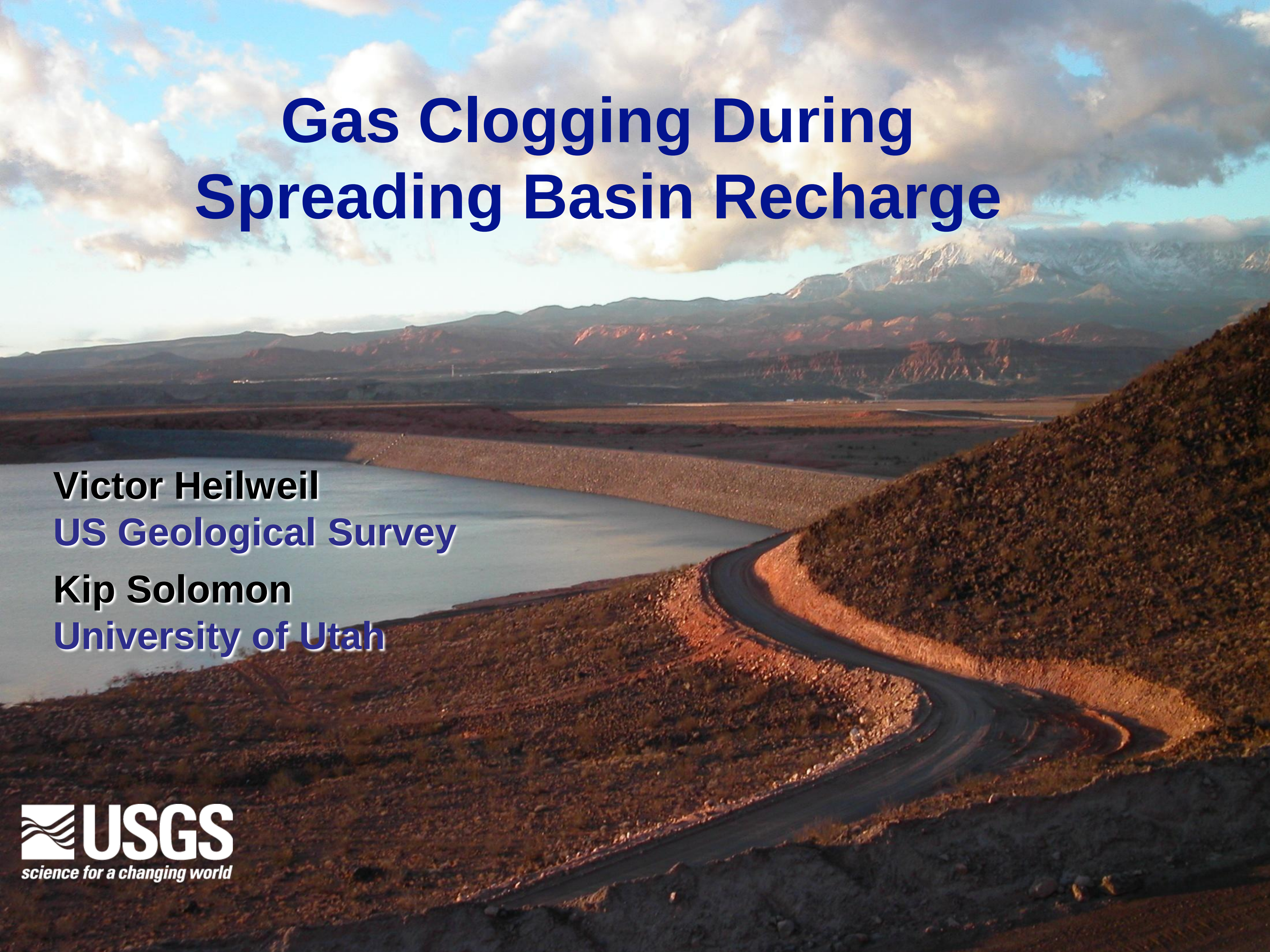
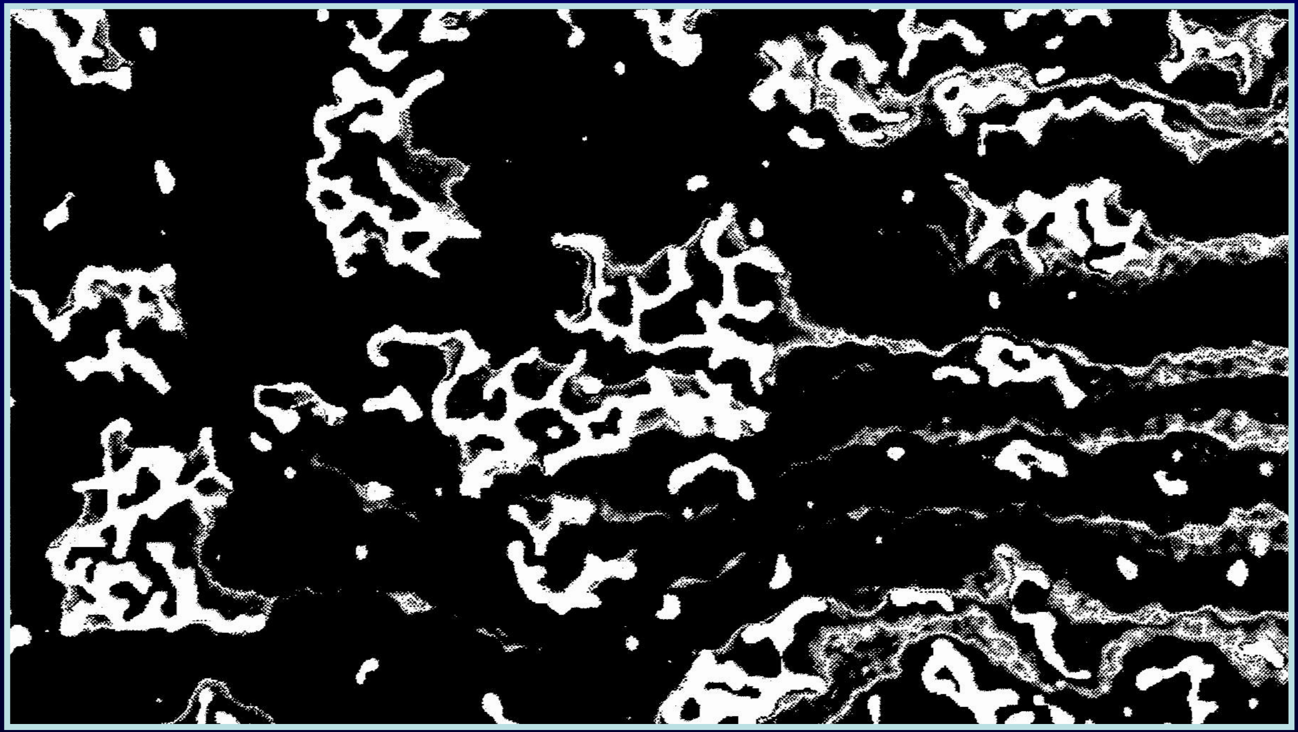


Gas Clogging During Spreading Basin Recharge

Victor Heilweil
US Geological Survey
Kip Solomon
University of Utah

USGS
science for a changing world

Entrapped gases in aquifers



From Glass and Nichols, GRL, 1995

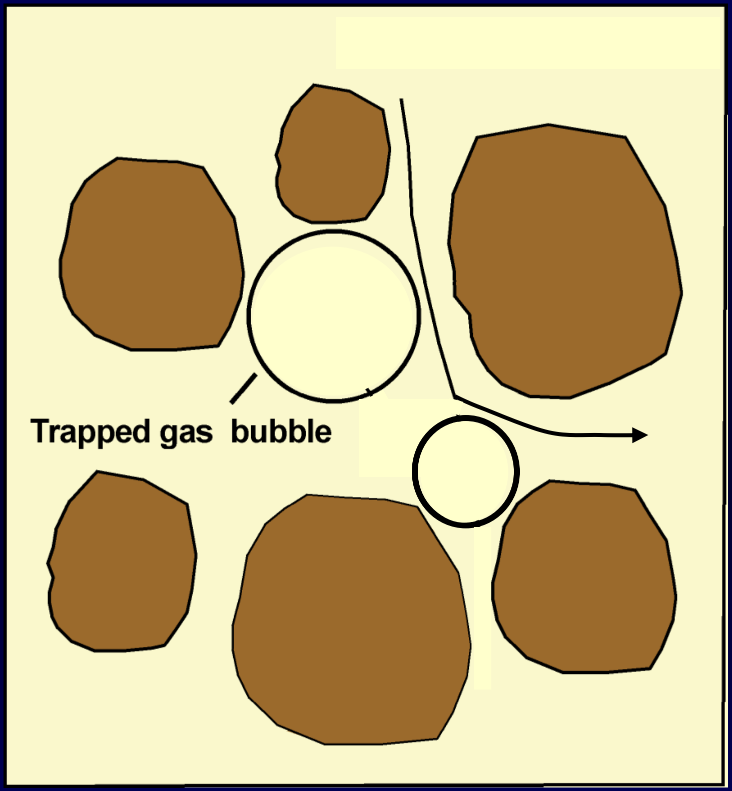
- Entrapped air is no longer connected to the atmosphere, occurring in the form of small, immobilized, disconnected bubbles (Faybishenko, WRR,1995)
- Entrapped air and other gases have been documented to occupy 7 to 20 % of otherwise saturated pore spaces (Beckwith and Baird, WRR, 2001; Heilweil et al., GW, 2004)

Sources of gas bubbles

- Entrapped air: bubbles formed during saturation as the water table rises in response to artificial or natural recharge (Constantz et al., SSSA, 1988; Holocher et al., EST, 2003)
- Biogenic gas production: CO_2 and CH_4 bubbles formed by respiration and decay of organic material in sediments beneath a spreading basin (Beckwith and Baird, WRR, 2001; Heilweil et al., BGM, 2009)
- Denitrification: N_2 gas bubbles produced during biodegradation by denitrifying bacteria (Oberdorfer and Peterson, GW, 1985)

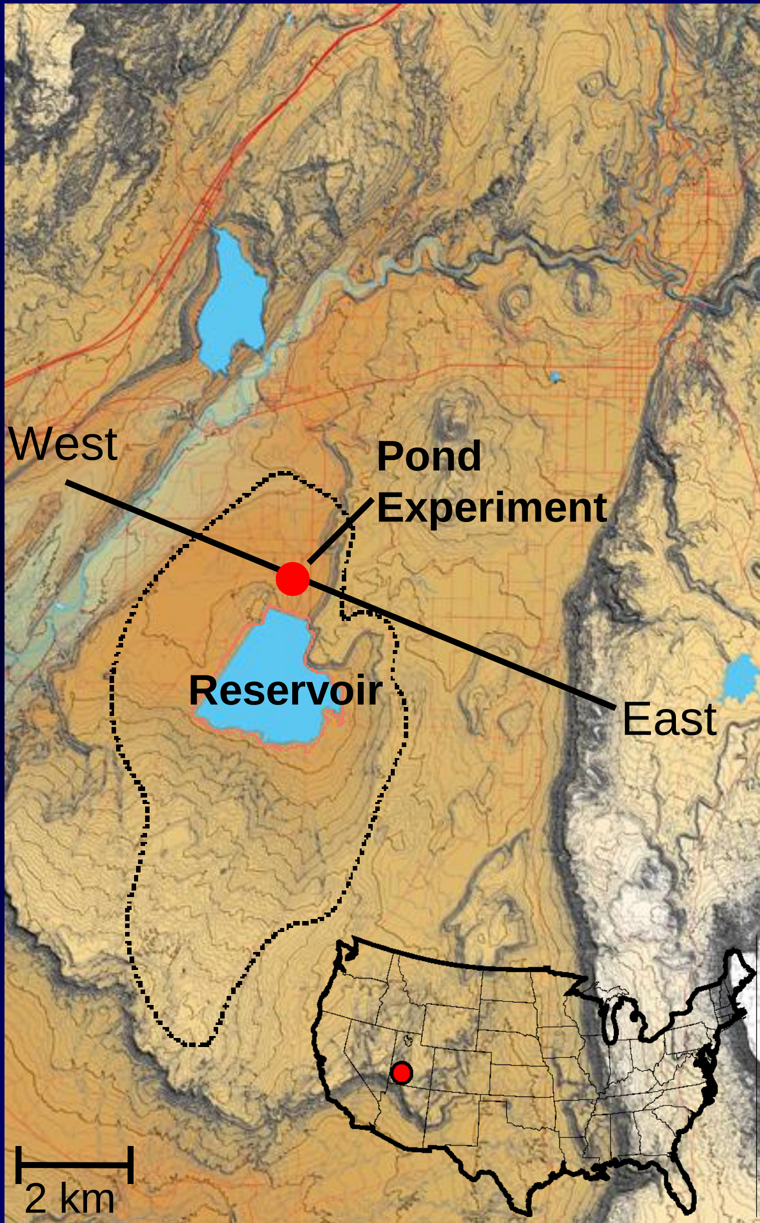
Pore-throat clogging reduces permeability

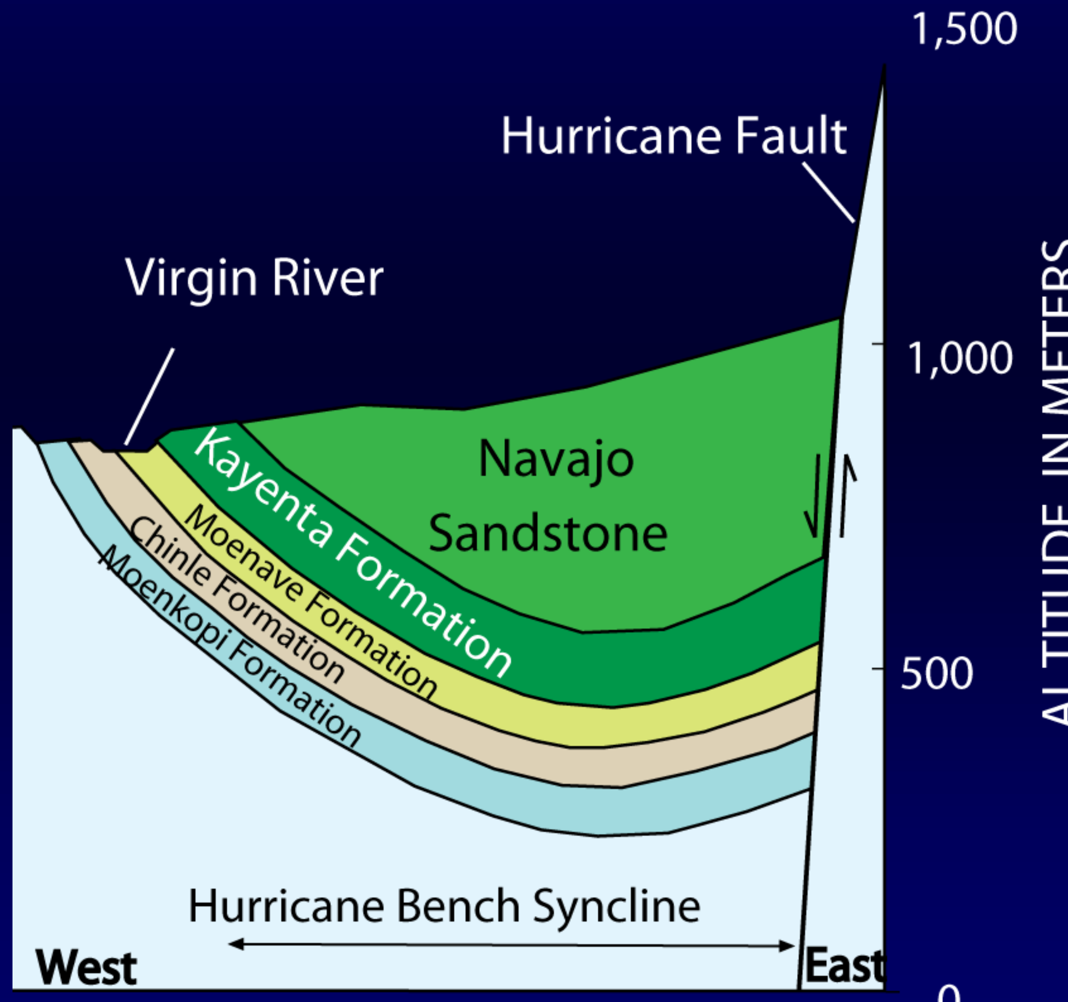
Entrapped gas bubbles typically block the largest pore throats, causing increased tortuosity and permeability reduction



Managed Aquifer Recharge at Sand Hollow

- Spreading basin MAR
- Navajo Sandstone Aquifer





Heilweil et al., USGS Tech Pub 116, 2000

Navajo Formation

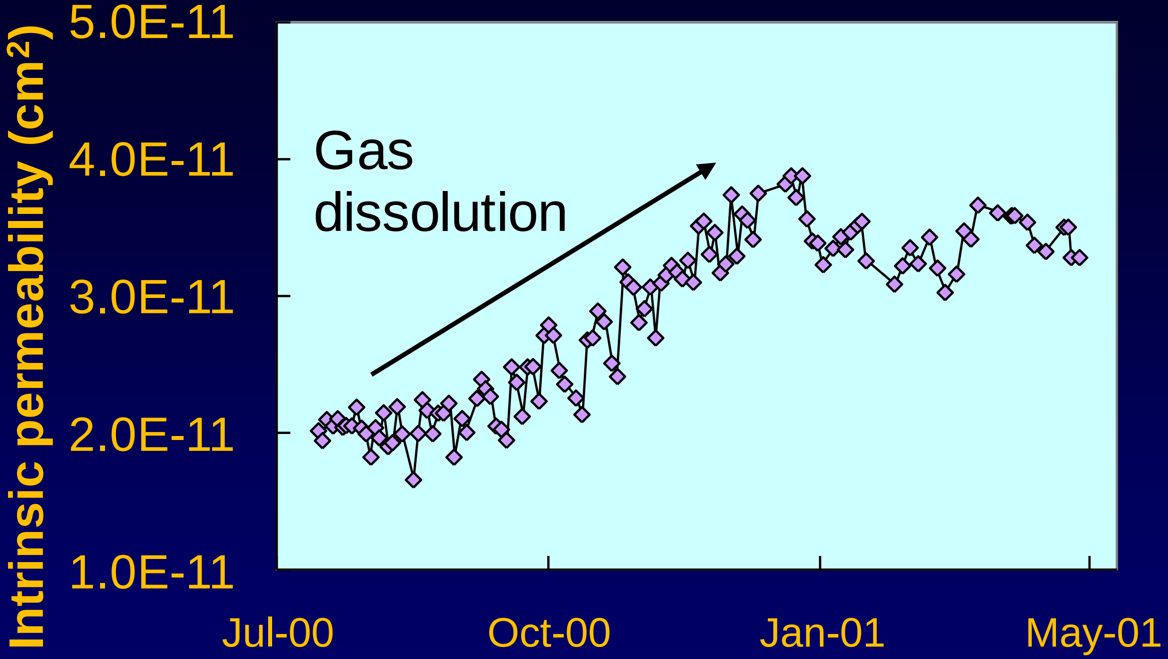
- Well-sorted eolian sandstone
- Porosity ~ 20 %
- K_{sat}~ 0.7 m/d

Pond Experiment, 2000-2001

<u>Goals</u>:
- Estimate long-term saturated infiltration rates
- Evaluate permeability reduction caused by trapped gas

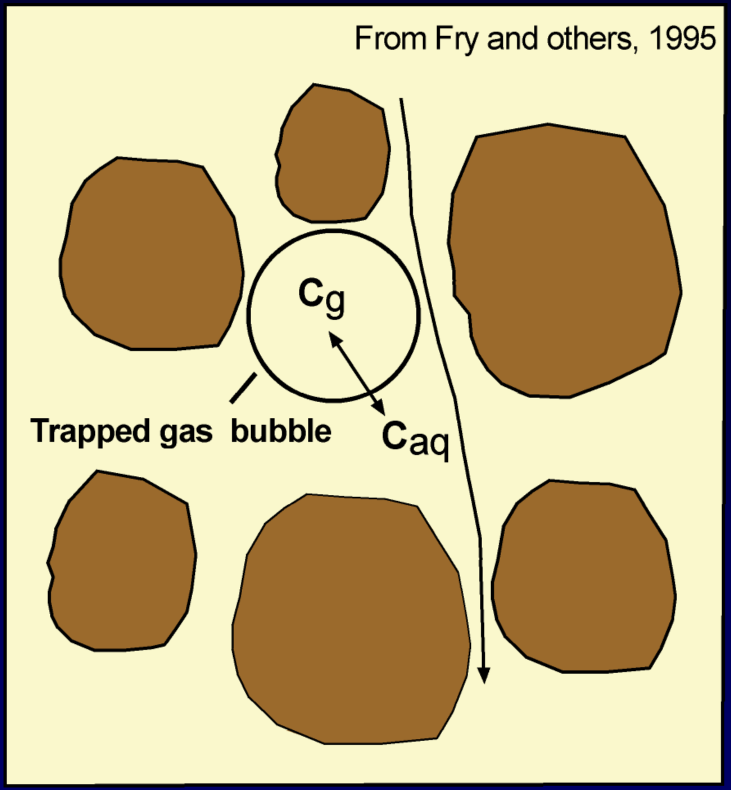
Intrinsic permeability doubled during the first four months

Increase caused by gas dissolution and 8% reduction in bubble volume with cooler temperatures cooled from 30˚ to 5˚C



Gas-partitioning tracer test

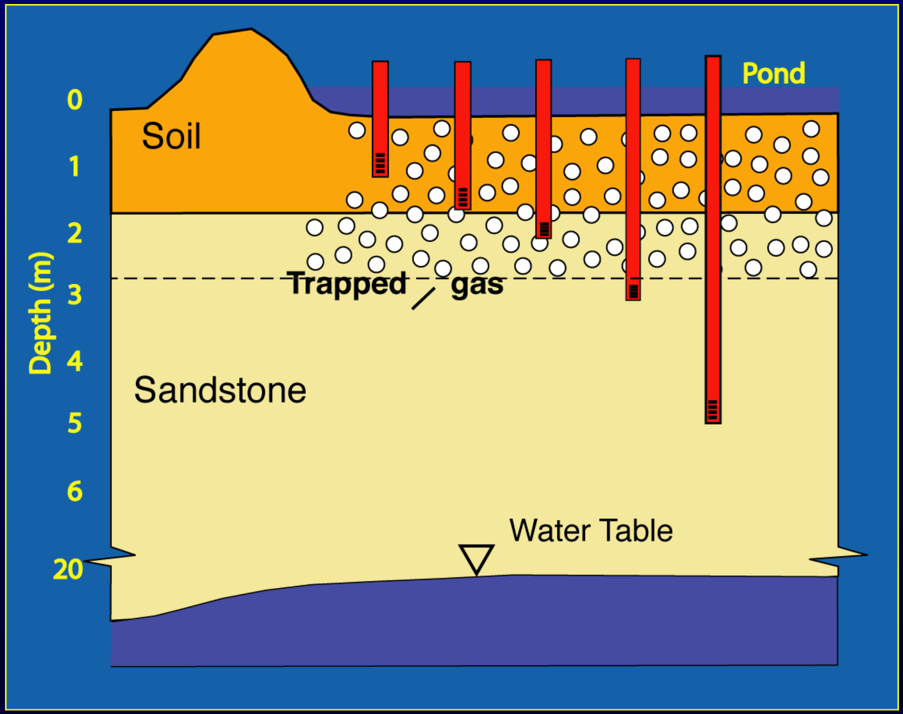
- Dissolved bromide and helium added to pond
- Helium is low solubility and partitions to gas phase, causing retardation



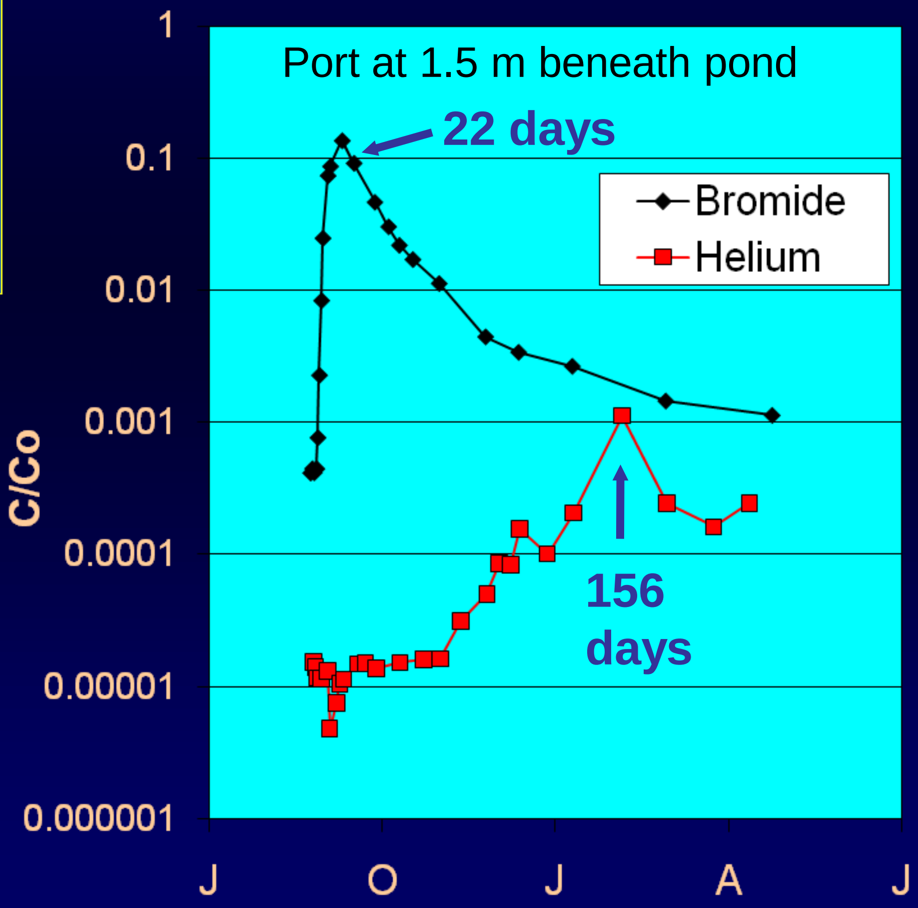
- Transfer from aqueous to gas phase determined by Henry's Law: $C_{aq} = H'C_g$

- If equilibrium transfer, gas-filled porosity calculated from retardation of helium:

$$\theta_g = (R-1)/H'$$

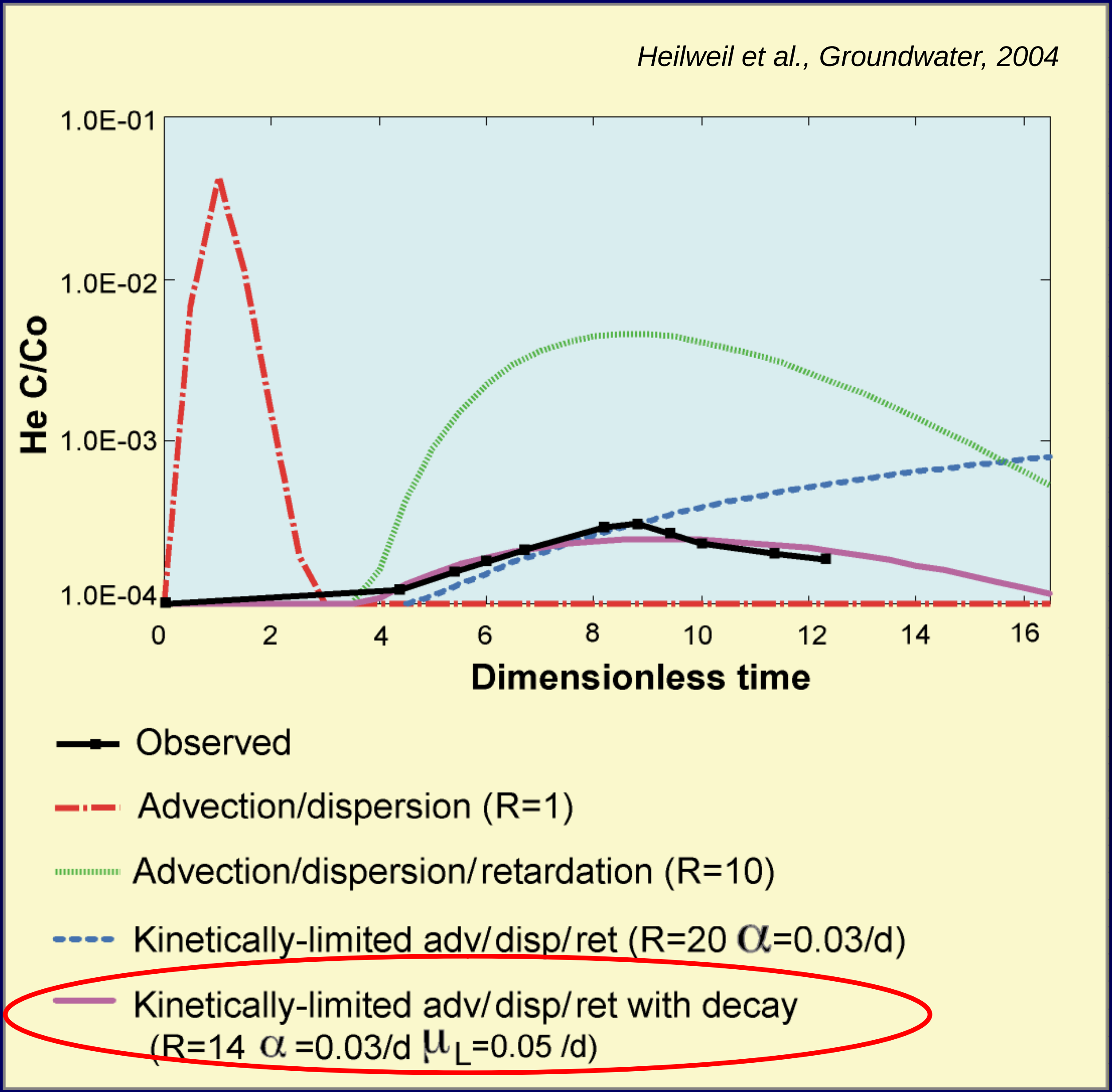


- Saturated conditions observed in upper 2 m beneath pond



- Helium substantially retarded at all ports
- Observed retardation factors of 2 to 12

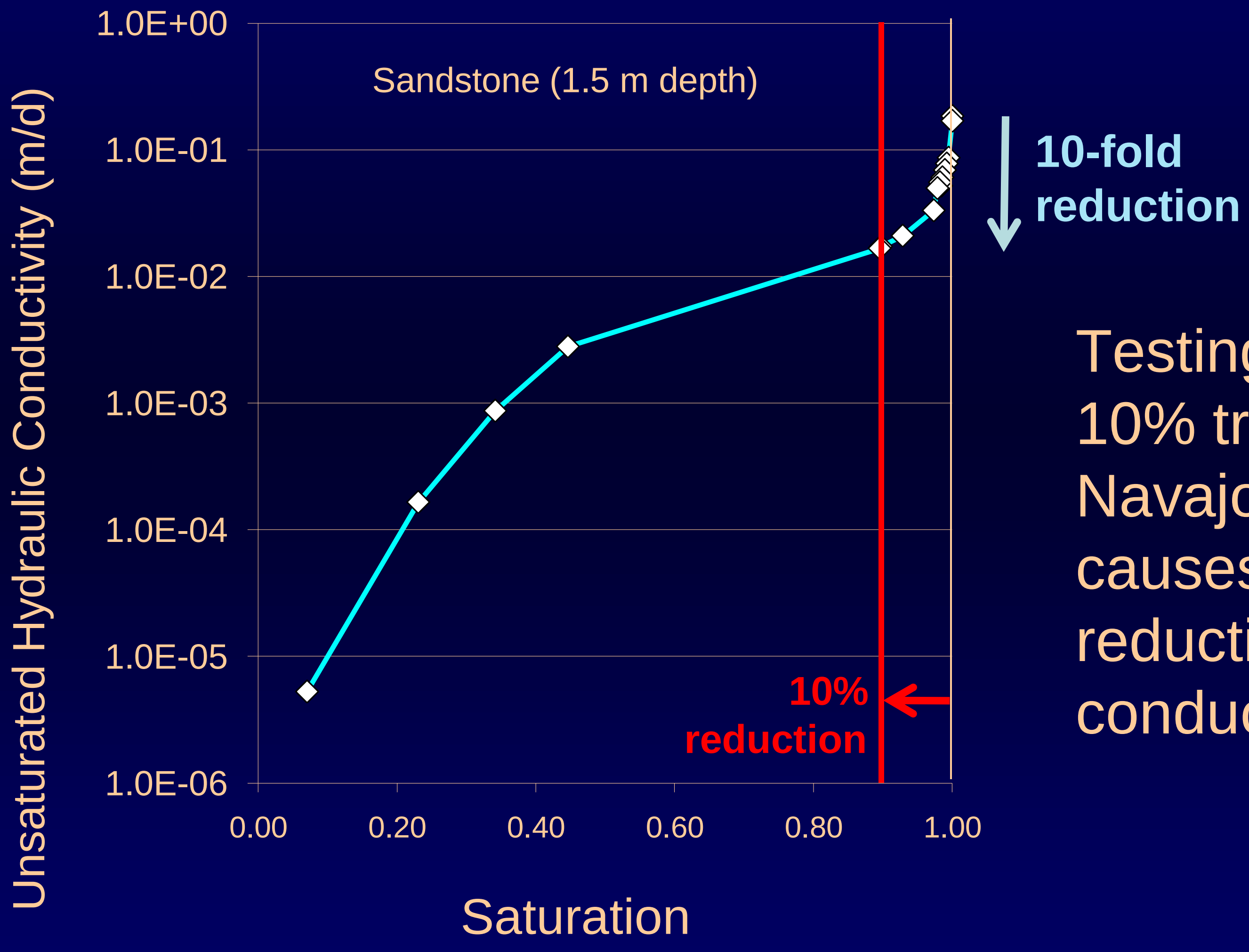
CXTFIT Modeling



(Heilweil et al., GW, 2004)

- Helium transfer was kinetically limited
- 7 to 13 % of porosity filled with trapped gas

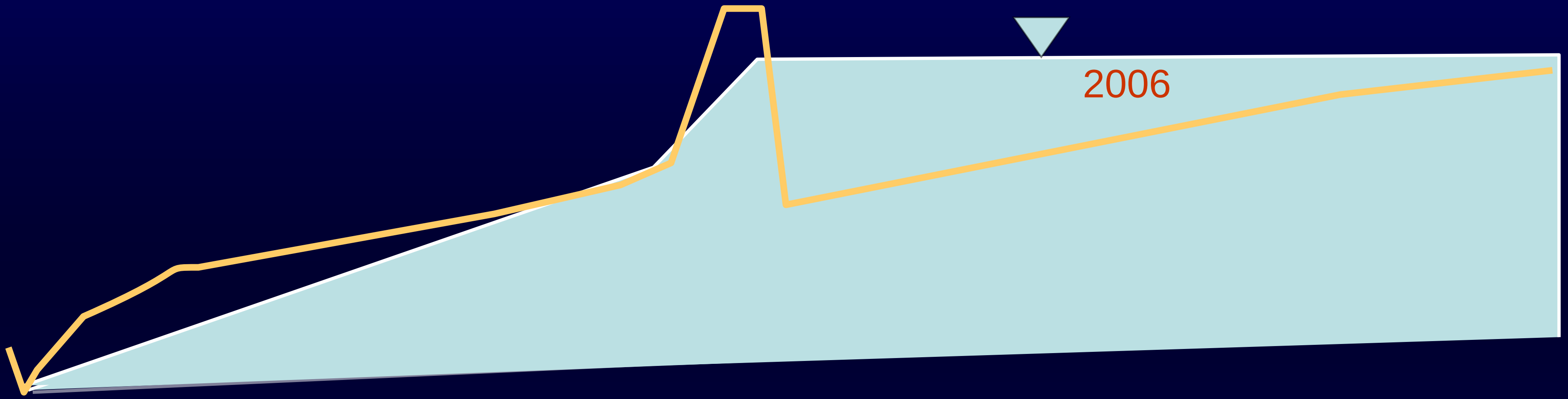
Unsaturated laboratory K(θ) results



Testing indicates that 10% trapped air in the Navajo Sandstone causes a 10-fold reduction in hydraulic conductivity


Sand Hollow Reservoir completed
2002

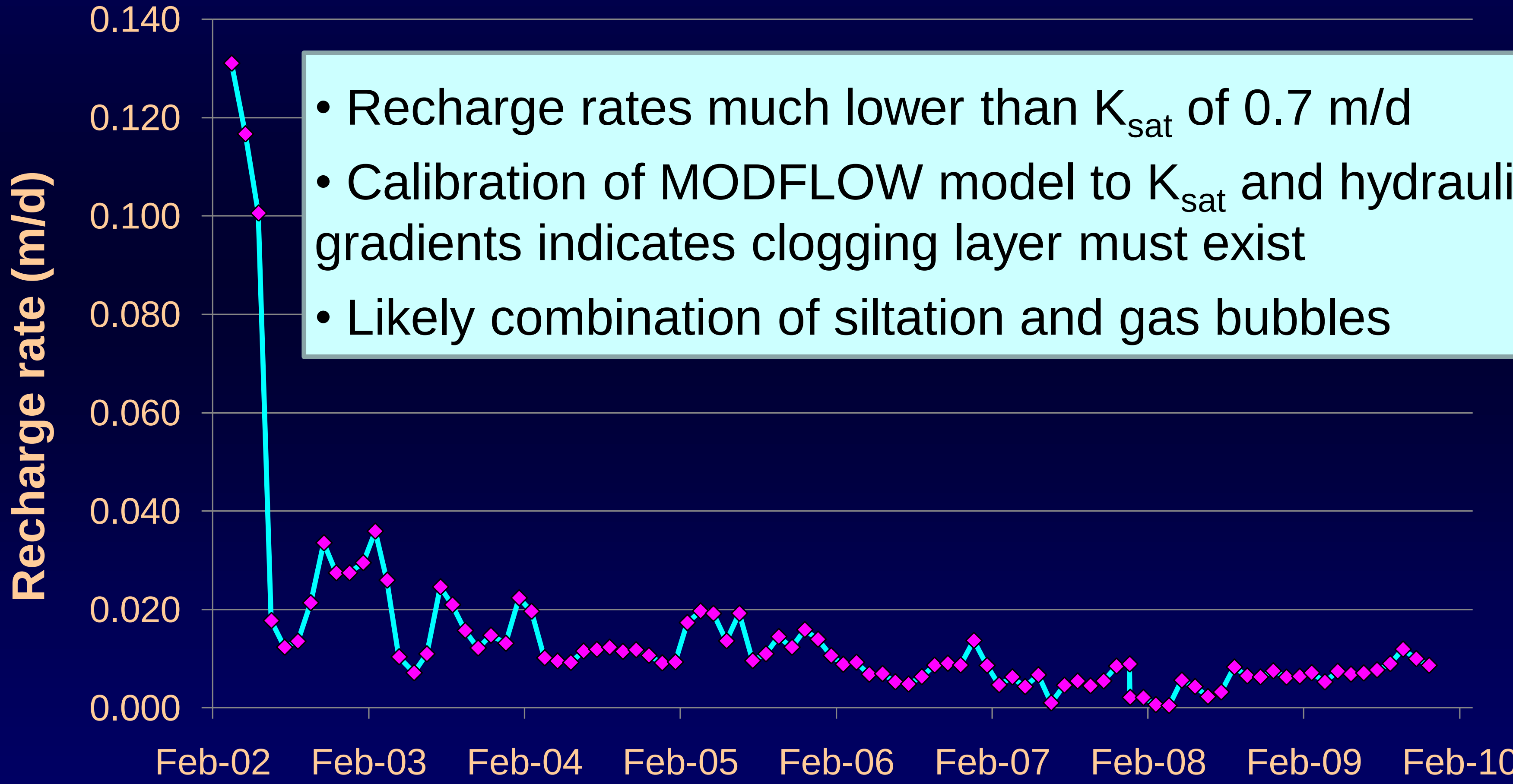
Conceptual Model



Vertical Exaggeration
100:1

Sand Hollow Reservoir Recharge

(Heilweil and Marston, USGS SIR, 2011)



- Recharge rates much lower than K_{sat} of 0.7 m/d
- Calibration of MODFLOW model to K_{sat} and hydraulic gradients indicates clogging layer must exist
- Likely combination of siltation and gas bubbles

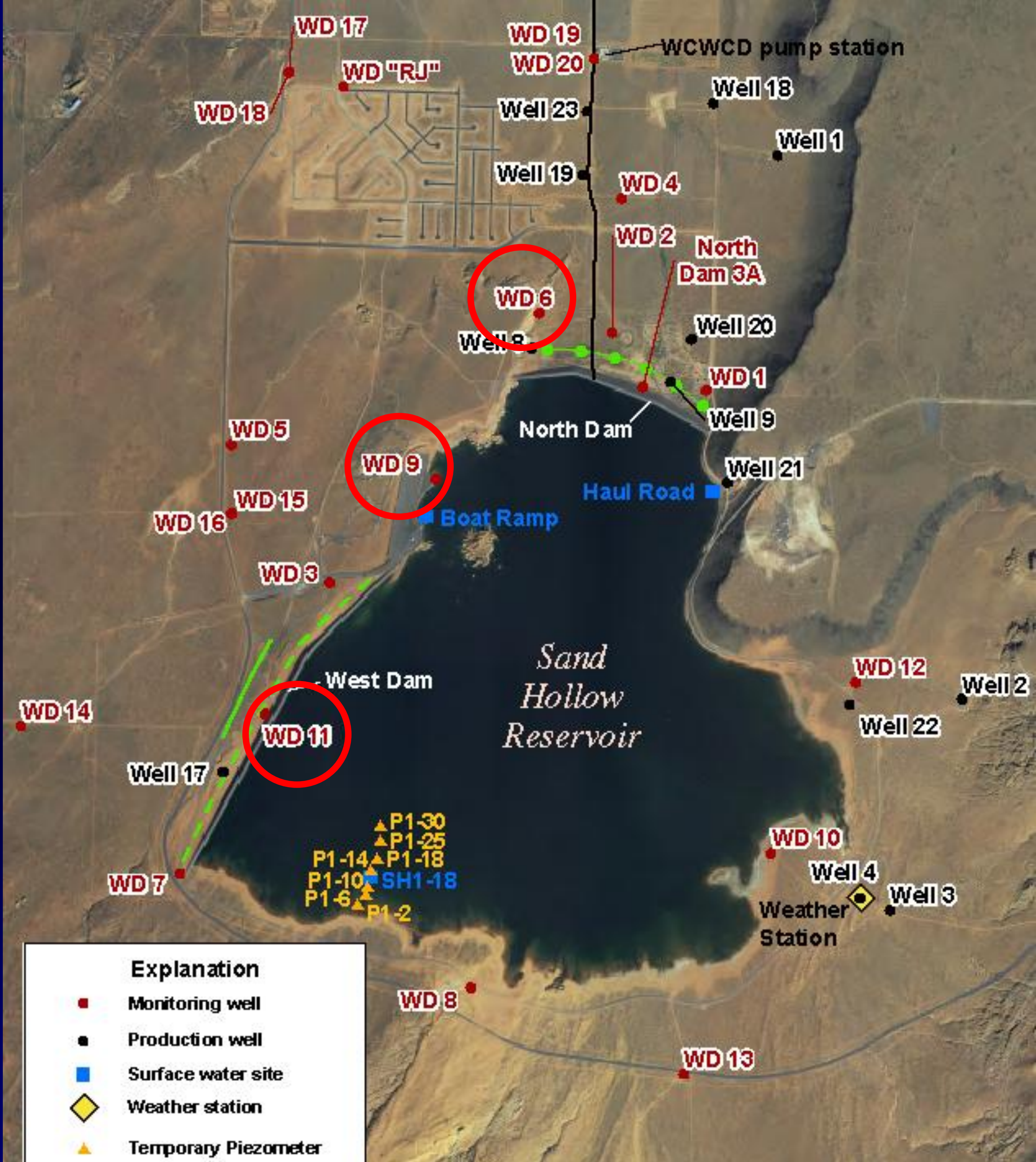
Dissolution of trapped gas bubbles

- Trapped gas bubbles will dissolve according to Henry's Law
- Dissolution of gases can occur as quickly as hours or as slow as years (Glass and Nicholl, GRL,1995; Heilweil et al., GW, 2004)
- Dissolution rate dependent on:
  - Water temperature (more soluble in cooler water)
  - Hydrostatic head (more soluble under higher pressure)
  - Rate of flow by gas bubble (number of pore volumes)
  - Gas solubility (O_2 dissolves more readily than N_2)

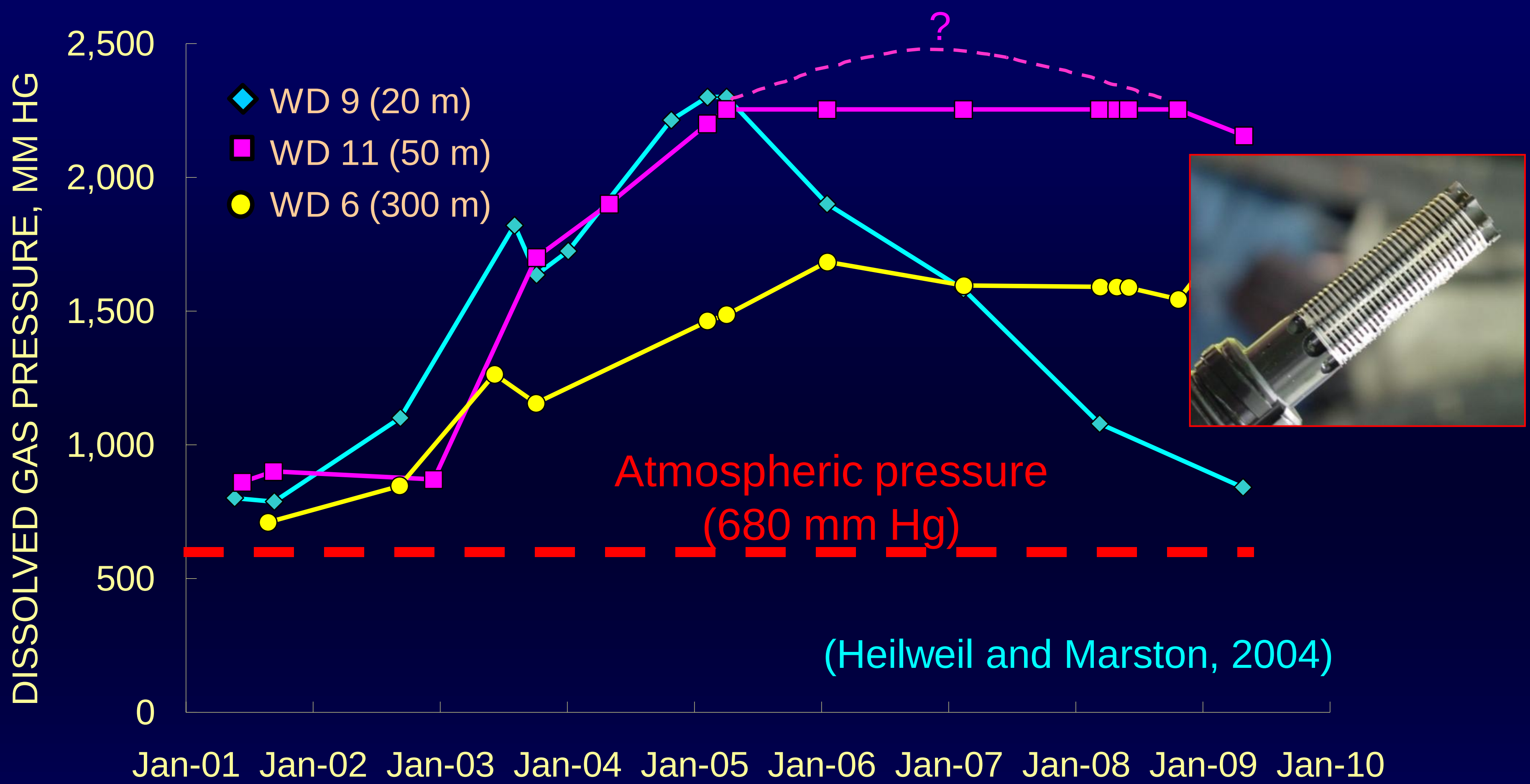
Excess Gas/Air

- Trapped gas/air dissolved to become excess gas/air (Heaton and Vogel, 1981)
- Since surface water contains little excess air, it can be used as a tracer of artificial recharge (Clark and Hudson, 2005; Massmann and Sultenfub, J. Hydrol. 2008)
- Potential tracers of artificial recharge include:
  - Total dissolved gas pressure (TDGP)
  - Dissolved oxygen (DO)
  - Neon excess (Δ Ne)
  - Noble-gas excess air (E_a)

Near-field monitoring wells for dissolved-gas sampling



Total Dissolved-Gas Pressure (TDGP)

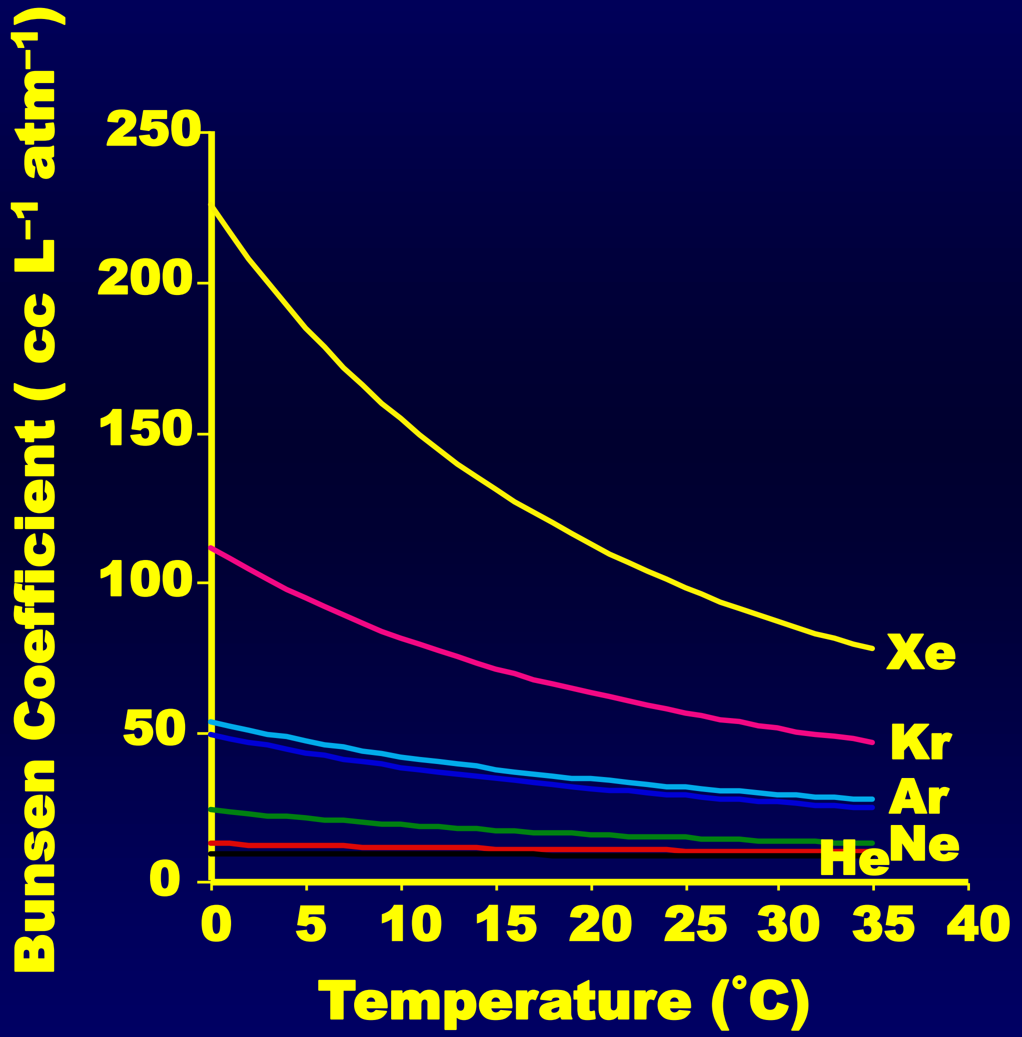


- Conservative tracer
- Measured with TDGP probe or Diffusion Sampler
- High pressures (> 3 atmospheres) = large amount of trapped gas

Dissolved Gas Tracer Peaks

Site	Distance from Reservoir (m)	Peak TDGP (mm Hg)	Peak DO (mg/L)	Peak Neon Excess
WD 9	20	>2250	26	250%
WD 11	50	>2250	25	320%
WD 6	300	1700	22	160%

Noble Gases



- Each gas has different solubility
- If a bubble partially dissolves, dissolved gases will be preferentially enriched in heavier noble gases (Xe, Kr)
- This fractionation factor (F) can be used to evaluate when trapped gas is dissolved

Calculation of time to dissolve trapped air

Assumptions:

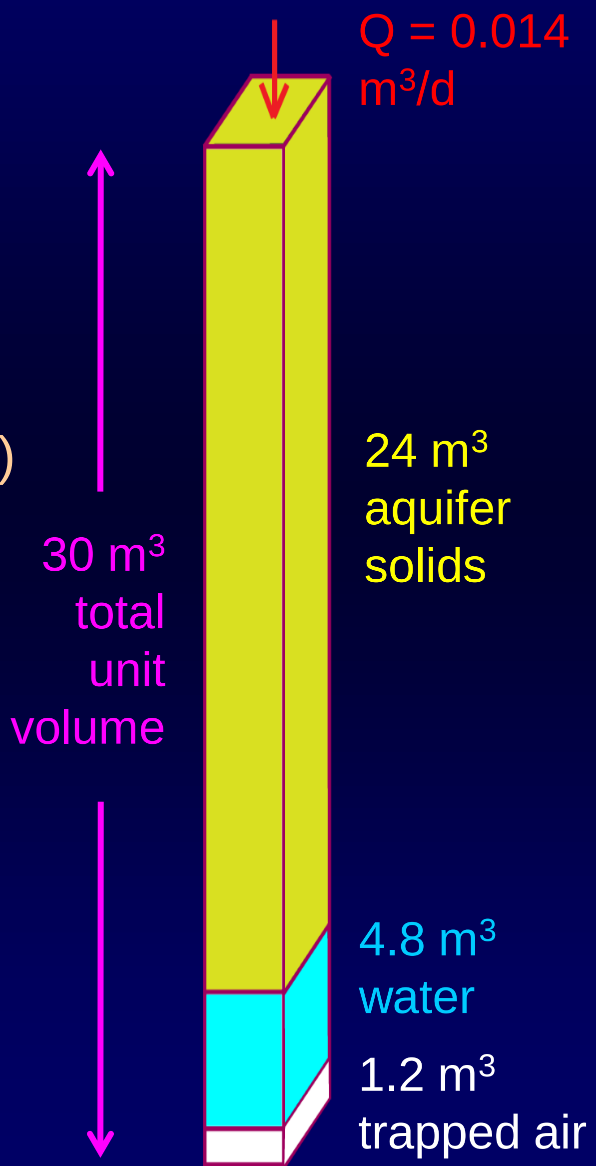
- 30 m^3 total volume
- 30-m rise in water table x 20% porosity = 6 m^3
- 20% air-filled porosity = 1.2 m^3 trapped air
- 80% saturated porosity = 4.8 m^3 water
- Trapped air predominantly N_2 (78% of atmosphere)
- Increased nitrogen solubility with hydrostatic pressure

Calculations:

- 45 m^3 of water to dissolve trapped air
- 9 pore volumes at Q = 0.014 m^3/d

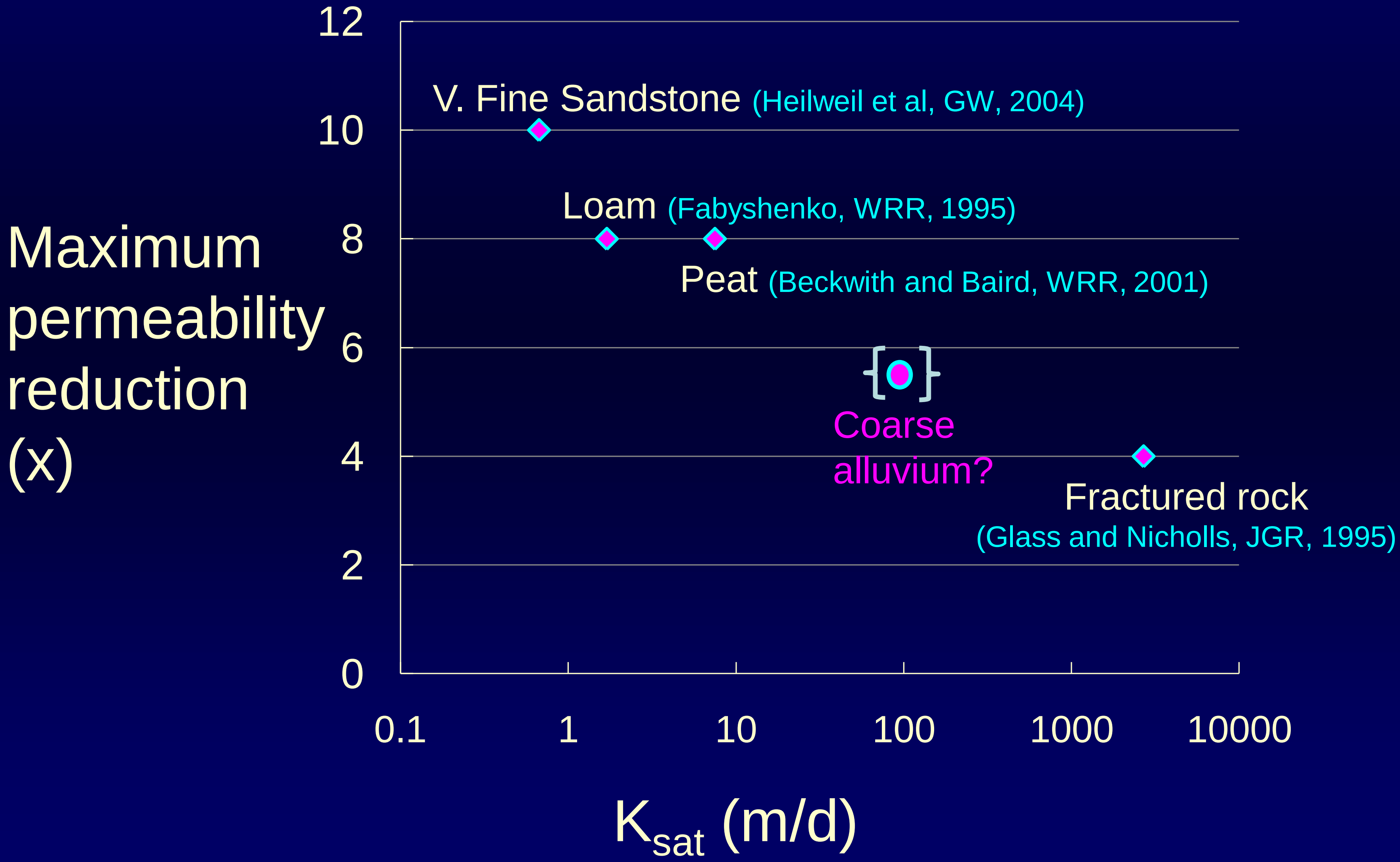
➢ 9 years to dissolve majority of trapped air

➢ Gas dissolution by 2010?



Increased recharge rates during 2008-2009 may be due to gas dissolution around edges of reservoir

Permeability reduction as function of hydraulic conductivity (K_{sat})



Same volume of trapped gas would dissolve much faster in more permeable materials

Material	K_{sat} (m/d)	$K(\theta)$ (m/d)	Q (m^3/d)	Estimated Dissolution Time (days)
Sandstone	0.7	0.12	0.014	3,200
Medium sand	5	1.04	0.125	360
Gravel	50	13.9	1.667	30
Cobbles	250	104	12.5	4

Summary

- Entrapped gas clogs pore throats and causes significant permeability reduction

- Effects are more pronounced in finer-grained materials

- Entrapped gas will eventually dissolve with increased hydrostatic pressure

- The dissolution process can be monitored with TDGP, DO, and noble gases (Neon Excess, A_{e}, F)

- It may take about a decade to dissolve most of the trapped gas beneath Sand Hollow; much less time for recharge facilities located on higher permeability sediments

Acknowledgements

Corey Cram and Ron Thompson, Washington County Water District

Dennis Watt, U.S. Bureau of Reclamation

Rut Sanchez, Gema Ortiz, Jose Antonio, Institúto Geológico y Minero de Espaňa

References

Beckwith and Baird, 2001, Effect of biogenic gas bubbles on water flow through poorly decomposed blanket peat, *Water Resources Research* 37 (3): 551-558.

Clark and Hudson, 2005, Excess Air: a new tracer for artificially recharged surface water, *Proceedings of the 5th International Symposium on Management of Aquifer Recharge*, UNESCO, Berlin: 342-347.

Constantz, Herkelrath, and Murphy, 1988, Air encapsulation during infiltration, *Soil Science Society of America Journal* 52: 10-16.

Faybishenko, 1995, Hydraulic behavoir of quasi-saturated soils in the presence of entrapped air: Laboratory experiments, *Water Resources Research* 31 (10): 2421-2435.

Fry, Istok, Semprini, O'Reilly, and Buscheck, 1995, Retardation of dissolved oxygen due to a trapped gas phase in porous media, *Ground Water* 33 (3): 391-398.

Glass and Nicholl, 1995,Quantitative visualization of entrapped phase dissolution within a horizontal flowing fracture, *Geophysical Research Letters* 22 (11): 1413-1416.

Heaton and Vogel, 1983, "Excess Air" in groundwater, *Journal of Hydrology* 50: 201-216.

Heilweil and Marston, 2011, Assessment of artificial recharge at Sand Hollow Reservoir, Washington County, Utah, Updated to conditions through 2009*, U.S. Geological Survey Scientific Investigations Report 2011-XXXX.*

References (cont.)

Heilweil, Solomon, Perkins, and Ellett, 2004, Gas-partitioning tracer test to quantify trapped gas during recharge*, Ground Water 42 (4)*: 589-600.

Holocher, Peeters, Aeschbach-Hertig, Kinzelbach, and Kipfer, 2003, Kinetic model of gas bubble dissolution in groundwater and its implications for the dissolved gas composition, *Environmental Science and Technology* 37 (7): 1337-1343.

Massmann and Sultenfub, 2008, Identification of processes affecting excess air formation during natural bank filtration and managed aquifer recharge, *Journal of Hydrology* 359: 235-246.

Oberdorfer and Peterson, 1985, Waste-Water Injection: Geochemical and biogeochemical clogging processes, *Ground Water* 23 (6): 753-761.