Slope Stability Monitoring

through

Impedance Imaging

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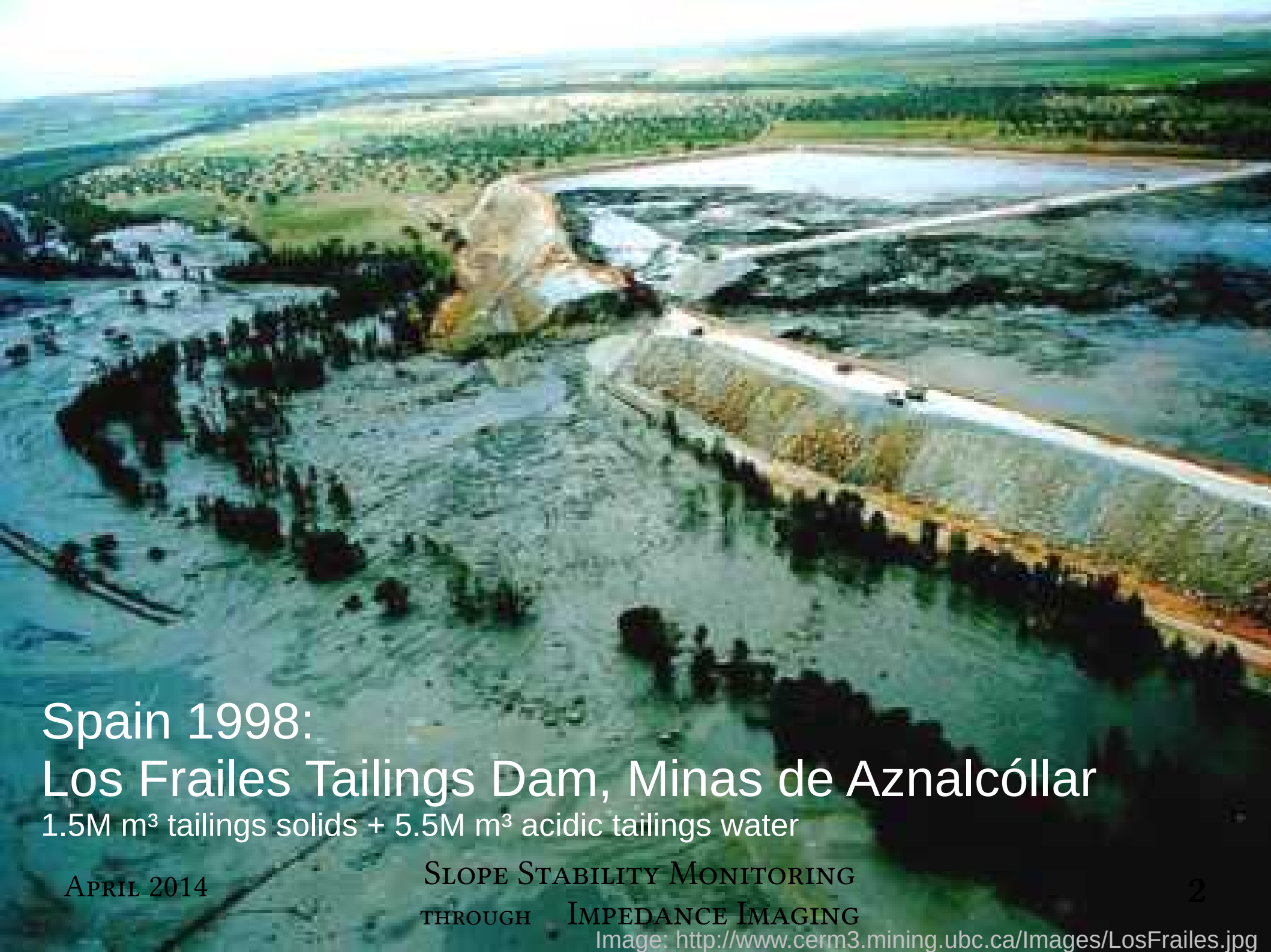
a collaboration between

Carleton UNIVERSITY

&

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL



Spain 1998:
Los Frailes Tailings Dam, Minas de Aznalcóllar

1.5M m^3 tailings solids + 5.5M m^3 acidic tailings water

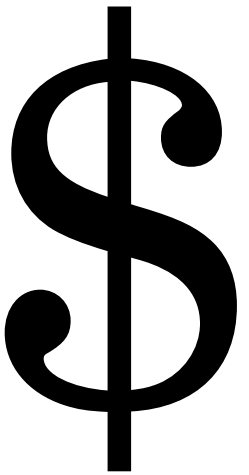
Image: http://www.cerm3.mining.ubc.ca/Images/LosFrailes.jpg

Provost, AB, Canada (2013)
CP Rail freight train; 17 potash cars derailed,
~100m track destroyed.

Image & report: http://www.tsb.gc.ca/eng/rapports-reports/rail/2013/r13e0069/r13e0069.asp

Slope Stability can represent

&



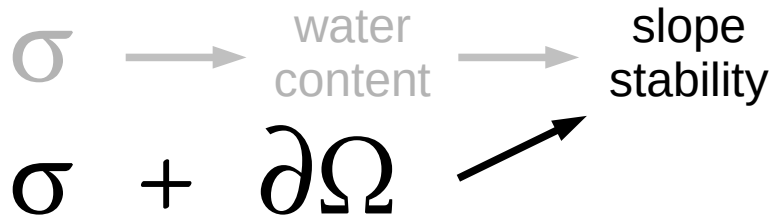
an environmental risk

effective mitigation:
a monetary benefit

Predictive: (?)

1) conductivity σ – water content:
- Archie's Law (sandstone)
- Waxman-Smits Equation (clay)

2) water content – slope stability:
- Static Slope Stability Analysis based on soil types and water content



Direct Monitoring:

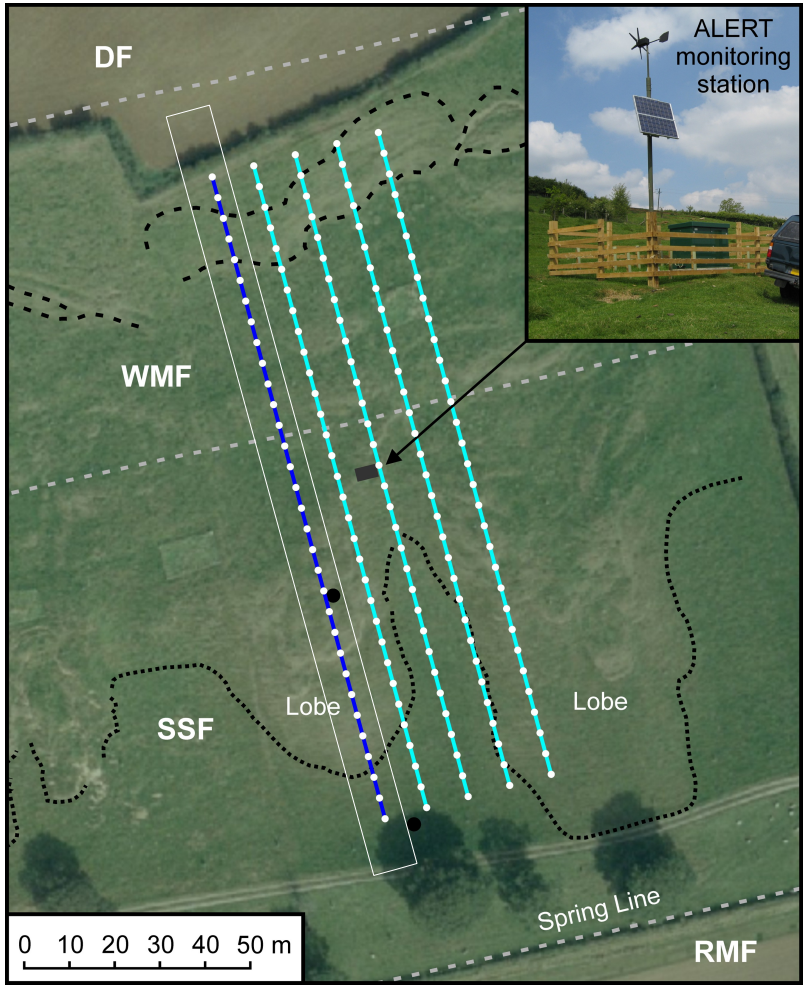
1) Direct movement estimate from reconstruction

- Online, remote monitoring
- Cost effective equipment vs.

Laser range finding

A Test Site

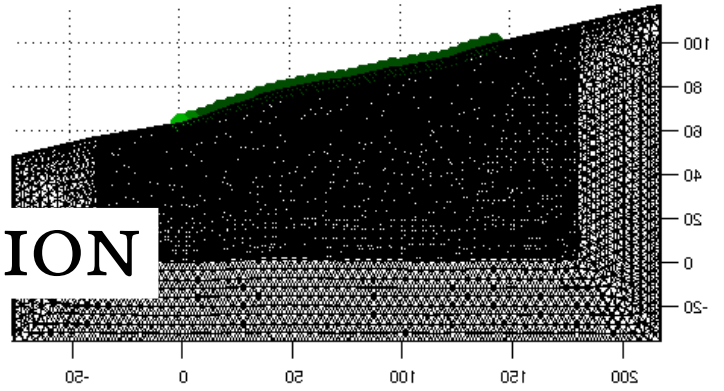
Hollin Hill, UK: A Slow Moving Landslide



[Paul Wilkinson et al.,"Geoelectrical Landslide Tracking", EAGE2010]

Absolute Solution

Measurements & Reconstruction



- 32 electrode, linear array, downslope
- Initial & final electrode positions & slope profile from RTK GPS

1) uniform initial σ est. based on best-fit, also used as fixed background σ

2) *apparent resistivity* = measurements scaled for geometry and stimulus
   - improved numeric stability by normalizing magnitudes

3) log σ: conductivity Jacobian (negativity constraint)

$$J_{\ln\sigma} = \partial\sigma = \frac{\partial b}{\partial \ln\sigma} = \frac{\partial b}{\partial\sigma}\frac{\partial\sigma}{\partial\ln\sigma} = \frac{\partial b}{\partial\sigma}\sigma = J_\sigma\sigma$$

4) movement Jacobian by perturbation; alternate electrode sites in model

5) 2.5D: fine 3D fwd model, coarse 2D inv model, fitted to electrode pos.

6) absolute iterative Gauss-Newton solution

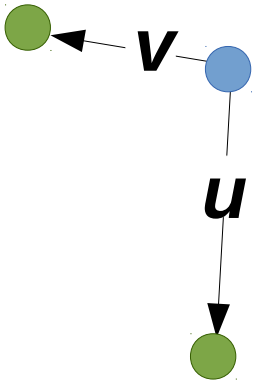
RTK: Real Time Kinematic; a differential GPS technology (± 1 - 4 cm absolute, 5mm relative to base station)

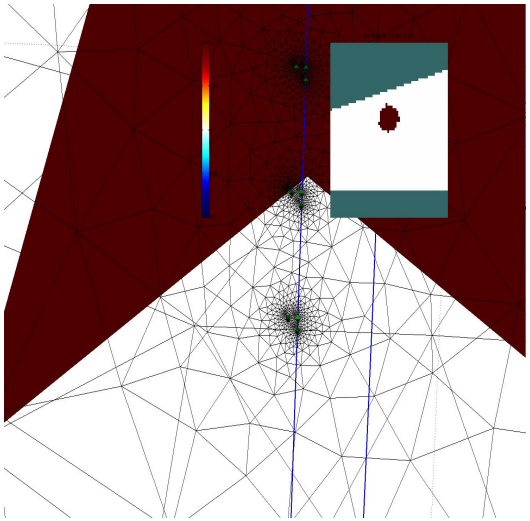
Absolute Solution

Jacobian & Regularization Terms

$$x = [\quad \ln\sigma \qquad u \qquad v \quad]^T$$

$$J = \begin{bmatrix} J_\sigma \sigma & J_u & J_v \end{bmatrix}$$





$J_\sigma \sigma$
scaled adjoint Jacobian calculation ln conductivity

J_u
electrode perturbation downslope

J_v
electrode perturbation cross-slope

Absolute Solution

Forward Solver Time

- Movement perturbation is computationally slow (a fine mesh), one forward solution per Gauss-Newton iteration

$$P_M = N_{el} D_{DoF} P_{orig}$$

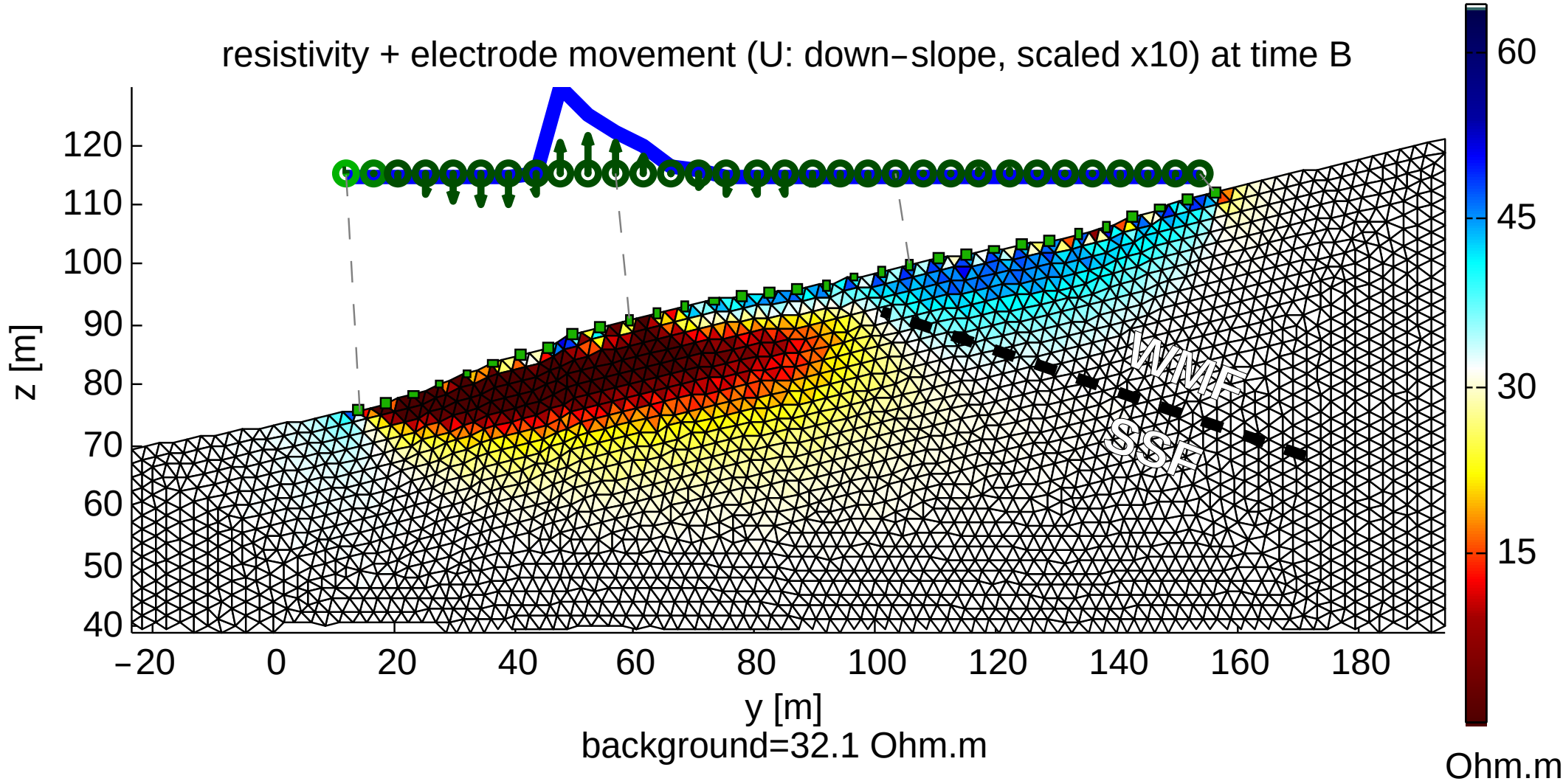
$$N_{el} = 32, D_{DoF} = 2, P_M \approx 37000$$

- Developed a generalized stim/meas improvement routine that rearranges stimulus and measurements to minimize matrix operations, skip redundant results, providing a transparent (to the user) optimization.
- Forward solution in 45 minutes becomes
  3.75 minutes for rearrangement + 15 seconds per solution
  ... run times were two orders of magnitude faster

Timings on an Intel Xeon 2.6GHz, 8 cores, 64GB memory

Reconstruction

Reasonable Agreement with "Ground Truth"



Discussion

- Resistivity distribution agrees with geological evidence
- Estimated movement is in reasonable agreement with GPS measurements
- Further Refinement:
  - Regularization and constraints for movement
  - Conjugate Gradient solver versus Gauss-Newton
  - Better iterative solver line search

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Thank You

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Potash – water soluble potassium salts

Main use: fertilizer

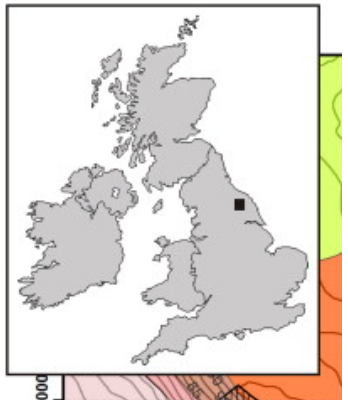
largest producer: CAN

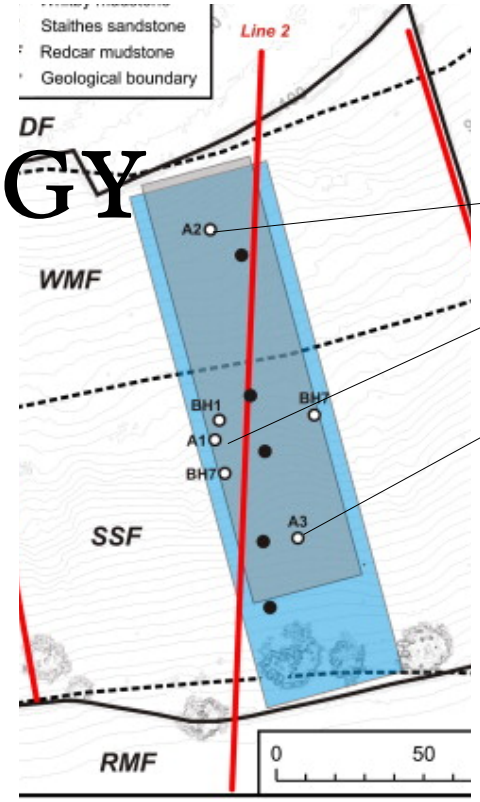
worldwide 30M tons/yr

http://en.wikipedia.org/wiki/Potash

Image: http://resourcescommittee.house.gov/subcommittees/emr/usgsweb/photogallery/

Geology





WMF: Whitby Mudstone Formations

SSF: Staithes Sandstone and Cleveland Ironstone

[Chambers et al. "Three-dimensional geophysical anatomy of an active landslide in Lias Group mudrocks, Cleveland Basin, UK" Geomorphology 125 (4) Feb 2011, p472–484]

Hand Drilling & Auguring