Real-Time Geological Inversion for Subsurface Decision-Making

Sergey Alayev saly@norceresearch.no

Picture form my last Geilo Winter School

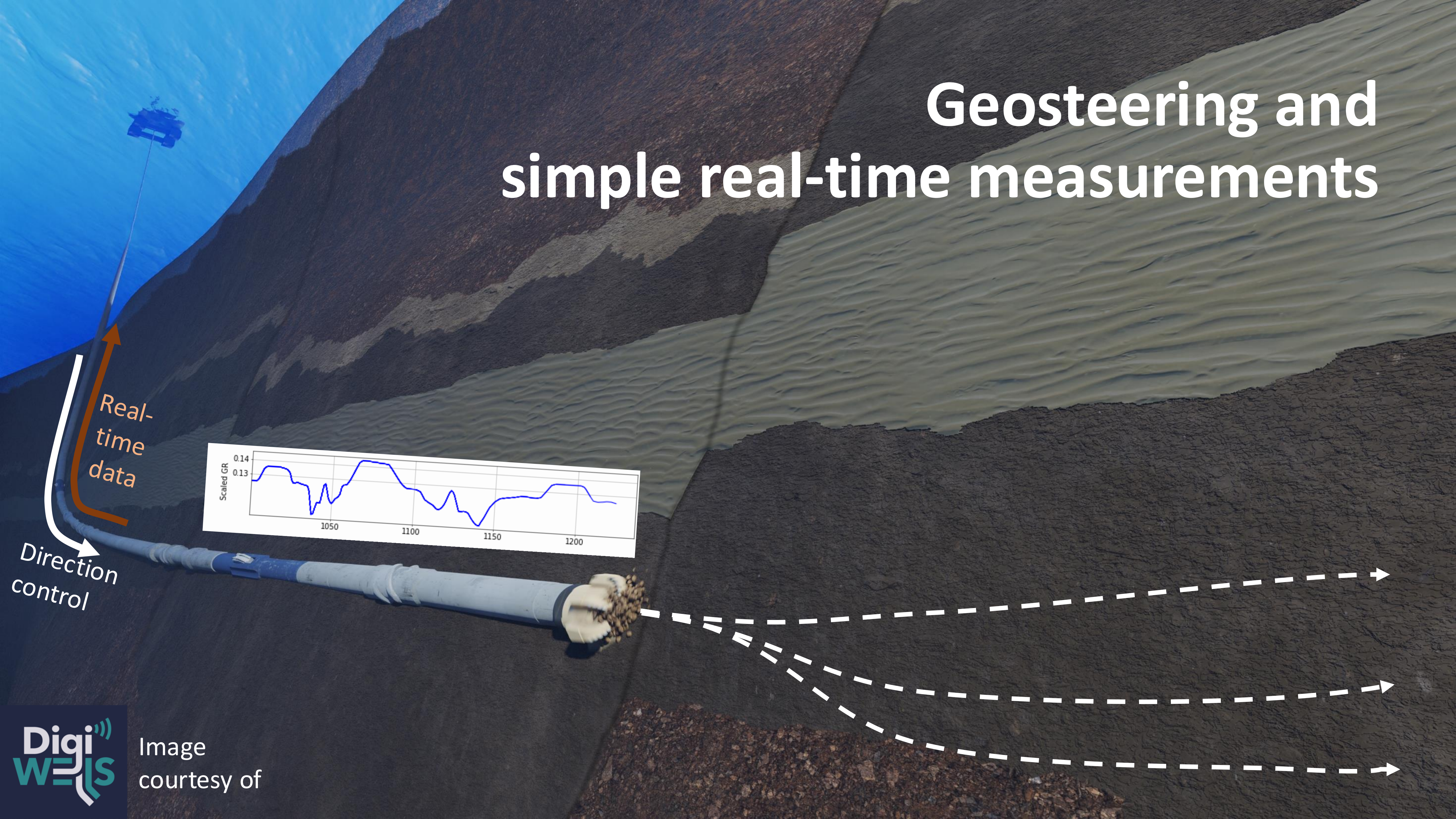
January, 2017

Outline

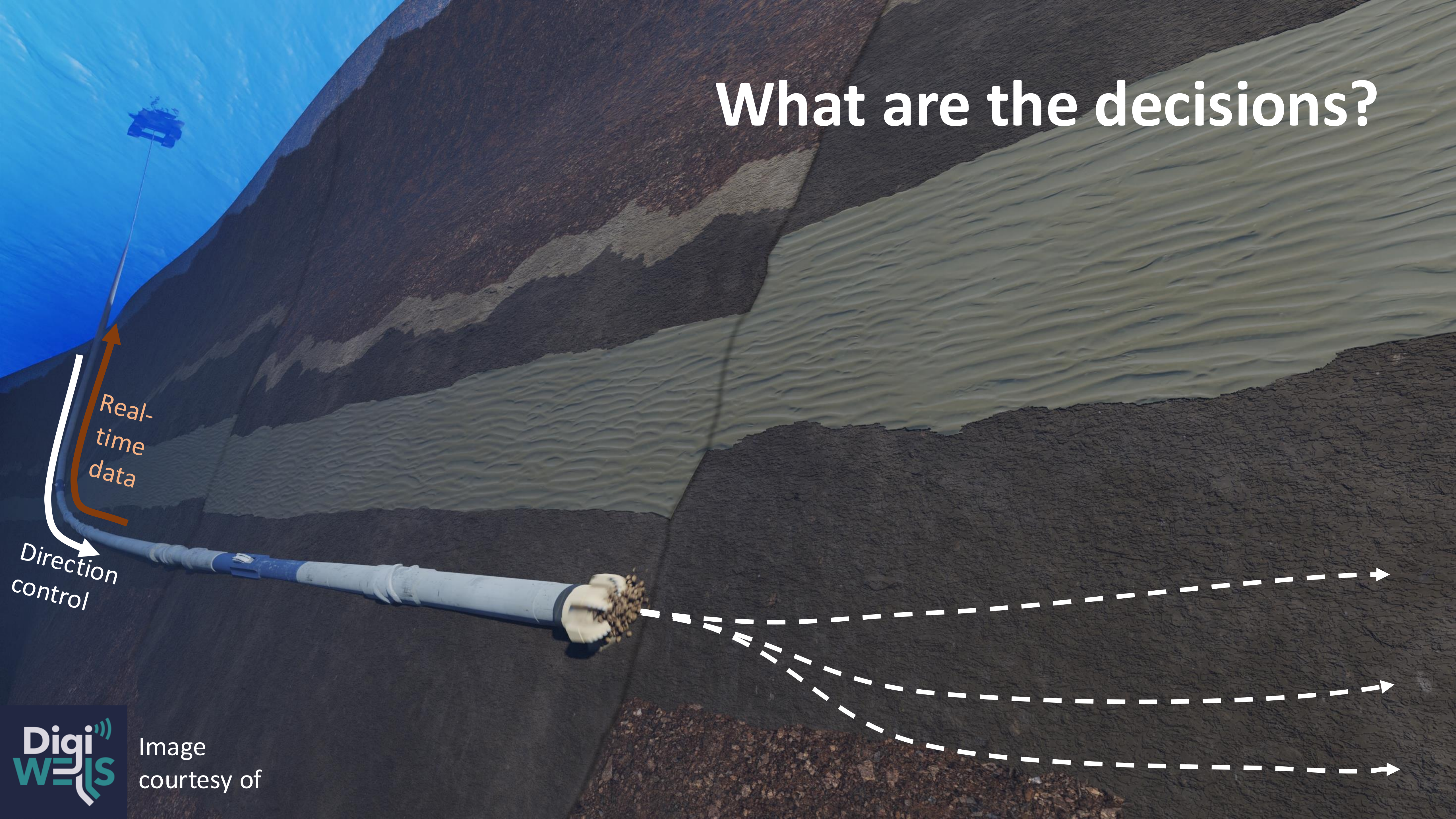
- Lecture 1: Geological inversion for geosteering
  - Overview of geosteering
  - Different types of data and inverse problems
  - Reference problem of sequential inversion
  - Simple inversion
  - Regularization
- Exercise
- Lecture 3: Filtering and multi-modal inversion
  - Particle filter
  - Direct multimodal inversion with machine learning

Lecture 1: Overview of geosteering and sequential inversion

Geosteering and simple real-time measurements



What are the decisions?



Bottom hole assembly overview

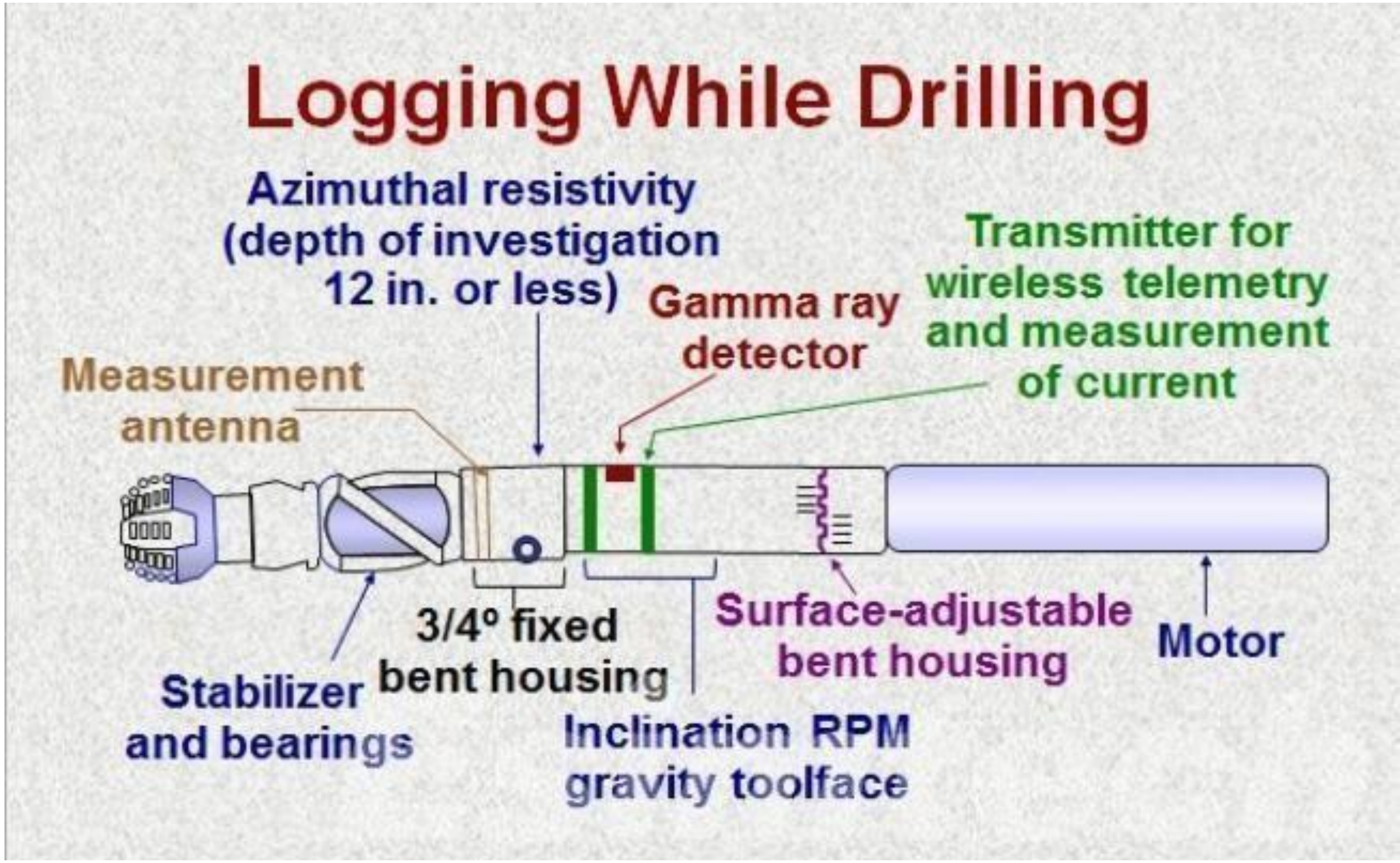
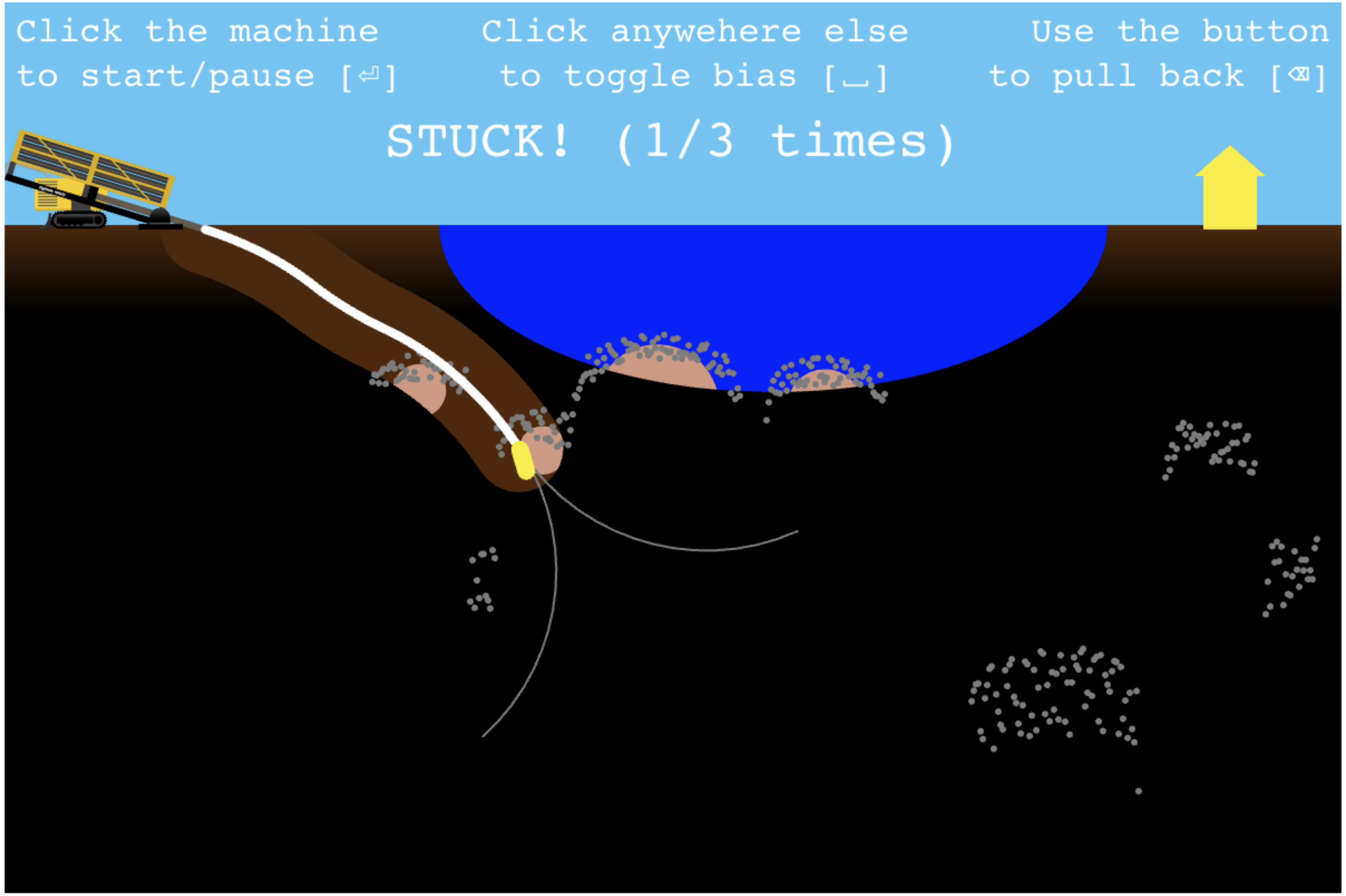


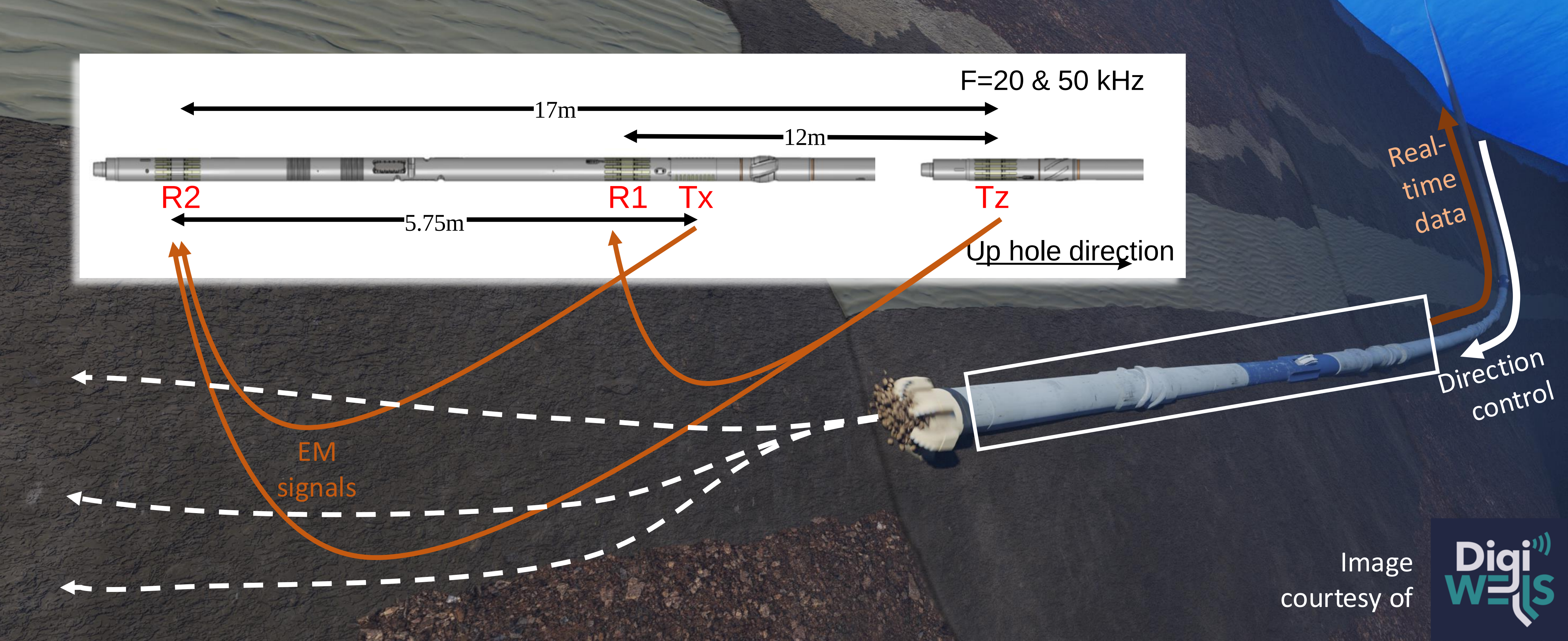
Image from
https://www.esimtech.com/the-vital-role-of-logging-while-drilling-revolutionizing-oil-exploration.html

Underbore game shows little-bit how it works

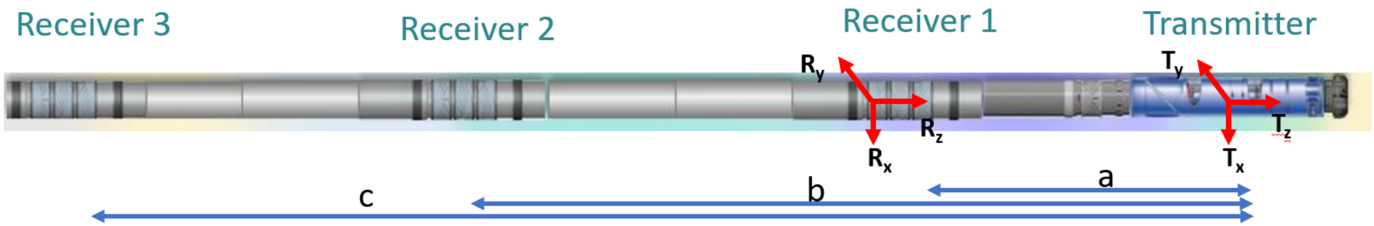


https://github.com/alin256/Directional-Boring

Geosteering and electromagnetic (EM) measurements



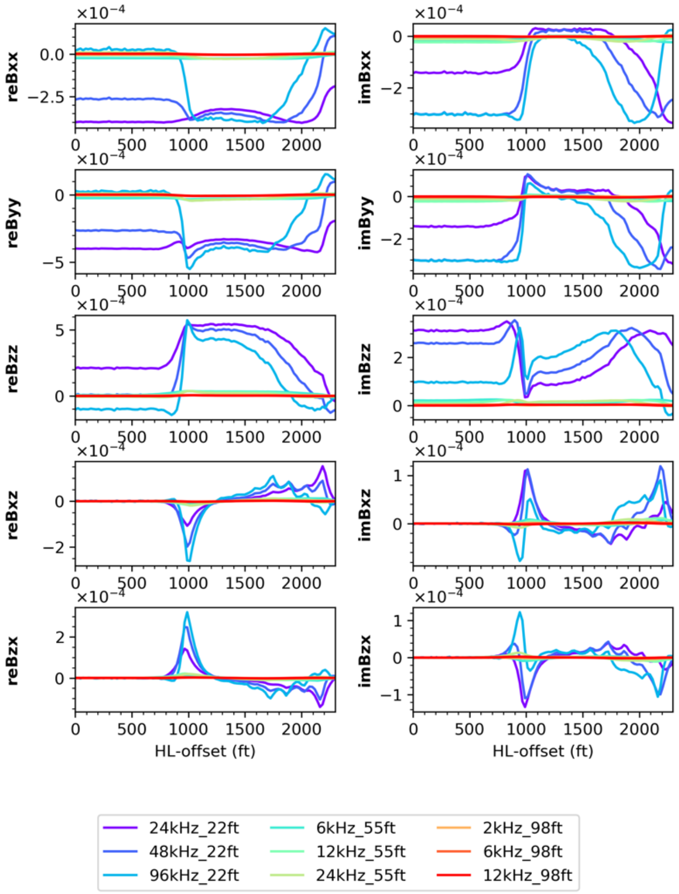
Inversion of Triaxial EM Measurements



Three tilted antenna coils

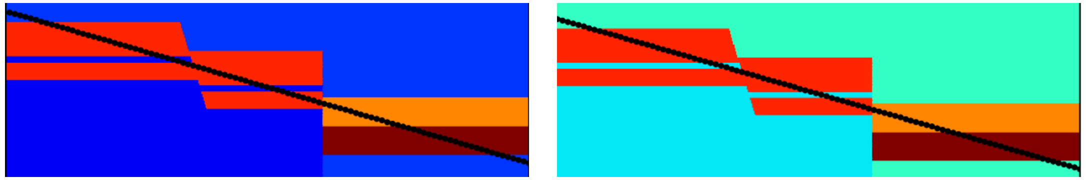
9 measured signals

XX, XY, XZ
YX, YY, YZ
ZZ, ZY, ZZ

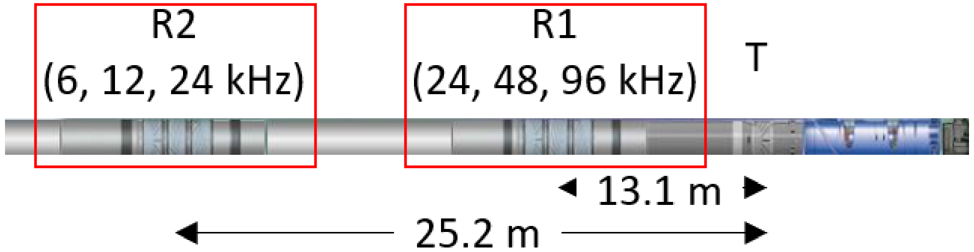


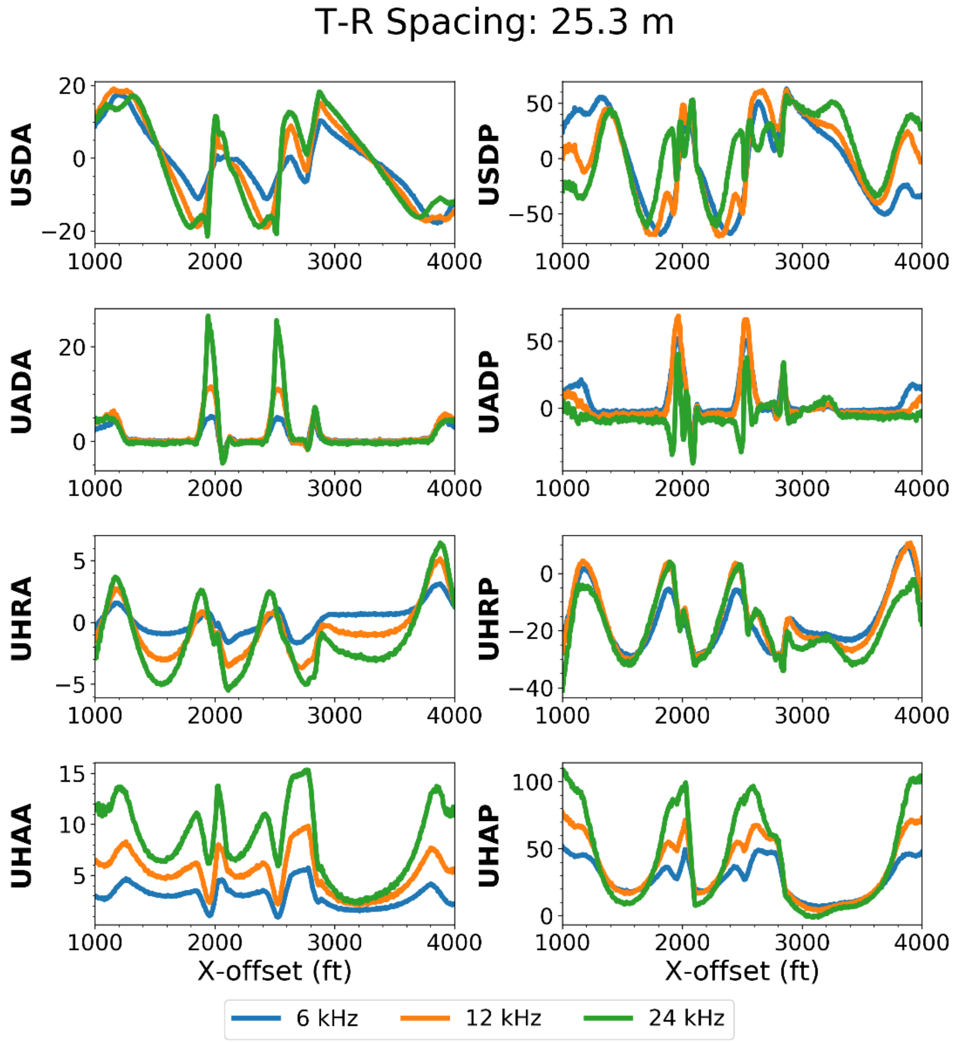
Slides from Nazanin Jahani et al.:
https://onepetro.org/SPWLAALS/proceedings/SPWLA24/4-SPWLA24/D041S013R002/545536

Anisotropic Two-Fault Model: Synthetic Data

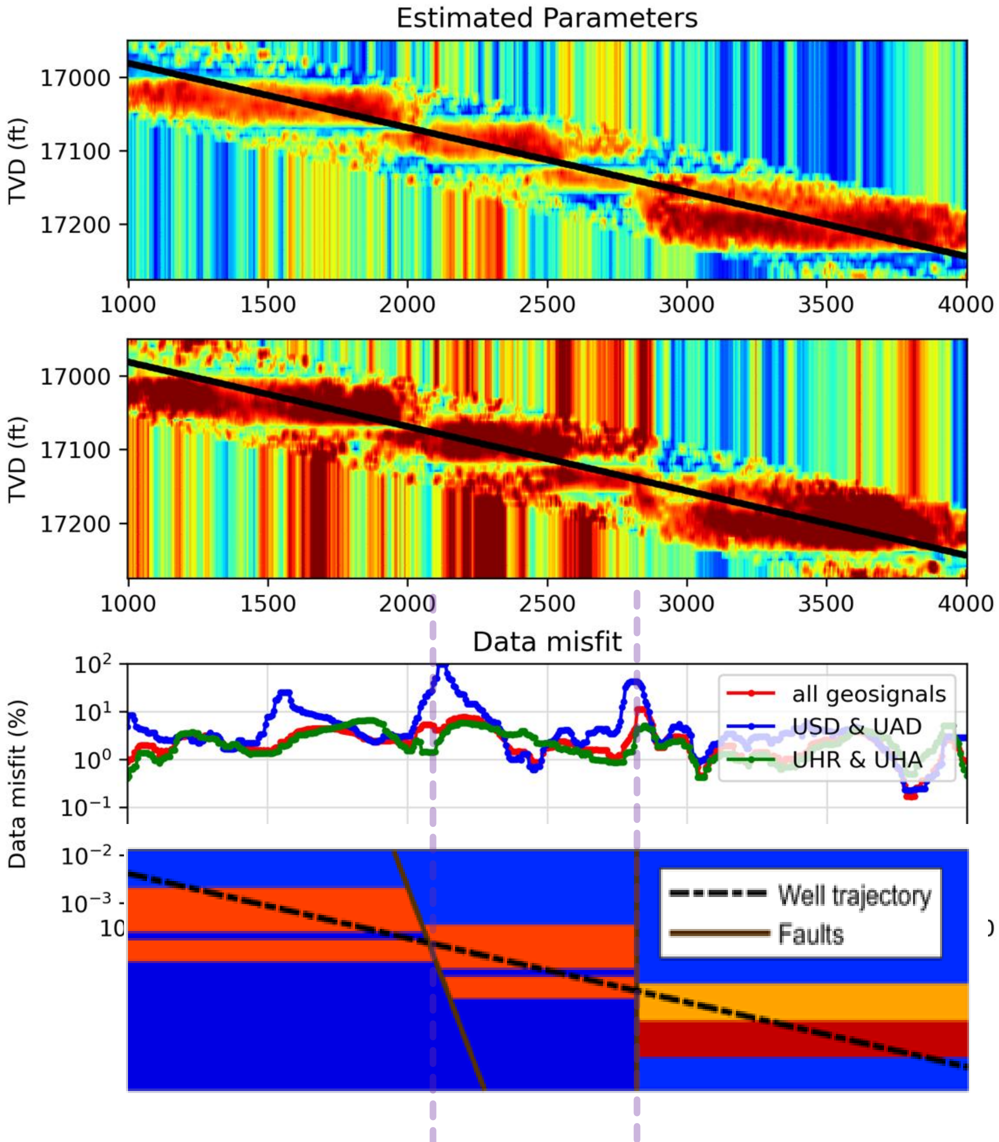


- Synthetic 3D geo-signal data from **LogSimulator3D_v2.3**
- + 2% Relative Noise

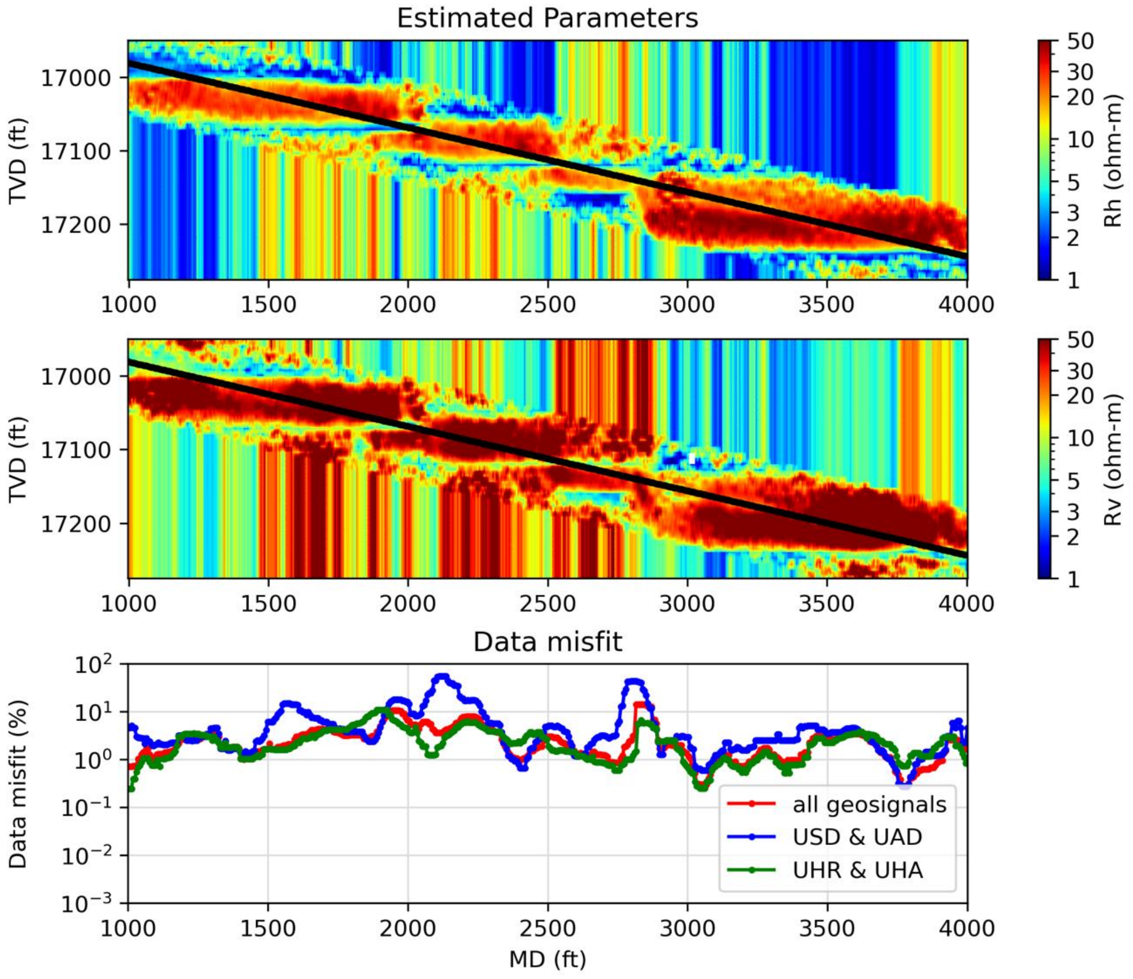




First Pass



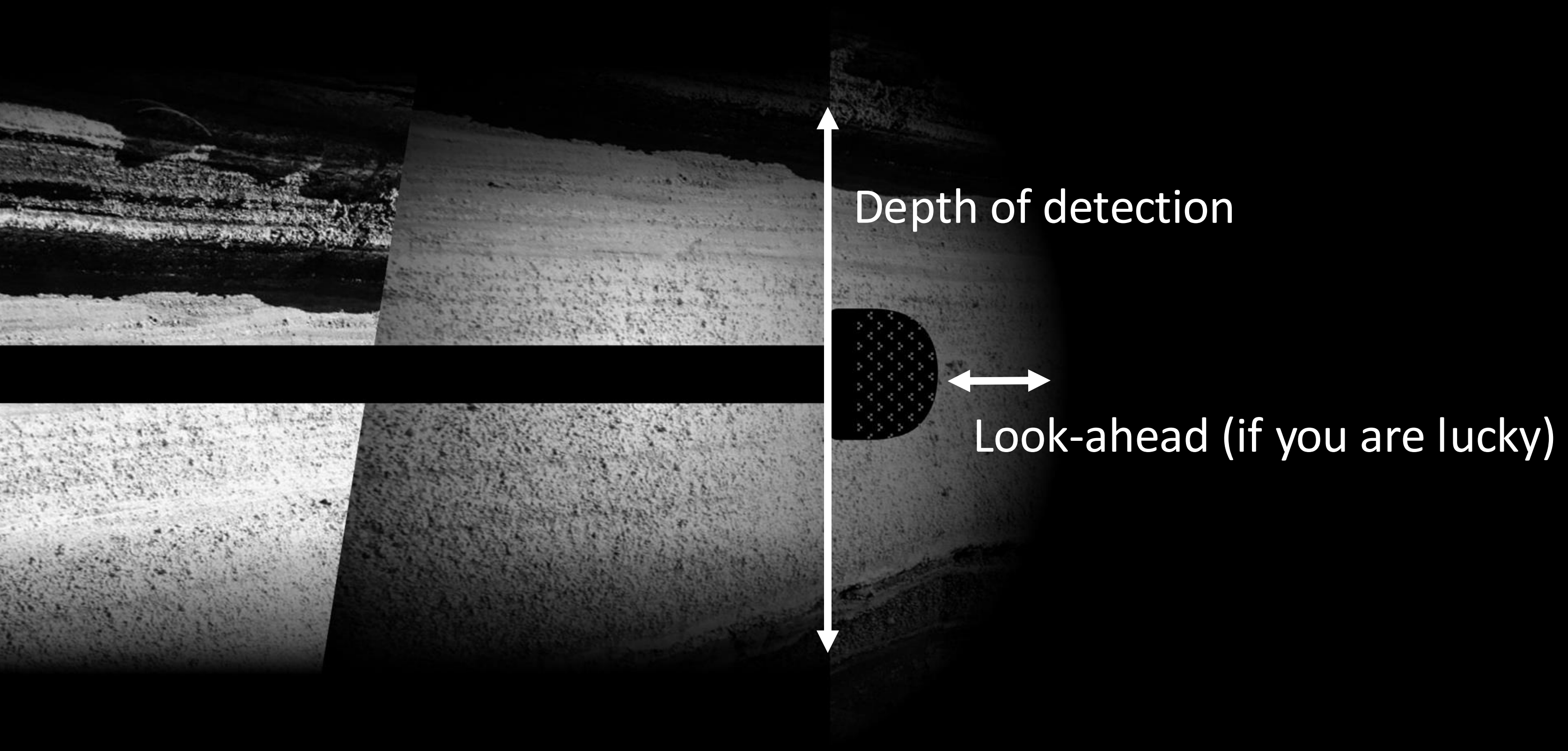
Second Pass



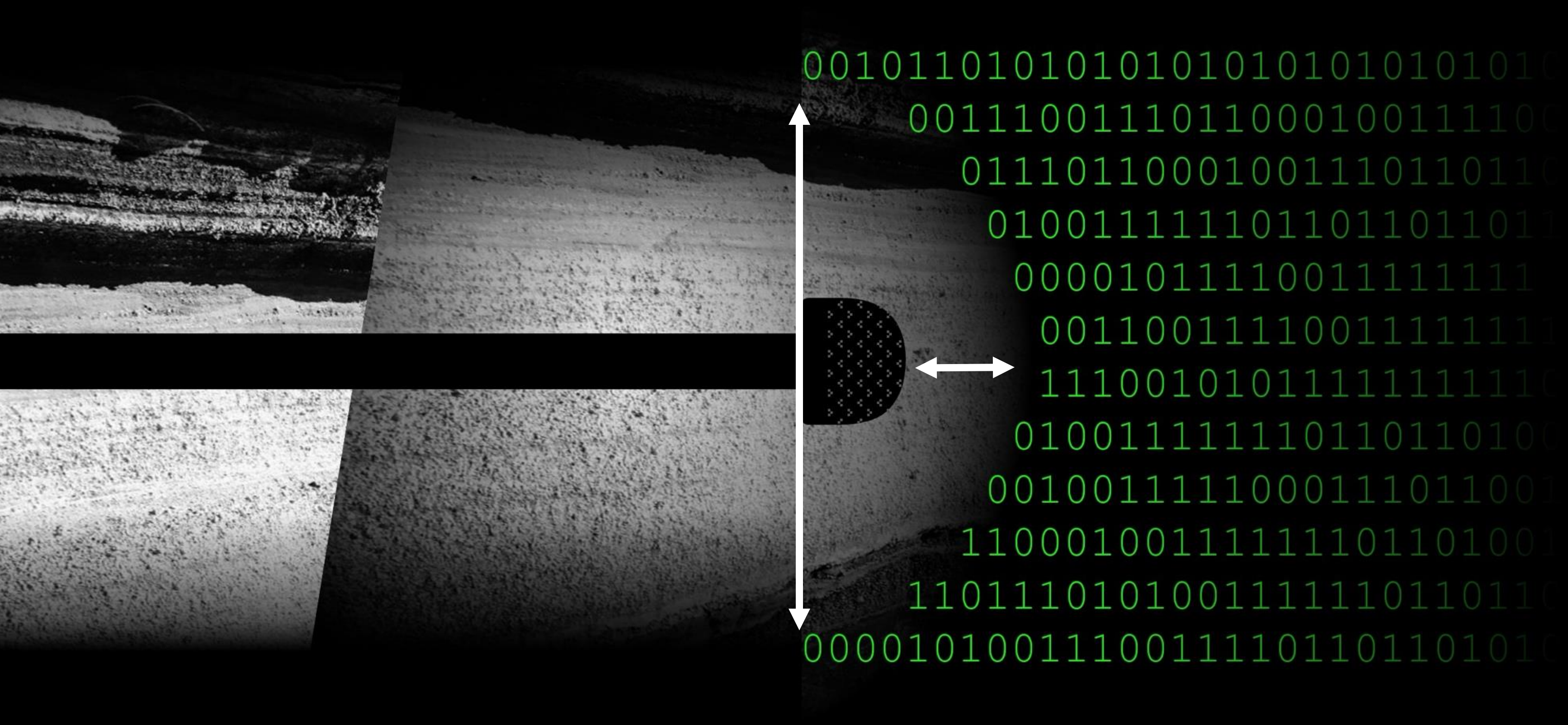
How do you use this inversion?

- ???

Reality (simplified)



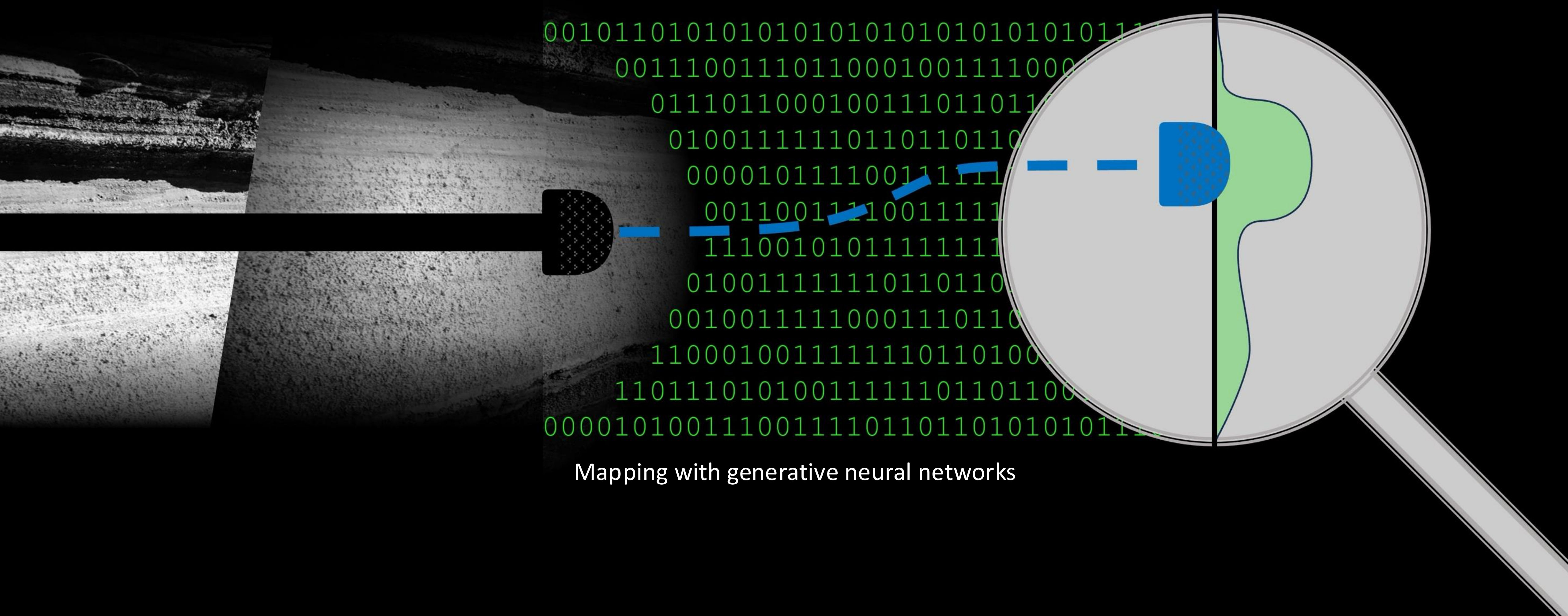
Our project: DISTINGUISH



Our project: DISTINGUISH convers data to prediction

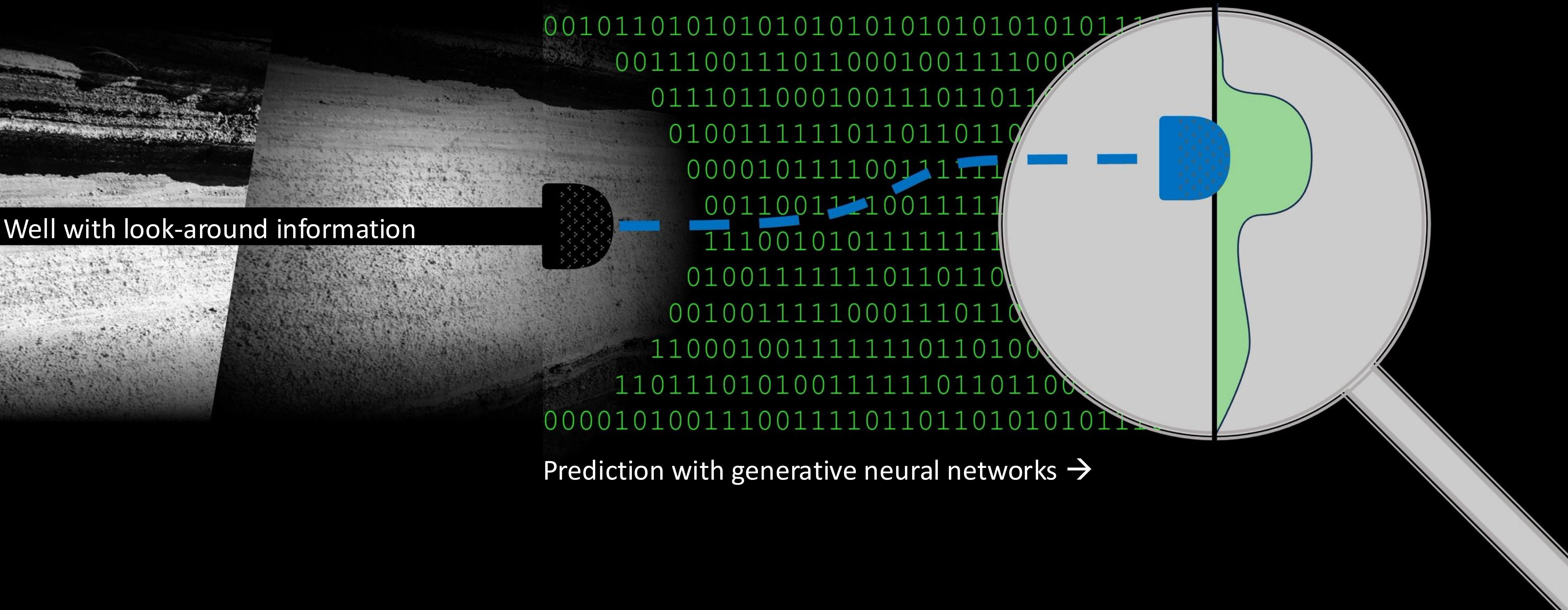
We want Probabilistic decision-support

We want Probabilistic decision-support



Mapping with generative neural networks

DISTINGUISH: Probabilistic decision-support



Simple real-time measurements and model-based geosteering

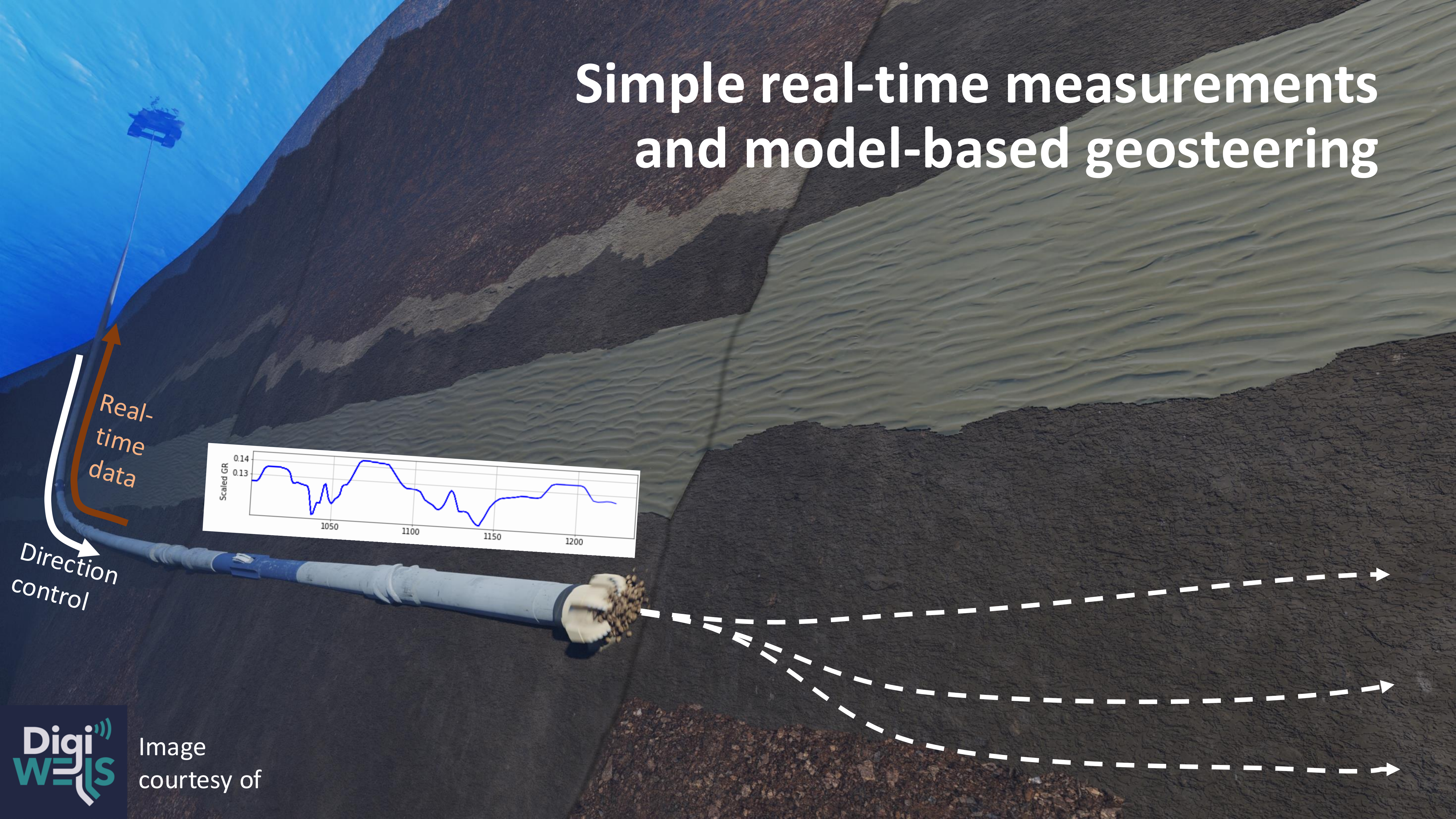
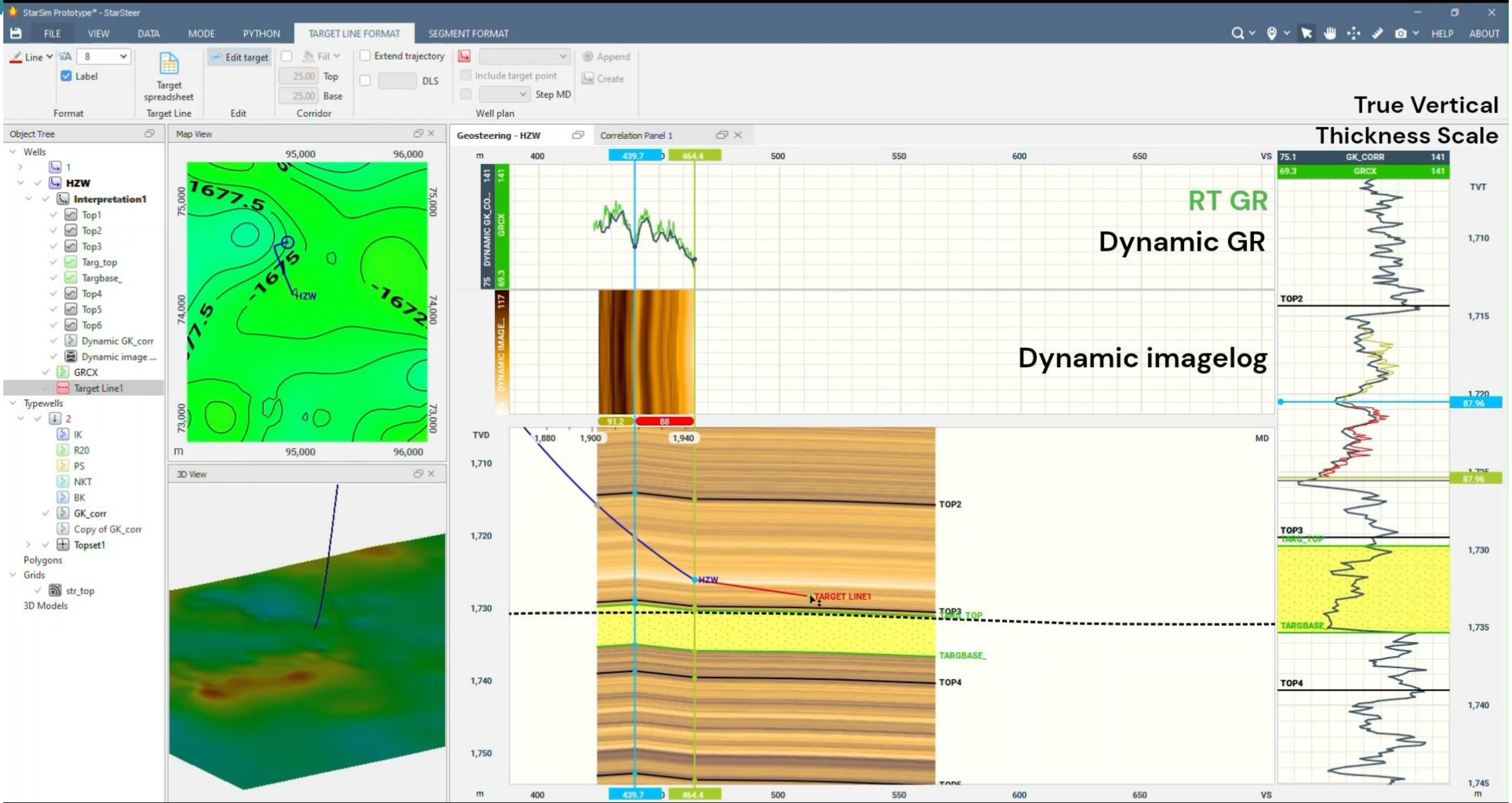
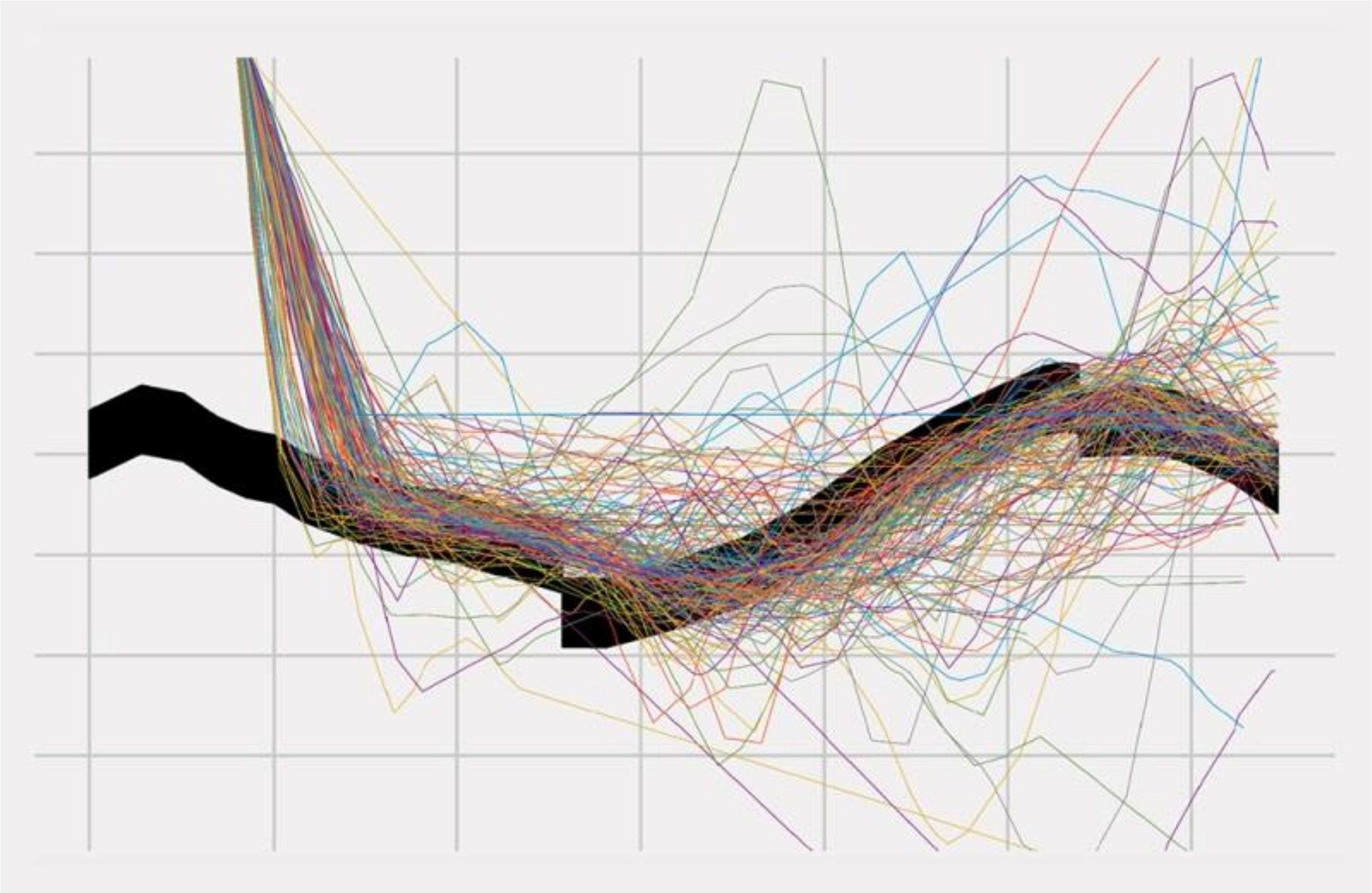


Image courtesy of

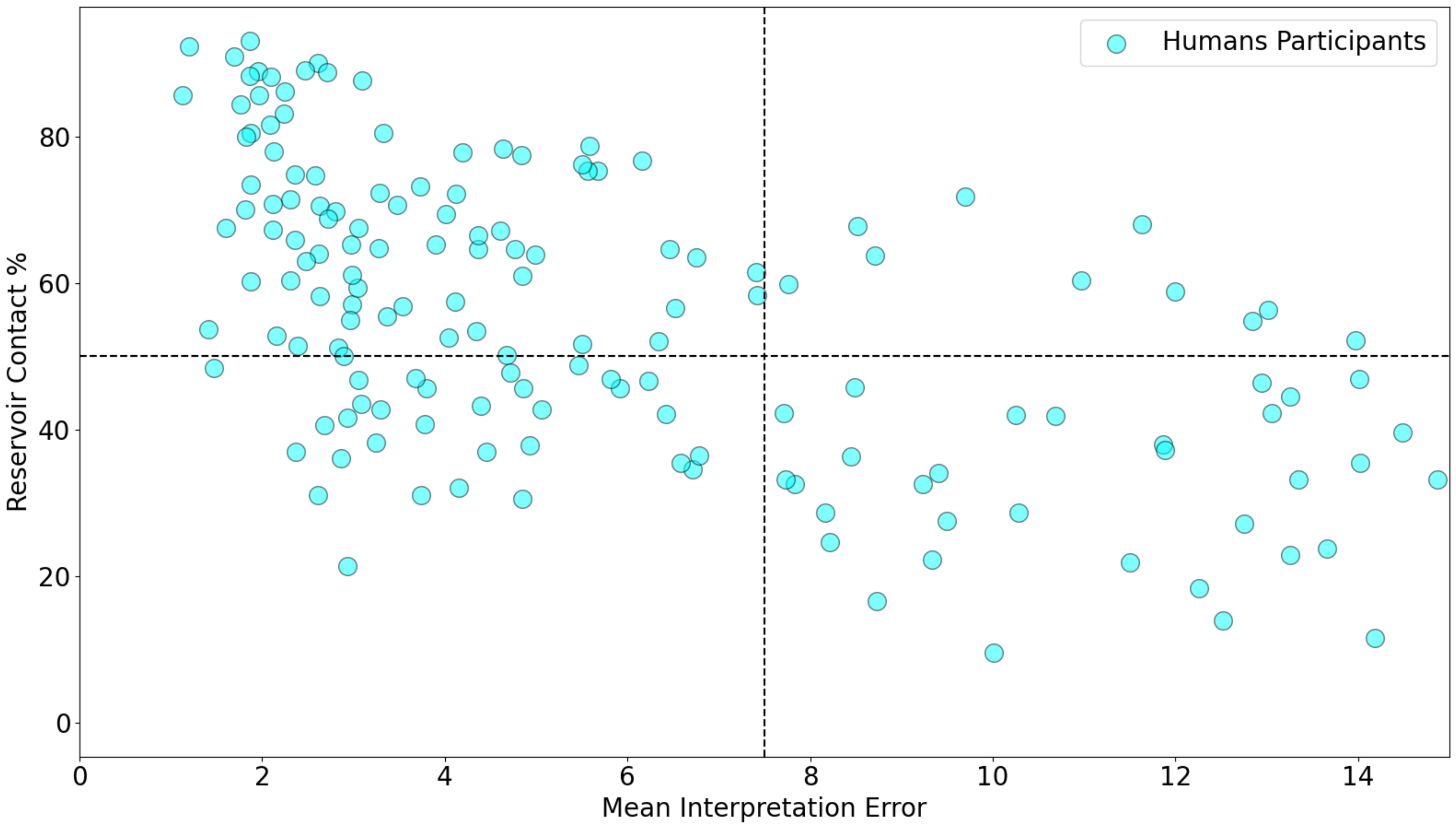

True Vertical
Thickness Scale
RT GR
Dynamic GR
Dynamic imagelog
StarSim Prototype* - StarSteer
FILE
VIEW
DATA
MODE
PYTHON
TARGET LINE FORMAT
SEGMENT FORMAT
HELP
ABOUT
Object Tree
Map View
3D View
Geosteering - HZW
Correlation Panel 1
TOP2
TOP3
TOP4
TARGBASE_
HZW
TARGET LINE1

Geosteering decisions are challanging



[What Can We Learn After 10,000 Geosteering Decisions? | SPE/AAPG/SEG Unconventional Resources Technology Conference | OnePetro]

The decisions depend on interpretation



Geological Interpretation

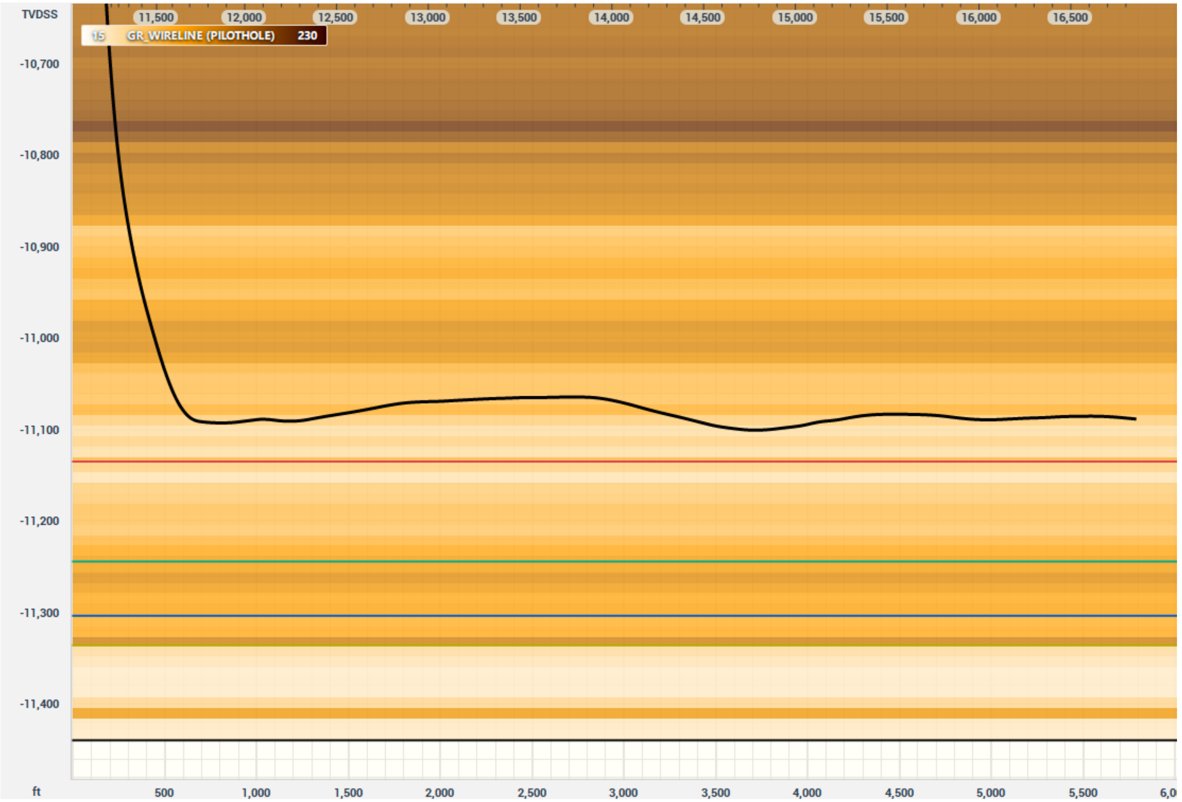
- the science (and art) of inferring the geology at some depth from data

Inverse problem

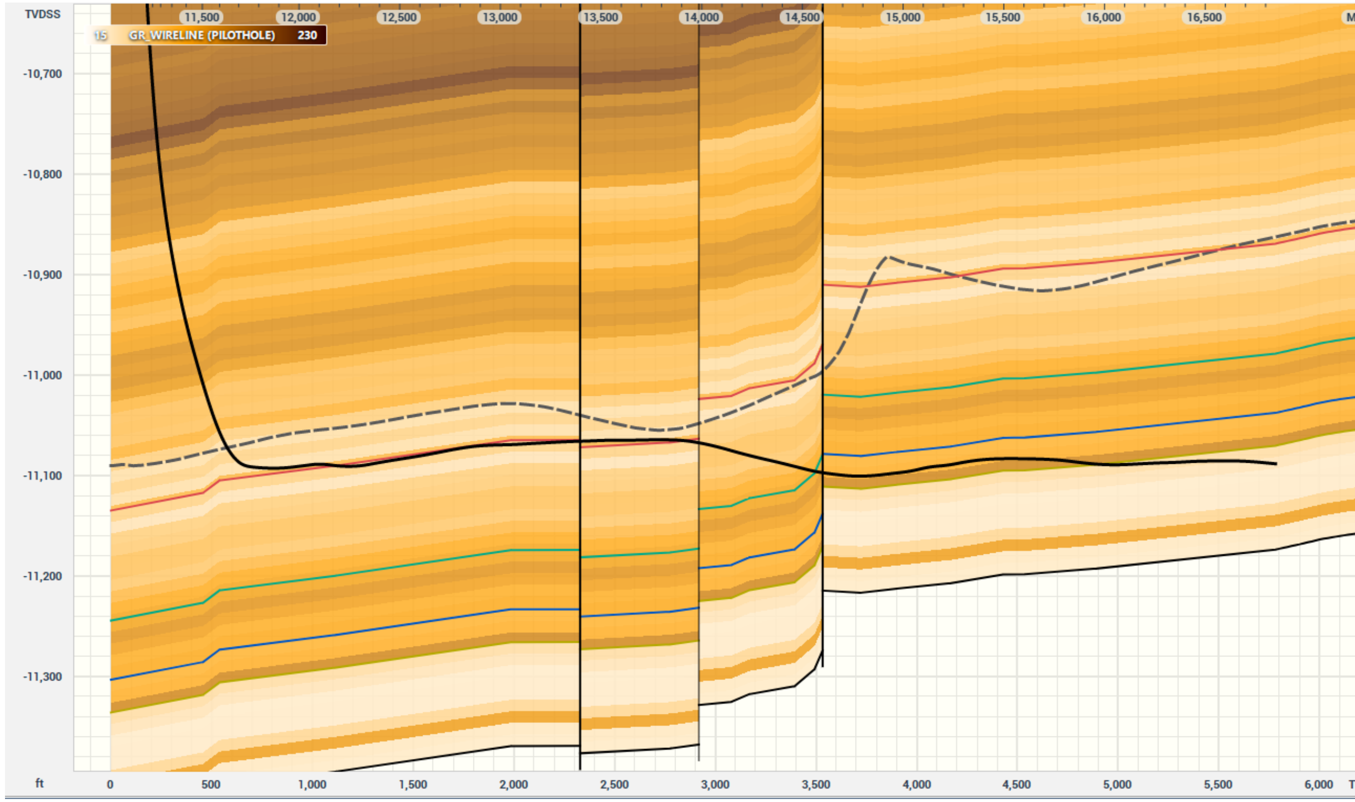
- (With cleverly defined regularizations and constraints)

Inverse problem

Geology with ideal thin layer cake



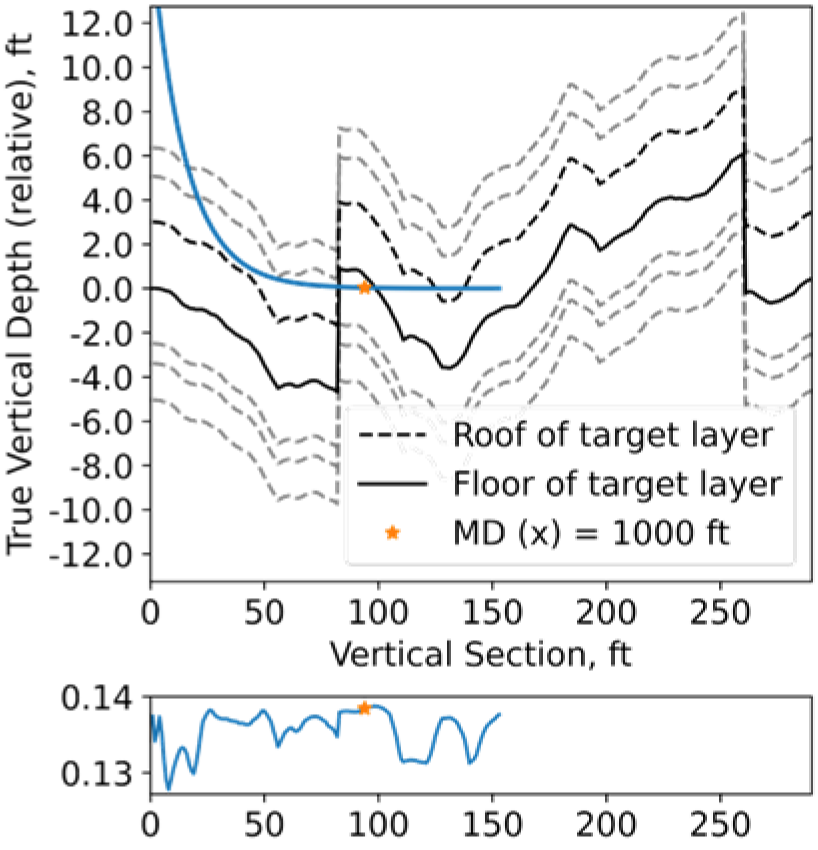
Layer cake with complex boundary



Inverse problem formulation

The most important slide

Find unknown geological strata



Assumptions:

- Layers have fixed thickness
- We can correlate to an offset well log

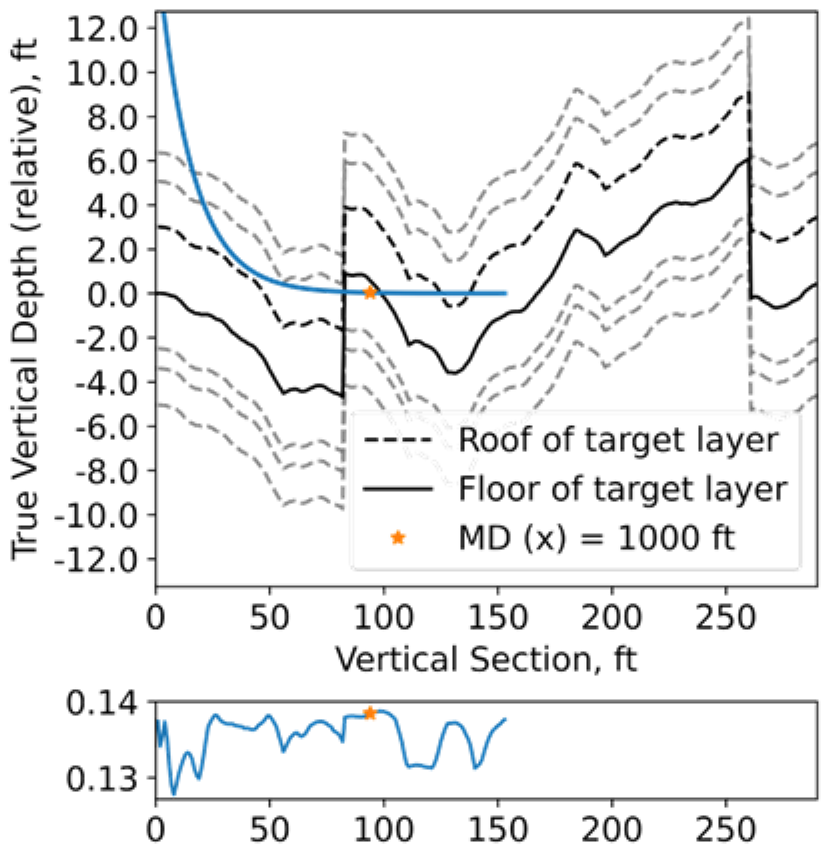
Stratigraphy can contain

- Varying dips (inclinations)
- Vertical faults

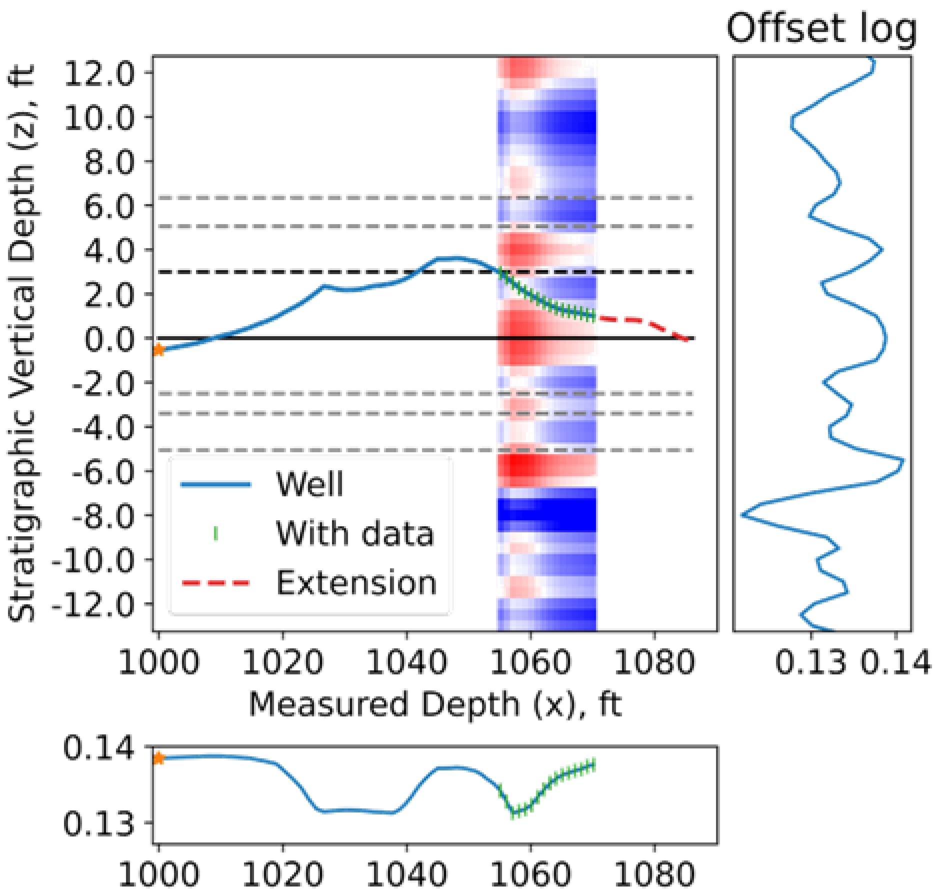
Inverse problem formulation

The most important slide

Find unknown geological strata

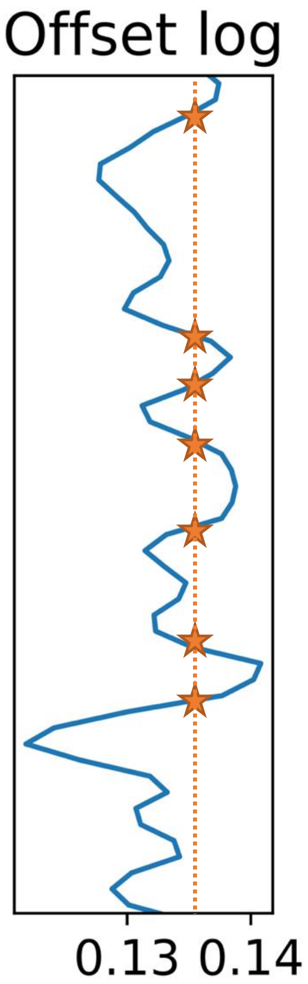


Find the well trajectory's **Boundary function**



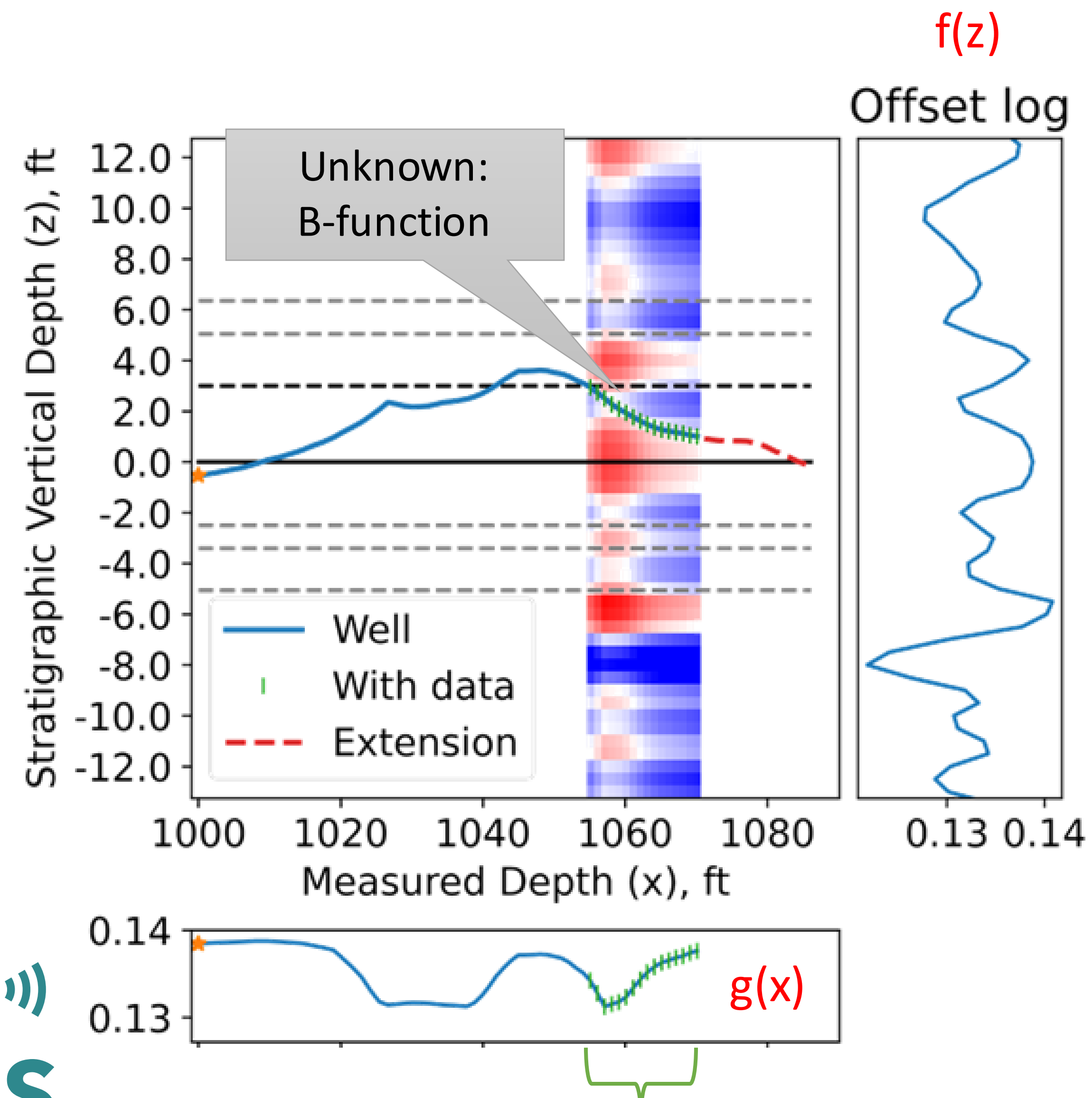
Difficulty with low-data geosteering

Interpretations
of a single data point



- Log data has multiple depth interpretations
- Picking one interpretation consistent with geology is difficult

Another way of visualization



Find the well trajectory's **Boundary function** representing relative geology

Find b(x)

$$f(b(x)) = g(x)$$

b(x) – boundary function
f(z) – offset (reference) measurements
g(x) – actual measurements

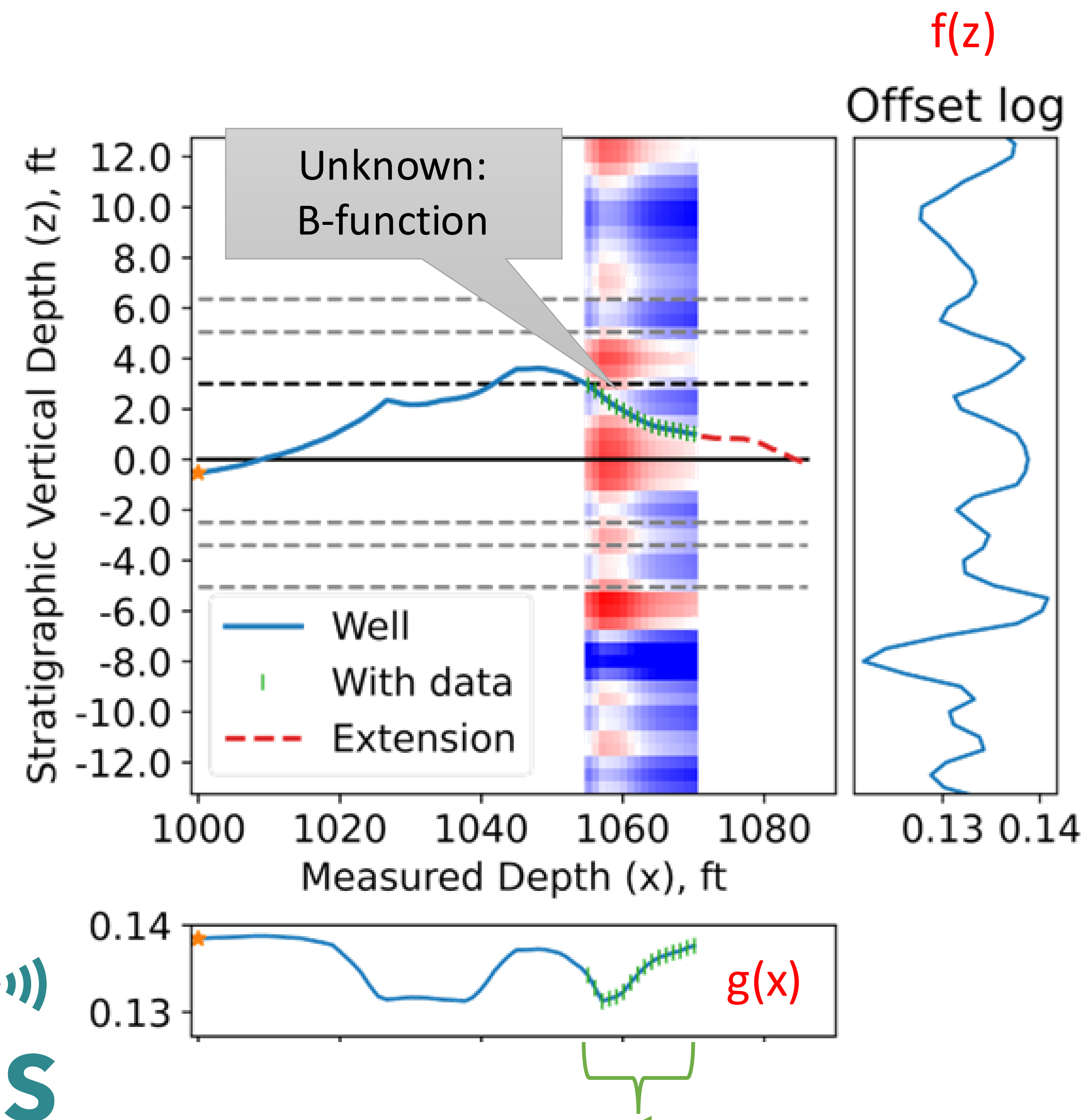
Inputs

Offset well log

Current well log

➔ **Heatmap image**

Another way of visualization



Find the well trajectory **Boundary function representing** relative geology

Find b(x)

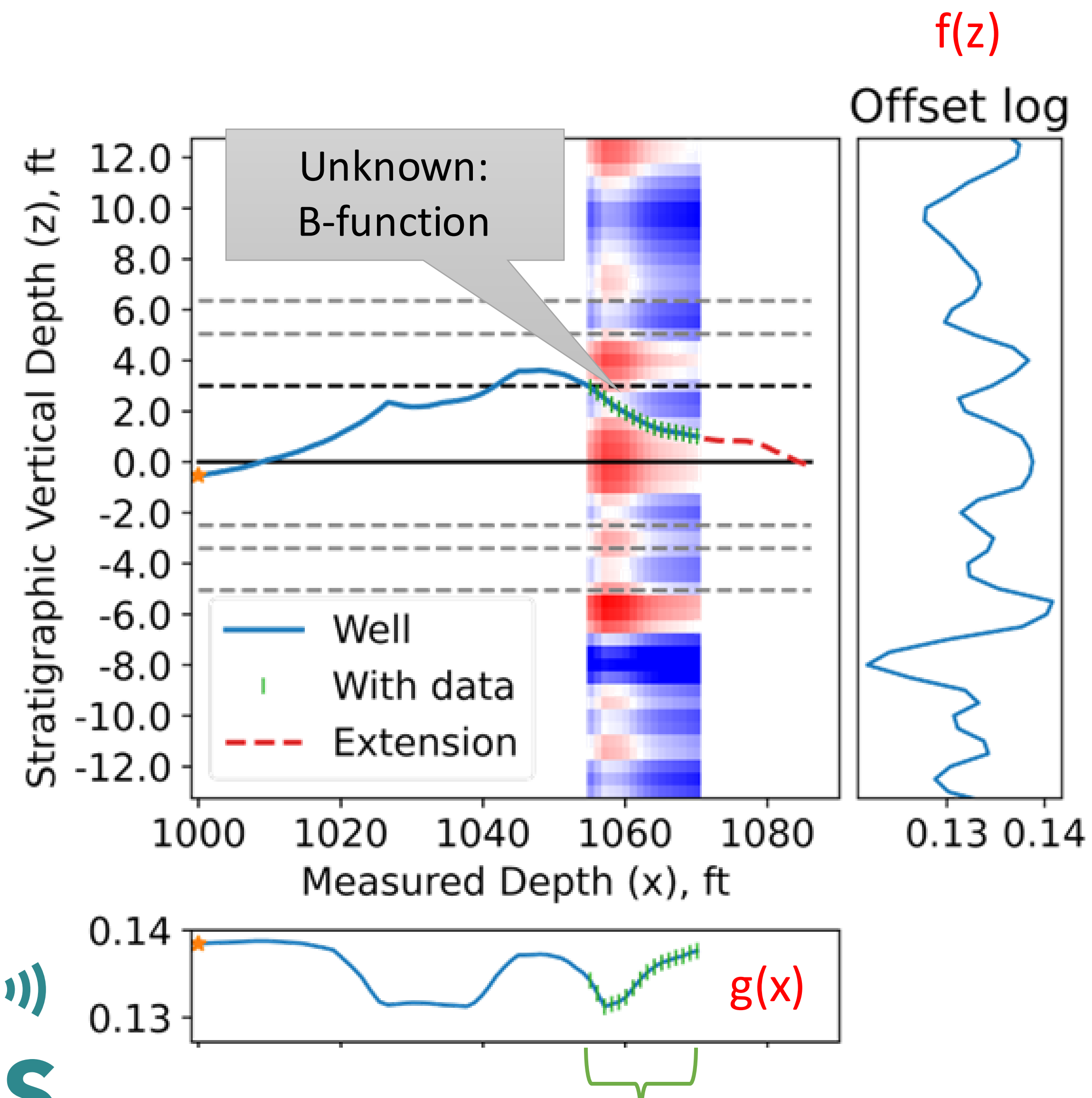
$$h_v(f(b(x))) = h_l(g(x))$$

b(x) – boundary function
f(z) – offset (reference) measurements
g(x) – actual measurements
In general, there might be a measurement function
h_v, h_l – direction-dependent measurement functions

Inputs
Offset well log
Current well log

➔ **Heatmap image**

Another way of visualization



Find the well trajectory's **Boundary function** representing relative geology

Heatmap image is useful to understand the data:

$$H(x, z) = f(z) - g(x)$$

Find $b(x)$

$$H(x, b(x))=0$$

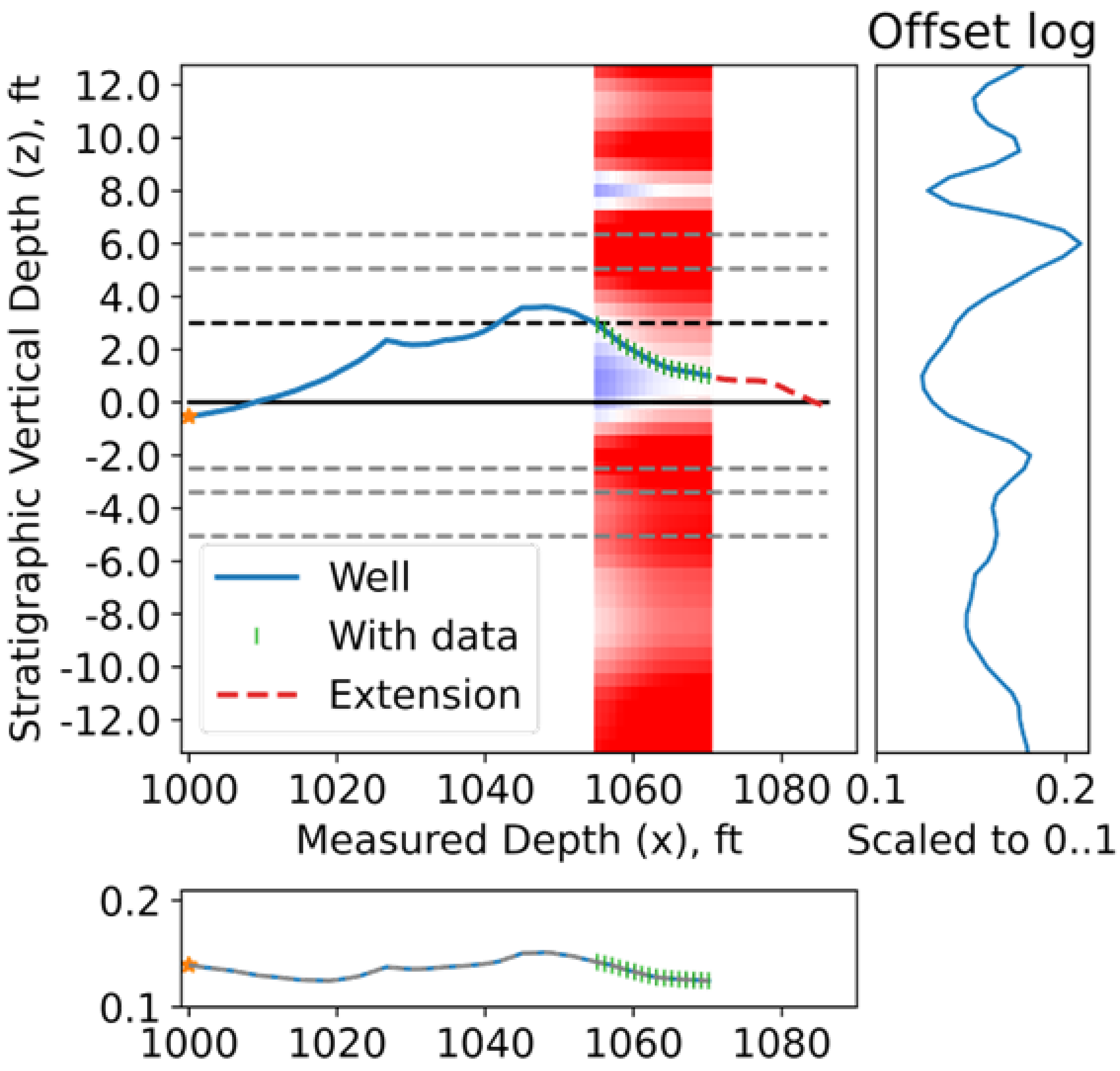
Inputs

Offset well log

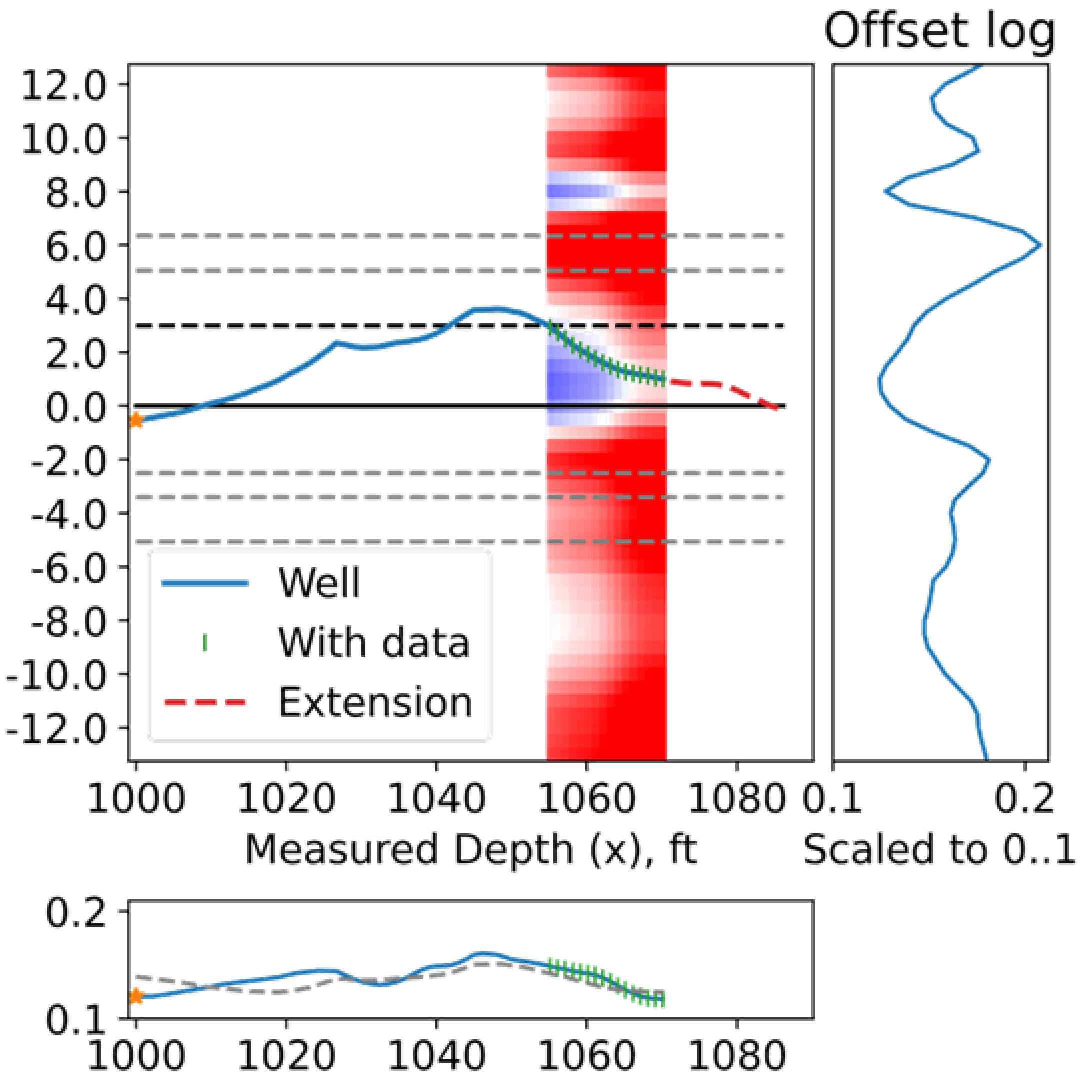
Current well log

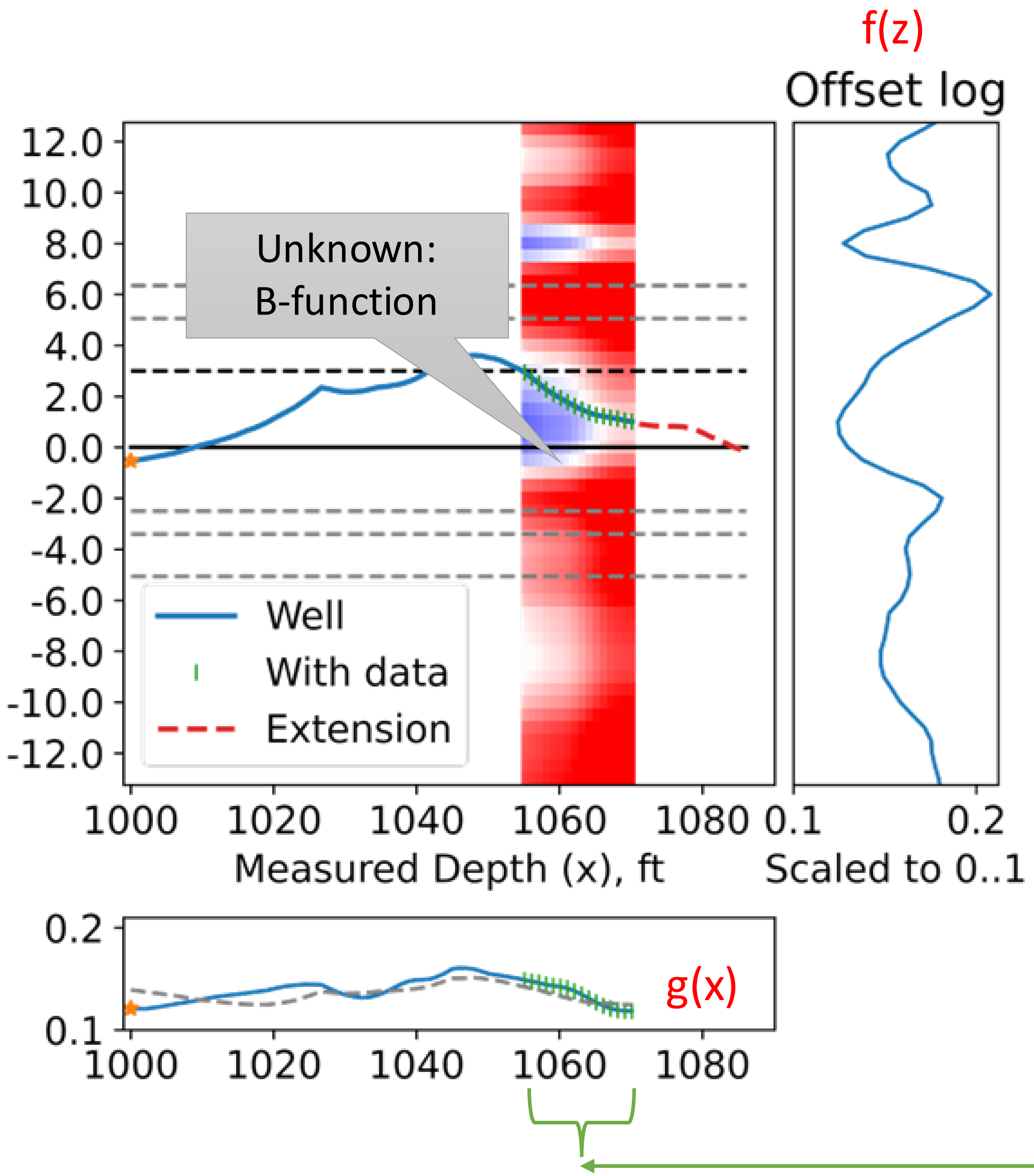
➔ **Heatmap image**

No noise



With noise





With noise

Find the well trajectory **Boundary function** representing relative geology

Find b(x)

$$f(b(x)) + w = g(x)$$

b(x) – boundary function

f(z) – offset (reference) measurements

g(x) – actual measurements

w – noise possibly corelated

includes the measurement error

and model error

Inputs

Offset well log

Current well log

Heatmap image

Boundary function to boundary

- $DZ_{geo}(x) = Z(x) - b(x)$
  - DZ – relative geological depth
  - b(x) – boundary function in the inverse problem
  - Z(x) – lateral well's depth

- For exercise purposes
  - $Z(x) = 0$
  - The well is horizontal

Other domains with fitting to reference data

- Autonomous vehicle positioning
- ???

The toy inverse problem

$$b^*(x) = \underset{b(x)}{arg\min}(\left\| f\big(b(x)\big) - g(x) \right\|_2^2)$$

Linear approximation:

- *b(x) = a*x + c*

Sequential inverse problem

- Find a 1D boundary function representing 1D geology
- We know a solution
  - $b_{i-1}(x)$ from x_{i-1} to x_i
- Find B function $b_i(x)$
  - $\boldsymbol{f(b_i(x)) = g(x)}$
- For x from x_i to x_{i+1}
  - $b_i\,(x_i) \approx b_{i-1}\,(x_i)$
  - b is reasonably continuous unless geological faults
- b is “reasonable” geologically
  - $t(x)$ – coarse scale geological trend

What is reasonable geologically?

- As a mathematician I would like to know that too…
- Data competition for generating 1D geology on Kaggle:
  - Small monetary prizes
  - Possibility to publish your work in a benchmark journal article
  - Submission deadline in June 2025

https://www.kaggle.com/competitions/geology-forecast-challenge/overview

What we solve

$$b_i^*(x) = \underset{b_i(x)}{\operatorname{argmin}}(\left\| f\big(b_i(x)\big) - g_i(x) \right\|_2^2 f\big(b_i(x)\big))$$

With slow geological variation, start with linear or piecewise linear

- $b_i(x) = a_i x + c_i$ $\qquad x$ in $x_i..x_{i+1}$

Additional data for regularization given multi-modality:

- Your previous solution was $b_{i-1}^*(x)$, x in $x_{i-1}..x_i$
- Coarse scale trend is $t(x)$

Better linear form

- $b_i(x) = a_i x + c_i$

Parametrized with data points:

- $b_i(x) = (z_{i+1} - z_i)/(x_{i+1} - x_i) * (x - x_i) \; + z_i$

Data-related parameters z_i
simplify formulating regularization and constraints

Alternative function

Piecewise linear within each interval:

- $b_i(x) = a_{i_1} x + c_{i_1}$ x in $x_{i-1}..x_*$
- $b_i(x) = a_{i_2} x + c_{i_2}$ x in $x_*..x_i$

B-spline

- $b_i(x) = p_n(x)$
- $p_n(x)$ is polynomial of degree *n*

Inverse solvers in scipy

`curvefit`

- Inputs
  - $f\left(b_i(x)\right)$
  - $g_i(x)$
- Solves
  - Find p, $f\left(b_i(x;p)\right) \approx g_i(x)$
  - $p = argmin\left\|f\left(b_i(x;p)\right) - g_i(x)\right\|_2^2$
- Paramerers
  - initial guess
  - Parameter constraints

Sea also underlying methods

- `least_squares`
- `leastsq`

These methods use gradient decent to solve non-linear least-squares problem

*The geological inversion is definitely not convex

Tikhonov Regularization

Fit to data:

- $p = argmin\left\| f\left(b_i(x;p)\right) - g_i(x)\right\|_2^{\ 2}$

Fit to beliefs (prior):

- $p = argmin\left\| b_i(x;p) - \tilde{b}(x)\right\|_2^2$

Regularized problem:

- $p = argmin\left(\left\| f\left(b_i(x;p)\right) - g_i(x)\right\|_2^2 + \kappa\left\| b_i(x;p) - \tilde{b}(x)\right\|_2^2\right)$

In the context of probabilistic estimation

$$p = \underset{p}{\operatorname{argmin}} \left(\left\| f\left(b_i(x;p)\right) - g_i(x) \right\|_2^2 + \kappa \left\| b_i(x;p) - \tilde{b}(x) \right\|_2^2 \right)$$

- Tikhonov solution is **Maximum A Posterior (MAP)** of probabilistic solution, if
- $\kappa = \sigma^2/\gamma^2$
  - σ^2 - variance of measurement errors *w*
  - γ^2 - variance (uncertainty) in beliefs errors *w*

https://www.sintef.no/globalassets/project/evitameeting/2015/bayesiantutorial.pdf

NEW: Reformulate using `least_squares`

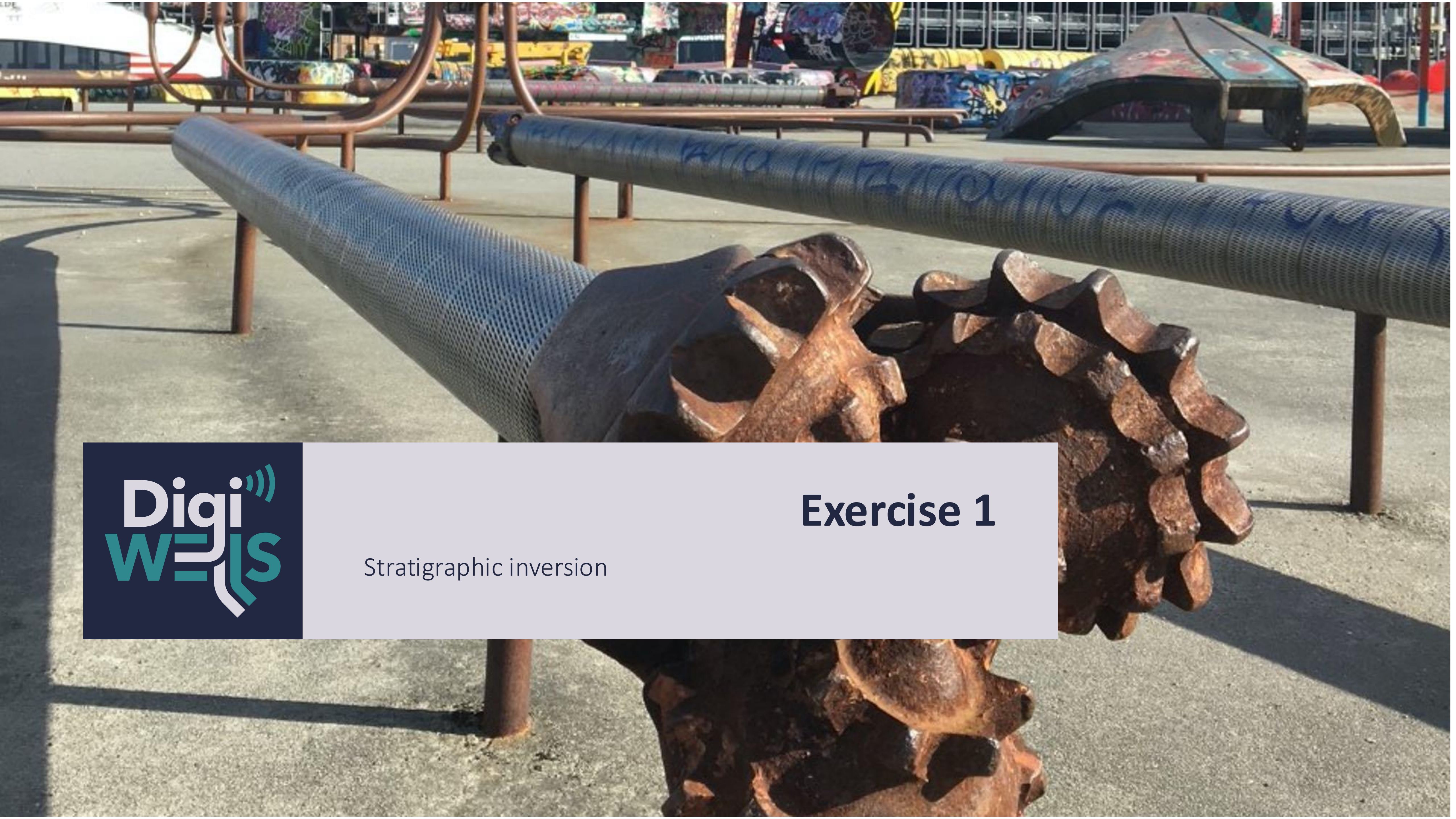
- Input is the function that returns vector of residuals
  - $\left\| f\left(b_i(x;p)\right) - g_i(x) \right\|_2^{\,2} + \kappa \left\| b_i(x;p) - \tilde{b}(x) \right\|_2^2$
- Equivalent to:
  - $f_k(x) = f\left(b_i(x_k;p)\right) - g_i(x_k),$ k < n = len(x)
  - $f_k(x) = \sqrt{\kappa}\,\left(b_i(x_{k-n};p) - \tilde{b}(x_{k-n})\right),$ k >=n = len(x)
- Staring guess vector
  - $param_0$ (x_0 in docs)
- Check auxiliary variables
- Check minimize function
- minimize F(param) = 0.5*sum(rho(f_k(param)**2), k = 0, ..., m - 1)
  subject to lb <= param <= ub

Reformulate using **`minimize`**

- Input is the minimization functional
  - $\left\| f\left(b_i(x;p)\right) - g_i(x) \right\|_2{}^2 + \kappa \left\| b_i(x;p) - \tilde{b}(x) \right\|_2^2$
- Staring guess vector
  - p_0
- Check auxiliary variables
- Check minimize function

Learnings

- Overview of geosteering as a sequential inverse problem
- Formulation of stratigraphic interpretation
- Basic preparation for exercise



Exercise 1

Stratigraphic inversion

Expected Learnings

- Hands-on experience with an optimization libraries for inverse problems: `scipy`
- Representing simple inverse problem as curve fitting
- Ability to formulate an inverse problem with regularizations and constraints

Expected Prize

not distributed to

Candies ~~taken from~~ kids on Halloween

Github link

- https://github.com/geosteering-no/inversion_school_geosteering

Scipy links

- https://docs.scipy.org/doc/scipy-1.15.0/reference/generated/scipy.optimize.curve_fit.html
- https://docs.scipy.org/doc/scipy-1.15.0/reference/generated/scipy.optimize.leastsq.html#scipy.optimize.leastsq
- https://docs.scipy.org/doc/scipy-1.15.0/reference/generated/scipy.optimize.least_squares.html#scipy.optimize.least_squares
- https://docs.scipy.org/doc/scipy-1.15.0/reference/generated/scipy.optimize.minimize.html