Geophysical Surveys

Geophysical exploration

Seismic

Electrical resistivity

Gravity

Magnetism

Radar

Geophysical surveys: from physics to practice

This lecture brings together everything from the course. We will look at four real surveys, each solving a different problem. The goal is not to memorize these examples but to understand how geophysicists make decisions.

"Given a problem, how do you decide what to measure, where to measure it, and how to interpret what you find?"

Before you go to the field

What physical property contrast do I expect?

- Velocity? Density? Resistivity? Permittivity?
- Does my target actually differ from its surroundings in this property?

What is my target?

- Depth, size, geometry, orientation
- Is it a sharp boundary or a gradual transition?

What are my constraints?

- Access, heritage protection, budget, time, personnel
- Can I put electrodes in the ground? Can I use explosives? Can I wait for dry season?

What question am I actually trying to answer?

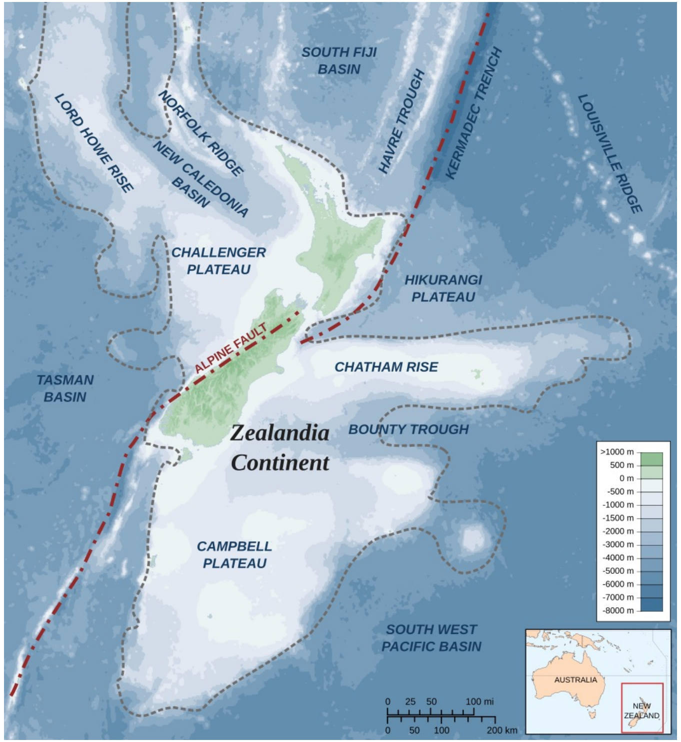
- "Where is the fault?" is different from "What is the slip rate?"
- "Is there something there?" is different from "What is it made of?"

Ultrahigh-resolution seismic reflection imaging of the Alpine Fault, New Zealand

The Alpine Fault is a geological fault that runs almost the entire length of New Zealand's South Island, being about 600 km long, and forms the boundary between the Pacific plate and the Australian plate.

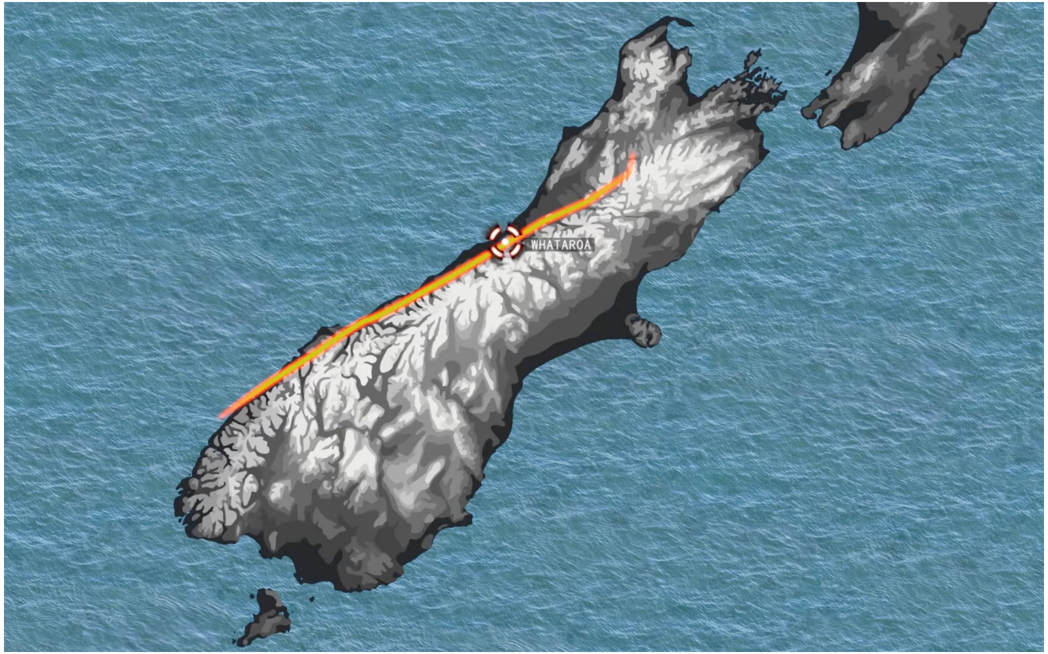
Most of the motion on the fault is strike-slip. The average slip rates in the fault's central region are about 38 mm a year (very fast!)

The last major seismic event on the fault was a great (magnitude of 8 or more) earthquake of Mw8.1± 0.1 in about 1717 AD.



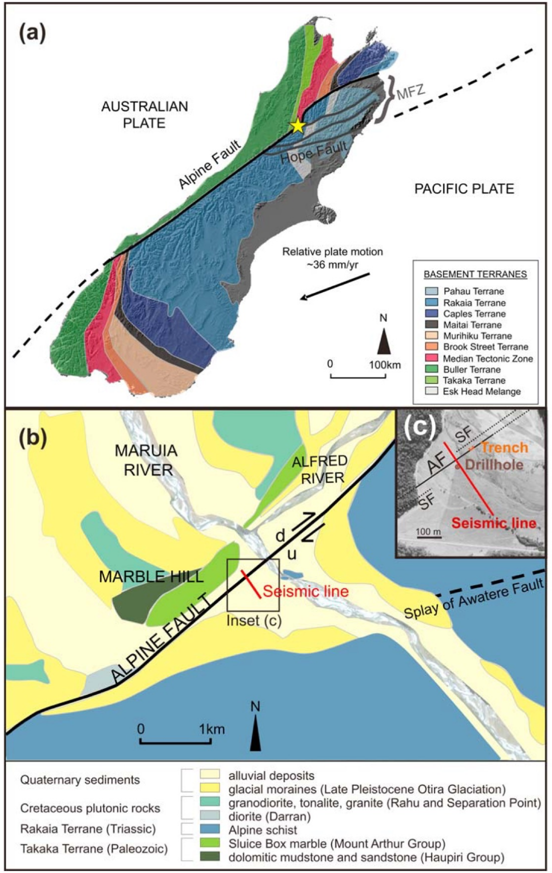
Ultrahigh-resolution seismic reflection imaging of the Alpine Fault, New Zealand

https://www.youtube.com/watch?v=mSidKstEI2U&t=148s



Imaging an active plate-boundary fault

- The survey was done at **Calf Paddock**, where the fault crosses abandoned terraces of the **Maruia River**.
- At the site, the Alpine Fault is marked by an approximately **2 m high linear fault scarp**.
- The shallow subsurface contains **late Quaternary alluvial/glaciofluvial/glaciolacustrine sediments** over basement, so it is a good place to test whether seismic reflection can image both the fault and the sediment-basement structure.



Survey design: what they actually did in the field

- The team acquired a **360 m 2D ultrahigh-resolution reflection line**.
- Source: **5 kg hammer, 6 stacked blows** per shot.
- Receivers: **240 channels, 30 Hz vertical geophones, 0.5 m receiver spacing**.
- **1 m source spacing, 0.25 m CMP spacing**, fold up to **~60**, record length **1500 ms**, sample rate **0.125 ms**.

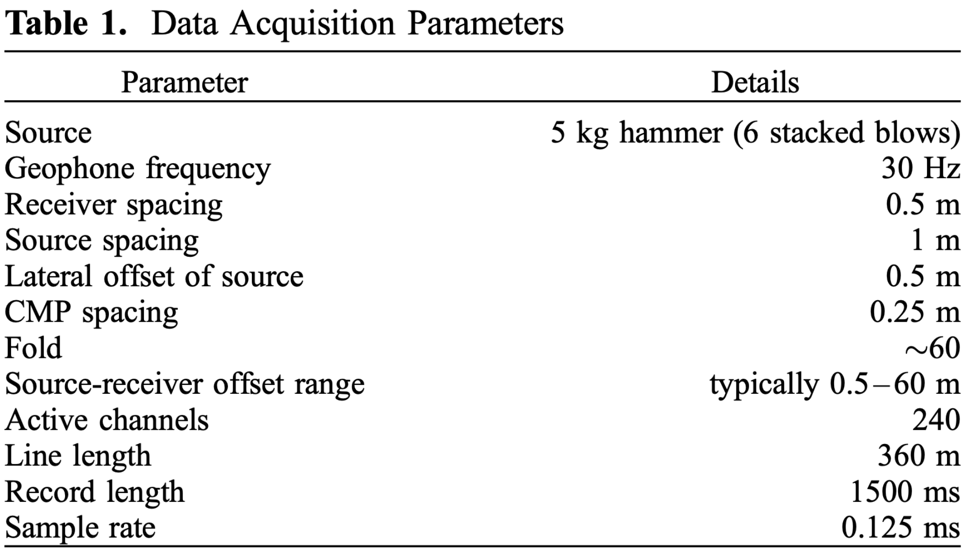


Table 1. Data Acquisition Parameters

Parameter	Details
Source	5 kg hammer (6 stacked blows)
Geophone frequency	30 Hz
Receiver spacing	0.5 m
Source spacing	1 m
Lateral offset of source	0.5 m
CMP spacing	0.25 m
Fold	∼60
Source-receiver offset range	typically 0.5 – 60 m
Active channels	240
Line length	360 m
Record length	1500 ms
Sample rate	0.125 ms

This is a very dense line: short spacing, high fold, short offsets. It is designed for ***very shallow, high-resolution imaging****, not deep crustal structure.*

Why shallow seismic reflection is difficult here

- The shallow data were strongly affected by **near-surface heterogeneity** and **source-generated noise**.

- A low-velocity near-surface layer caused **static shifts of up to ~3 ms**.

- The authors used **refraction tomography**, **refraction statics**, and **residual statics** before stacking and migration.

- The survey shows clearly that if you do not correct these effects, reflectors appear distorted or discontinuous.

Why seismic data are messy before processing

1. Near-surface heterogeneity = the shallow ground is uneven

The top few meters are not the same everywhere: soil, gravel, weathered rock, and water content change laterally. So seismic waves travel faster in some places and slower in others.

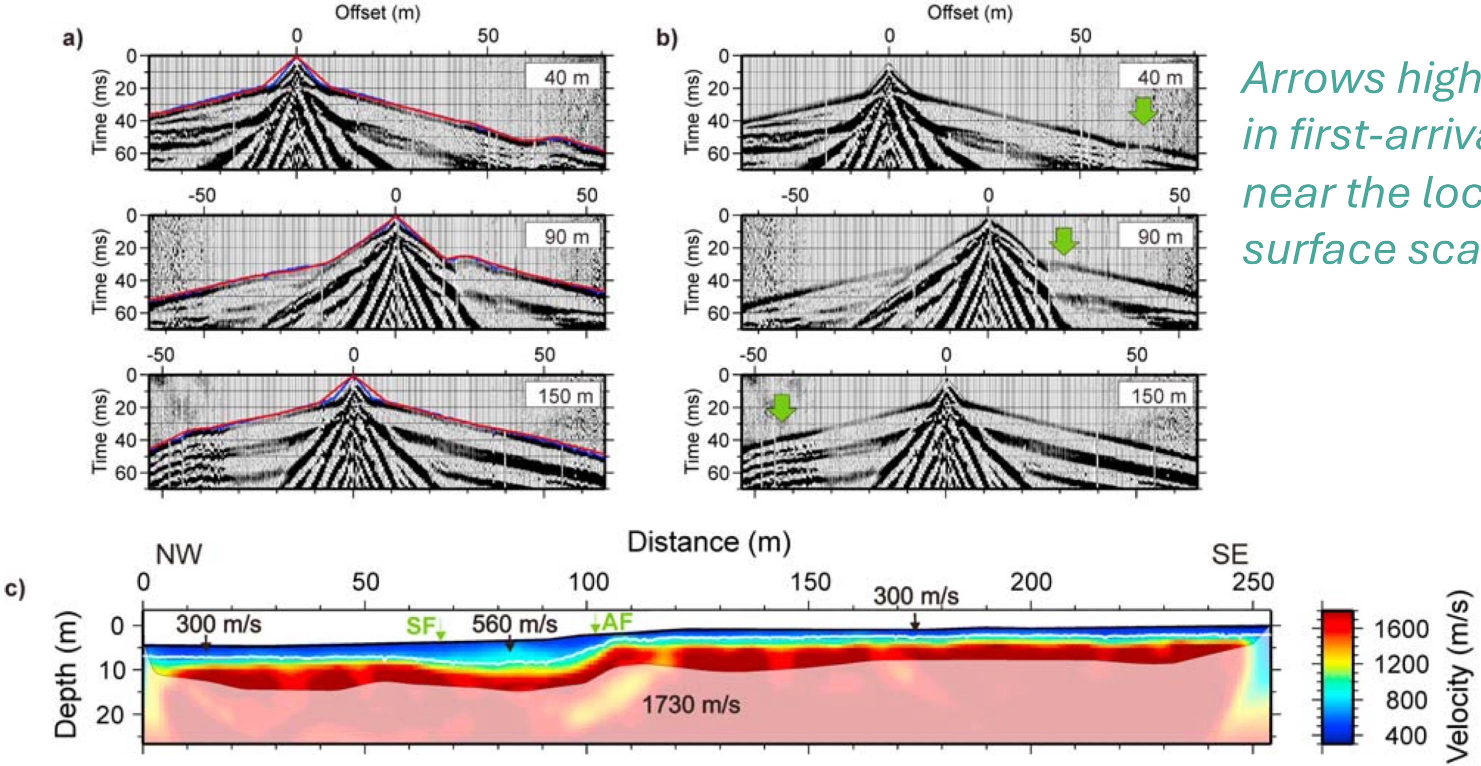
2. Static shifts = fake time delays caused by that uneven shallow layer

If one trace passes through a slower shallow patch, the reflection arrives later, even when the deeper layer is actually at the same depth. Result: a continuous reflector can look bent, broken, or offset on the raw section.

3. Source-generated noise = energy that does not image the target

The hammer does not produce only useful reflected waves. It also generates unwanted energy such as ground roll, guided waves, and multiples, which can hide weak reflections from the fault zone.

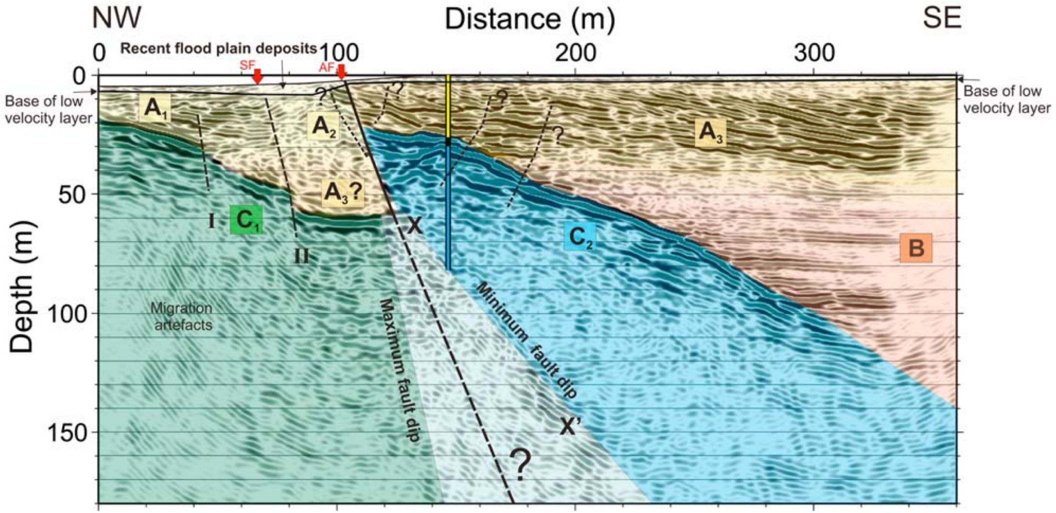
Why shallow seismic reflection is difficult here



Arrows highlight reductions in first-arrival undulations near the location of the surface scarp.

What was learned, and what seismic reflection could not resolve

- The Alpine Fault dips about **75-80° southeast** through the Quaternary sediments.
- The top of basement is vertically offset by about **35 m** across the fault.
- Using the vertical offset and fault dip, they estimate a **provisional dip-slip rate of 2.0 ± 0.6 mm/yr** at this site.
- But the line is **2D**, so it cannot determine the more important **dextral-slip rate**. That limitation is important to state explicitly.

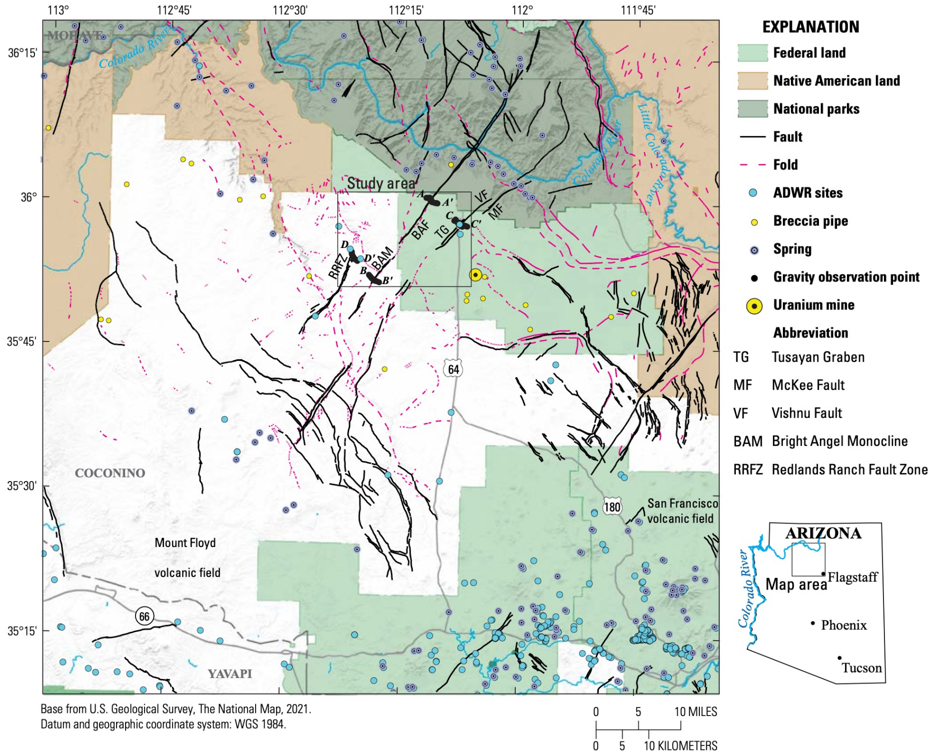


Gravity transects across faults and grabens for groundwater-related structure

Coconino Plateau, Arizona, USA

Why did USGS do this study?

- The study area is the Coconino Plateau in northern Arizona, near the Grand Canyon.
- This region contains major geological structures such as faults, folds, and grabens.
- These structures may influence how groundwater moves underground.
- USGS wanted to test whether gravity measurements could detect lower-density zones near these structures.
- If such zones exist, they may indicate more open rock, more fractures, or more pore space, which could affect groundwater flow.

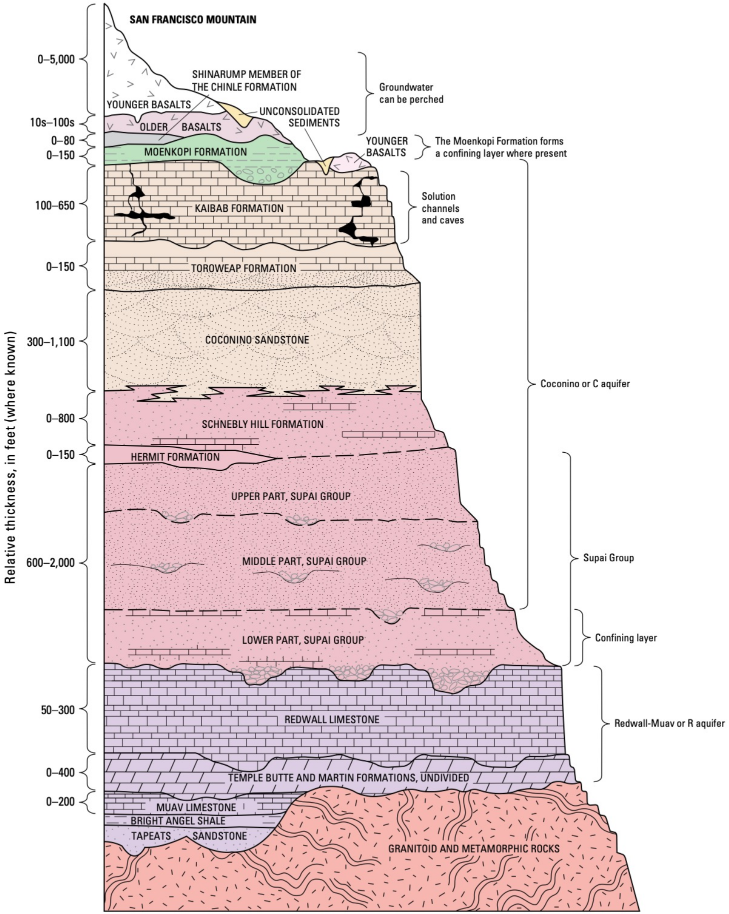


Base from U.S. Geological Survey, The National Map, 2021.
Datum and geographic coordinate system: WGS 1984.

What was the geological idea behind the project?

- The plateau contains layered sedimentary rocks that host two important groundwater systems: the C aquifer and the R aquifer.
- The idea was that faults or related structures might create zones of higher porosity.
- Porosity means the amount of empty space in the rock. More porosity often means lower density.
- Lower-density zones can sometimes be detected with gravity, because they produce a slightly lower gravity signal than denser rocks.

So the question was: Can gravity detect these hidden porous zones?



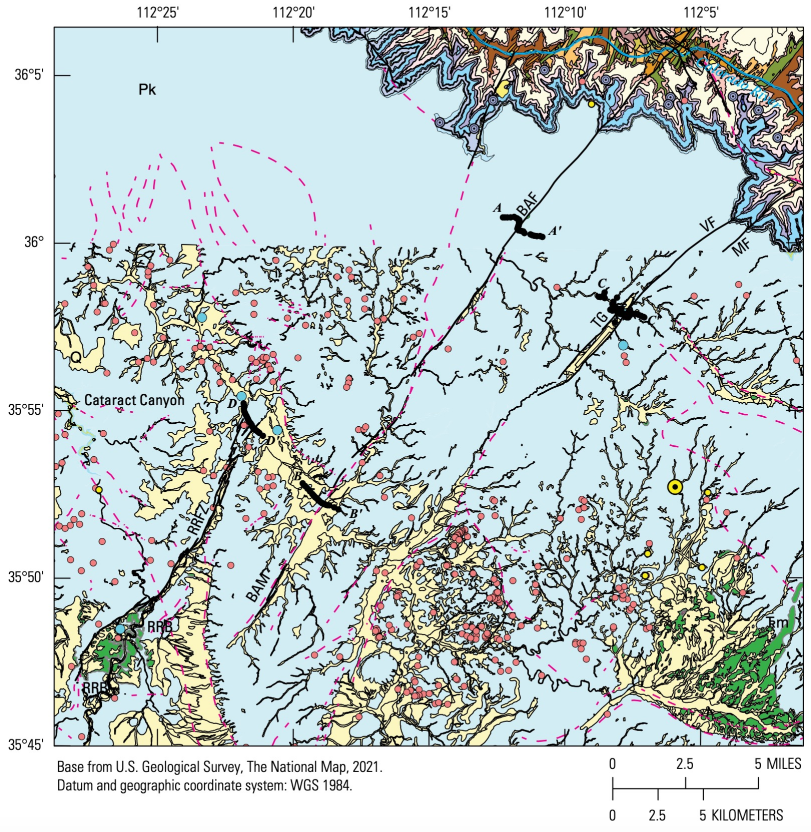
Modified from Bills and others, 2016

How did they design the gravity survey?

- USGS collected gravity data along four transects across four geological features.

- The lines were designed to cross the structures roughly at right angles. Each transect extended about 1 km on each side of the mapped fault or fold axis.

- The goal was to see whether the gravity signal changed as the survey crossed the structure. The team then compared the measured gravity pattern with simple subsurface models to test whether a low-density zone could explain the observations.

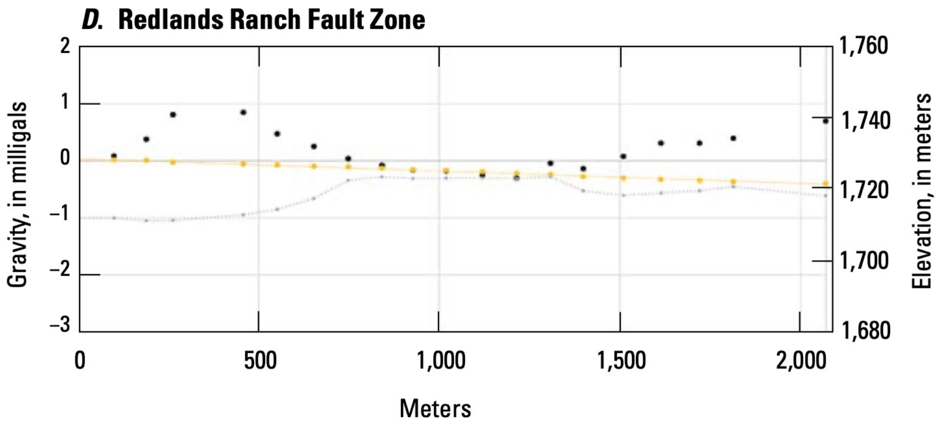


Base from U.S. Geological Survey, The National Map, 2021.
Datum and geographic coordinate system: WGS 1984.

What did they find?

The results indicated that for 3 transects there is no clear evidence for an enhanced-porosity zone within 1 km of the feature.

Only the Redlands Ranch Fault Zone showed a negative gravity anomaly, meaning a lower-gravity signal consistent with lower-density material.



This was important because it showed that gravity does not automatically detect a porous zone at every fault or graben. In other words: the method can be useful, but the answer may be yes in one place and no in another.

What does the result mean, and what are the limits?

- At Redlands Ranch, the gravity profile showed a negative anomaly in the middle of the transect.

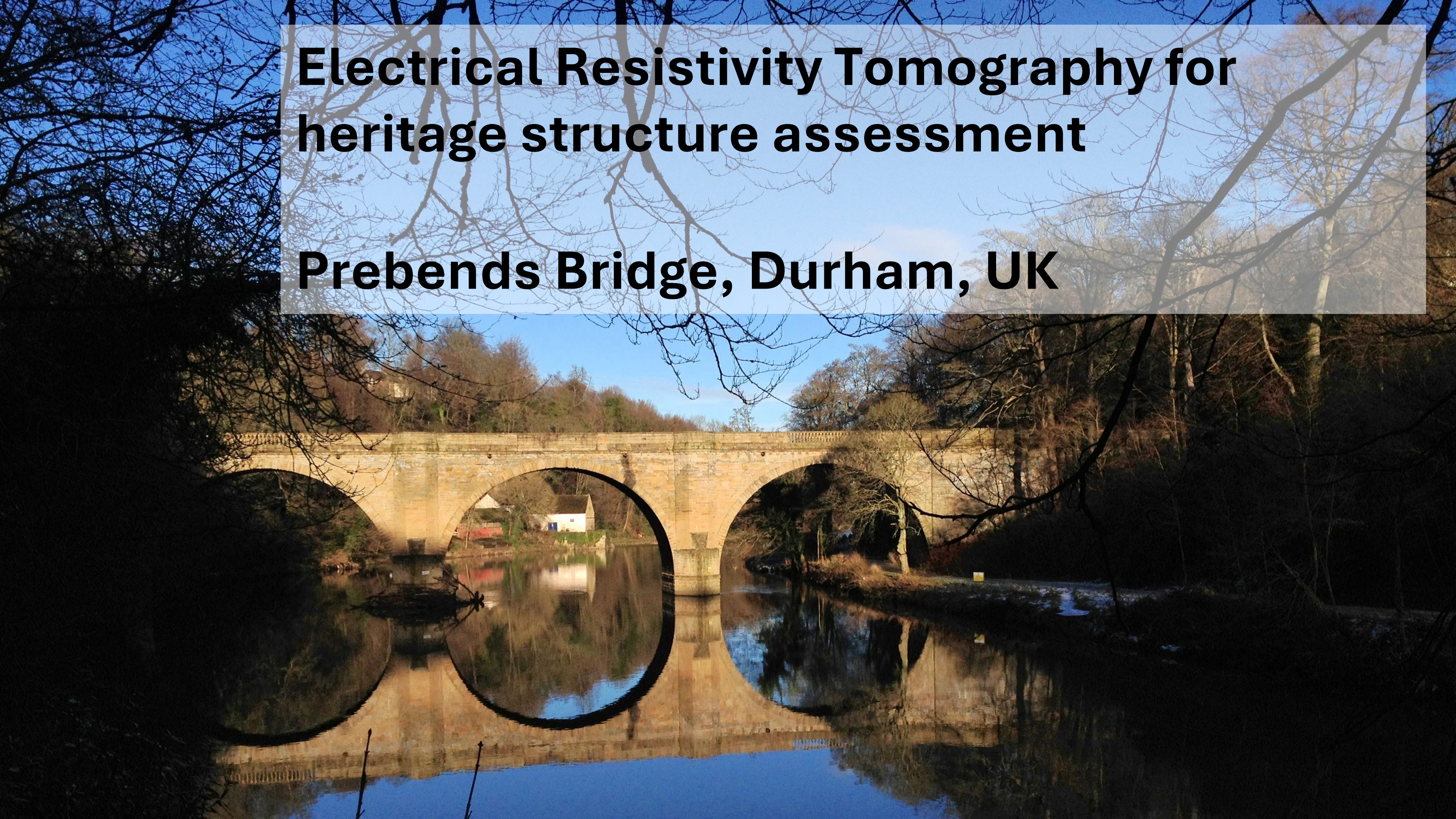
- USGS showed that this anomaly could be matched by a modeled low-density zone about 800 m wide and 1,000 m deep.

- The interpretation is that this could represent a relatively shallow low-density zone, possibly linked to more fractured or more porous rock. But the result is not perfect or unique: the model does not explain every part of the gravity curve equally well.

- The final lesson is that gravity is useful for screening and identifying targets, but it usually needs to be combined with more geology or more data before making strong conclusions.

Electrical Resistivity Tomography for heritage structure assessment

Prebends Bridge, Durham, UK

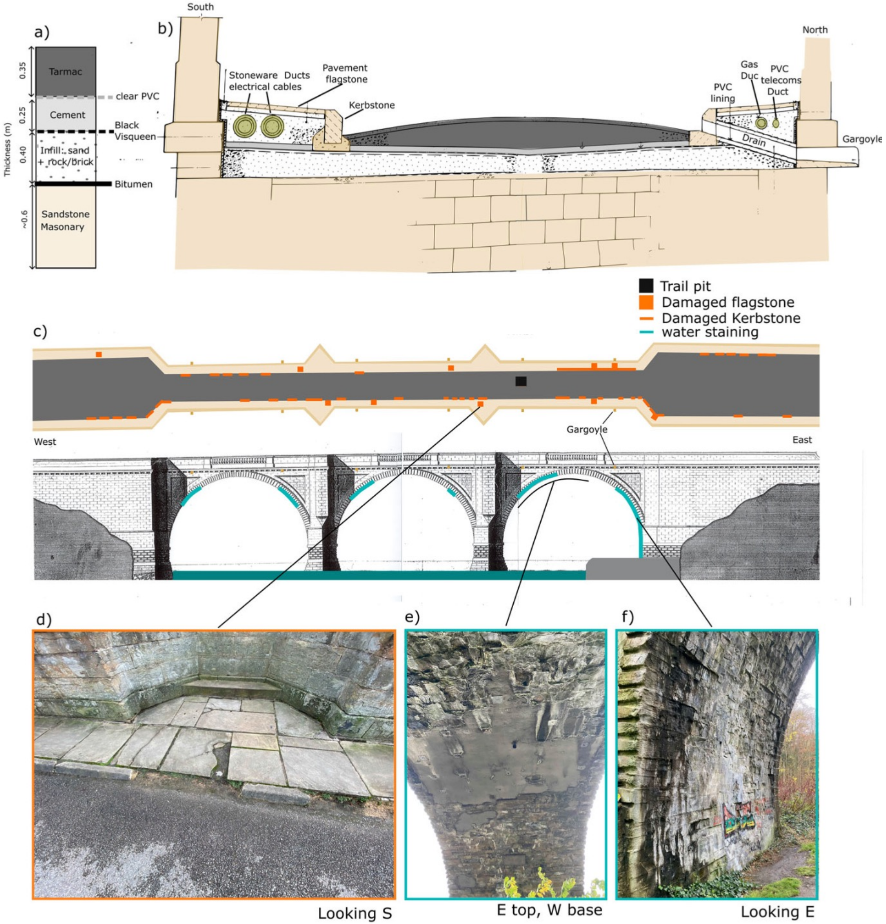


Electrical Resistivity Tomography for heritage structure assessment

- Case study: Mapping water infiltration in a historic 18th-century masonry bridge
- Location: Durham, UK – bridge constructed in 1778
- Challenge: Water damage observed externally; need to locate internal pathways non-destructively
- Method: Electrical Resistivity Tomography (ERT) adapted for built structures

Motivation: Detecting water pathways without damage

- Prebends Bridge is listed as heritage structure, invasive techniques not permitted
- External signs of water damage and previous unsuccessful repair attempts
- Conventional methods (drilling, coring) would damage the historic fabric
- ERT principle: Water-saturated stone has lower electrical resistivity than dry stone
- Dry sandstone: ~1000-10,000 Ω·m
- Water-saturated sandstone: ~100-500 Ω·m



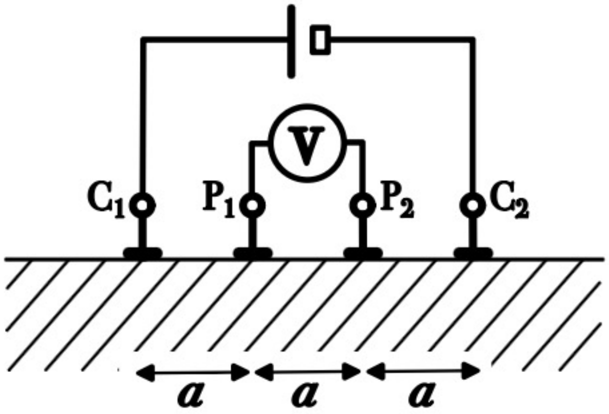
How was the survey designed?

- Electrodes placed on the paved surface
- Linear transects placed along the pavement on each side of the eastern arch

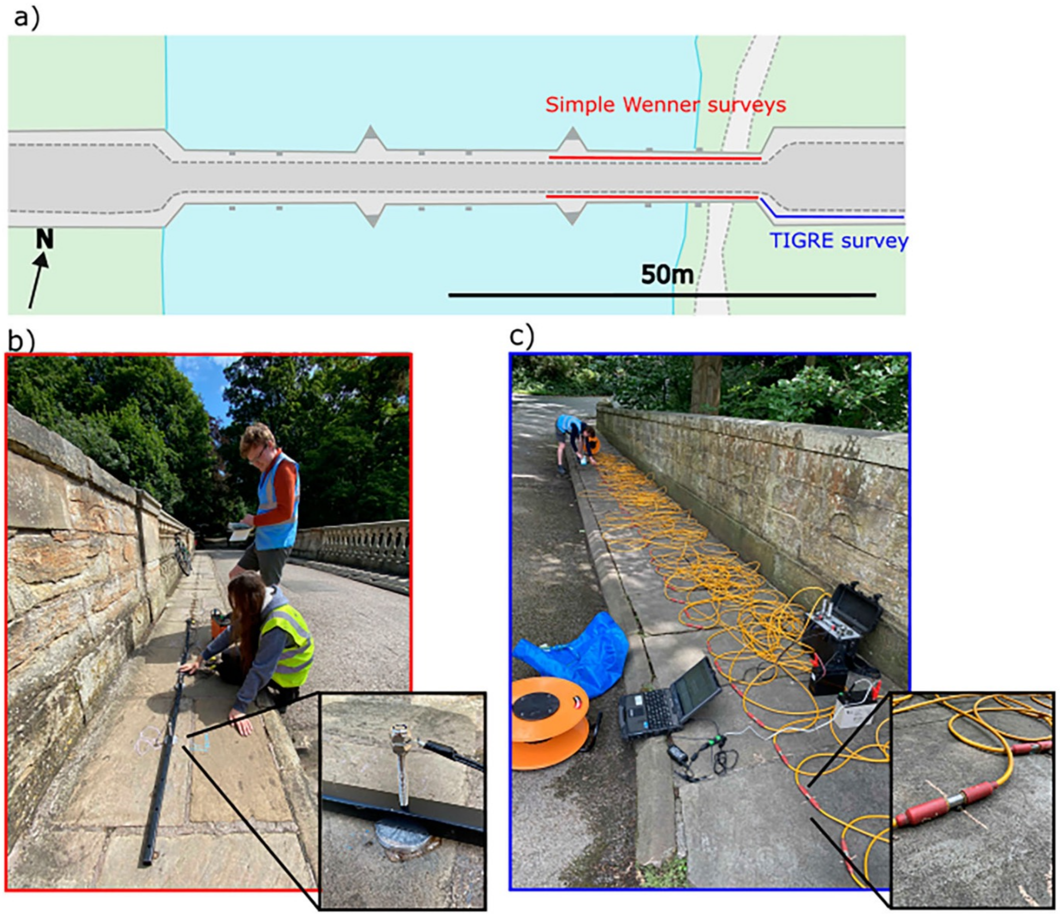
- Electrode spacing: Determines both resolution and depth of investigation:
  - Smaller spacing → higher resolution, shallower penetration
  - Larger spacing → lower resolution, deeper penetration

- Survey conducted over several weeks in July–August 2023 during a wet period

Classic Wenner electrode array configuration



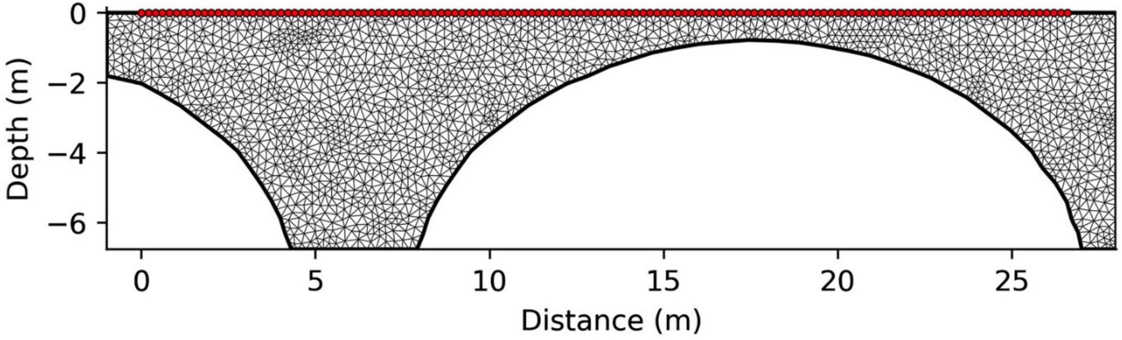
How was the survey designed?



Data Processing: Apparent Resistivity (True Resistivity Model)

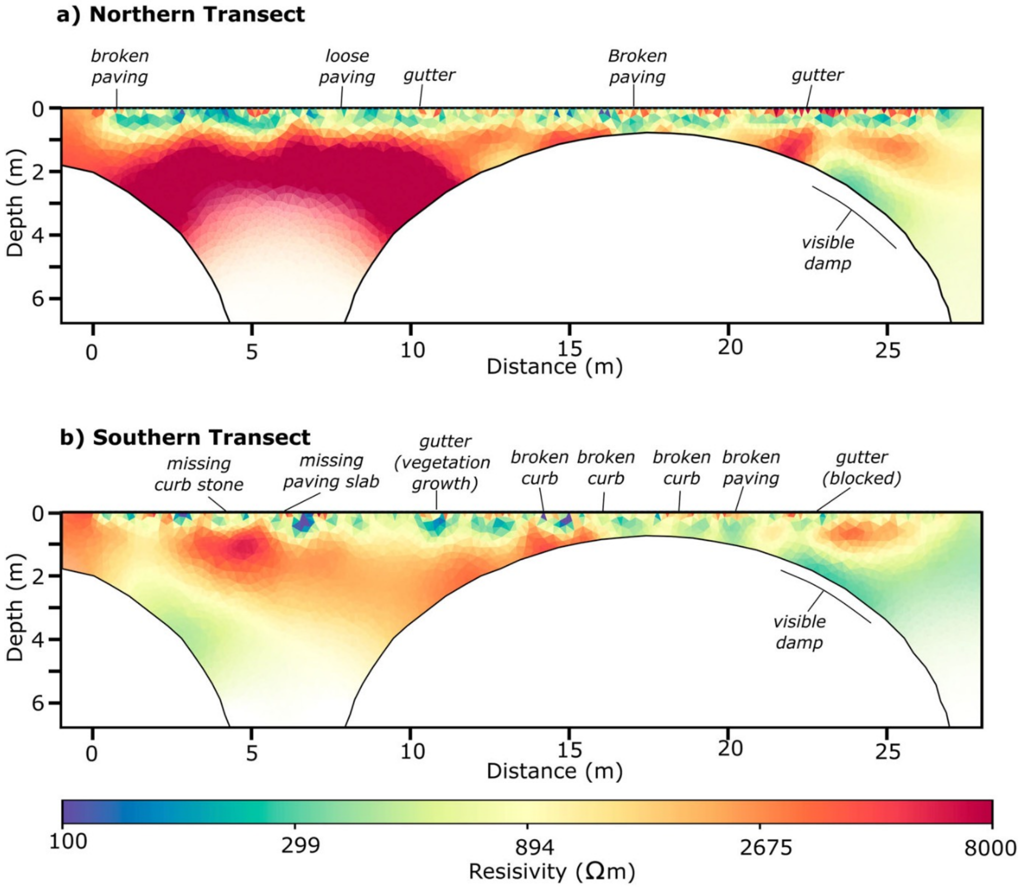
- Raw data = apparent resistivity (what the instrument measures)
- Solves an inverse problem: "What resistivity model produces the data we measured?"

- Key challenge: The bridge has complex 3D geometry (arch shape, not flat ground)
- Forward modeling: Calculate what data we would expect from a given model
- Iterative inversion: Adjust model until calculated data matches measured data



Inversion results: mapping water infiltration

- Low resistivity zones (shown in blue/cool colors) → interpreted as water-saturated stone
- High resistivity zones (shown in red/warm colors) → dry, intact masonry



a) Northern Transect

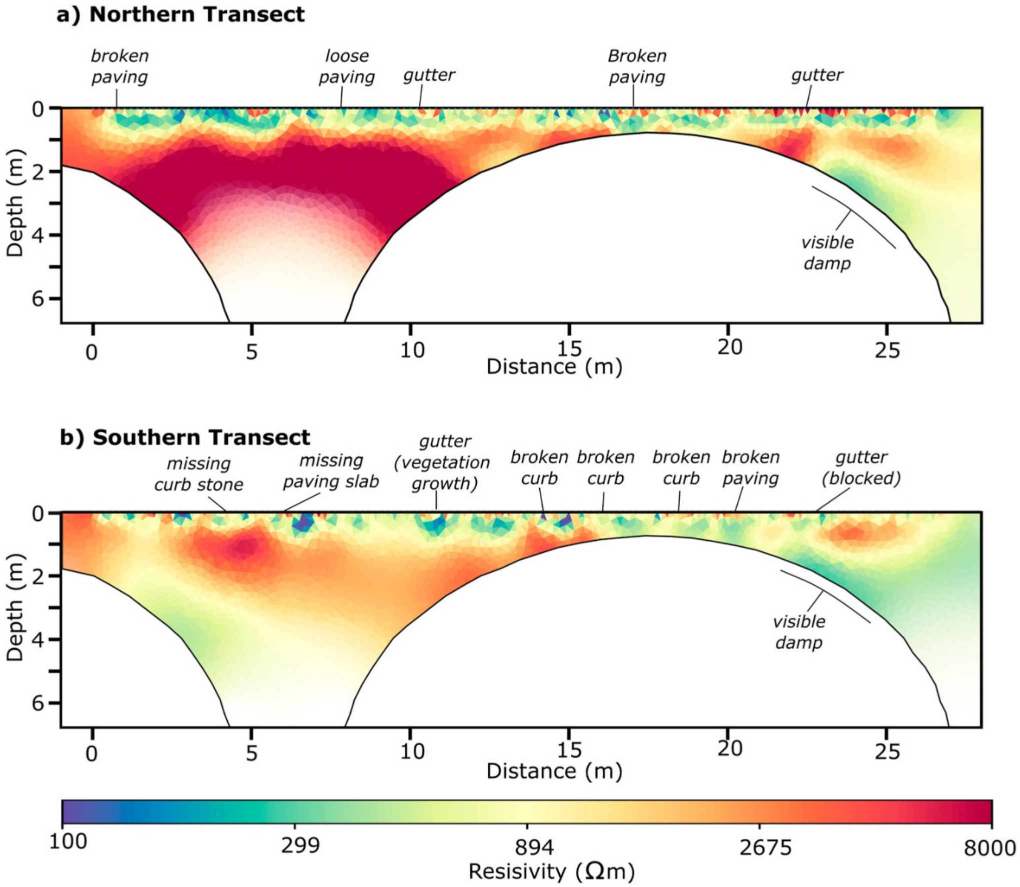
b) Southern Transect

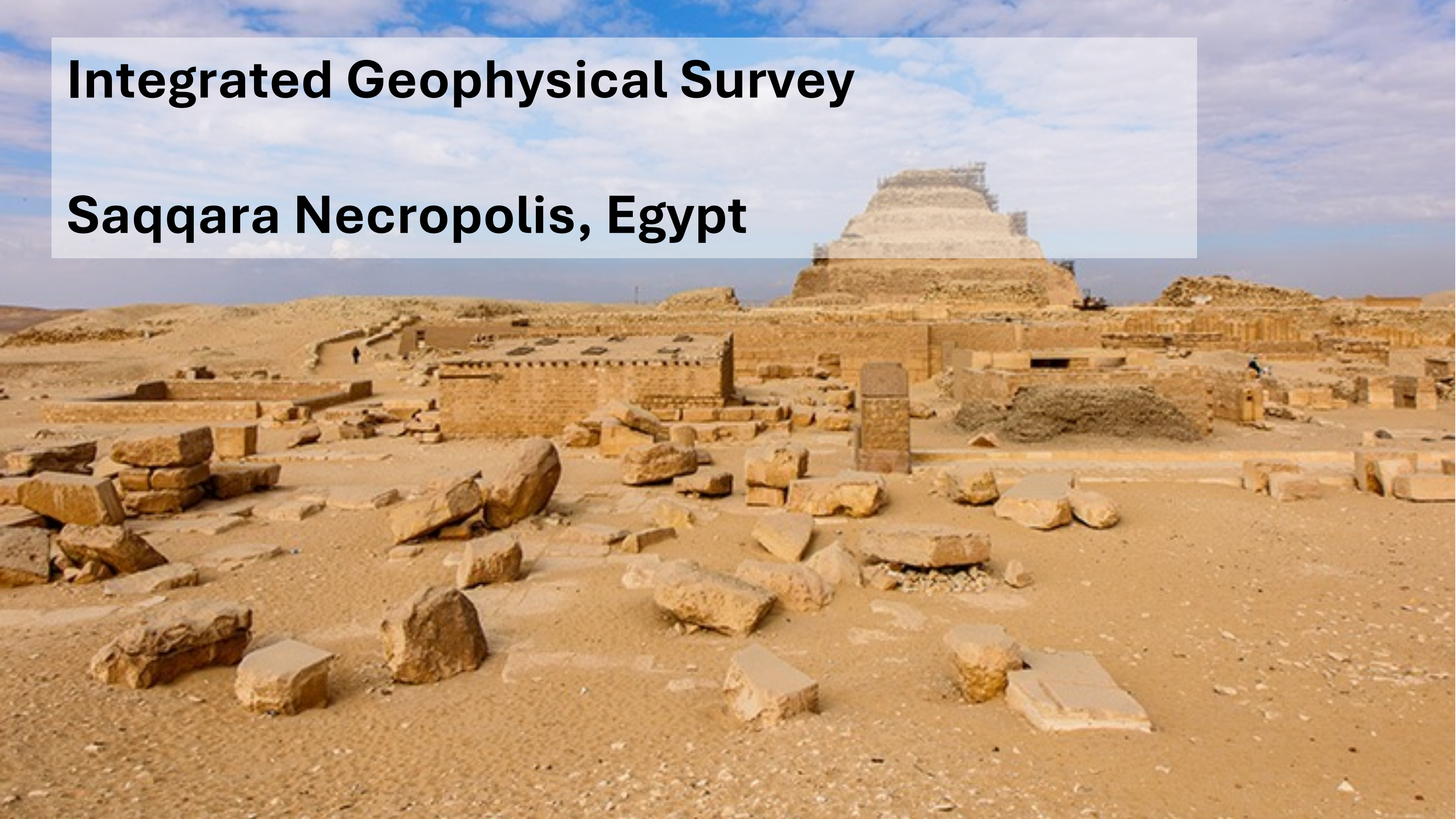
Inversion results: mapping water infiltration

Results reveal:

1. Water accumulation concentrated beneath the pavement surface
2. Pathways extending down into the arch structure
3. Spatial correlation with externally visible damage

Results will guide targeted remediation, repair efforts can focus on identified pathways





Integrated Geophysical Survey

Saqqara Necropolis, Egypt

Integrated shallow geophysical methods for Archaeological Exploration: Saqqara Necropolis, Egypt

Location maps showing Egypt with Saqqara position in the southern Nile Delta, and zoomed view of the research area within the Cairo University concession.

Motivation: How do you find Buried archeological features without destroying them?

Saqqara is one of the most important archaeological sites in the world. It served as a burial ground for over 3000 years, from the Early Dynastic Period through the New Kingdom. The site contains thousands of tombs, chambers, and structures buried beneath meters of sand and debris.

The question becomes: *Can we "see" what is underground before we dig, so we can target excavations precisely and avoid unnecessary destruction?*

Integrated shallow geophysical methods for Archaeological Exploration: Saqqara Necropolis, Egypt

- Location: Saqqara necropolis, 15 km SW of Cairo, UNESCO World Heritage site
- Objective: Detect and map buried tombs and chambers non-invasively
- Methods: Three complementary techniques combined:

1. Seismic Refraction Tomography (SRT)
2. Ground Penetrating Radar (GPR)
3. Electrical Resistivity Tomography (ERT)

Context: Part of Cairo University's ongoing exploration project (Phase II)

Site context: a 6000-year burial ground

Geological setting:

- Limestone plateau (Upper Eocene, Maadi Formation) at 40-58 m elevation
- Covered by 0.5-3 m of aeolian (wind-blown) sand accumulated over 6000 years
- Calcareous debris from Old Kingdom construction activities

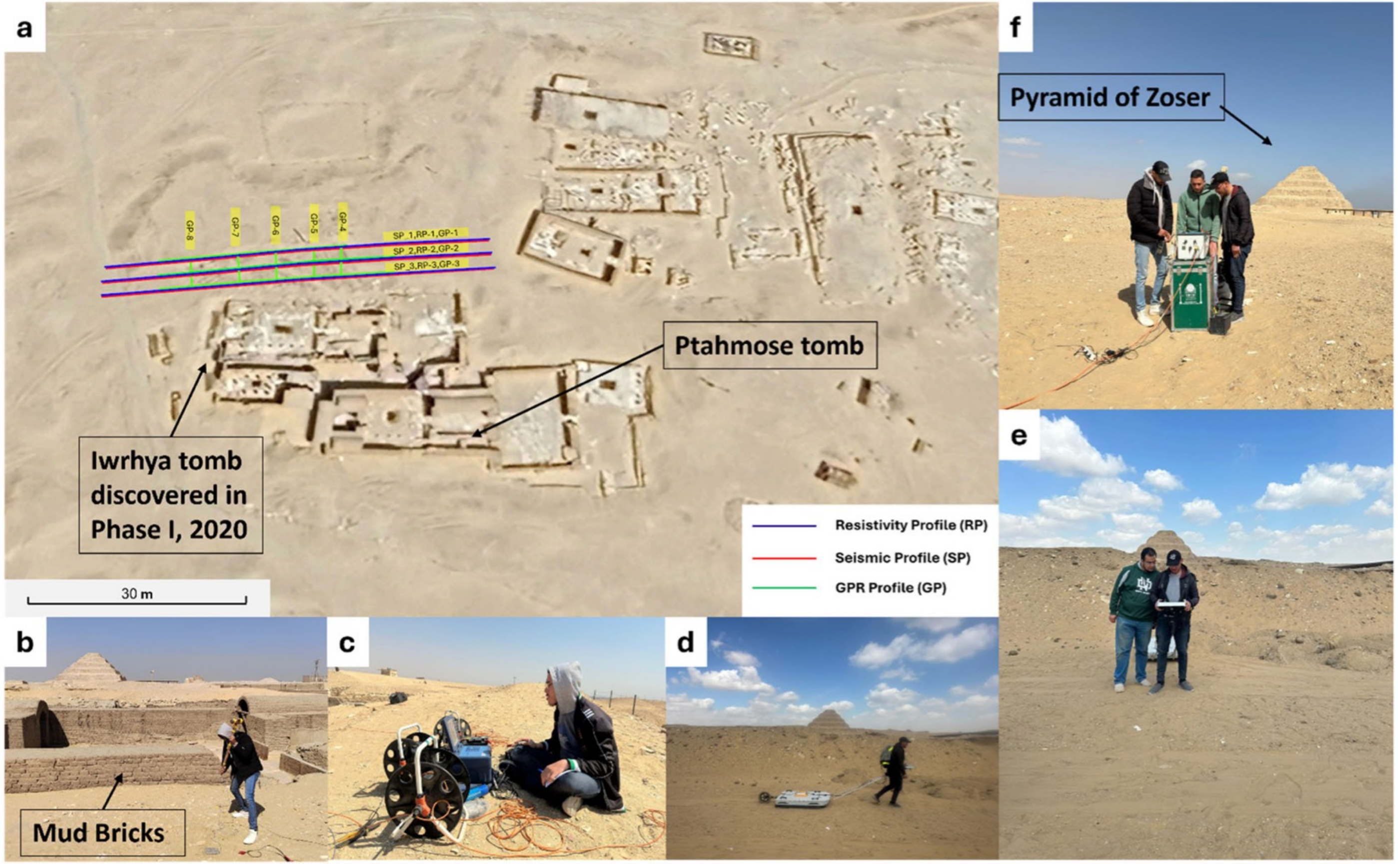
Archaeological structures:

- Greco-Roman burials: sarcophagi and mummies in sand or shallow limestone
- Old Kingdom structures: mud brick and stone cult chapels with burial shafts

Challenge:

- Complex stratigraphy mixing natural deposits and man-made structures

Site context: a 6000-year burial ground



Multi-method strategy

No single method sees everything: each has trade-offs in resolution/depth/sensitivity

Seismic Refraction Tomography (SRT):

- Measures P-wave velocity (how fast seismic waves travel)
- Good for: Layer boundaries, bedrock depth, detecting voids (low velocity)
- Limitation: Lower horizontal resolution

Ground Penetrating Radar (GPR):

- Sends electromagnetic pulses and records reflections
- Good for: High-resolution imaging of walls, voids, shallow features (0.5-4 m)
- Limitation: Signal attenuates in conductive materials (clay, wet soil)

Electrical Resistivity Tomography (ERT):

- Measures how easily current flows through the ground
- Good for: Detecting clay-filled features, mud bricks, moisture variations
- Limitation: Lower resolution than GPR

Survey design and data acquisition

Seismic Refraction Tomography (SRT):

- Source: 20 kg sledgehammer
- 3 profiles, 72 m long, 3 m geophone spacing

Ground Penetrating Radar (GPR):

- 3 inline profiles (40 m long, 3 m apart) + 4 crossline profiles (5 m long)

Electrical Resistivity Tomography (ERT):

- Array: Dipole-dipole (chosen for good horizontal resolution of vertical structures)
- 3 profiles, 69 m long, 3 m electrode spacing, penetration depth 14-16 m

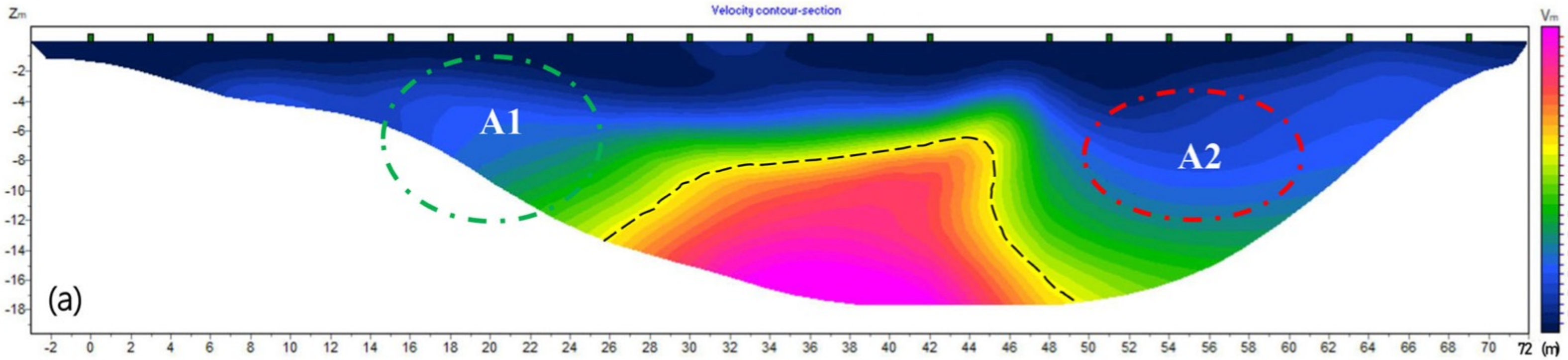
Seismic results: refraction tomography

2 layer model identified:

- Layer 1 (shallow): Vp = 400-1100 m/s → Sandstone/sand, depth 0.5-7 m
- Layer 2 (deep): Vp = 1200-1900 m/s → Limestone bedrock, starts at ~7 m depth

Key anomalies detected:

- A1 and A2: Basin-shaped low-velocity zones (Vp < 600 m/s)
- Dimensions: ~6 m × 2 m each, at depth ~1.5 m
- Interpretation: Potential halls or chambers filled with loose/friable sand



GPR results: Walls, Chambers, and Reflectors

Anomalies detected at 0.5-4 m depth:

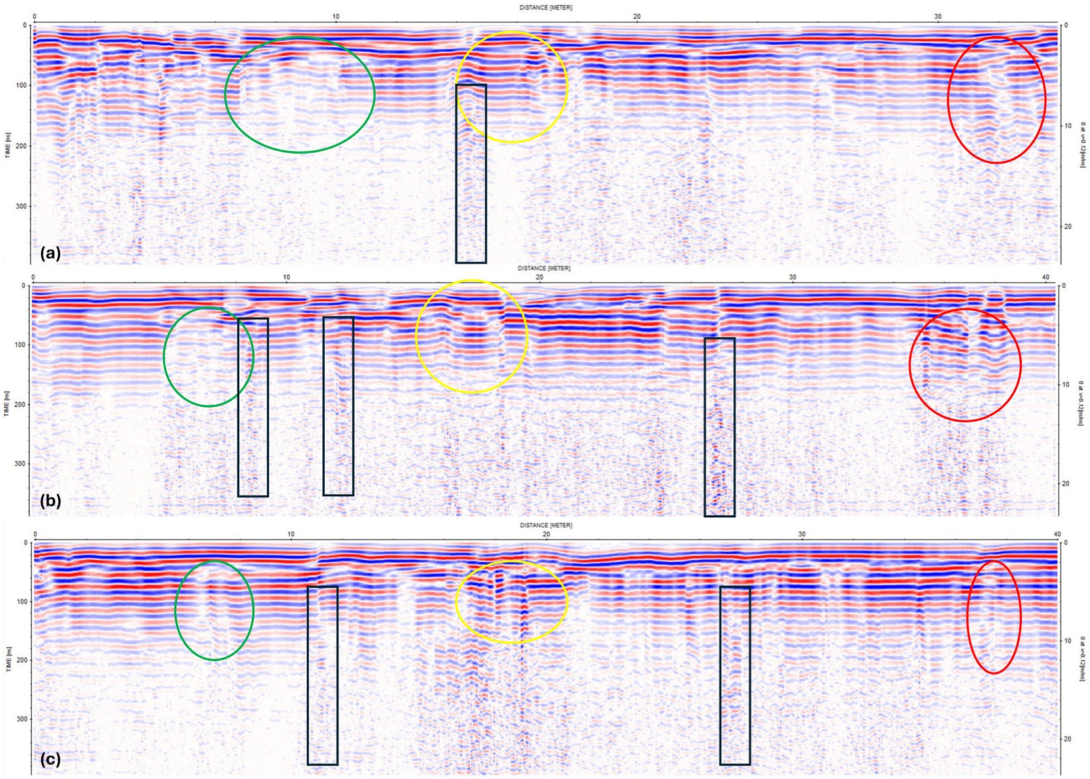
Low-amplitude anomalies (green): Suggest chambers filled with conductive material (clay, mud bricks)

High-amplitude anomalies:

Black rectangles: Interpreted as walls (strong reflectors)

Yellow circles: Flat anomalies suggesting horizontal halls

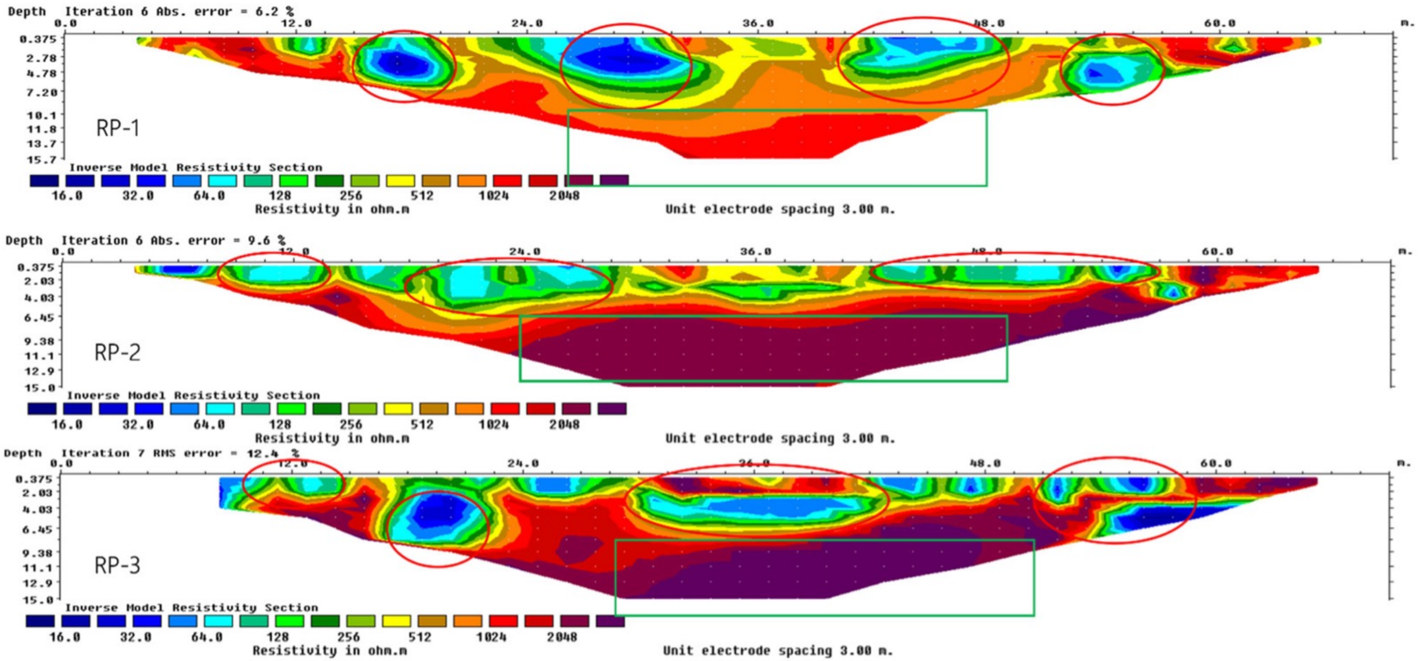
Red circles: Subsurface chamber based on shape



Electrical Resistivity Tomography Results

High-resistivity zones (red/warm colors):

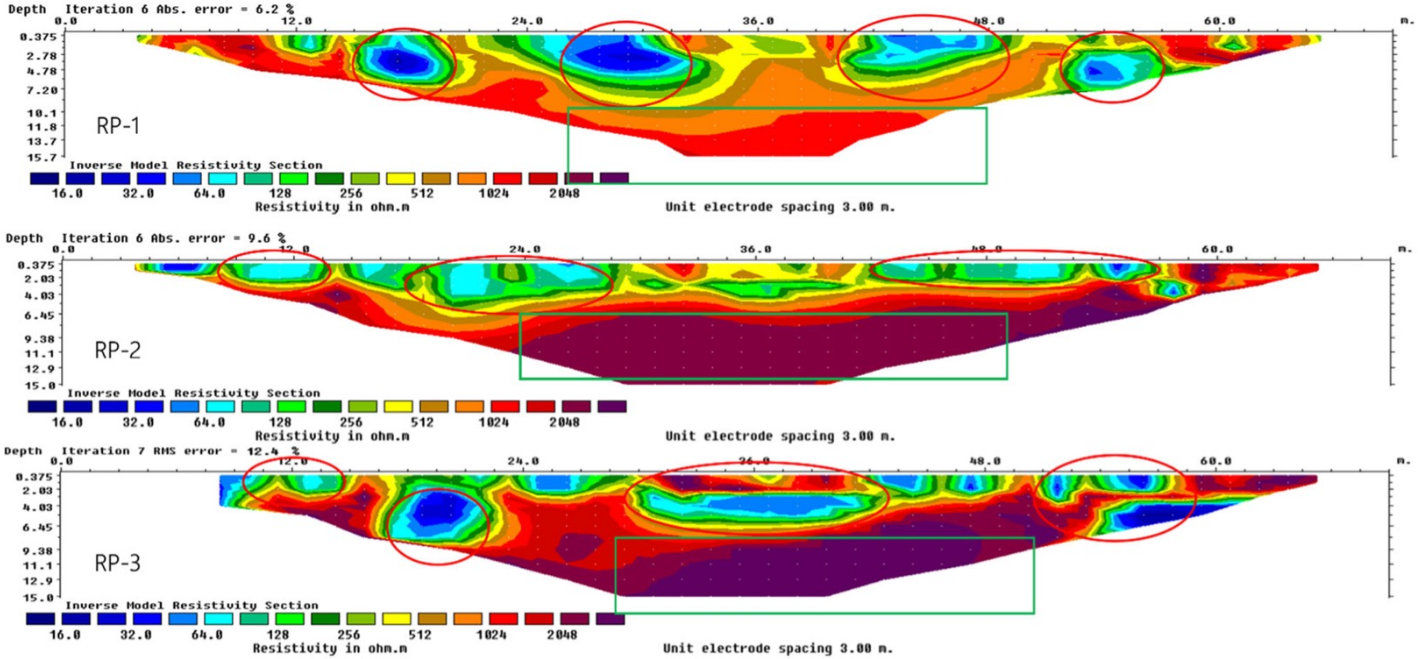
- **Located at 6-8 m depth**
- **Interpretation: Limestone bedrock (compact, dry rock = high resistivity)**



Electrical Resistivity Tomography Results

Low-resistivity anomalies (blue/green, cool colors):

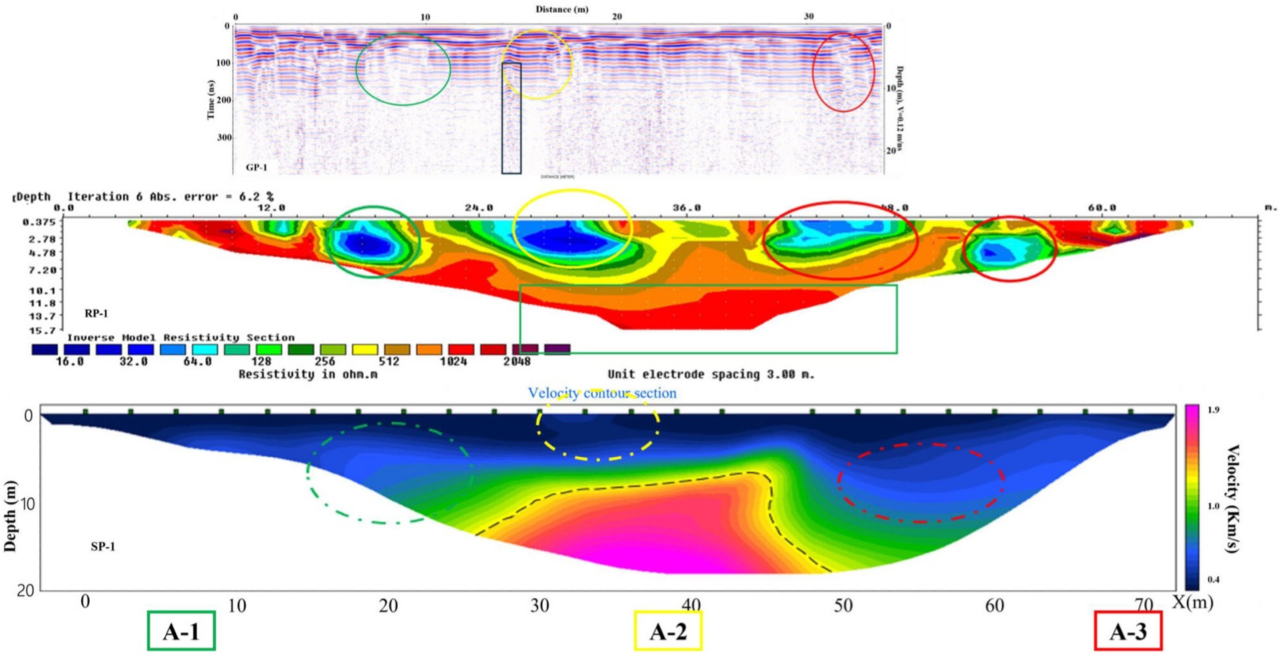
- Shallow features marked by red circles (clay-filled voids or mud brick structures)
- Mud bricks have low resistivity due to clay mineral content



Joint interpretation: combining all 3 methods

Three main anomalies identified across all datasets:

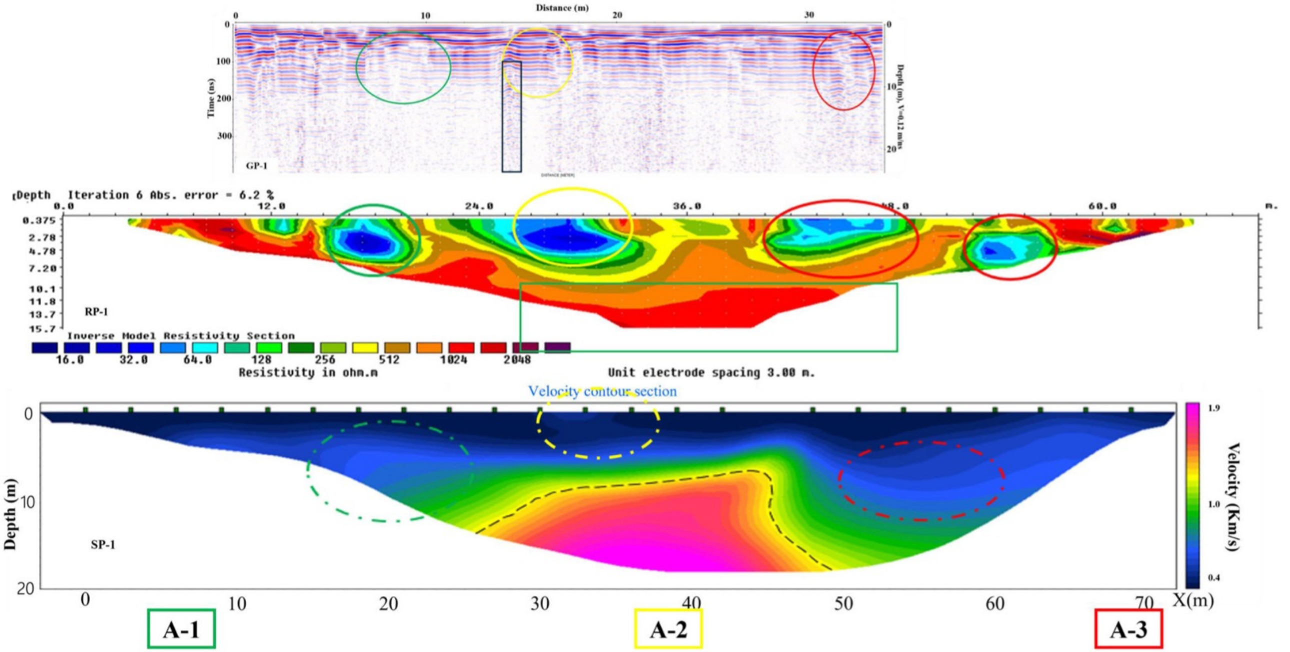
- **A-1:** Low GPR amplitude + low resistivity + low velocity = Room filled with conductive material (mud brick), ~2 m × 6 m, depth ~2 m



Joint interpretation: combining all 3 methods

Three main anomalies identified across all datasets:

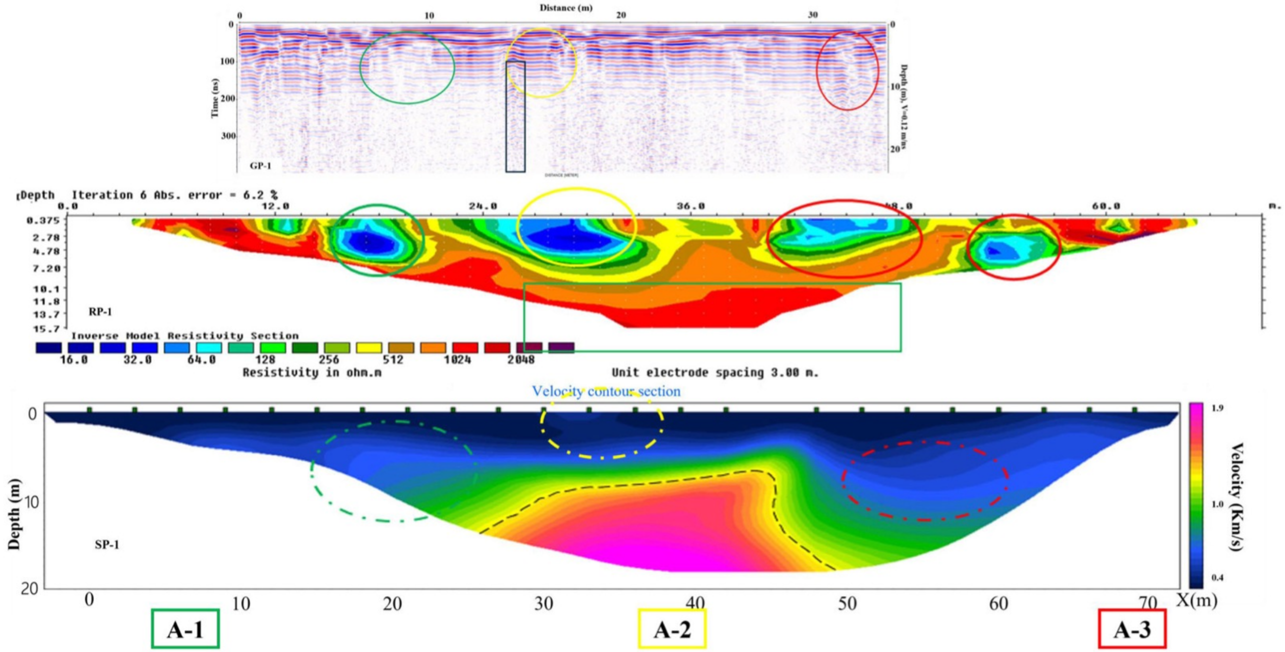
- **A-2:** Flat GPR anomaly + low resistivity + low velocity = Hall surrounded by sediments, depth ~1.5 m, extends ~6 m



Joint interpretation: combining all 3 methods

Three main anomalies identified across all datasets:

- **A-3:** Low GPR amplitude + sharp low resistivity + low velocity = Subsurface chamber, ~2 m × 6 m, depth ~1 m; possible shaft below



What connected these studies?

3 main anomalies identified across all datasets:

- Point 1: Every study started with a clear physical question
- Point 2: Every study adapted standard methods to site-specific conditions
- Point 3: Every study had limitations, and they stated them explicitly

When you encounter a geophysical problem (in research, industry, or consulting):

- Define the question precisely.
- Identify the expected physical property contrast. No contrast, no method will help.
- Consider what could go wrong. Noise, ambiguity, non-uniqueness, site access.
- Choose the simplest approach that can answer your question.
- State your limitations.

Student questions and topics for next week

For next week’s session, please submit any topics, concepts, or specific questions you would like to discuss.

The **deadline for submission is Wednesday, April 8th (end of day).**

https://docs.google.com/forms/d/e/1FAIpQLScPnSL_Fc2nsTlCmijNstv-Ap2JAgy7MliOXZadfgMIMeizCg/viewform?usp=publish-editor