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Beneficial hydraulic fracture propagation during in situ chemical oxidation

Simon A. Mathias[1], Adrian P. Butler[1], Geoff Fowler[1], Ian Fielding[2], Adrian Shields[3], John Barber[4], Paddy Daly[5]

1. Imperial College London, 2. WorleyParsons,
3. Environment Agency, 4. National Grid Property Holdings Ltd

Contaminant Source Zone Characterisation and Remediation
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Abstract

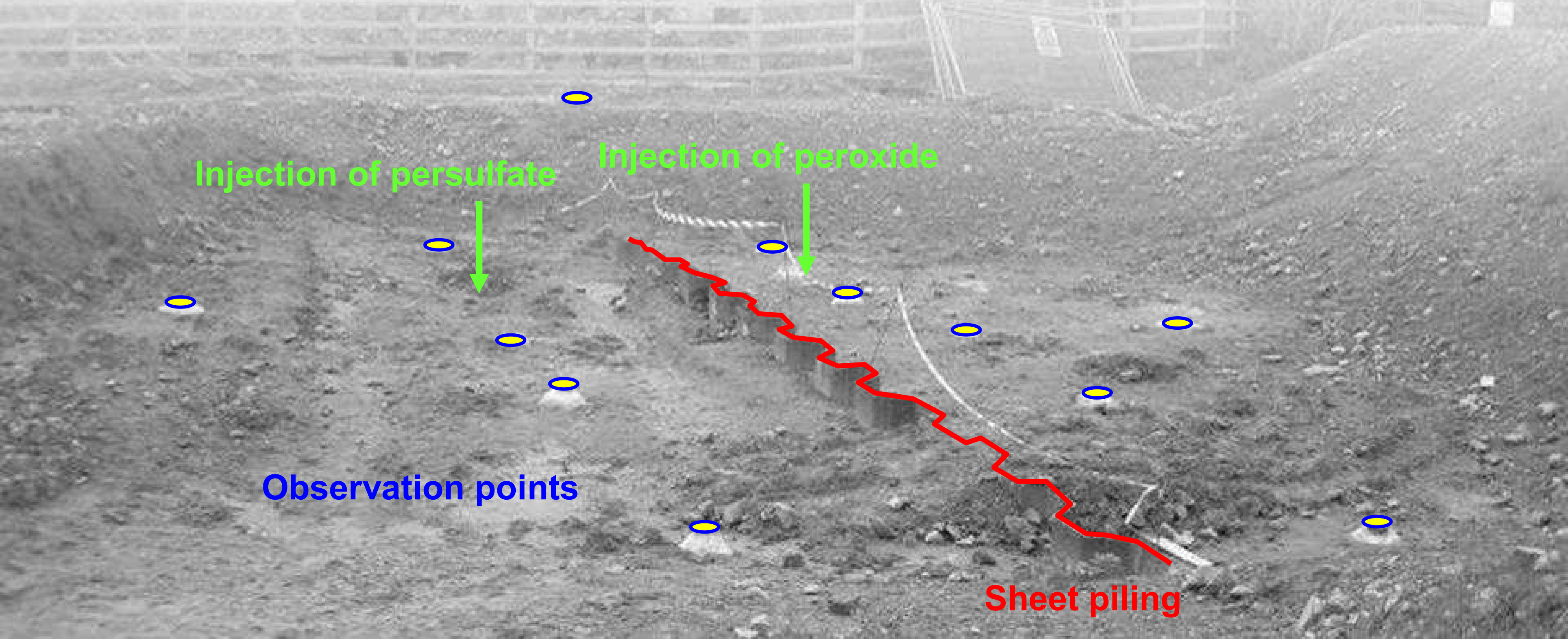
There is a continuous increase in the use of In-Situ Chemical Oxidation (ISCO) techniques for the treatment of contaminated sites in the UK. ISCO involves the direct delivery of chemical oxidants to contaminants residing in the subsurface such that rapid and total transformation to carbon dioxide or less toxic daughter compounds is achieved. Commonly used oxidants include permanganate (1.7V), hydrogen peroxide (1.8V), ozone (2.1V), persulfate (2.1V), activated persulfate (2.6V), and catalysed hydrogen peroxide (2.8V). Delivery is generally via an array of high pressure well-points. The spacing of injection points is generally planned on the basis that individual injection points produce a near-spherical plume of oxidant. As part of a Technology Strategy Board project, a set of intensely monitored ISCO injections of persulfate and catalysed hydrogen peroxide were performed at a contaminated site in the North of England. Observed variables included groundwater pressure, electrical conductivity, oxidant concentration, tracer concentration, redox potential, dissolved oxygen and pH. The observed spatial distributions of pressure and tracer indicated that the injected oxidant became distributed in areally extensive zones of limited vertical thickness. The site geology is relatively isotropic and homogeneous, hence such behaviour is postulated to be due to hydraulic fracturing. Hydraulic fractures are known to develop when pore pressures exceed the in situ minimum principal stress. ISCO injection typically occurs at relatively shallow depths (5 to 20 m below ground surface). Therefore hydraulic fracturing can be expected at relatively modest injection pressures. Interestingly, emplacing oxidant in thin self-driven hydraulic fractures is operationally preferable to spherical plumes due to the associated increase in surface area. In this paper, it is proposed that hydraulic fracturing is an improved delivery mechanism for ISCO and provides a new basis for injection-point array design.

Introduction

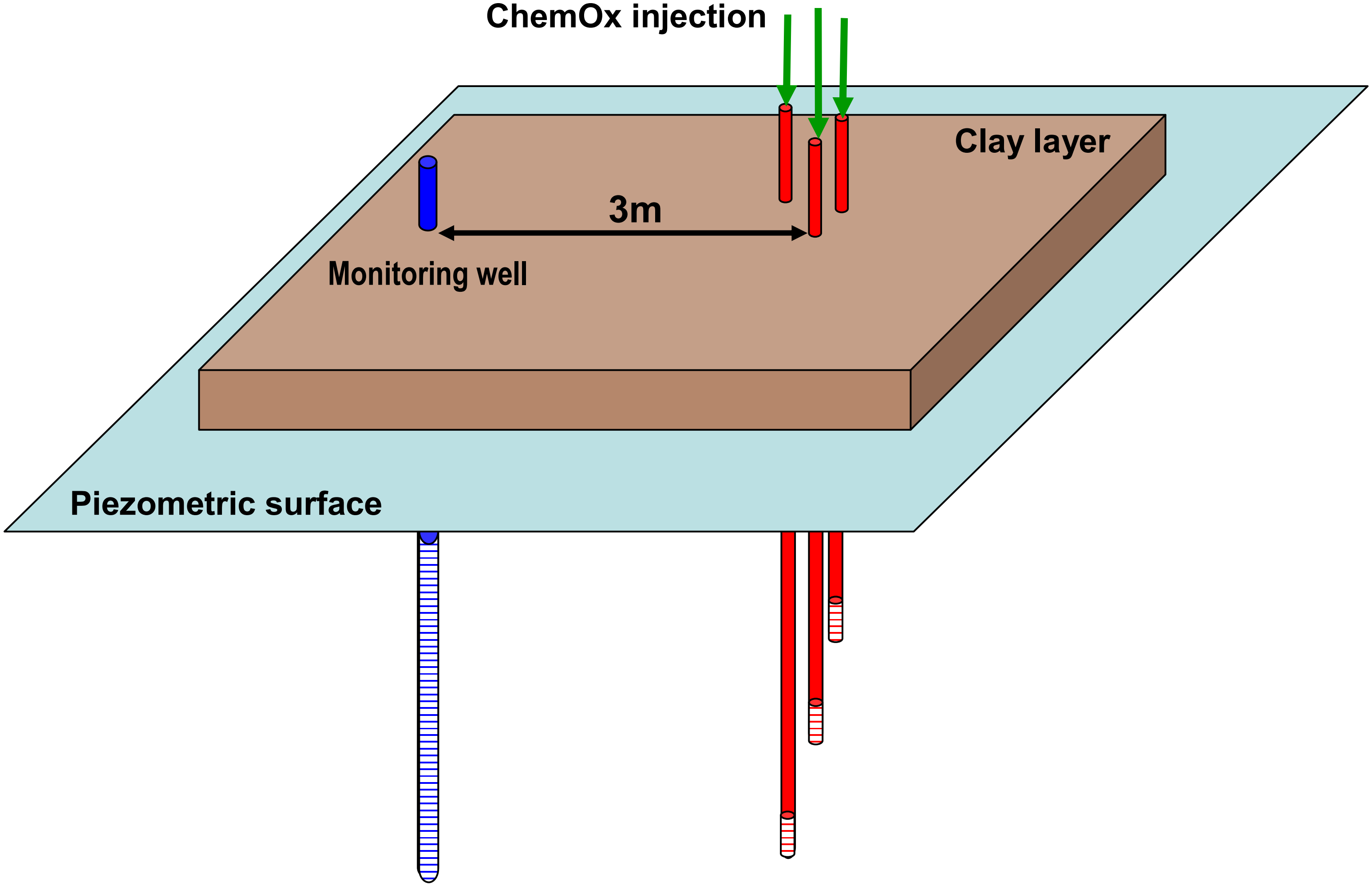
- There is a continuous increase in the use of In-Situ Chemical Oxidation (ISCO) techniques for the treatment of contaminated sites in the UK.
- ISCO involves the direct delivery of chemical oxidants to contaminants residing in the subsurface such that rapid and total transformation to carbon dioxide or less toxic daughter compounds is achieved.
- Commonly used oxidants include permanganate, hydrogen peroxide, ozone, persulfate, activated persulfate and catalysed hydrogen peroxide.
- Delivery is generally via an array of high pressure well-points.
- The spacing of injection points is generally planned on the basis that individual injection points produce a near-spherical plume of oxidant.

Field programme

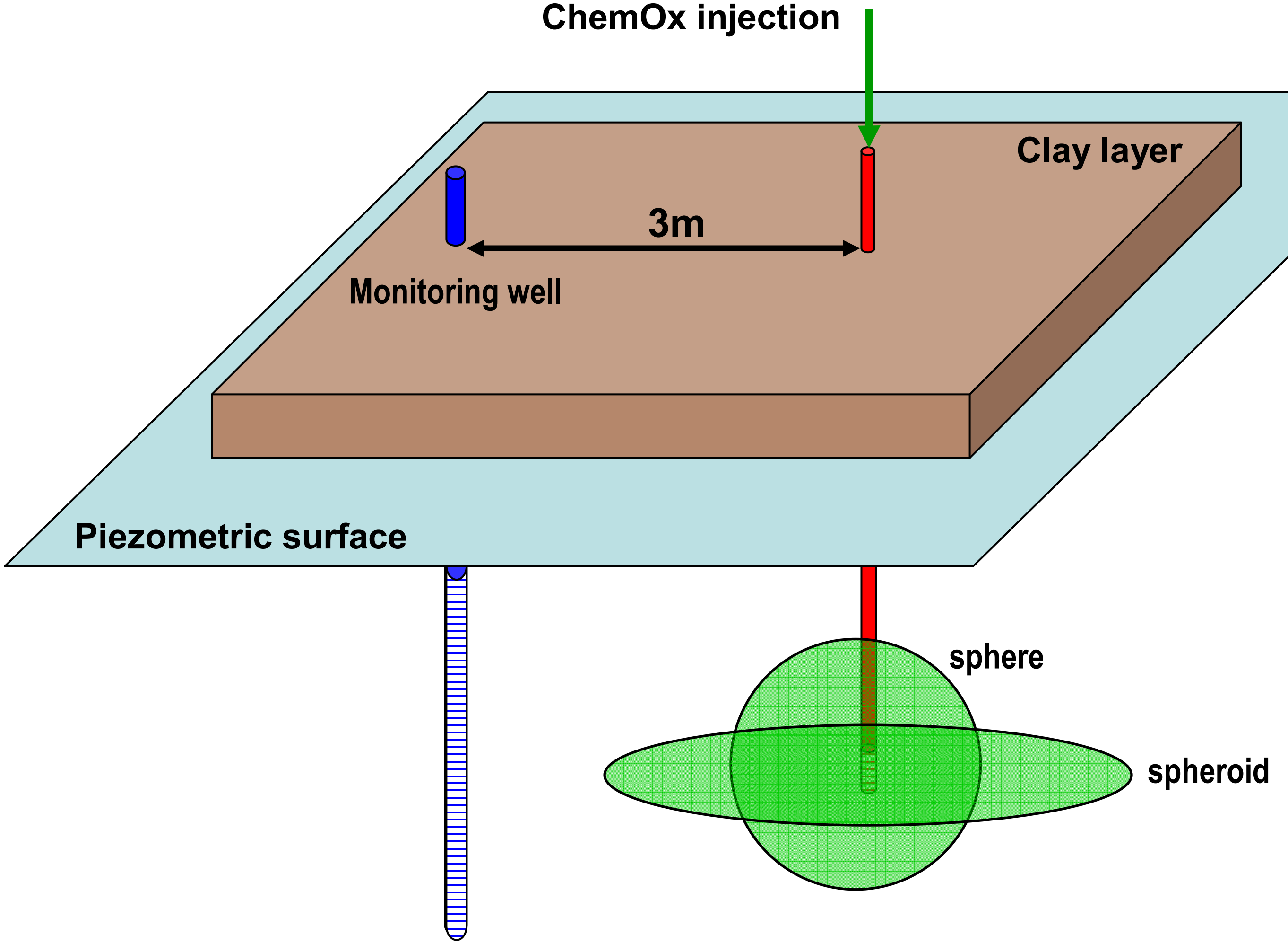
- As part of a Technology Strategy Board project, a set of intensely monitored ISCO injections were performed at a contaminated site in the North of England.
- 4000 L of 2% v/v sodium persulfate injected over 1.33 hrs.
- 4000 L of 2.5% v/v catalysed hydrogen peroxide injected over 2.2 hrs.
- Lithium bromide was added to the oxidant prior to injection - conservative tracer.



Schematic of system

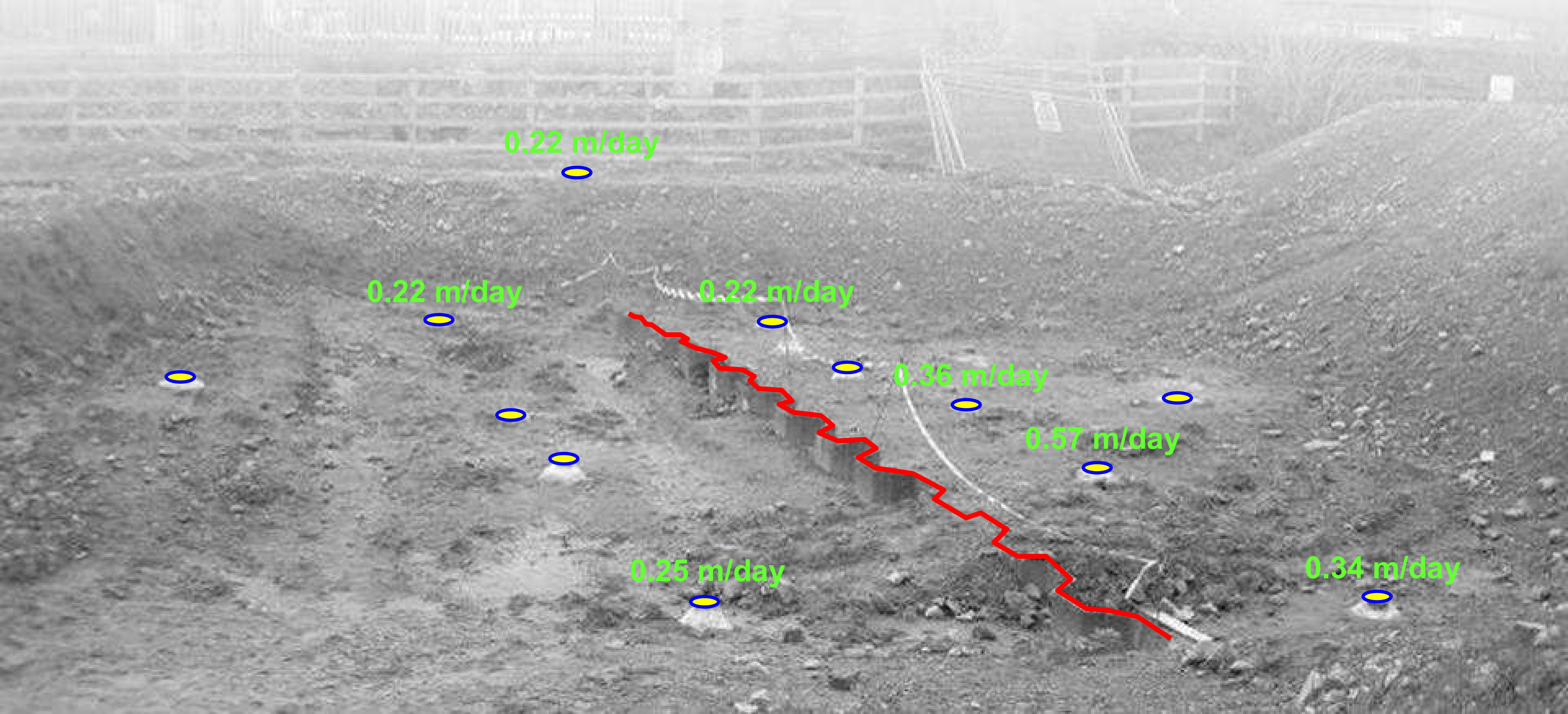


Schematic of system

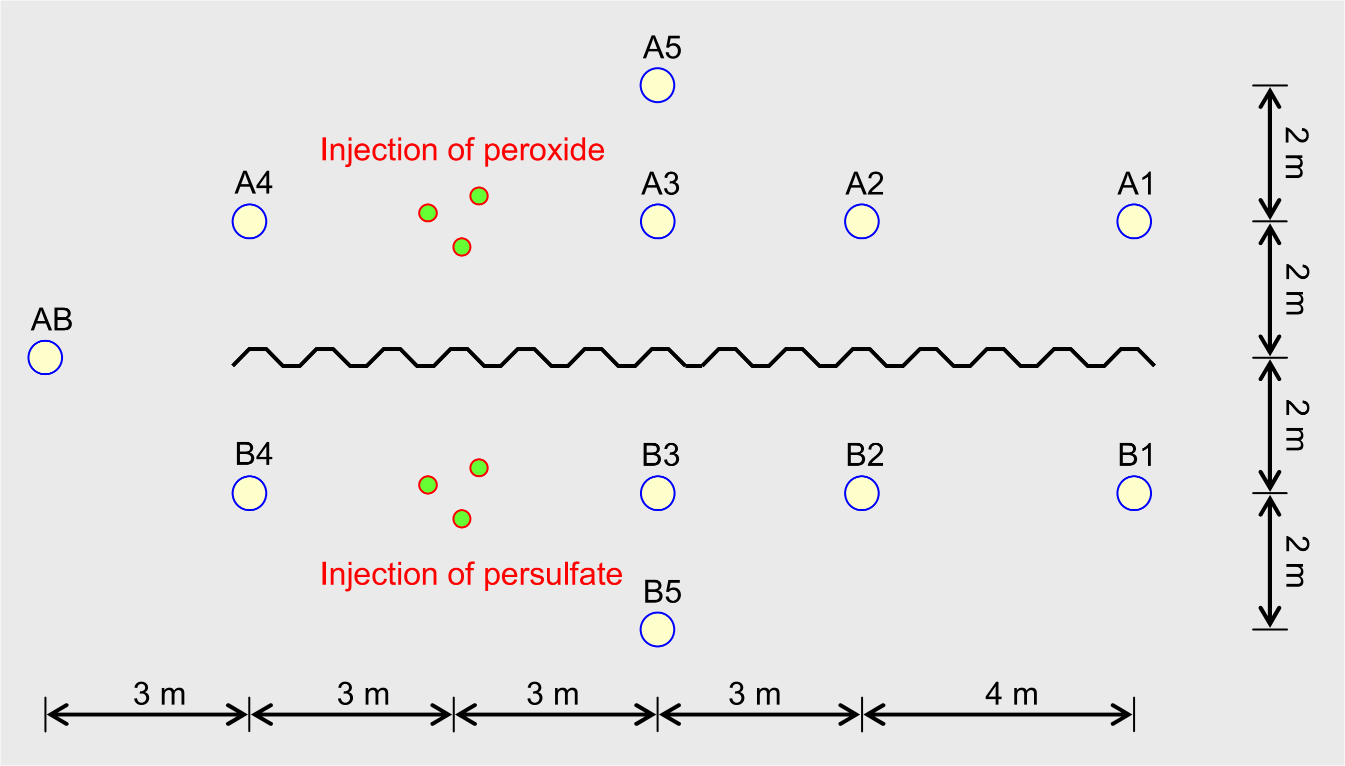


Hydrogeology

- Hydraulic conductivity obtained via slug testing.
- Water levels are about 1 m below ground surface.
- Water levels indicate minimal water movement prior to oxidant injections.

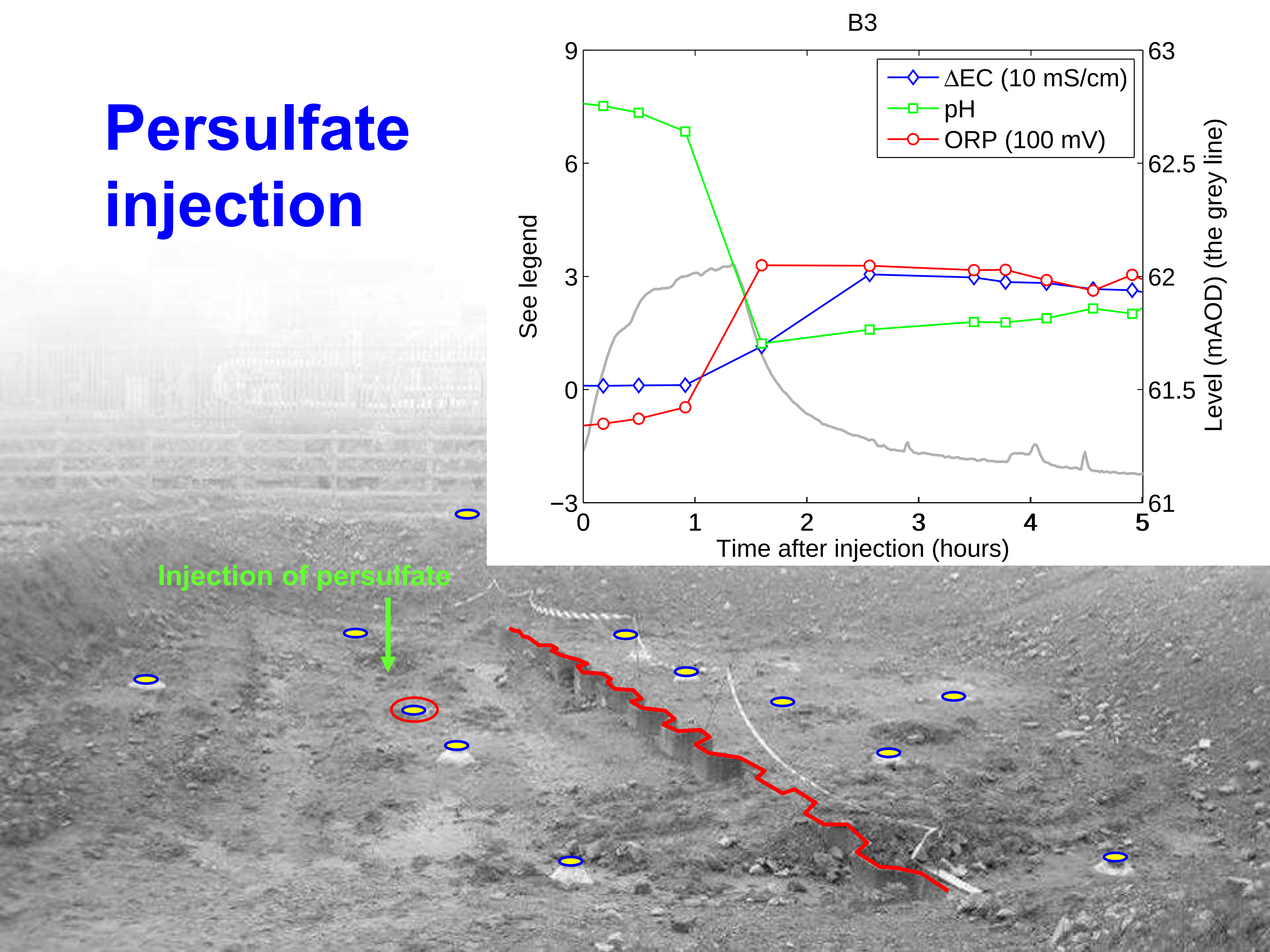


Injection volume and radius

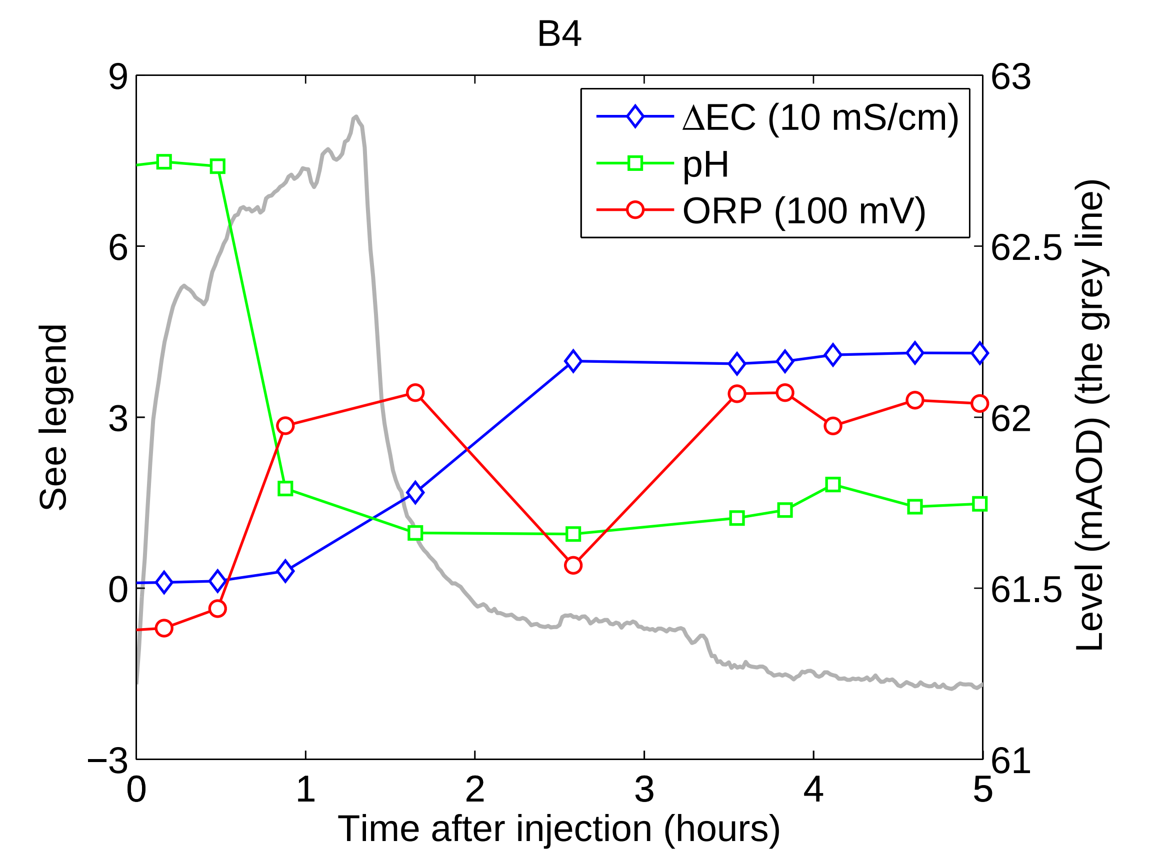


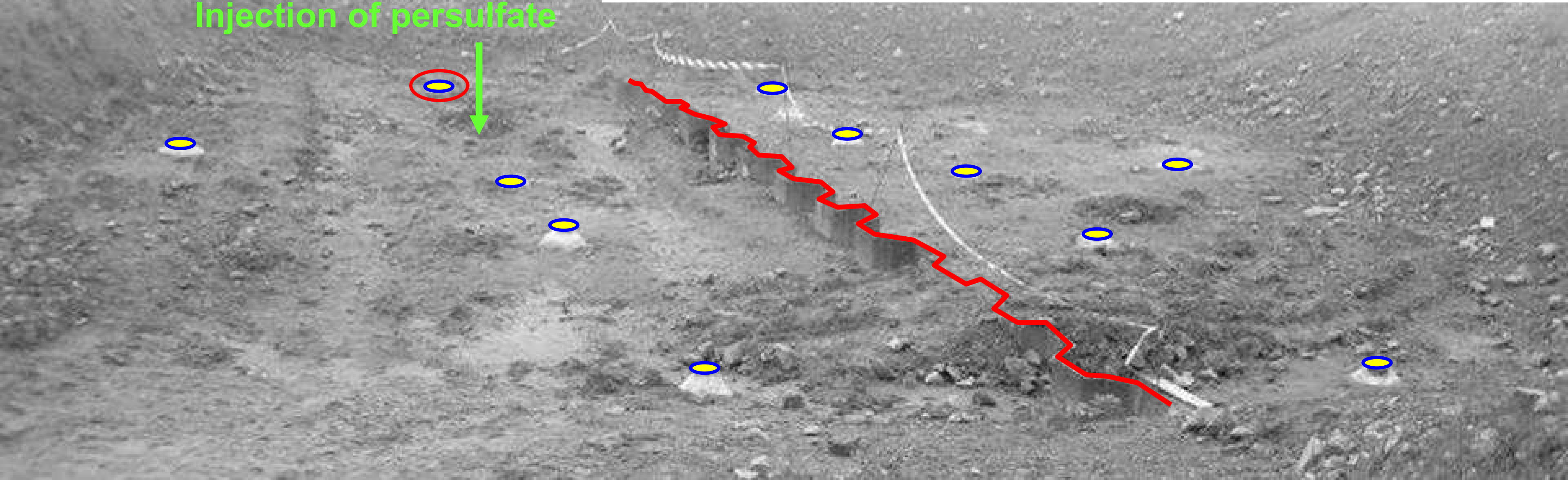
- Total volume of oxidant injected was 4 m^3
- Split between three points gives 1.33 m^3
- Assuming a porosity of 0.25 gives 5.33 m^3
- Assuming a spherical geometry gives a radius 1.08 m
- The oxidant shouldn't reach the monitoring points?

Persulfate injection

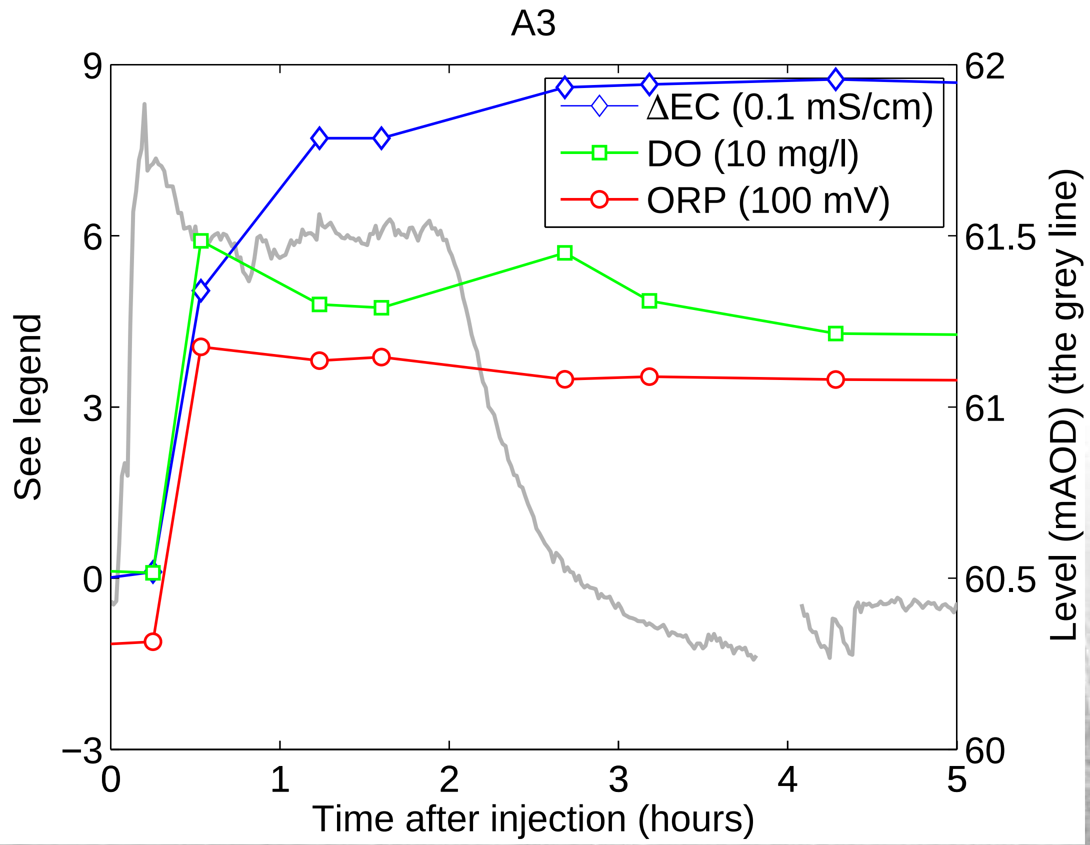


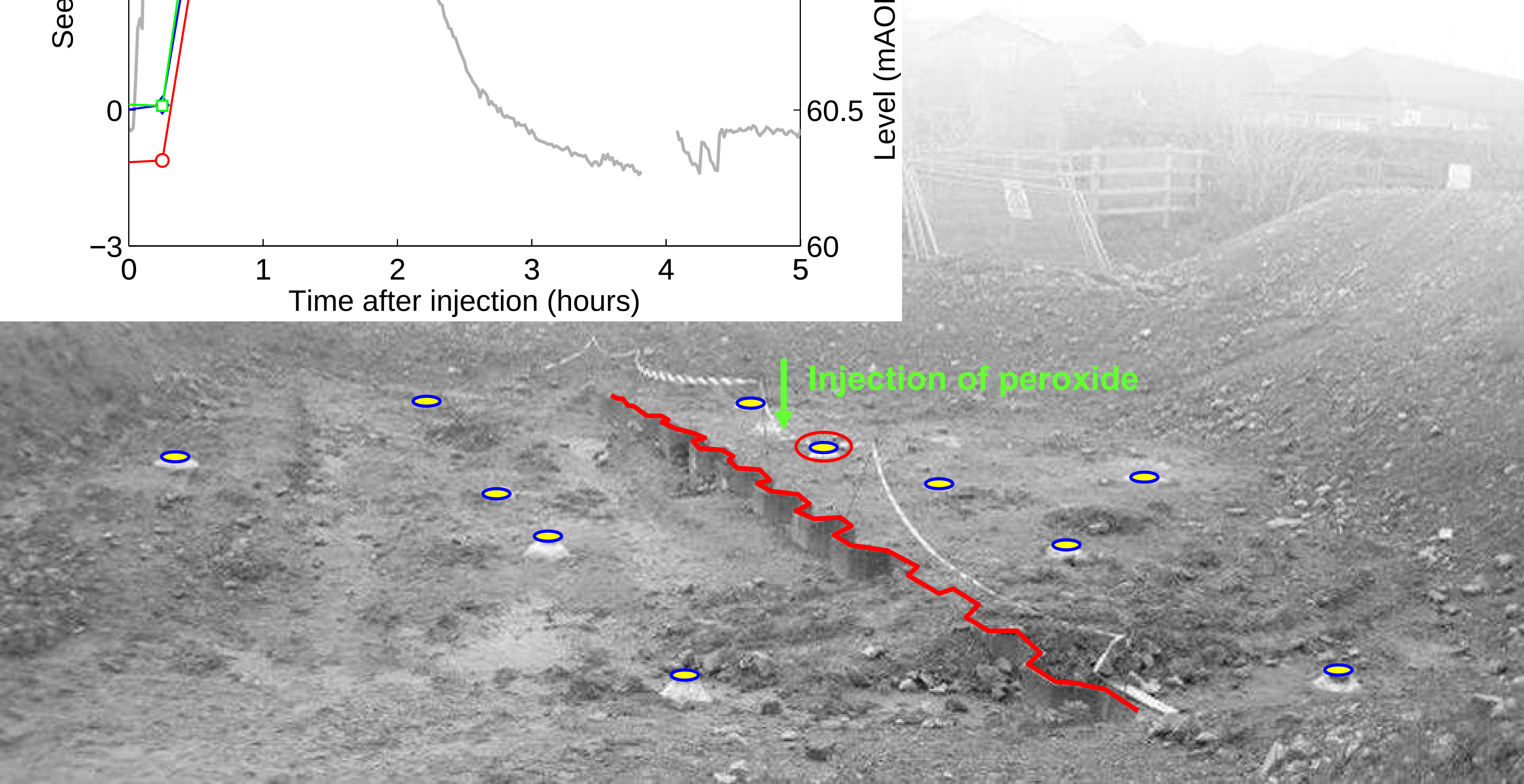
Persulfate injection



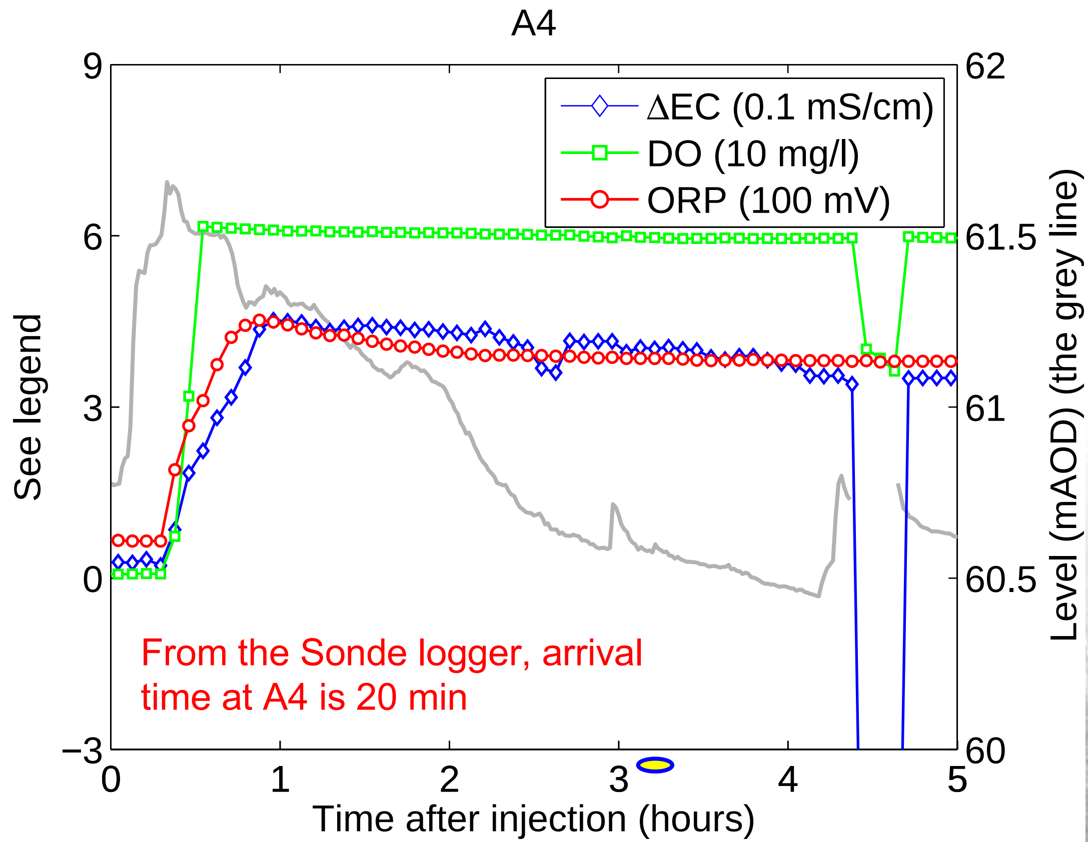


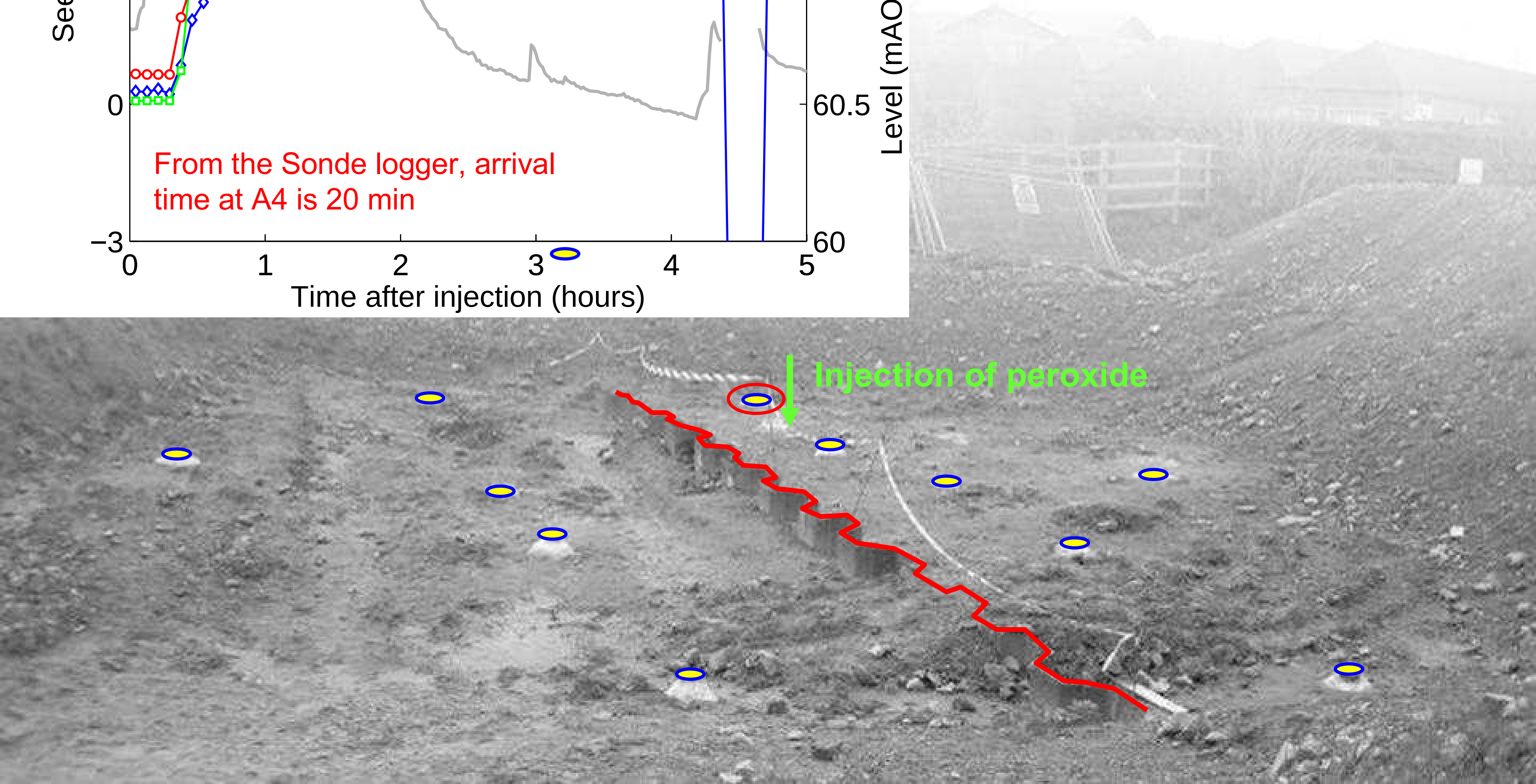
Peroxide injection





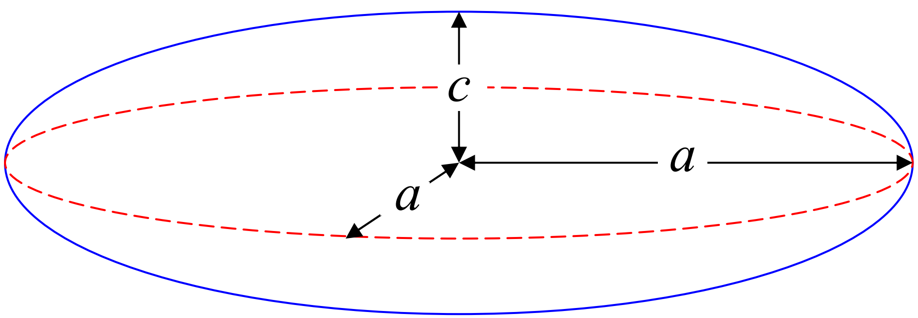
Peroxide injection





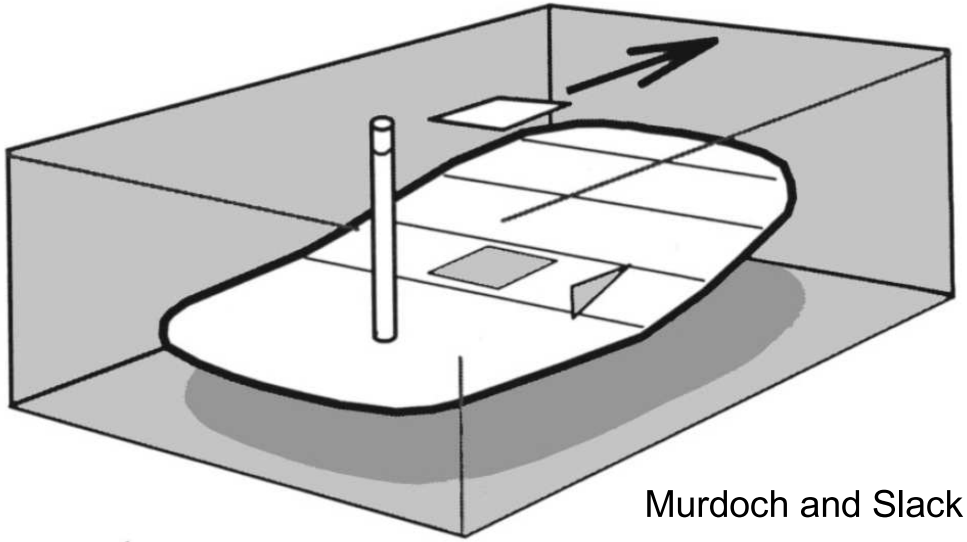
Injection volume and radius

- So oxidant travelled 3 m in just 20 min
- Total volume (4 m^3) was injected over 2.2 hours
- In 20 min that's around 0.60 m^3
- Through three rods with 0.25 porosity, 0.80 m^3
- Assume a spheroidal geometry
- The thickness of the spheroid = 2.12 cm!



$$V = \frac{4}{3}\pi a^2 c$$

Hydraulic fracture propagation

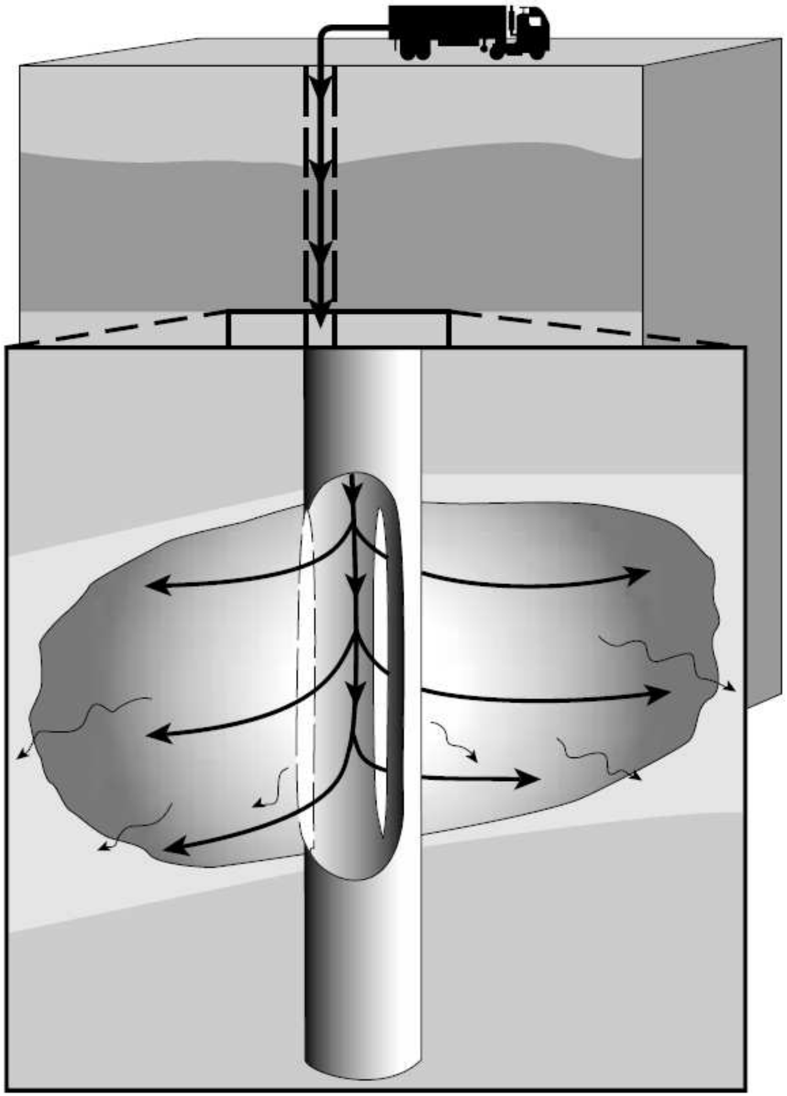


Murdoch and Slack (2002)

- Hydraulic fractures occur when fluid pressures exceed the minimum principal stress.
- In over-consolidated shallow situations fractures are sub-horizontal.
- An estimate of the fracturing stress can be obtained from the overburden.
- Injection pressure used to force oxidant in was around 0.20 MPa.
- The shallowest injection point was 2 m below ground surface.
- Assume density of 2200 kg/m^3, overburden is 0.04 MPa.

Modelling hydraulic fractures

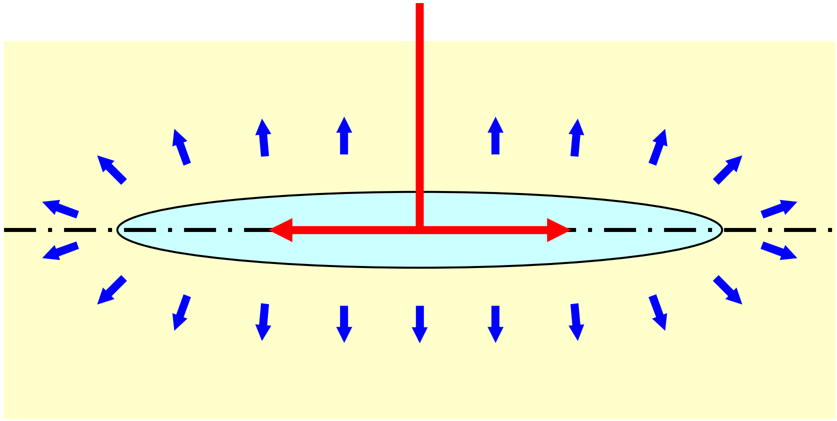
- Engineering applications of hydraulic fractures:
  - reservoir stimulation,
  - underground caving operations,
  - disposal of waste drill cuttings…
- Modelling hydraulic fracture propagation involves coupling fracture mechanics model with a geological reservoir model.
- The reservoir model is needed to forecast the rate of fluid leak-off from the propagating fracture.
- The rate of leak-off strongly affects how far a fracture propagates.



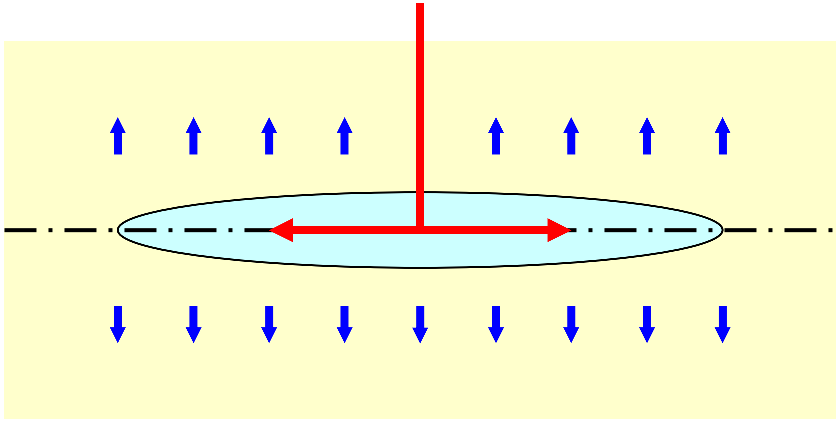
Economides and Nolte (2000)

Leak-off models

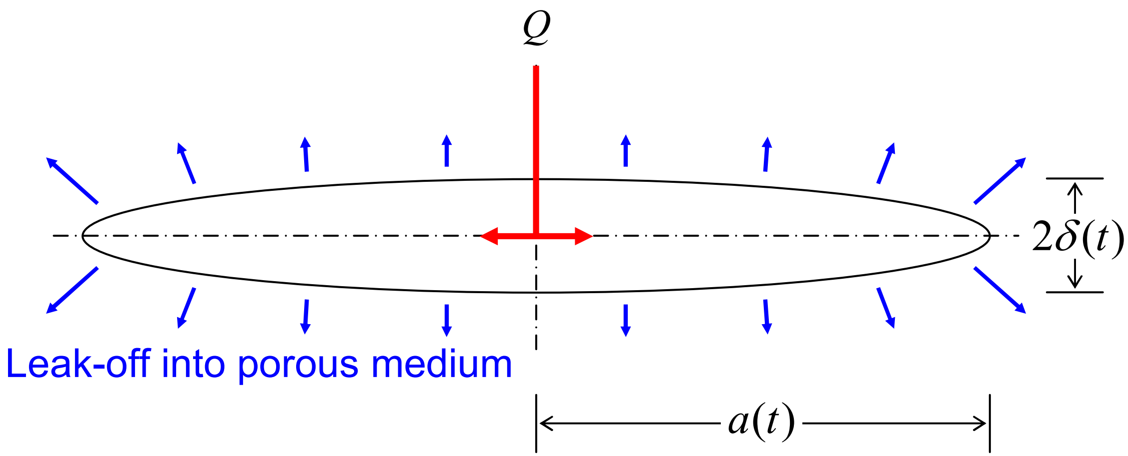
Reality: Three-dimensional leak-off



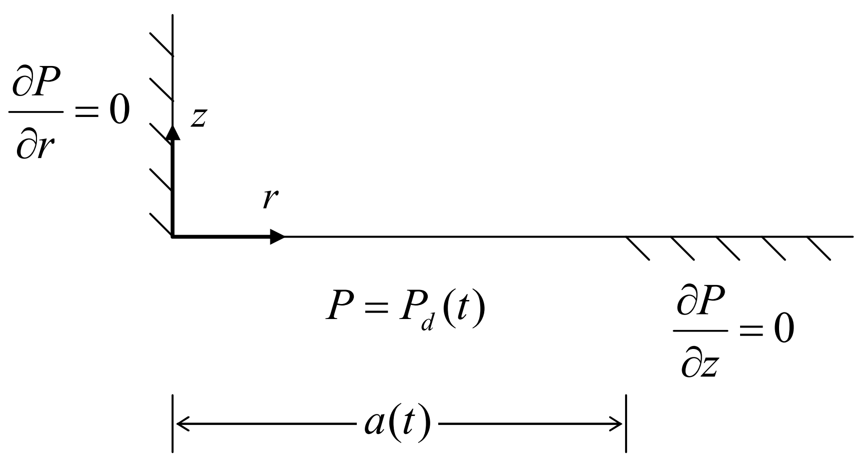
Common assumption: One-dimensional leak-off



PK-Radial with 3D leak-off



a) Section through center of fracture.



b) Schematic of boundary value problem.

Fracture mechanics:

Deflection (Sneddon, 1946)

$$\delta = \frac{4\left(1-\upsilon^2\right)P_d a}{\pi E}\left[1-\left(\frac{r}{a}\right)^2\right]^{1/2}$$

Specific surface energy (Sack, 1946)

$$G = \frac{2\left(1-\upsilon^2\right)P_d^2 a}{\pi E}$$

Dimensional analysis

Dimensional analysis shows there is one important parameter group

$$\varepsilon = \frac{ES(k_z / k_r)^{1/2}}{\left(1536\pi^2\right)^{-1/5}\left(1-\upsilon^2\right)}$$

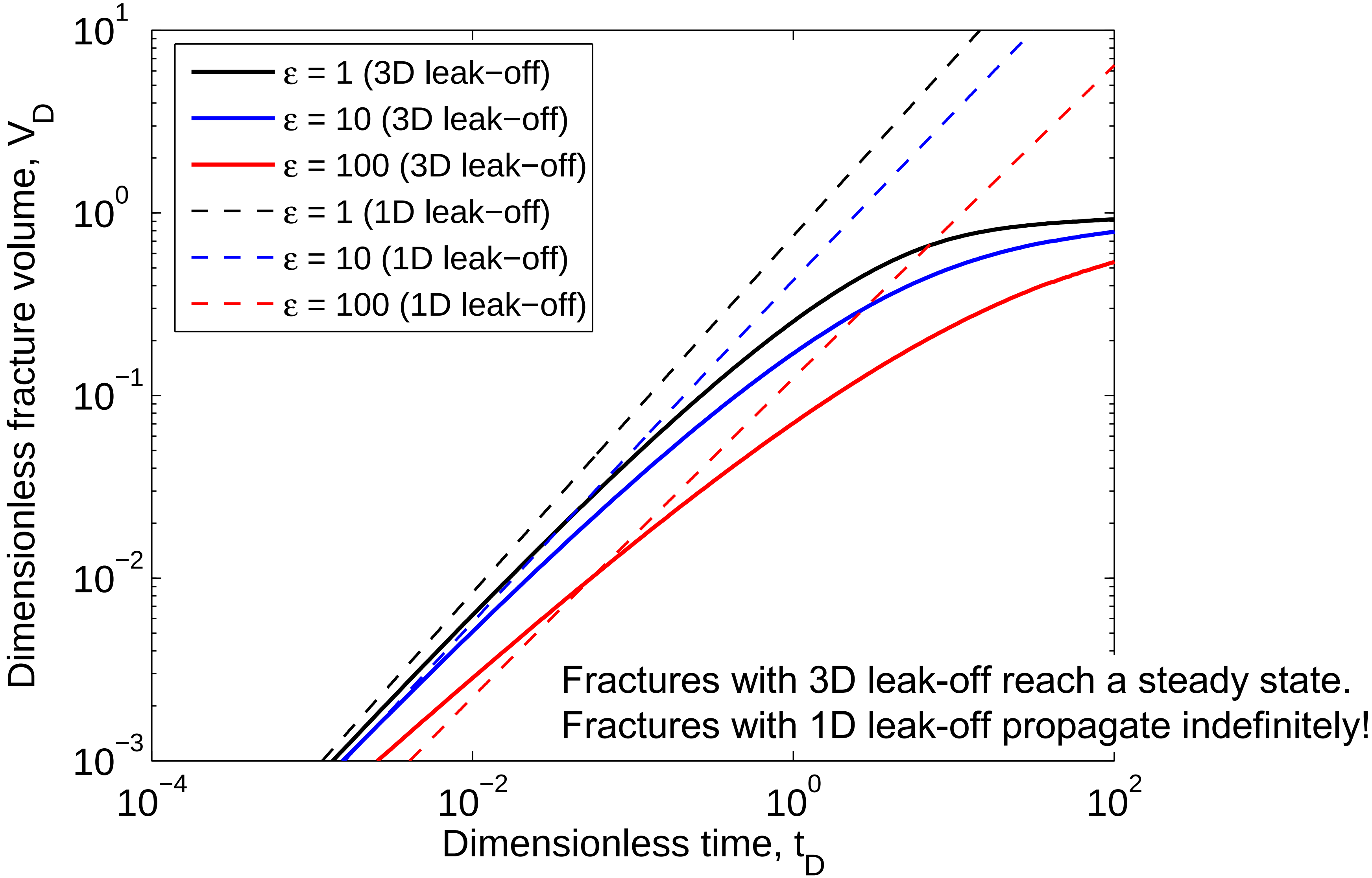
and this seems to range from 1 to 100.

Table 1 Poroelastic parameters for various rocks (from Jaeger et al. 2007, Table 7.2) and corresponding S and ε values

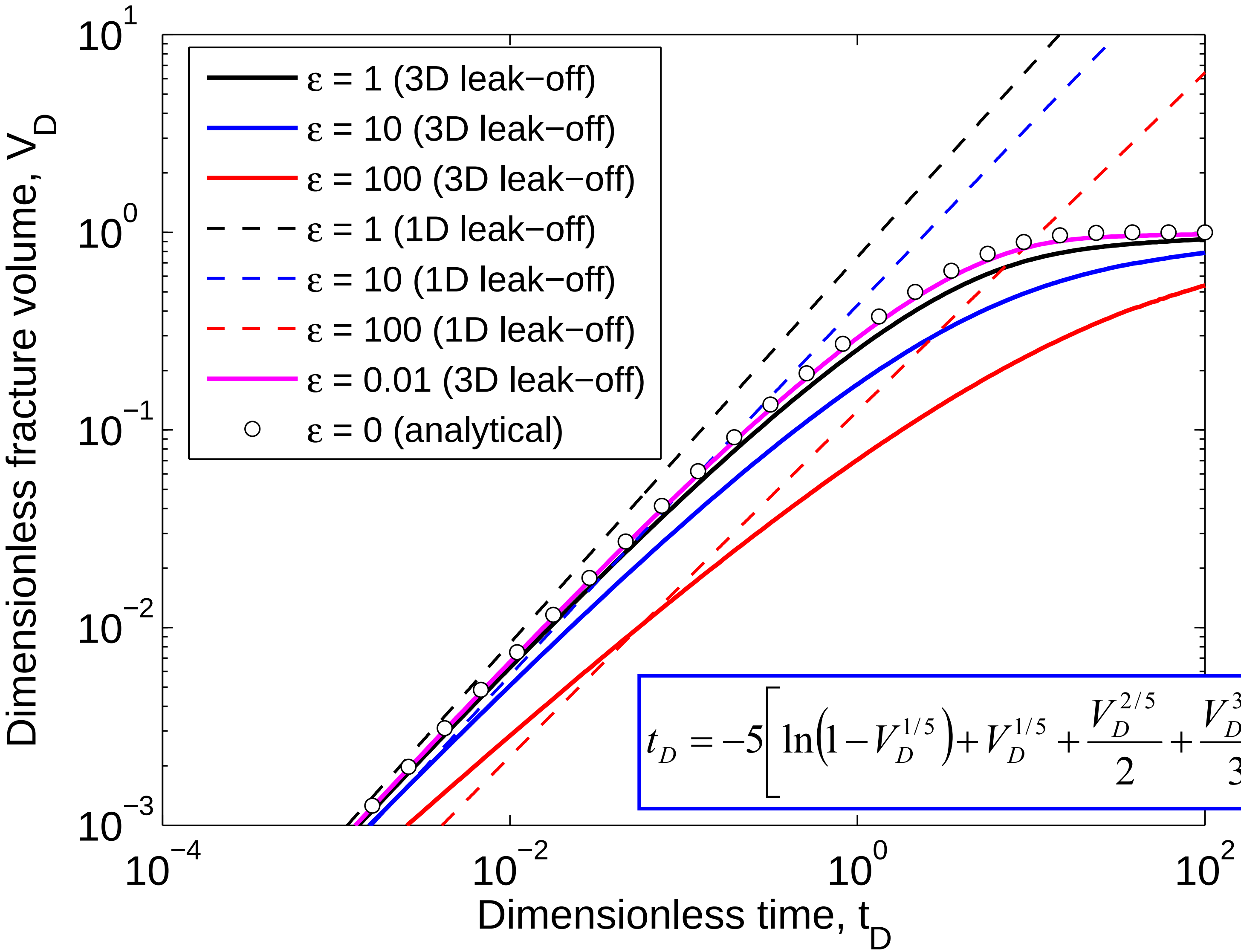
Rock	K (GPa)	ν (-)	α (-)	M (GPa)	E (GPa)	S (GPa^{-1})	ε (-)
Ruhr sandstone	13.0	0.12	0.65	41.0	29.1	0.038	7.7
Tennessee marble	40.0	0.25	0.19	81.0	60.0	0.013	5.3
Charcoal granite	35.0	0.27	0.27	84.0	48.3	0.013	4.3
Berea sandstone	8.0	0.20	0.79	12.0	14.4	0.122	12.1
Westerly granite	25.0	0.25	0.47	75.0	37.5	0.018	4.7
Weber sandstone	13.0	0.15	0.64	28.0	27.6	0.050	9.4
Ohio sandstone	8.4	0.18	0.74	9.0	16.0	0.142	15.7
Pecos sandstone	6.7	0.16	0.83	10.0	13.7	0.147	13.8
Boise sandstone	4.6	0.15	0.85	4.7	9.7	0.284	18.8

Permeability is assumed isotropic such that $k_z / k_r = 1$

Model comparison

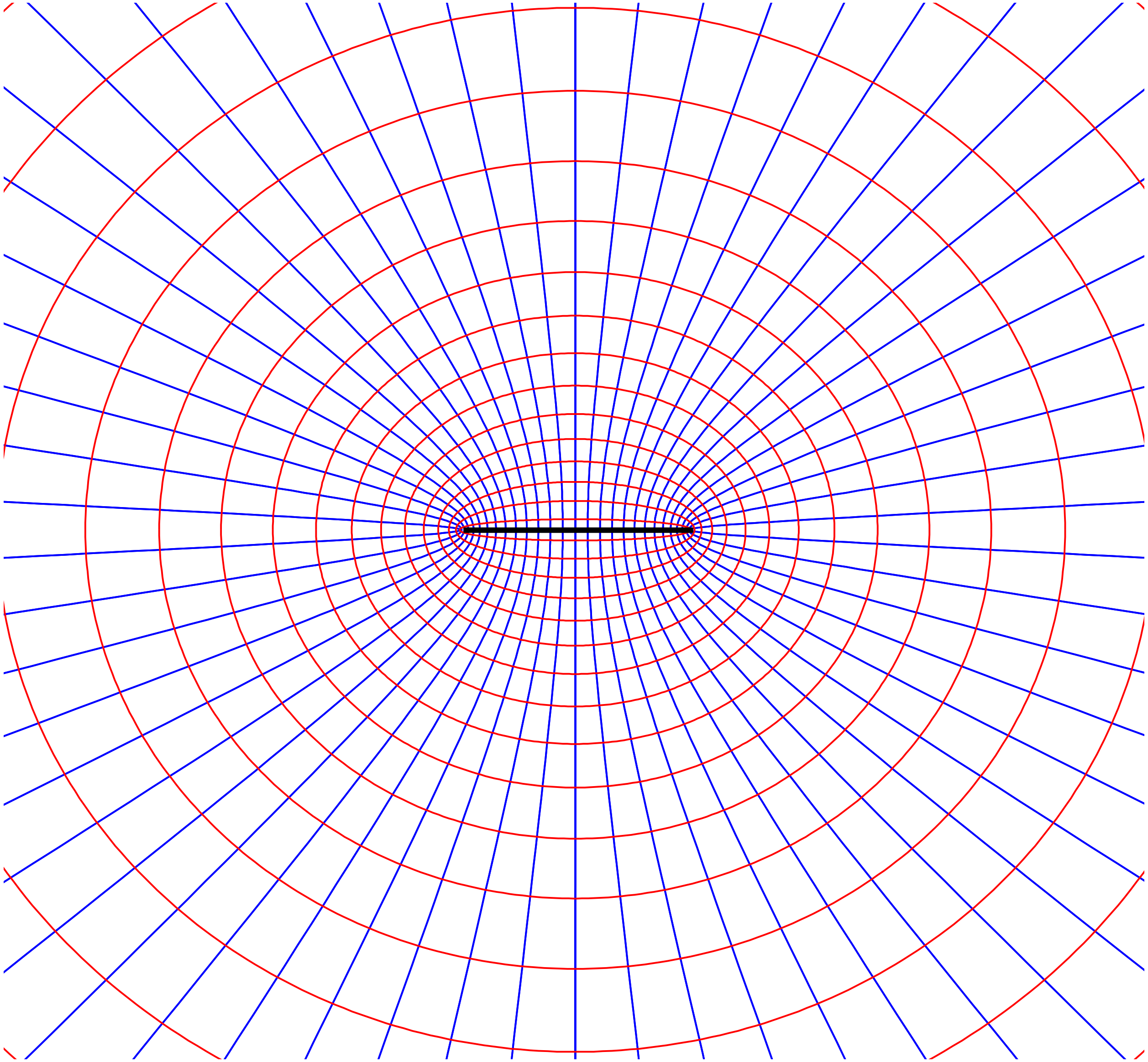


Analytical solution



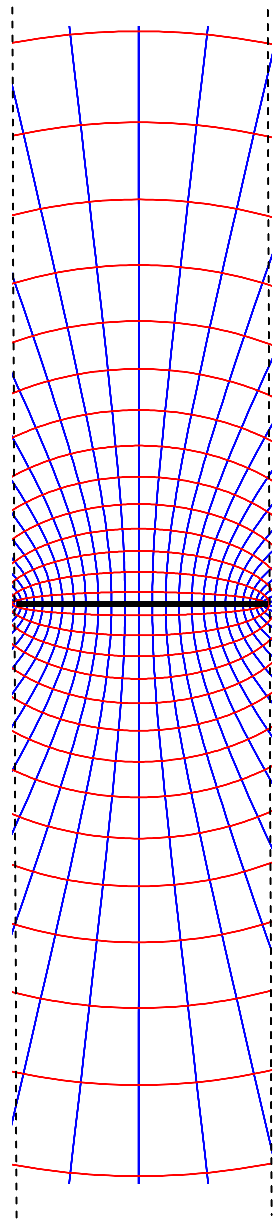
$$t_D = -5\left[\ln\left(1 - V_D^{1/5}\right) + V_D^{1/5} + \frac{V_D^{2/5}}{2} + \frac{V_D^{3/5}}{3} + \frac{V_D^{4/5}}{4}\right]$$

So why such a difference?



So why such a difference?

- Assuming 1D leak-off ignores a large amount of available storage capacity.
- Consequently leak-off is underestimated and the fracture grows faster and to a larger extent.



Mathias and van Reeuwijk (2009)

How far could the fractures have gone?

$$\boxed{t_D = -5\left[\ln\left(1 - V_D^{1/5}\right) + V_D^{1/5} + \frac{V_D^{2/5}}{2} + \frac{V_D^{3/5}}{3} + \frac{V_D^{4/5}}{4}\right]}$$

Time, $t = \dfrac{Q^4}{1536\pi^2 G^2}\left(\dfrac{1-\upsilon^2}{E}\right)^3\left(\dfrac{\mu}{k}\right)^5 t_D$

Volume, $V = \dfrac{Q^5}{1536\pi^2 G^2}\left(\dfrac{1-\upsilon^2}{E}\right)^3\left(\dfrac{\mu}{k}\right)^5 V_D$

Radius, $a = \left[\dfrac{18}{256\pi G}\left(\dfrac{E}{1-\upsilon^2}\right)\right]^{1/5} V^{2/5}$

$Q = 5\times10^{-4}$ m^3/s - fluid injection rate

$k = 3\times10^{-13}$ m^2 - permeability

$\mu = 10^{-3}$ Pa s - fluid viscosity

$\upsilon = 0.25$ - Poisson's ratio

Based on 3 m in 20 min:

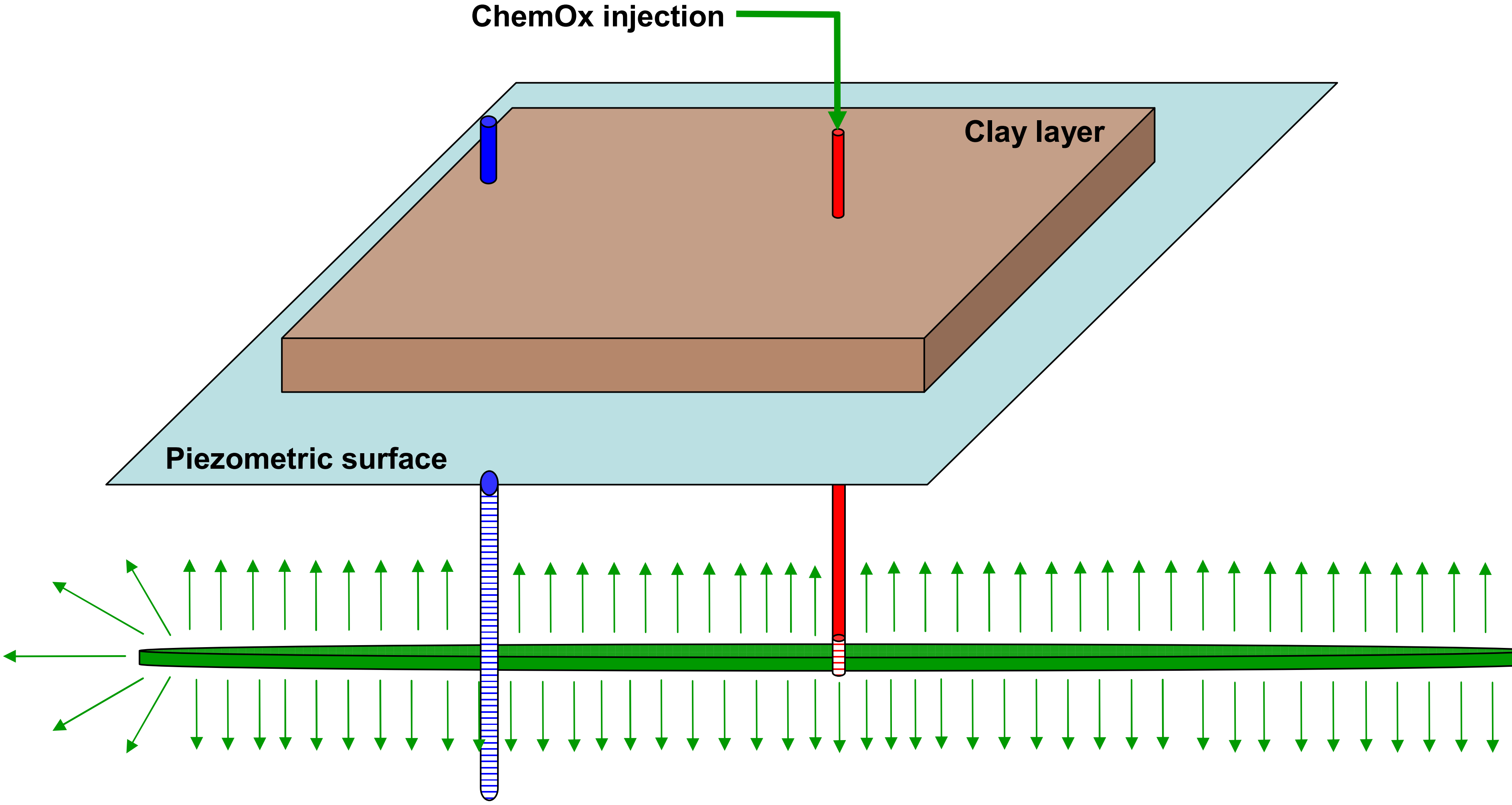
$E = 0.01$ GPa - Young's modulus

$G = 2000$ kg/s - Specific surface energy

At time = 2.2 hours the fracture has grown to 3.36 m

Lots of assumptions!!

Conceptual model



Concluding remarks

- Success of ISCO relies on effective mixing of oxidant within contamination zone.
- High pressure injection can result in hydraulic fracturing of subsurface.
- In shallow over-consolidated conditions, fractures propagate sub-horizontally.
- High fluid pressure within the fracture causes flow of oxidant into surrounding formation.
- Result is a substantial increase in the mixing of oxidant with ambient groundwater.
- Work is ongoing to develop modelling tools for designing optimal injection strategies.

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