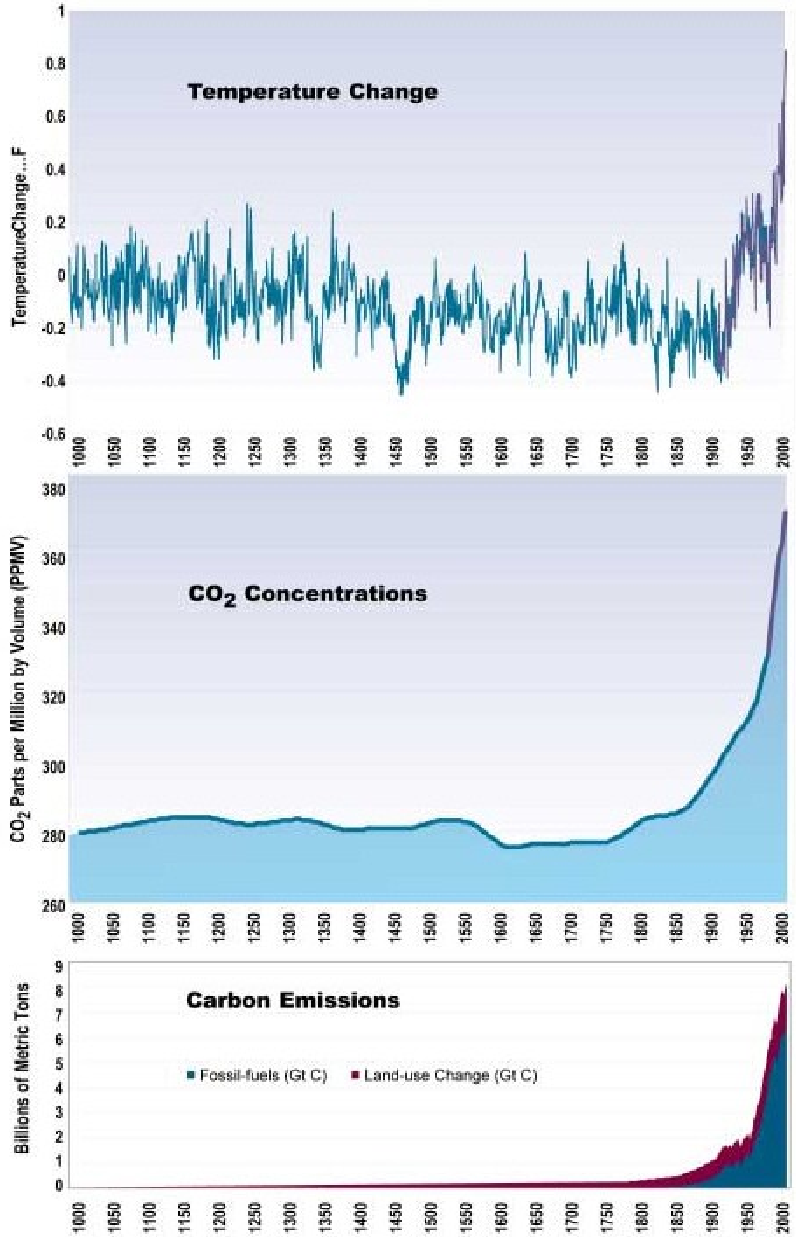
- Mean per person ~ 4 t/yr (USA ~ 20, UK ~ 10, Aus. ~ 18, Nepal ~ 0.1)

- Atmospheric / Oceanic CO_2 content ~ 2,800 / 160,000 Gt

- Natural CO_2 production ~ 700 Gt/yr

- Atmosphere and oceans sensitive to extra input

1000 Years of Global CO_2 and Temperature Change



Carbon capture

- from the atmosphere
- post combustion capture

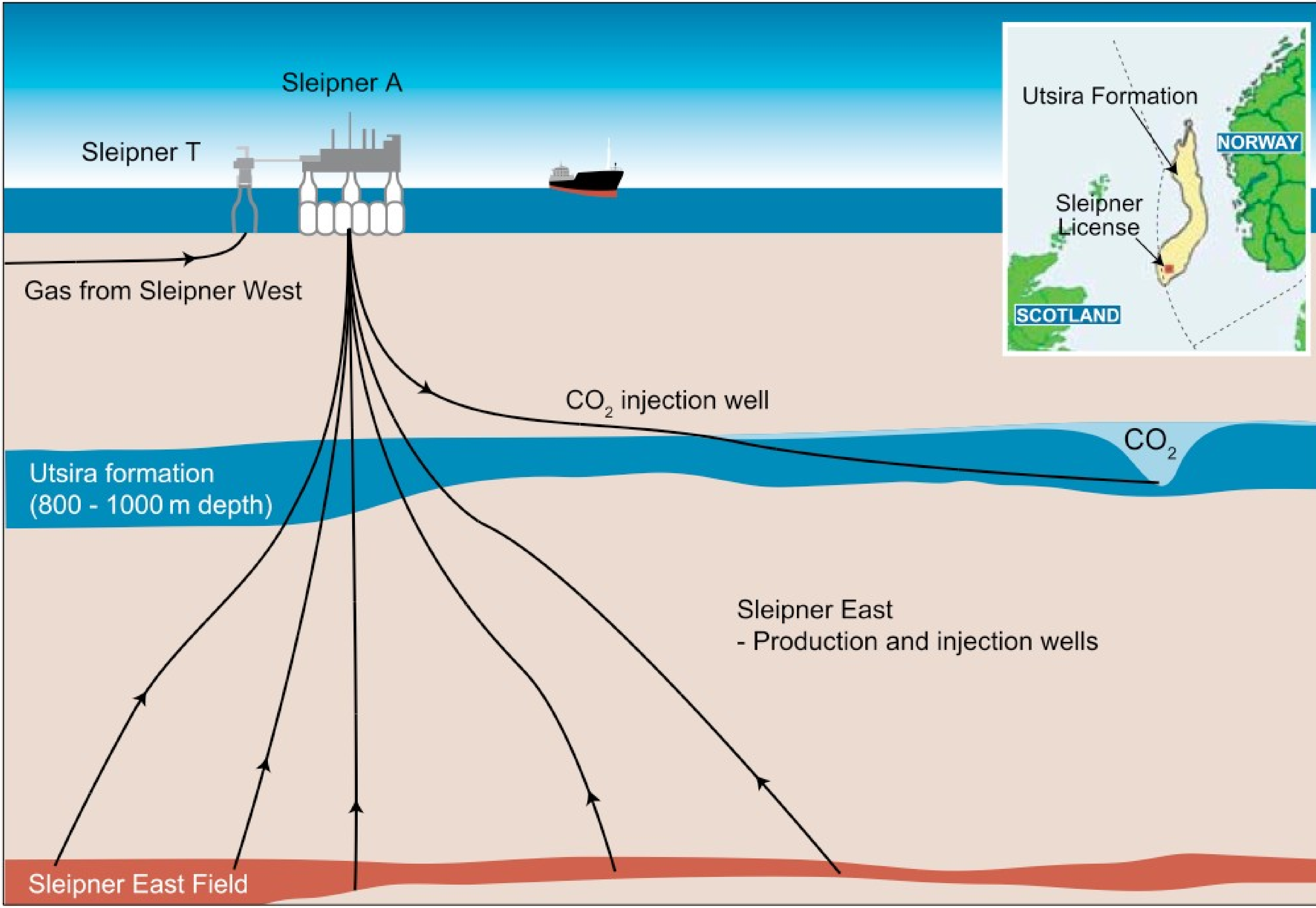
  from point sources like power stations
- pre combustion capture

- oxy-fuel combustion

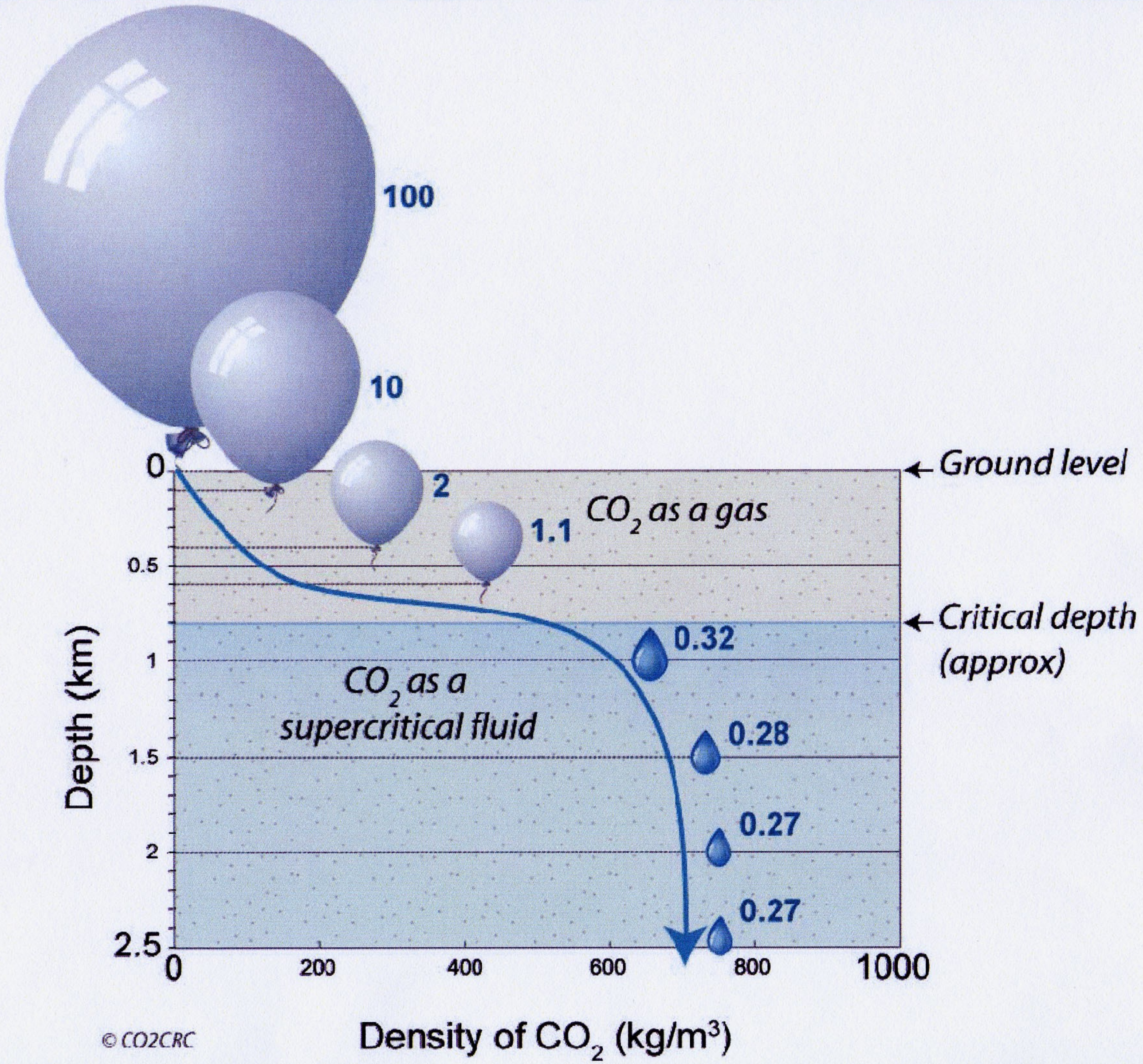
  burned in oxygen rather than air
- stored in cement (Celera)

Storage, or sequestration

- Store in: ecosystems; bottom of the oceans; depleted oil reservoirs; brown coal seams; mineralisation; saline aquifers; .....

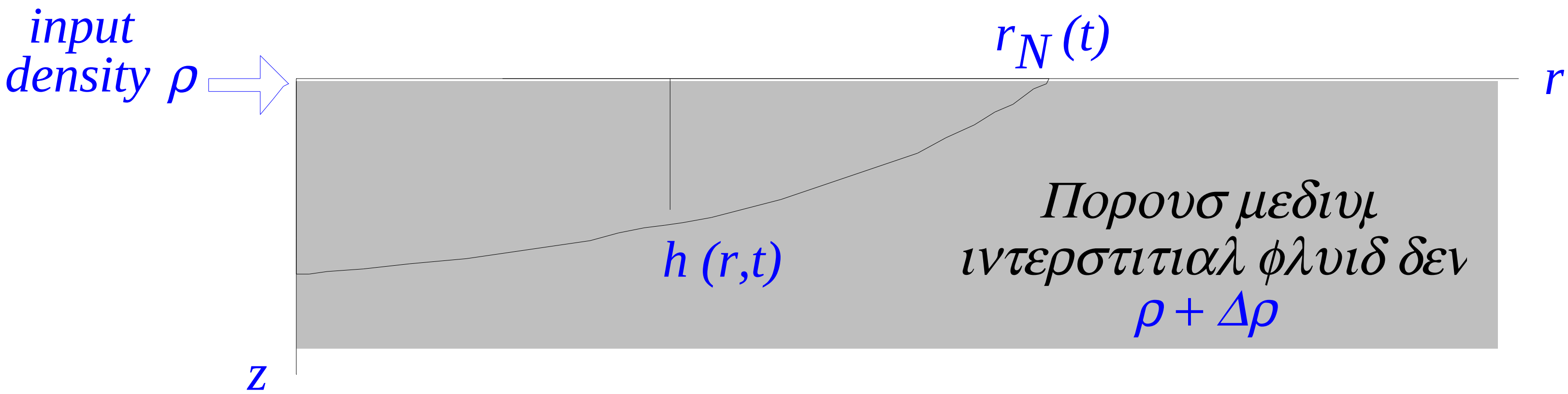

Sleipner A
Sleipner T
Gas from Sleipner West
Utsira Formation
NORWAY
Sleipner License
SCOTLAND
CO_2 injection well
CO_2
Utsira formation
(800 - 1000 m depth)
Sleipner East
- Production and injection wells
Sleipner East Field

As CO_2 is compressed its state changes from a gas to a supercritical fluid, and it significantly reduces in volume



4. Fluids I: source in porous medium

Axisymmetric gravity currents in a porous medium
(Lyle et al., *JFM* **543**, 293-302, 2005)



Gravity current due to horizontal pressure gradient of (unknown) free surface slope.

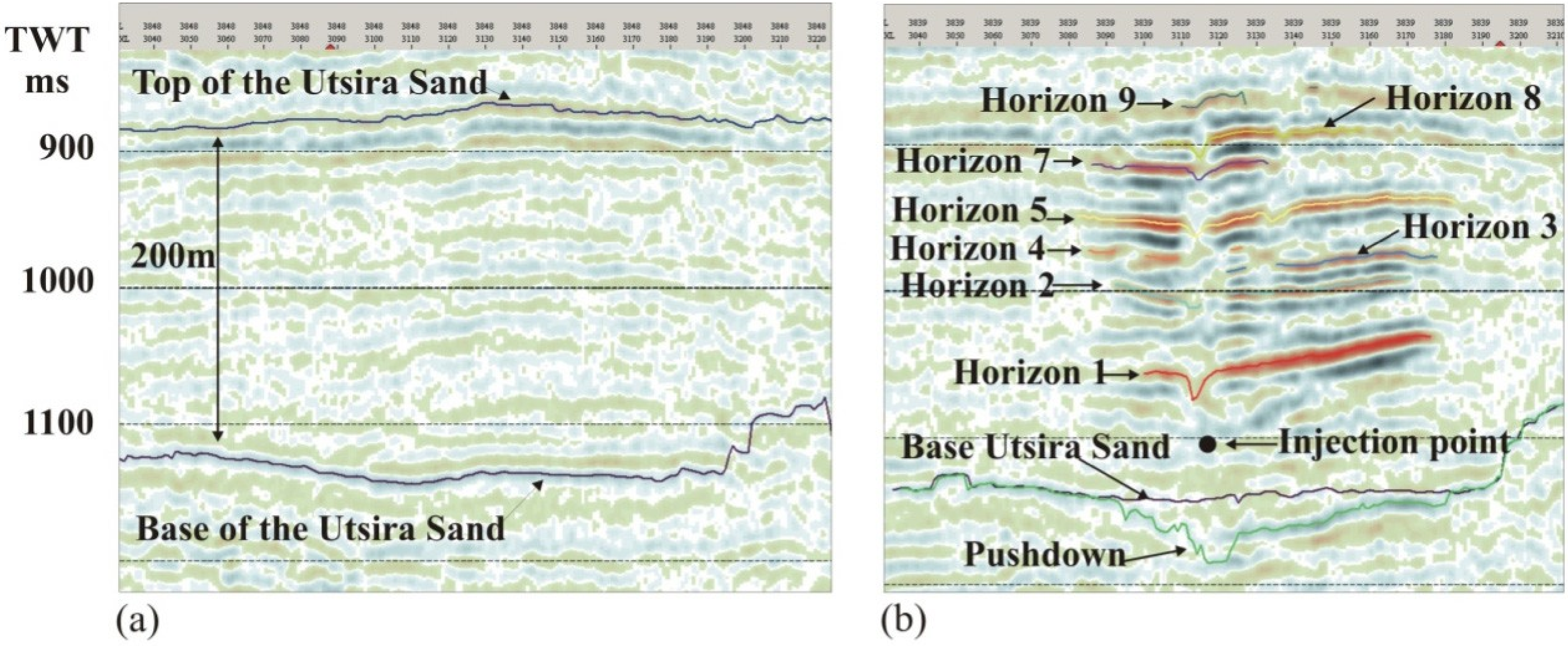
$$r_N(t) \qquad (\gamma\Theta/\phi)^{1/4}\,\tau^{1/2}$$

Q : *volume flux* f : *porosity* $\gamma = \rho k g / (f\, m)$ LT^{-1}

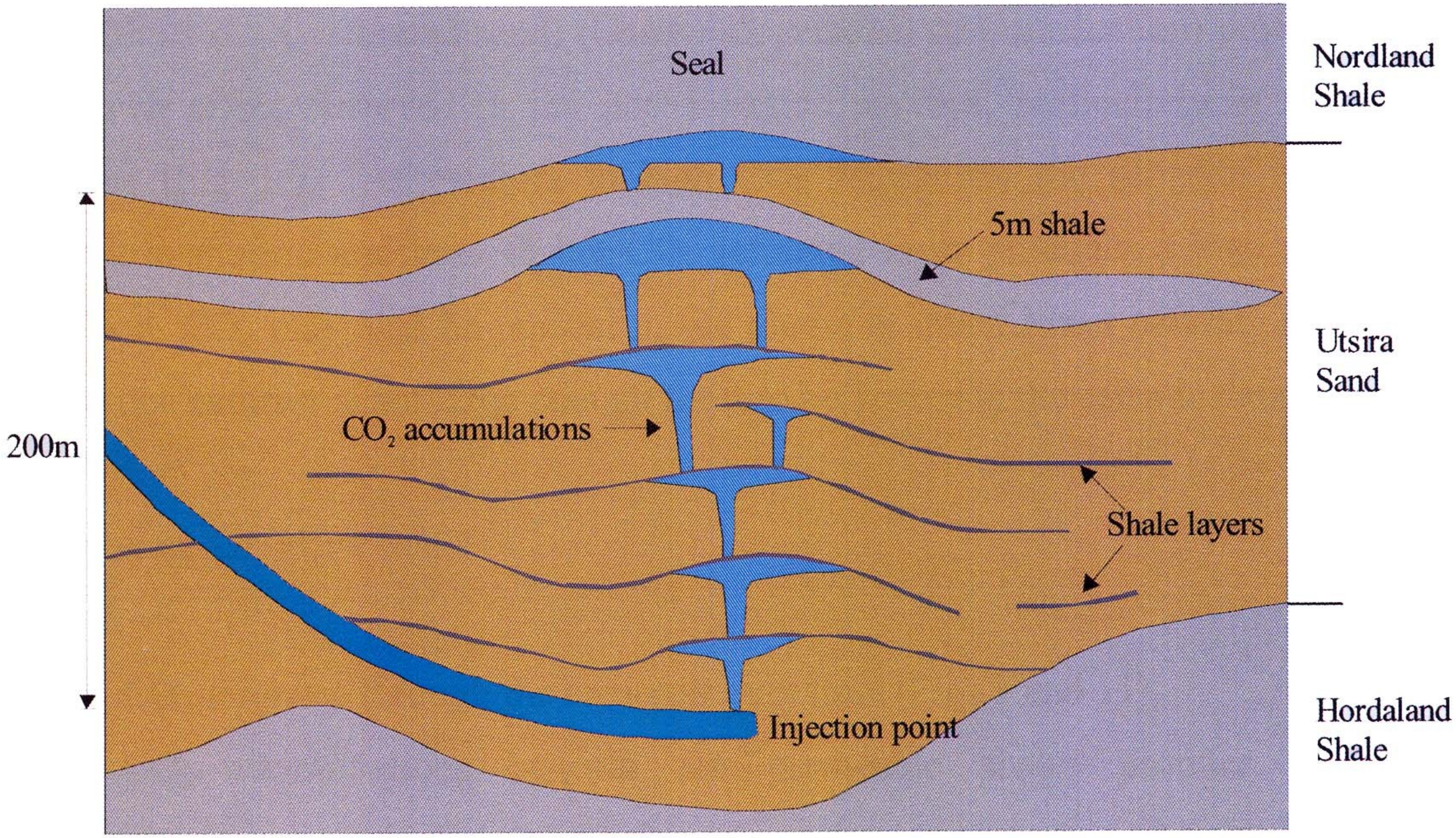
k: permeablity μ: δψναμιχ ϖισχοσιτψ οφ ινπυ

5. Application to Sleipner

Analytical modelling at Sleipner: implications
(Bickle *et al. EPSL*, **225**, 164-176)

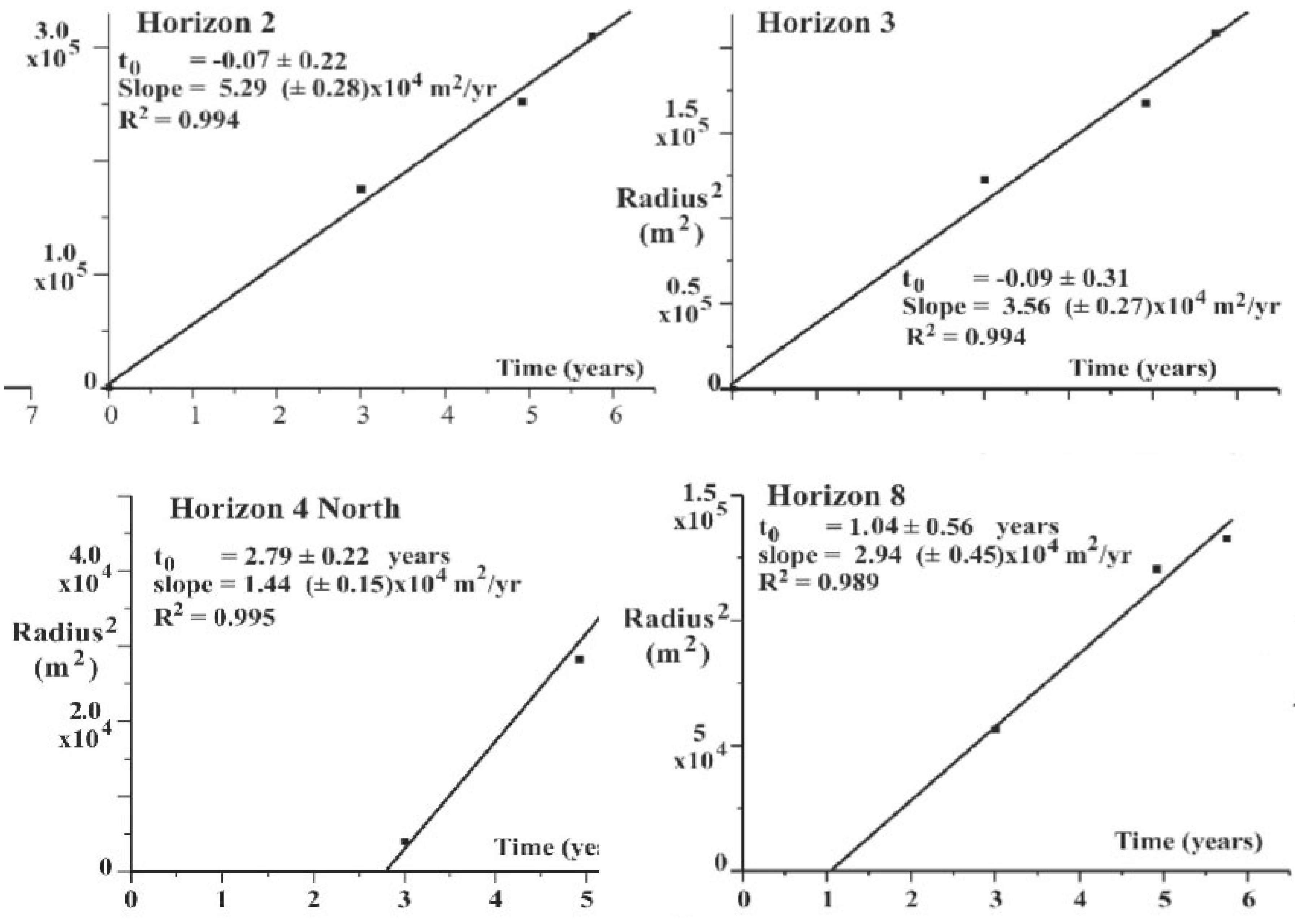


Sleipner oil and gas f eld



~ 1 Mt/yr   since 1996   ~ $US15/tonne   (<$US200)

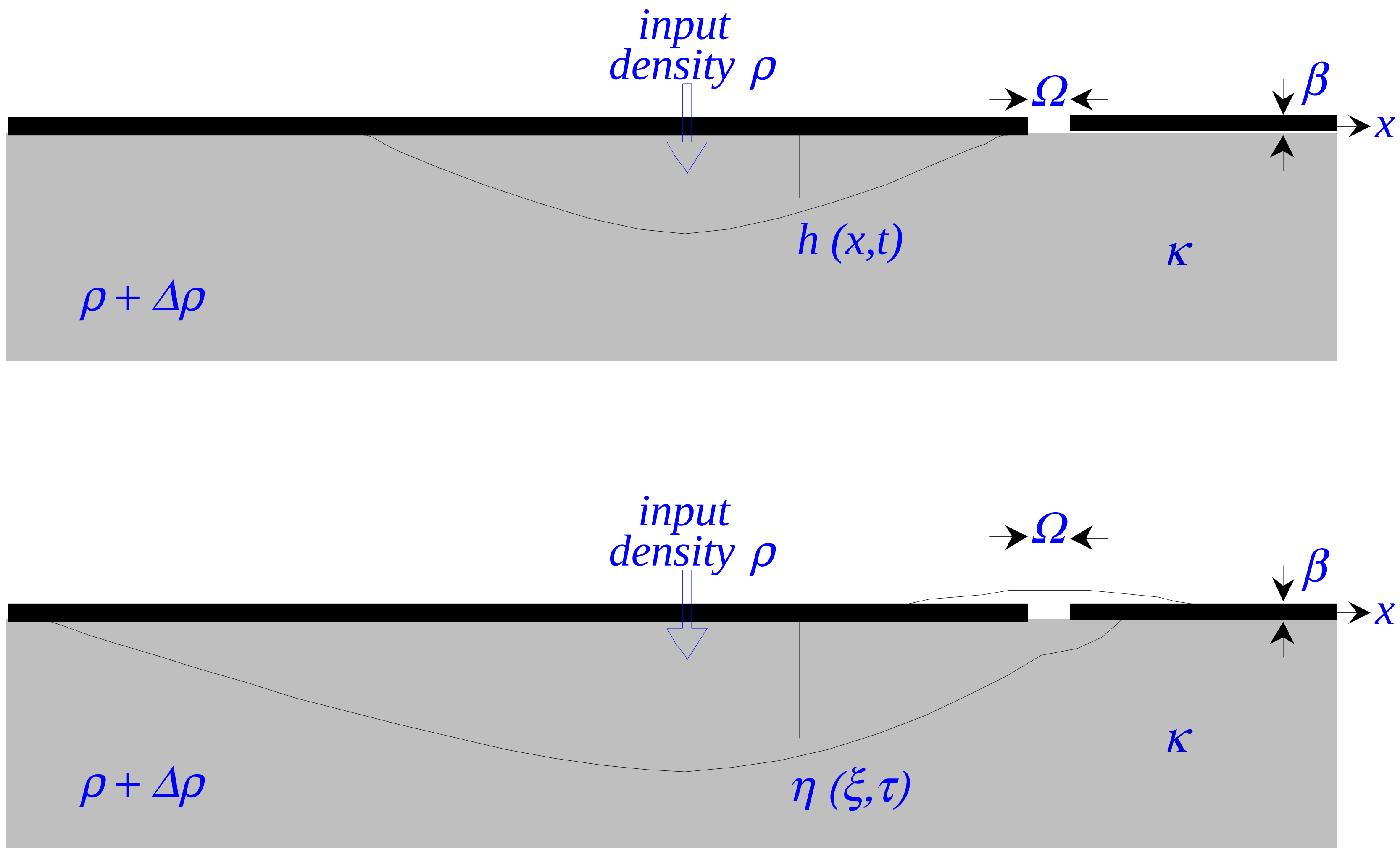
Monitored by 3D seismic surveys in 1999, 2001, 2, 4, 6 & 8



Horizon 2
t0 = -0.07 ± 0.22
Slope = 5.29 (± 0.28)x10^4 m^2/yr
R^2 = 0.994
3.0 x10^5
1.0 x10^5
0
Time (years)
7
0
1
2
3
4
5
6
Horizon 3
1.5 x10^5
Radius^2 (m^2)
0.5 x10^5
t0 = -0.09 ± 0.31
Slope = 3.56 (± 0.27)x10^4 m^2/yr
R^2 = 0.994
Time (years)
0
Horizon 4 North
t0 = 2.79 ± 0.22 years
slope = 1.44 (± 0.15)x10^4 m^2/yr
R^2 = 0.995
4.0 x10^4
Radius^2 (m^2)
2.0 x10^4
0
Time (ye
0
1
2
3
4
5
Horizon 8
1.5 x10^5
t0 = 1.04 ± 0.56 years
slope = 2.94 (± 0.45)x10^4 m^2/yr
R^2 = 0.989
Radius^2 (m^2)
5 x10^4
0
Time (years)
0
1
2
3
4
5
6

7. Point leakage

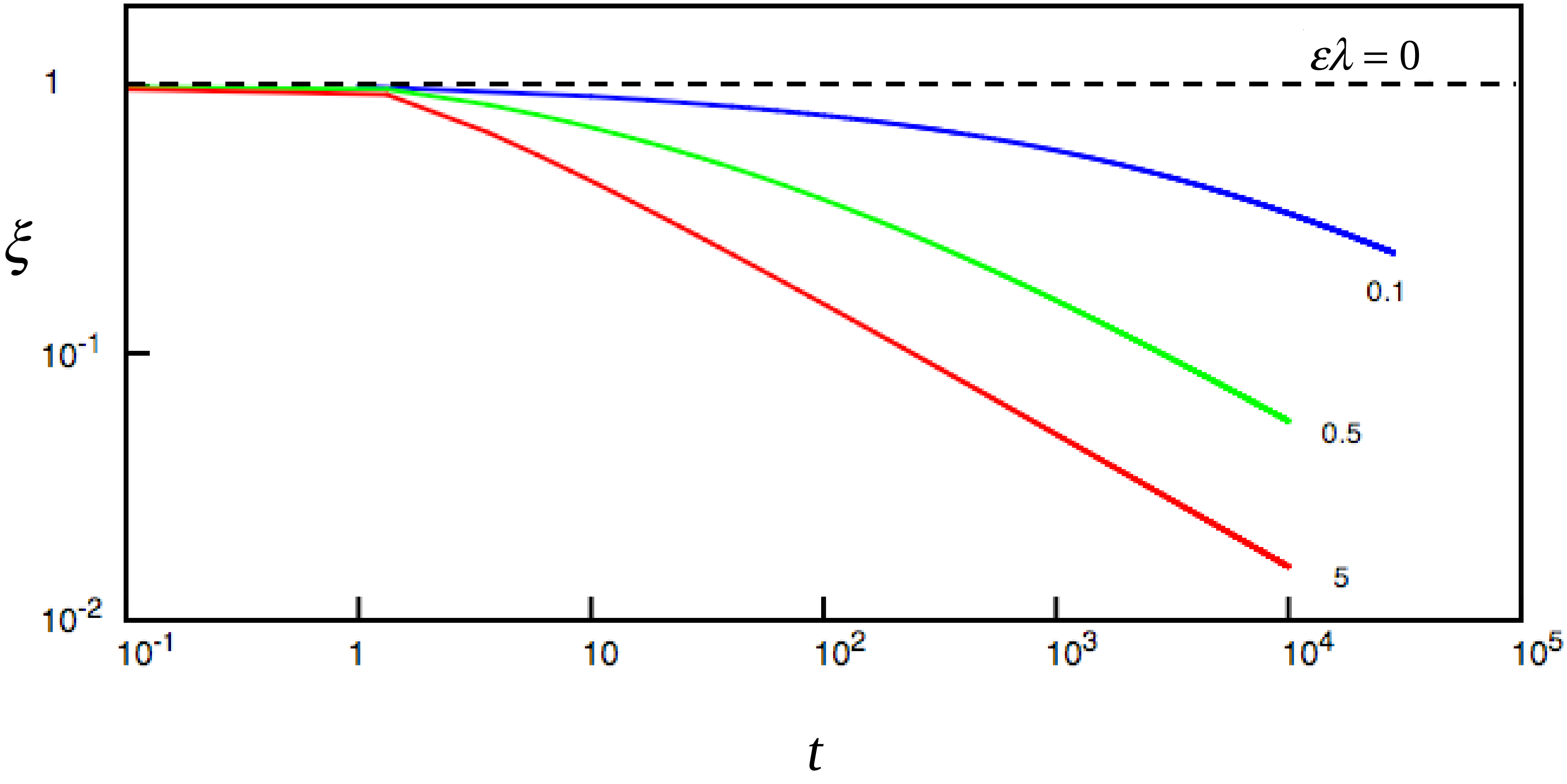
(Neufeld, Vella, HEH & Lister, JFM x 3)



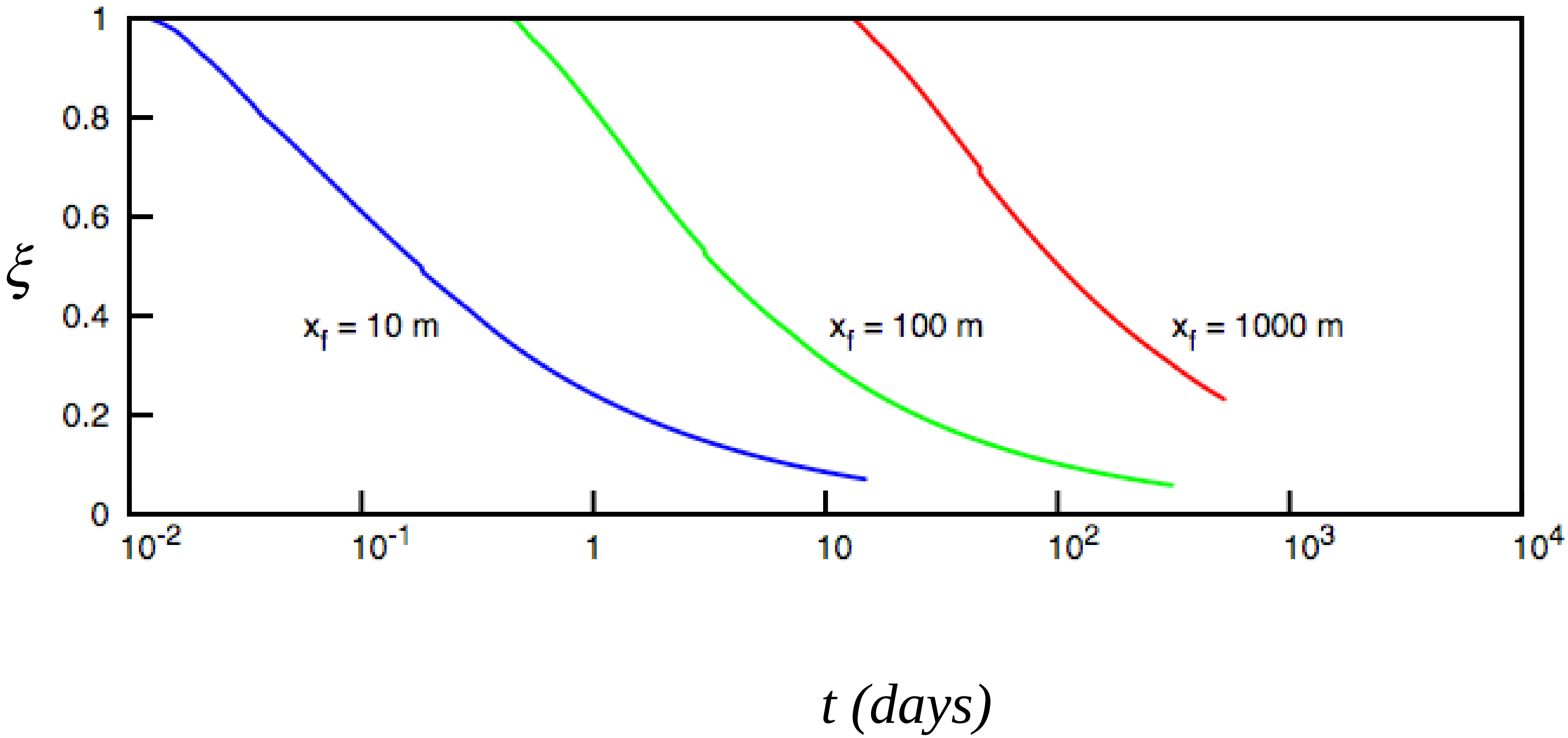
$$x = \frac{\text{volume in current}}{\text{volume injected}} = \text{efficiency of storage}$$

$$t^{-1/2} \quad (t \qquad)$$

i.e. asymptotically it all leaks

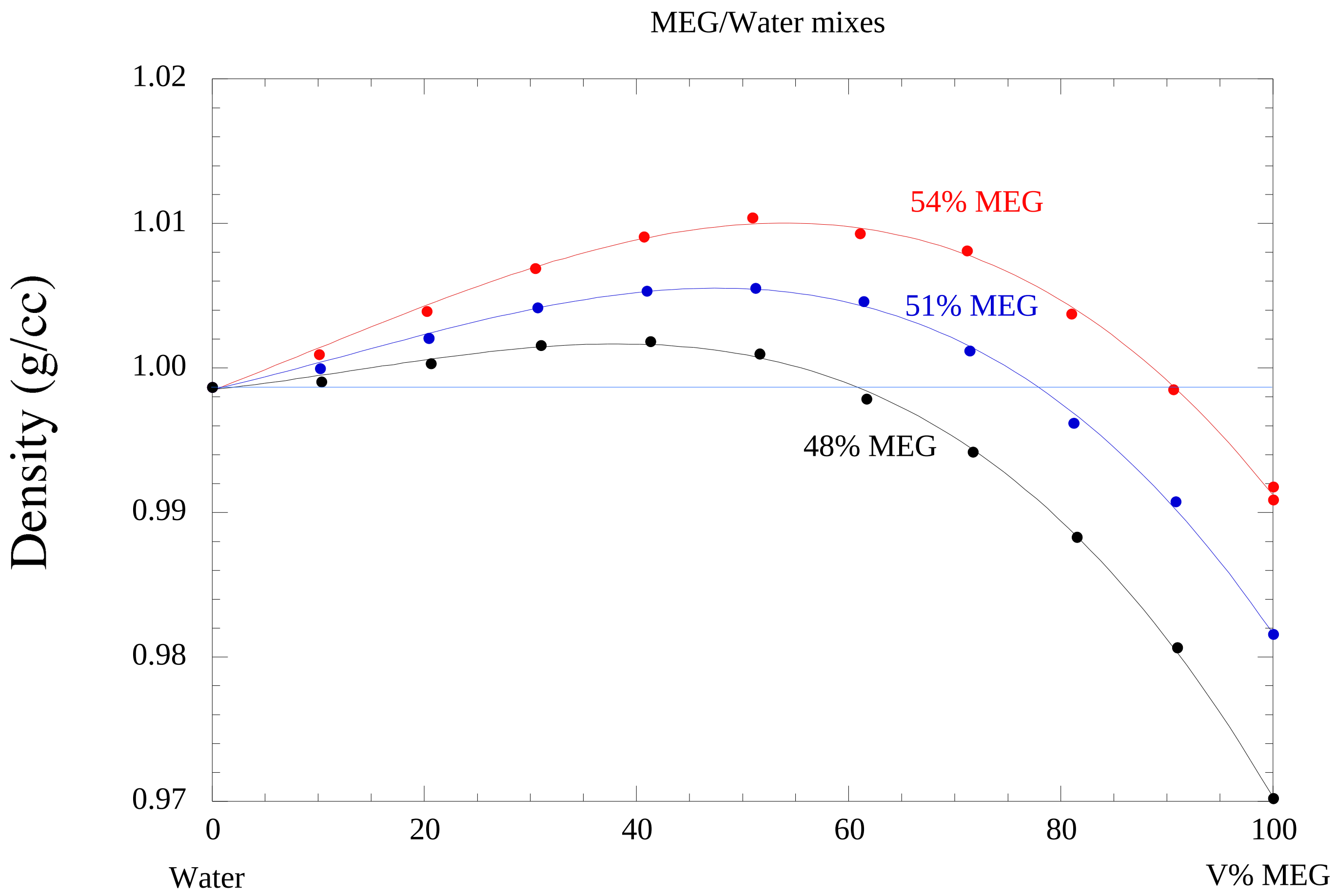


Using parameters relevant to Sleipner

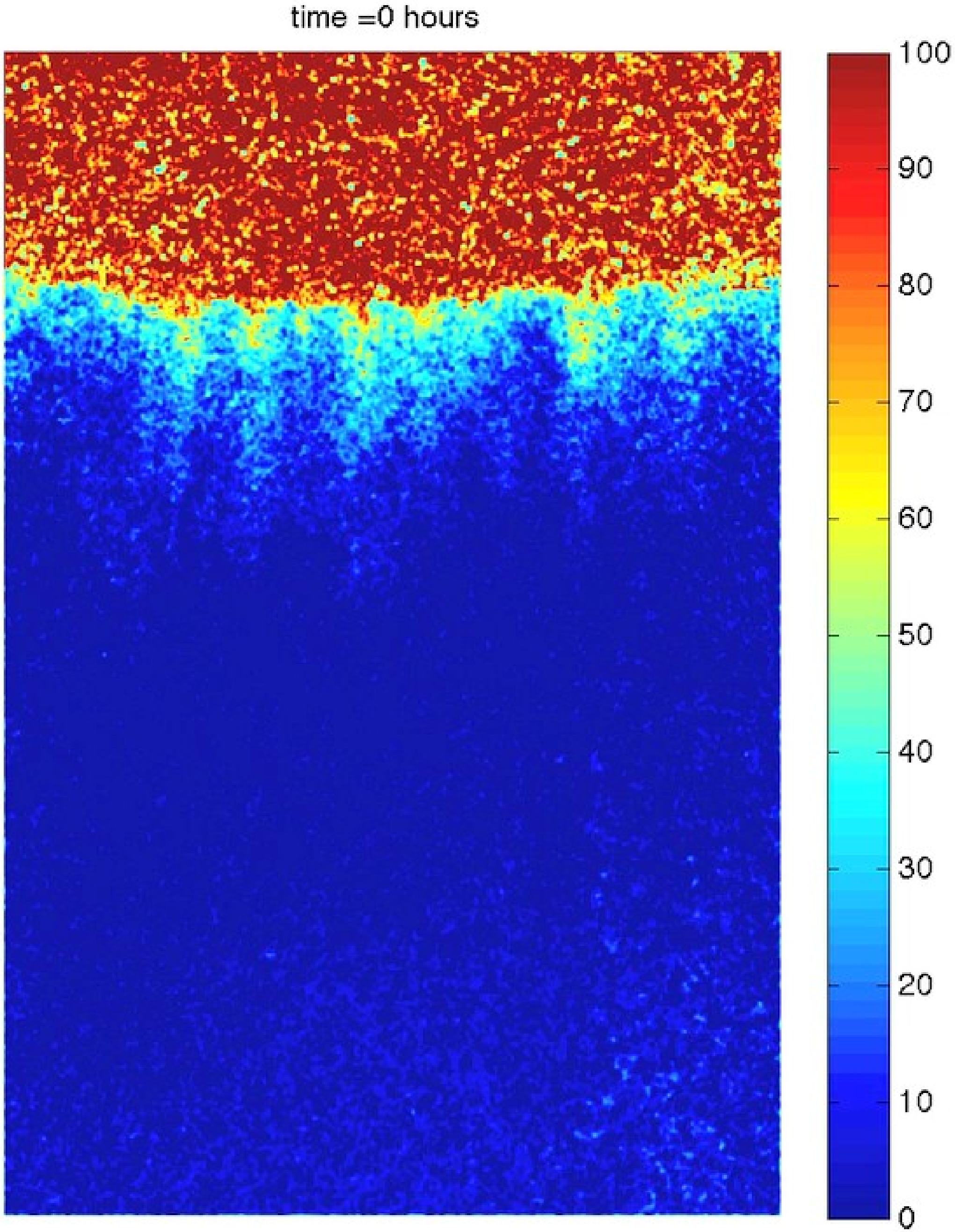


8. Convective dissolution

J. Neufeld, M. Hesse, A. Riaz, M. Hallworth, H. Tchelpi & HEH, *Nature*



MEG = methanol plus ethylene glycol


time =0 hours
100
90
80
70
60
50
40
30
20
10
0

At Sleipner

k = 2.5 x 10^{9} m^{2} H ~ 20m $\rho\Delta\_$: 10.5 kg/m μ : 4.5 x 10^{6} Pa s

$$Ra = 1.4 \text{ x } 10^{4} \quad >> 1$$

$$F_{CO_2} = 18 \text{ kg m}^{2} \text{ yr}^{-1}$$

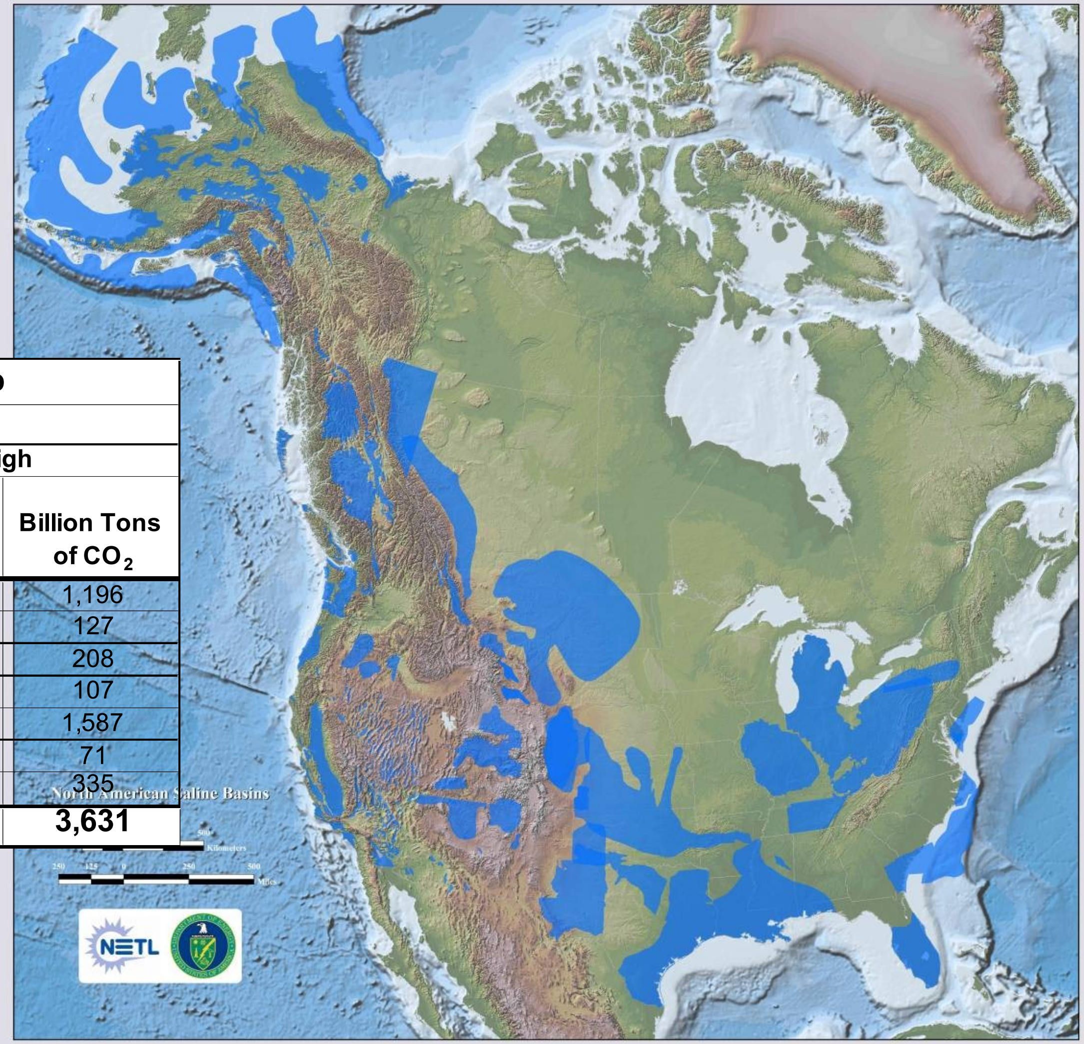
A ~ 5.6 x 10^{6} m^{2}

$$F_{CO_2} A : \; 0.1 \text{ MT yr}^{-1}$$

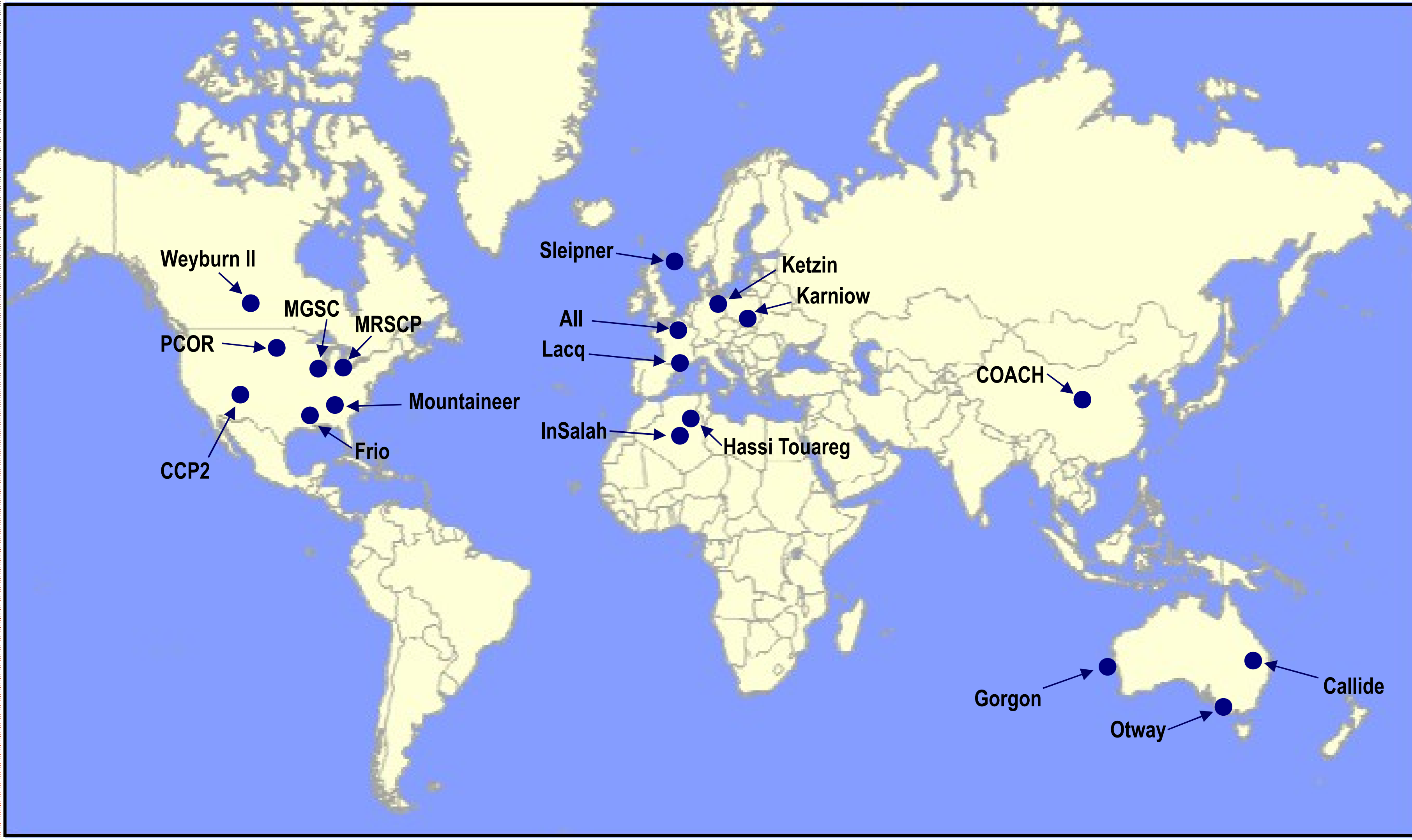
9. Field Studies

US Sequestration Opportunities

CO_2 Capacity Estimates by Partnership				
Deep Saline Formations				
	Low		High	
	Billion Metric Tons of CO_2	Billion Tons of CO_2	Billion Metric Tons of CO_2	Billion Tons of CO_2
BIG SKY	271	299	1,085	1,196
MGSC	29	32	115	127
MRCSP	47	52	189	208
PCOR	97	107	97	107
SECARB	360	397	1,440	1,587
SOUTHWEST	18	20	64	71
WESTCARB	76	84	304	335
Total	**898**	**991**	**3,294**	**3,631**



Current sequestration projects



Major Scientif c Problems (yet to be solved)

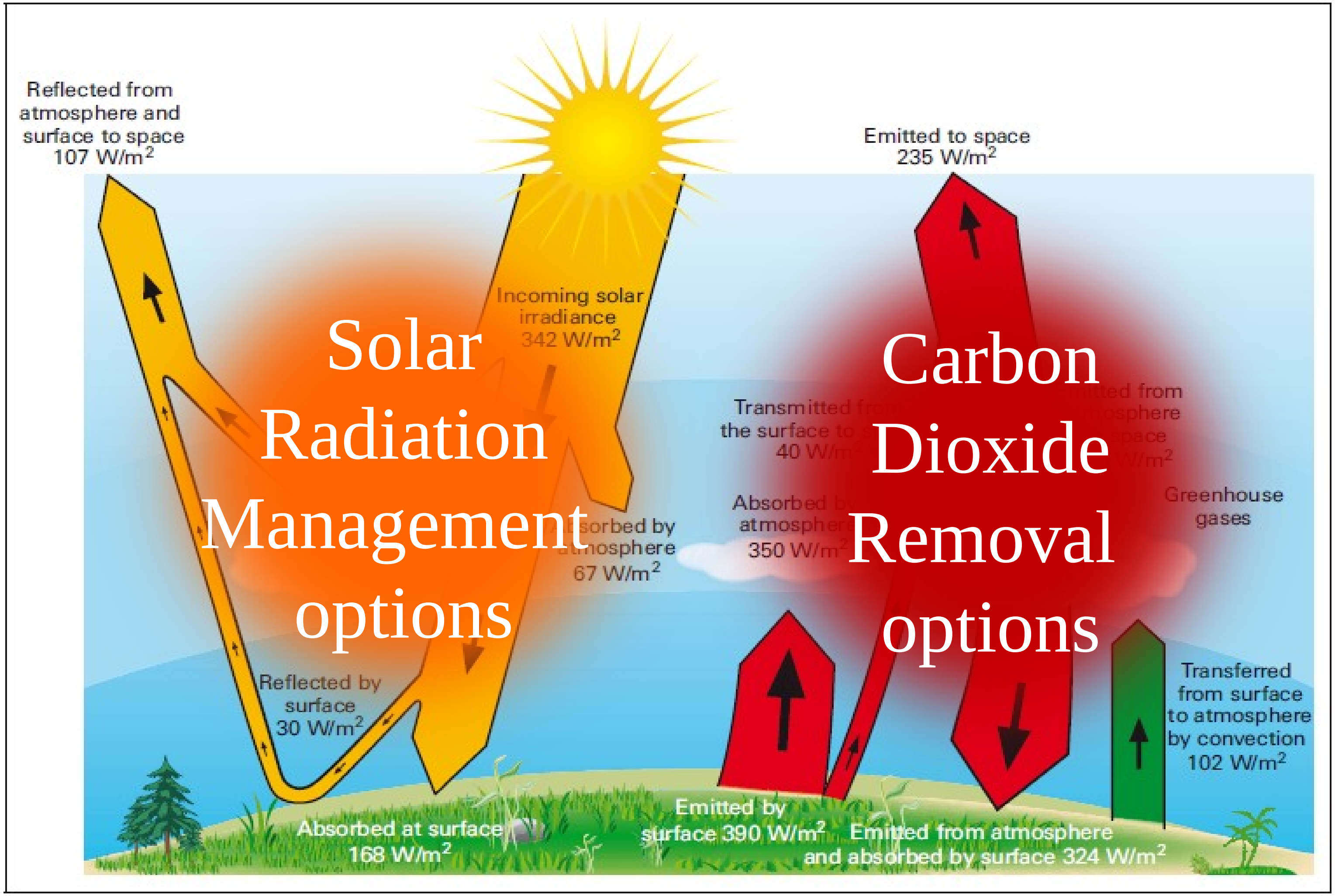
- What is extra stress f eld generated by CO_2 input?
- What is its inf uence on rock structure?
- What is resultant surface deformation: small or large?
- How much leakage; how quickly and in what form?
- Can dissolution between CO_2 and water stabilize the system; and in what time scale?
- Where does the displaced water in a saline aquifer go?

  Not in aquifers holding drinking water.
- Can chemical reactions and kinetics with rocks be used to help sequestration? Over what time scale?

Summary

- Over the last 150 years, the mean temperature and CO_2 content of the atmosphere have increased considerably.
- We are probably responsible.
- Acting in a responsible manner, we should probably do something about it.
- Fluid mechanics matters, and helps.

Managing Earth's climate system:
two basic methods: SRM & CDR



3. Geoengineering the Climate

a) Solar radiation Management (SRM)

mirrors in space, stratospheric aerosols, white roofs, cloud albedo enhancement, sulpher dioxide hose, ...

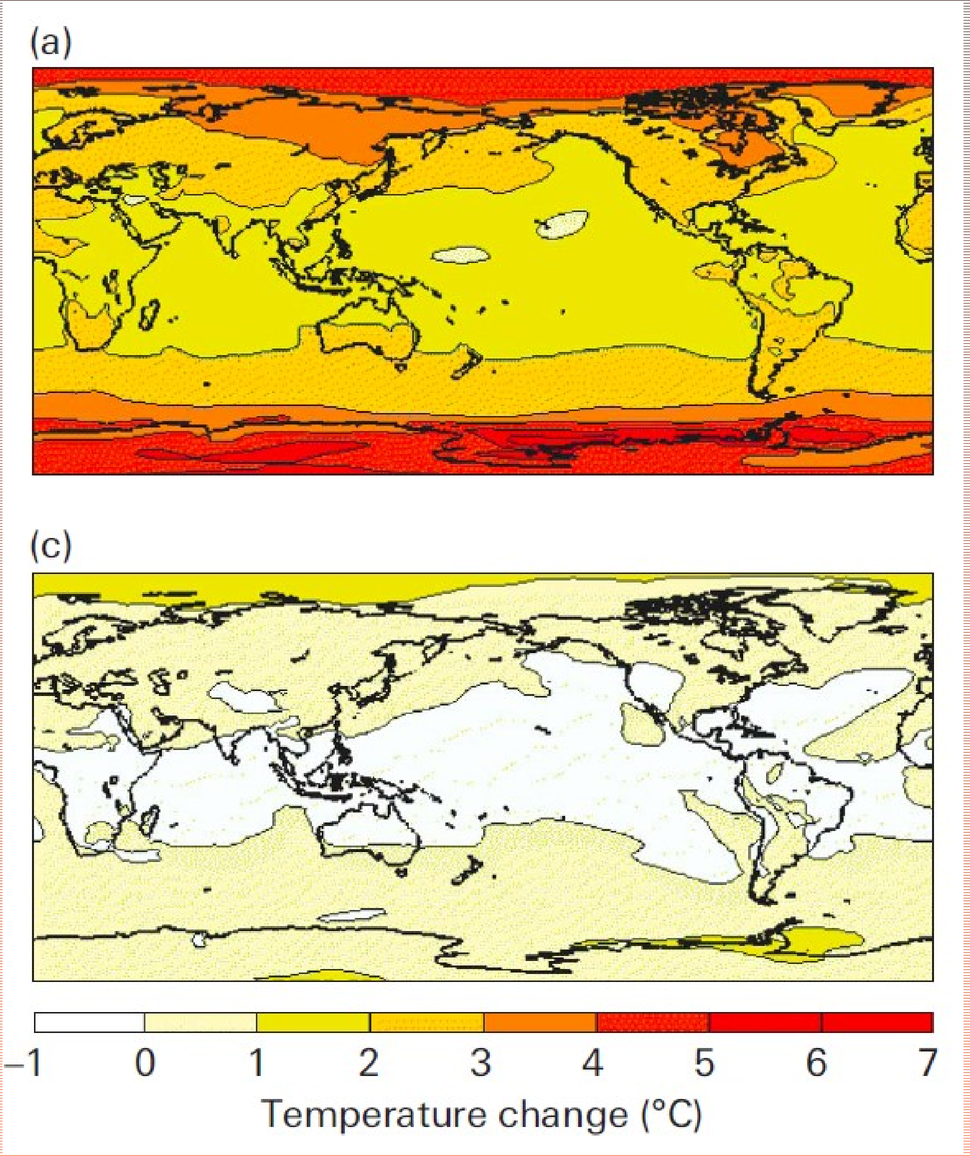
Fast

b) Carbon Dioxide Removal (CDR)

ocean fertilisation, engineered CO_2 capture from air, capture from power stations etc., sequestration, ...

Slow

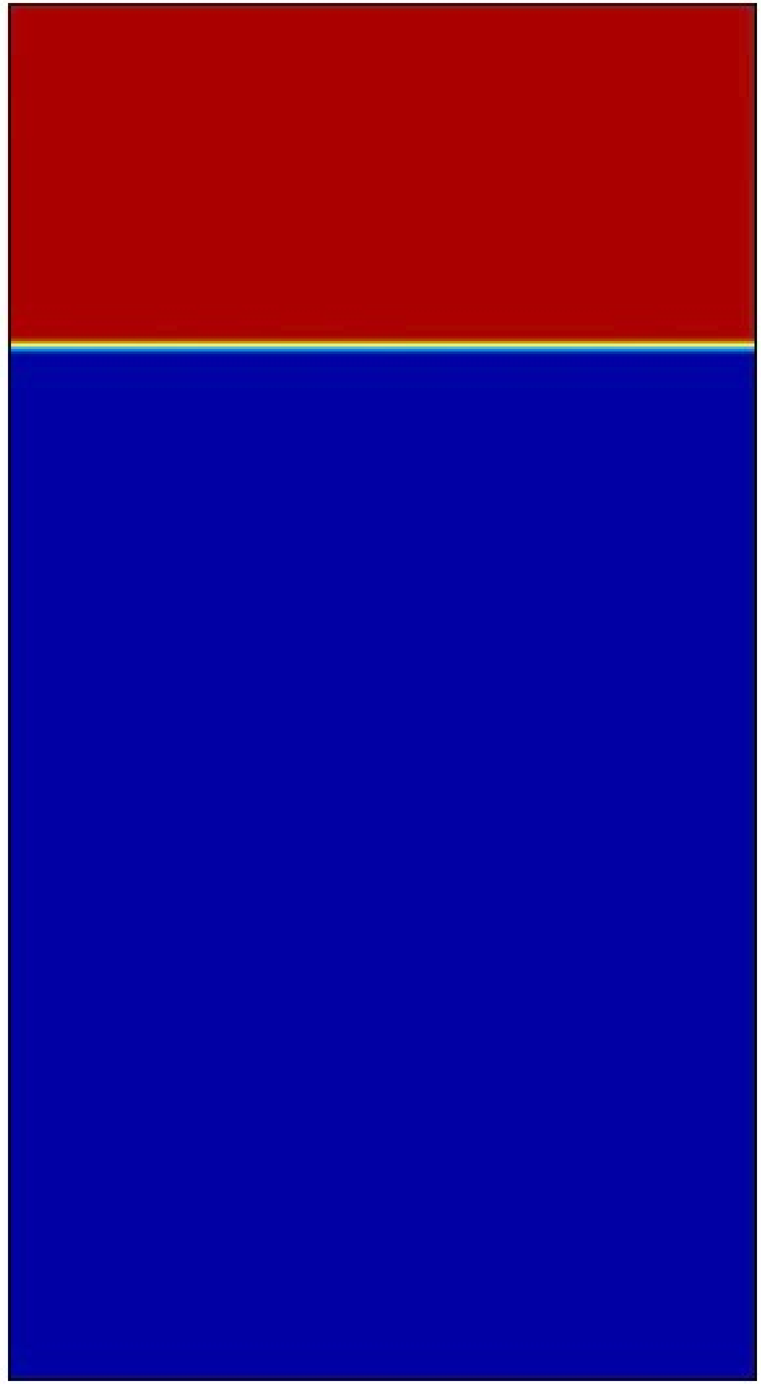
Stratospheric aerosols: approximate cancellation of warming



From Caldeira & Wood 2008

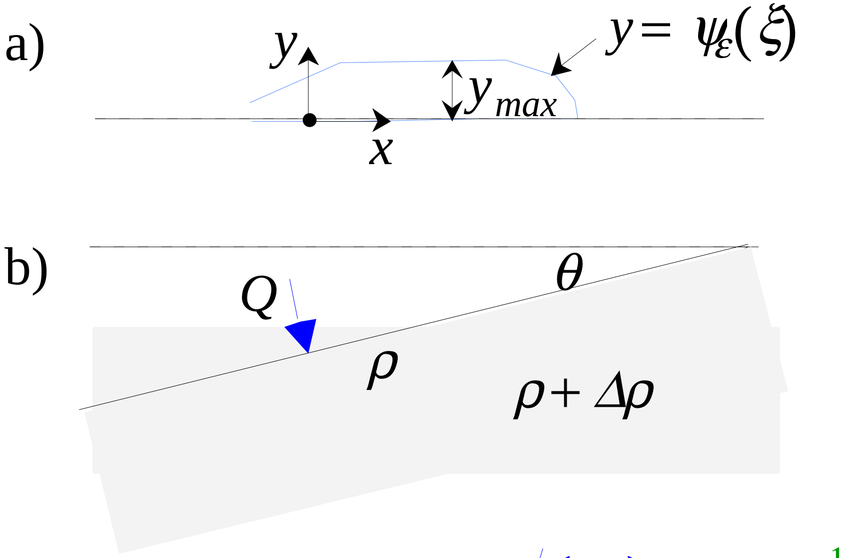
Overview of SRM and CDR techniques

- possibly feasible
- need new technologies
- uncertainties & risks on environmental impact
- potentially very important
- slow CDR possibly better than fast SRM
- further input needed on scientif c, social, legal, political, f nancial, technical, …… dimensions.



6. *Sloping cap rock*

Gravity currents in a porous medium at an inclined plane.
(Vella and HEH,*JFM*, **555,** 353-362)



$$V = \rho\kappa\gamma\, \sigma\iota\nu\,\theta / \phi\mu$$

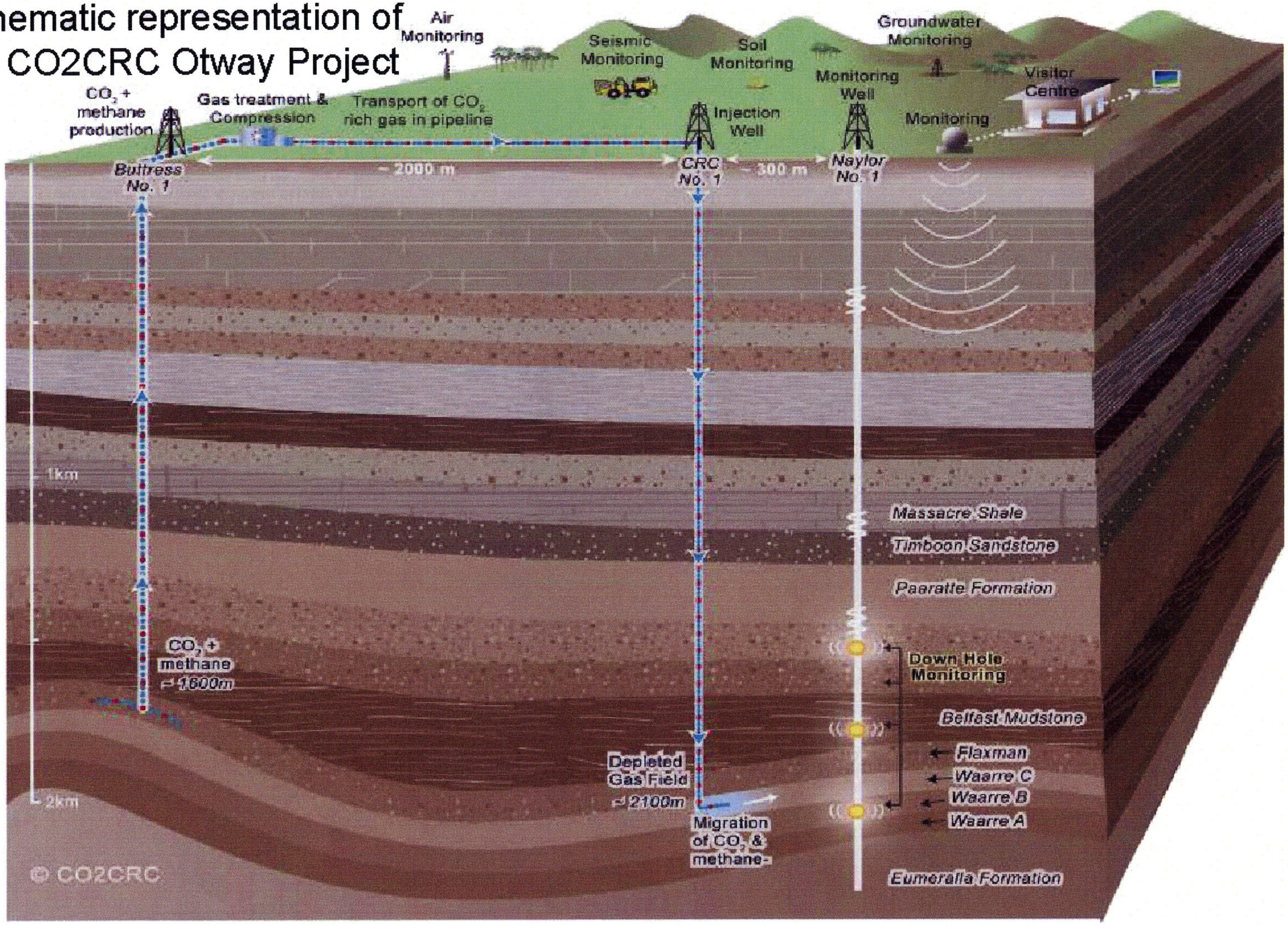
$$\gamma = \rho\kappa\gamma / (\phi\mu) \qquad \Lambda T^{-1}$$

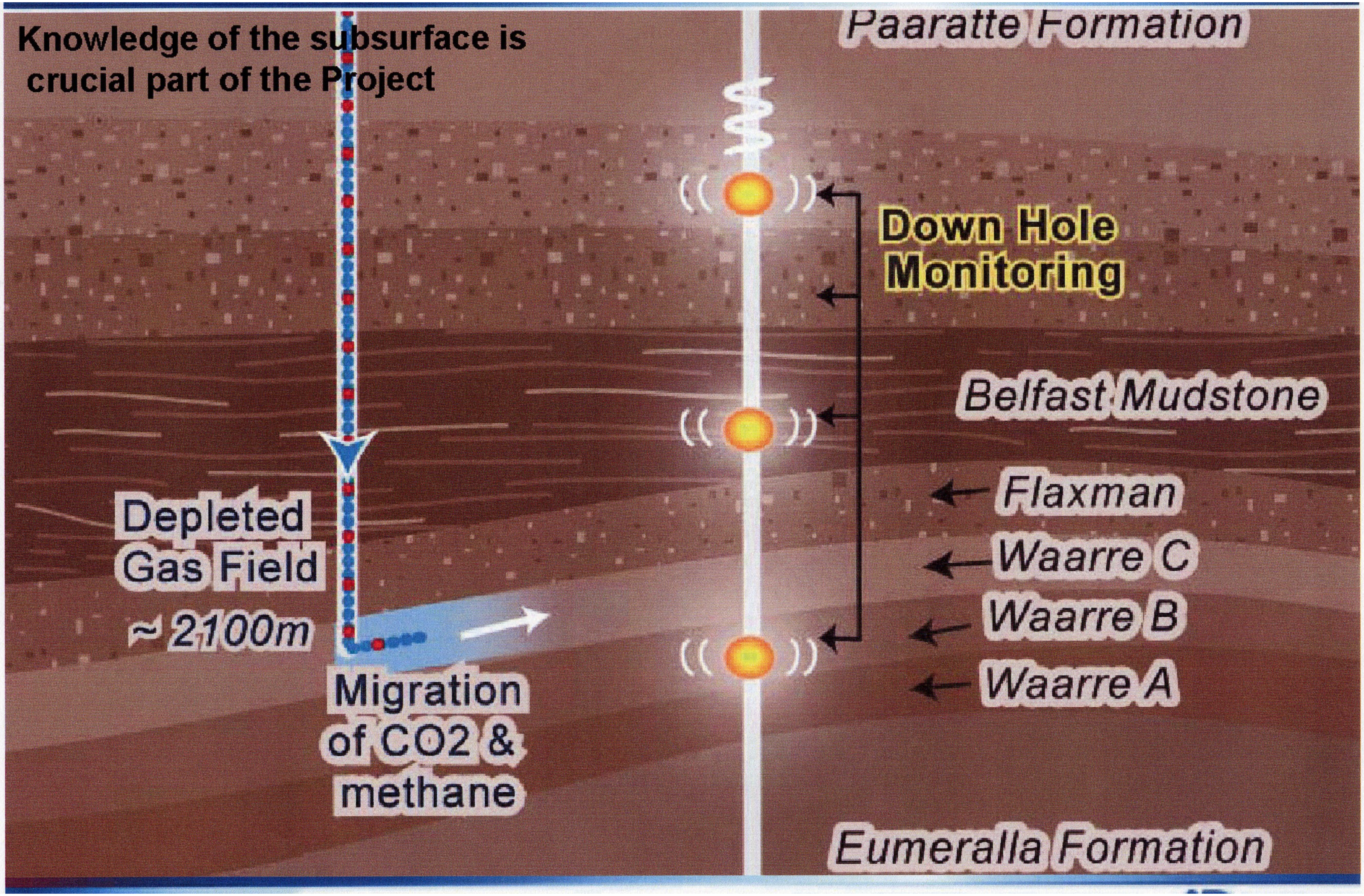
$$\tau = \left(\varsigma^{3}\, \tau\alpha\nu\,\theta / \Theta\right)^{-1/2}$$

$t << \tau \qquad \xi \sim \psi \sim \left(\varsigma\Theta / \tau\alpha\nu\,\theta\right)^{1/4} \tau^{1/2}$ (axisymmetric)

$\tau >> \tau \qquad \xi \sim \varsigma\tau, \qquad \psi \sim \varsigma\, \tau\left(\tau / \tau\right)^{1/3}$ (linear upstream prominence)

Schematic representation of the CO2CRC Otway Project




Knowledge of the subsurface is
crucial part of the Project
Paaratte Formation
Down Hole
Monitoring
Belfast Mudstone
Flaxman
Waarre C
Waarre B
Waarre A
Depleted
Gas Field
~ 2100m
Migration
of CO2 &
methane
Eumeralla Formation

$$V = 1.1\, \kappa\rho\gamma\, \sigma\iota\nu\theta / (\mu\phi)$$

$$\tau_* = \left(\frac{\Theta}{\phi\varsigma^{3}\tau\alpha\nu\theta} \right)^{1/2}$$

Otway Waarre C

$k = 10^{-12}\ \mu^{2}$

$\rho = 700\ \kappa\gamma\,\mu^{-3}$

$\Delta\rho = 300\ \kappa\gamma\,\mu^{-3}$

$\gamma = 4\ \mu\sigma^{-1}$

$\sigma\iota\nu\theta = 0.1$

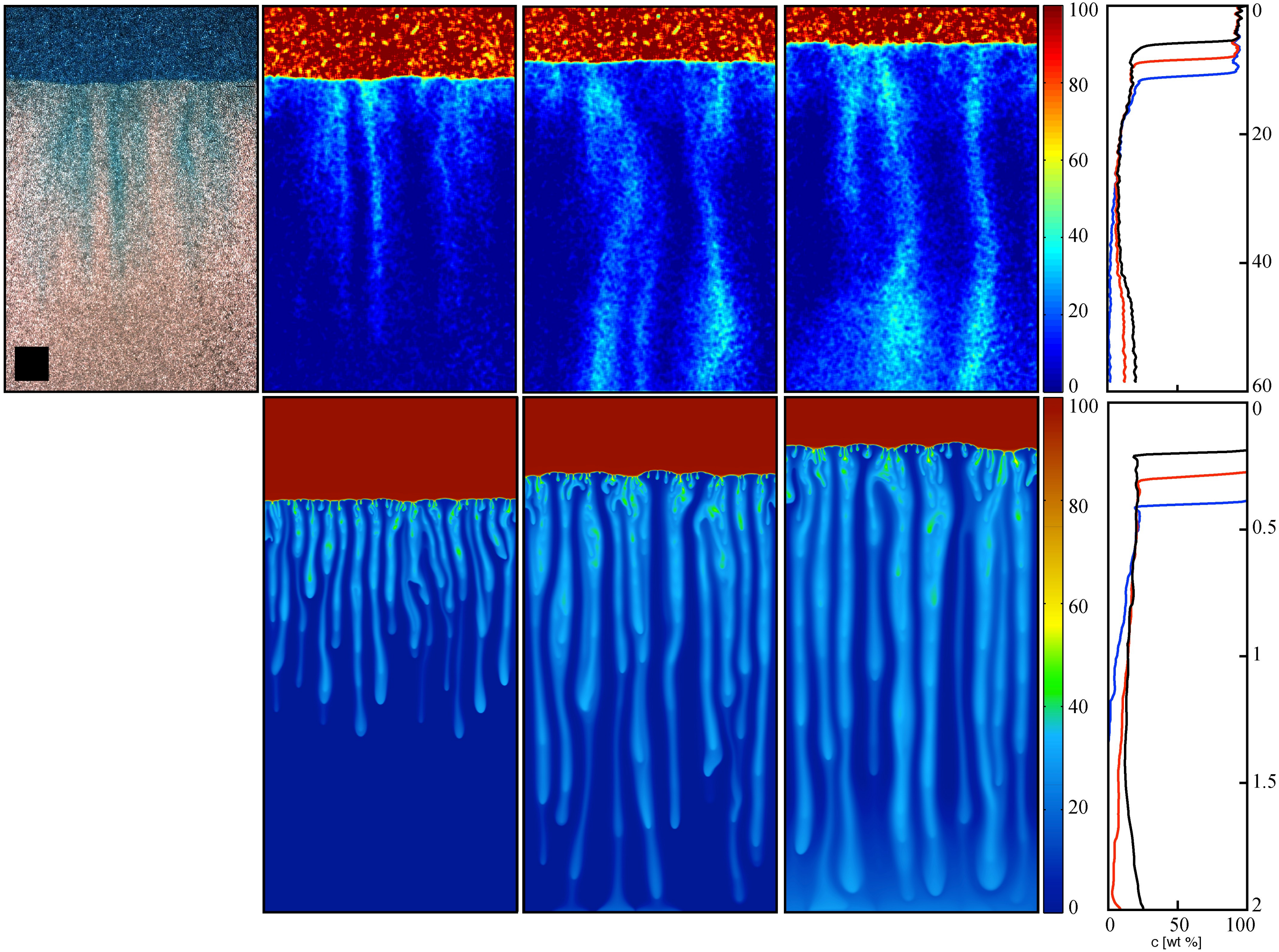
$\mu = 4\ \xi\ 10^{-5}\ \Pi\alpha$

$\phi = 0.3$

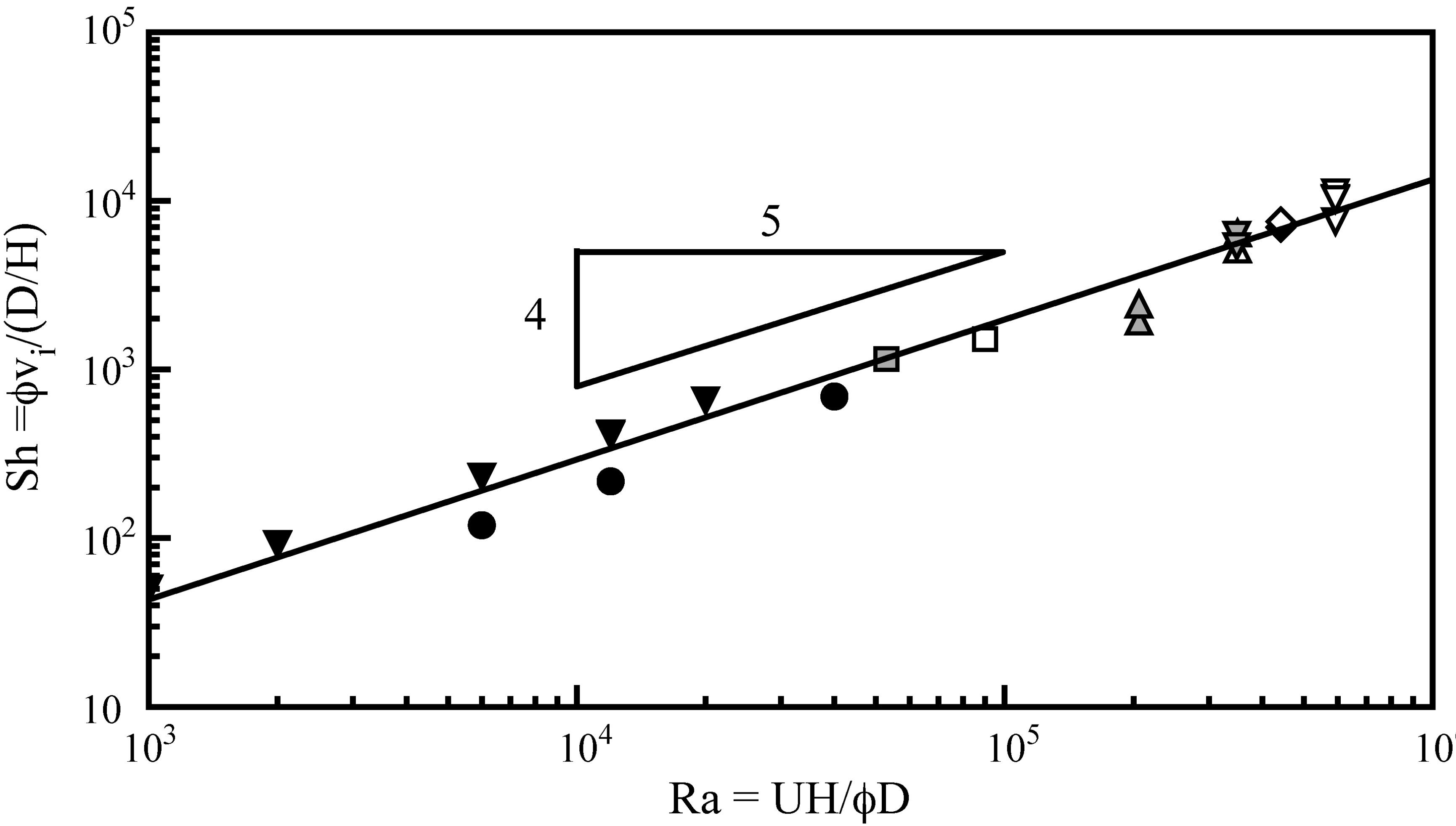
$\Theta = 0.004\ \mu^{3}\sigma^{-1}$

$$V = 2.2\ \mu/\delta\alpha\psi = 119\ \delta\alpha\psi\sigma/300\mu$$

$$\tau_* \sim 27\ \delta\alpha\psi$$

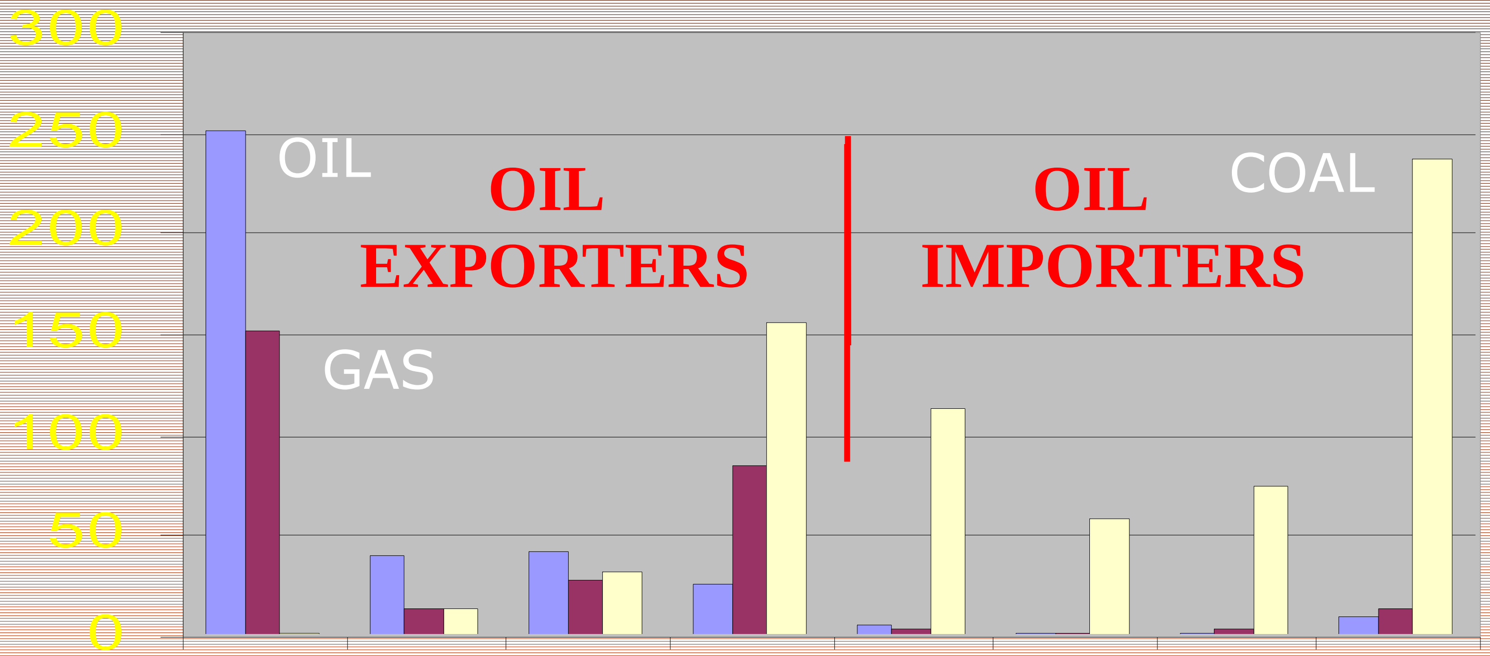


100
80
60
40
20
0
0
20
40
60
100
80
60
40
20
0
0
0.5
1
1.5
2
0
50
100
c [wt %]



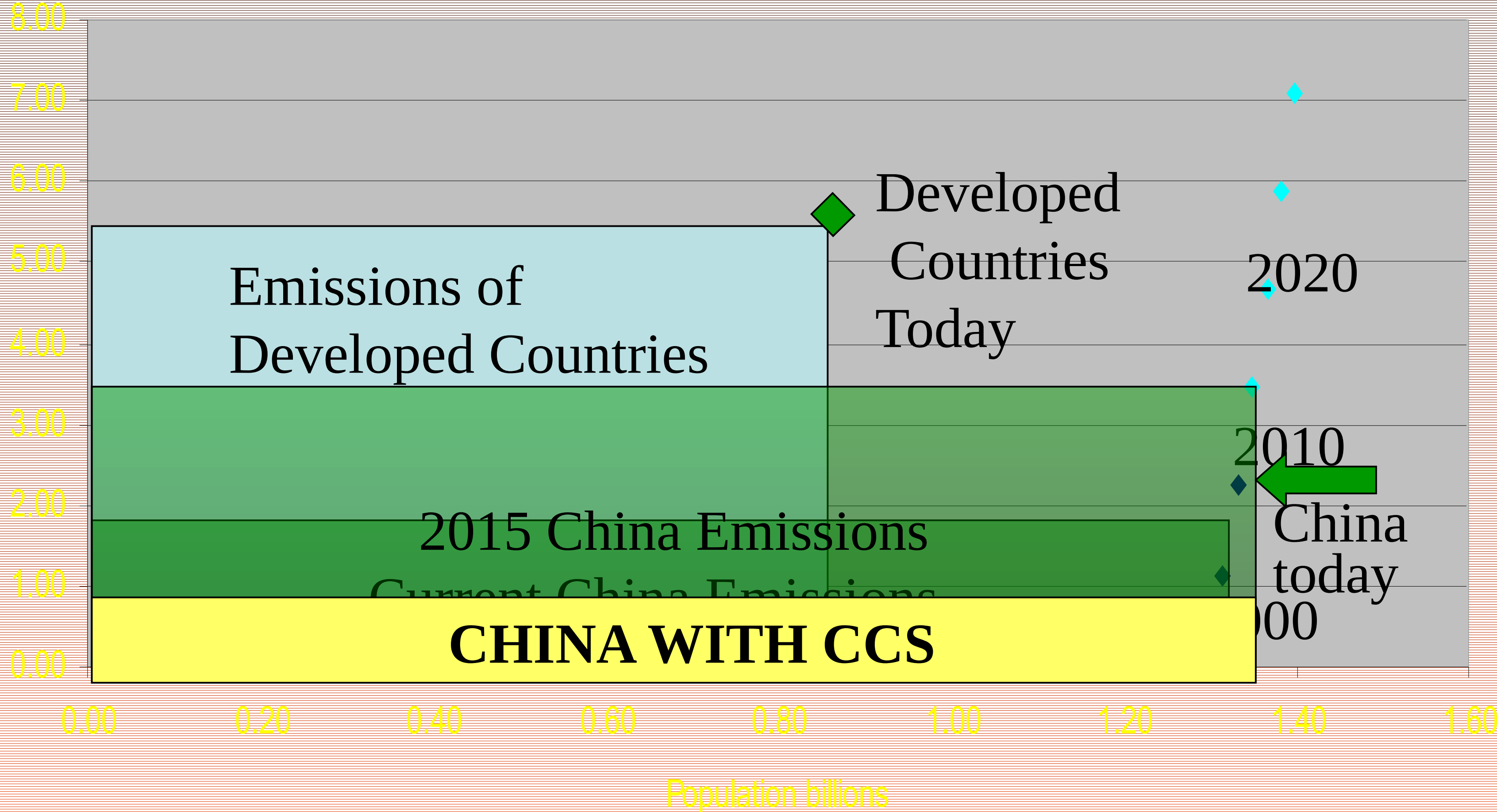
Sh = φv_i/(D/H)
Ra = UH/φD
10^5
10^4
10^3
10^2
10
10^3
10^4
10^5
10^6
5
4

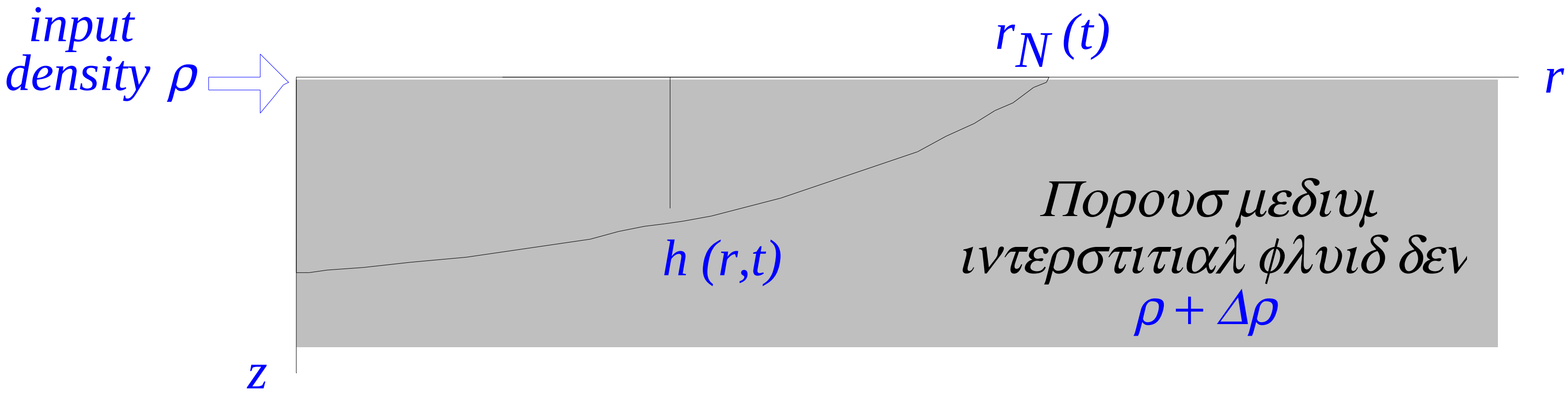
Oil, Gas and Coal Reserves



BP Statistics 2009

Energy & Emissions
China & Developed Countries





$$\frac{h}{t} - \frac{g}{r}\frac{}{r}\; rh\frac{h}{r} = 0$$

$$h = (gQ/f)^{-1/4} r t^{-1/2} \qquad r_N(t) = h_N \; (gQ/f)^{1/4} t^{1/2}$$

Q : *volume flux* $\qquad f$: *porosity* $\qquad \gamma = \rho k g/(f m) \qquad$ LT^{-1}

$$h(r,t) = \chi\,(\Theta/\phi\gamma)^{1/2}\;\phi[\psi \quad \eta(\rho,\tau)/\eta(\rho_N,\tau)] \qquad (0 < \psi < 1)$$

$\phi(\psi) \sim \frac{1}{2}(1 - \psi)$ $\qquad$ (λινεαρ $\qquad$ $\chi \sim (6/\pi)^{1/4}$

Contents

- Background
- Current developments
- Geoengineering the Climate
    - Solar Radiation Management
    - Carbon Dioxide Removal