The Inaccessible Earth

Scales, Instruments, and the Logic of Geophysical Inference

ESS 314 — Geophysics | Lecture 2 | April 1, 2026

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Learning Objectives

By the end of this lecture:

- **[LO-2.1]** Calculate the fraction of Earth accessible to direct sampling; explain why geophysical inference is unavoidable
- **[LO-1.3]** Place geophysical processes on a space–time scale diagram; explain why no single method spans the full range
- **[LO-4.2]** Describe what each of five geophysical instruments actually records, and identify one intrinsic limitation per instrument
- **[LO-3.1]** Formulate the forward problem for two methods; explain why the inverse problem is non-unique

How Little Have We Seen?

The Kola Superdeep Borehole (Russia, 1970–1989):

- Deepest borehole: **12.262 km**
- Stopped because rock temperature > 180°C — not technology failure

$$f = \frac{z_{\max}}{R_\oplus} = \frac{12.262}{6{,}371} = \mathbf{0.19\%}$$

Access mode	Depth	Fraction of $R_\oplus$
Mponeng Mine	4 km	0.06%
Kola borehole	12.2 km	0.19%
Seismic refraction	~50 km	0.8%
Global seismic waves	6,371 km	**100%**

Key point: Seismic waves are the only tool that samples the entire Earth. Every deep layer boundary was found by listening to earthquakes.

Eratosthenes (230 BCE): First Geophysical Measurement

Two observations, one distance, one result:

- At Syene (Aswan): Sun directly overhead at summer solstice noon
- At Alexandria (800 km north): rod casts shadow at **7.2°** from vertical

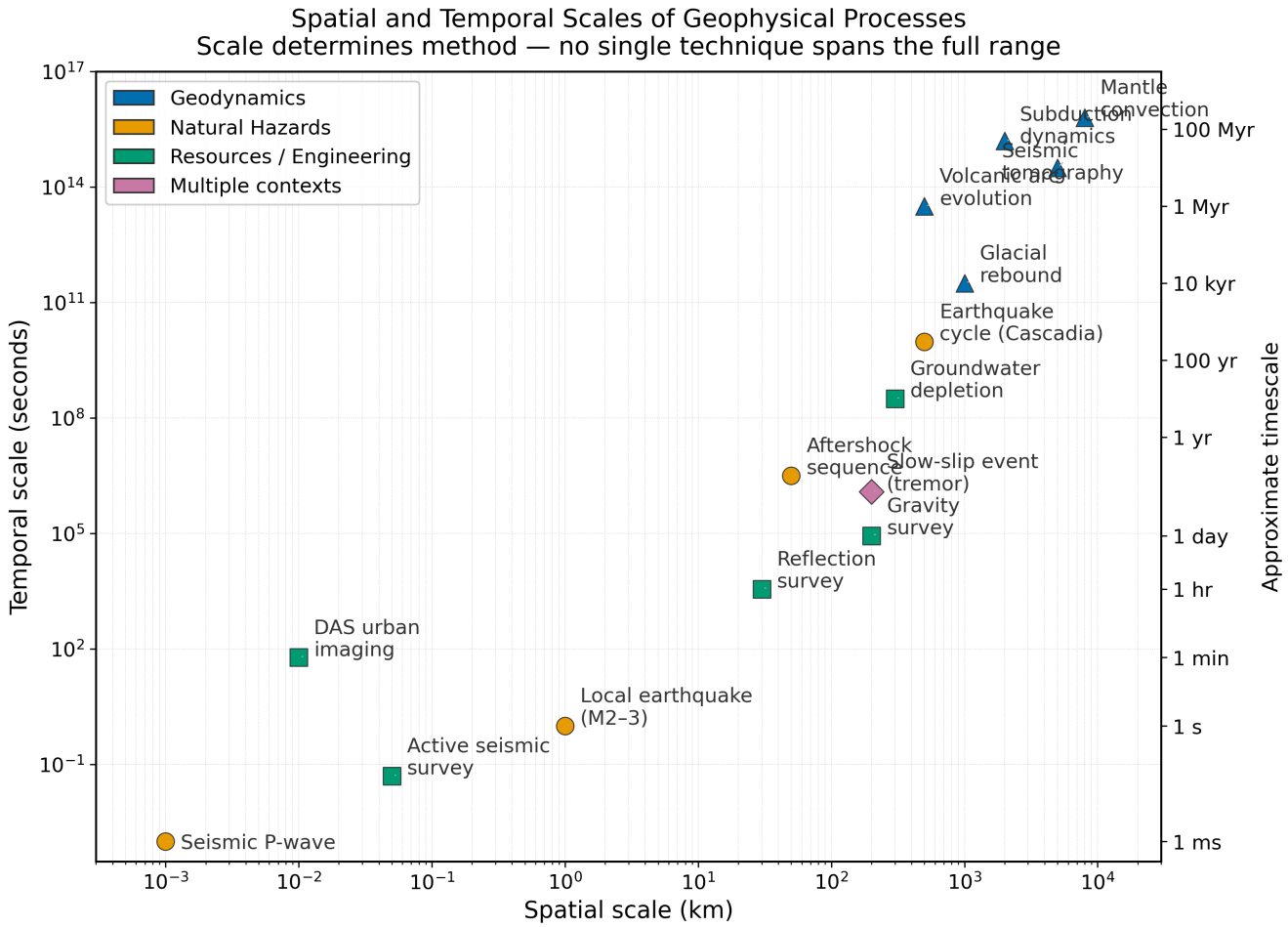
$$C_\oplus = \frac{360^\circ}{7.2^\circ} \times 800\ \mathrm{km} = 40{,}000\ \mathrm{km}$$

$$R_\oplus = \frac{C_\oplus}{2\pi} \approx 6{,}366\ \mathrm{km} \quad (\text{modern: } 6{,}371\ \mathrm{km})$$

Assumptions: parallel Sun rays, spherical Earth, same meridian, known distance

Key point: Every geophysical measurement embeds model assumptions. Identifying those assumptions is the first step in evaluating an inference.

Scale Diagram: Scale Determines Method



Key point: No single instrument spans 15 orders of magnitude in time and 10 in space. The scale of the process dictates the appropriate method.

Three Insights from the Scale Diagram

1. Same material, different physics

- Mantle = elastic solid on seismic timescales (seconds)
- Mantle = viscous fluid on convection timescales (millions of years)
- Which description applies depends on the ratio of observation time to material relaxation time

2. Scale dictates resolution

- A seismometer measuring arrivals in seconds cannot sense million-year flow
- A continental gravity survey cannot resolve a 10-cm void in concrete

3. Gap distance and non-uniqueness

- The further an observable is from the process of interest, the more assumptions are needed to connect them — and the more non-unique the inference

Key point: Before choosing a method, identify the spatial and temporal scale of the target process.

What Seismometers Actually Record

A seismometer measures **ground velocity** (or displacement/acceleration) as a function of time.

Every seismogram entangles:

1. **Source** — the earthquake's rupture history and radiation pattern
2. **Path** — modifications from Earth's heterogeneous velocity structure
3. **Site** — amplification or attenuation by local geology

Separating these three contributions is itself an inverse problem.

Frequency range: 0.003 Hz (Earth free oscillations, ~300 s) to 50+ Hz (local microseismicity)

Key point: A seismogram is not a direct recording of the earthquake — it is a convolution of source, path, and site effects. Every interpretation requires a model for at least two of these three.

What Gravimeters, Magnetometers, and Heat Flow Probes Record

Gravimeter:

- Measures g to ~1 μGal (10^{-8} m/s²) = 1 part per billion
- Lateral density contrasts → gravity anomalies
- GRACE-FO: measures monthly gravity change from satellites (ice, groundwater, postseismic)

Magnetometer:

- Measures **B** to a few nanotesla against Earth's ~50,000 nT background
- Remanent magnetization in crustal rocks → magnetic anomalies → seafloor spreading history

Heat flow probe:

$$q = -k\frac{dT}{dz} \quad [\mathrm{W/m^2}]$$

- Temperature gradient + thermal conductivity → surface heat flux

GPS and InSAR: Measuring Surface Deformation

GPS (continuous):

- Position accuracy: millimeters in 3D
- Time series: daily to sub-hourly at fixed stations
- Captures: interseismic strain (1–10 mm/yr), coseismic displacement (cm–m), postseismic relaxation, volcanic inflation, glacial rebound

InSAR (spatially dense snapshots):

- Satellite radar phase difference between two acquisitions → displacement map
- Covers: thousands of km^2 at cm–mm precision
- Limitation: line-of-sight only; temporal aliasing possible

Key point: GPS gives continuous time series at points; InSAR gives spatially dense maps at moments. Both are passive — the signal source is satellite navigation or microwave radar, not the Earth.

The Forward Problem

Given a model of Earth properties, predict the observations:

$$\mathbf{d} = \mathbf{G}(\mathbf{m})$$

- $\mathbf{d}$ = observed data (travel times, gravity values, magnetic readings, ...)
- $\mathbf{m}$ = model parameters (density, velocity, conductivity at every point)
- $\mathbf{G}$ = physical operator derived from the governing equation

Two examples:

Method	Model $\mathbf{m}$	Operator $\mathbf{G}$	Observable $\mathbf{d}$
Gravity	$\rho(\mathbf{r})$	$\nabla^2\Phi = 4\pi G\rho$; $g = -\partial_z\Phi$	$g(x, y)$ at surface
Travel time	$\alpha(\mathbf{r})$	$t = \int ds/\alpha$ (ray tracing)	t_P at stations

Key point: The forward problem is well-posed — a unique answer exists for any given model. Solving it is computation, not inference.

The Inverse Problem

Given observations, infer the model:

Find $\mathbf{m}$ such that $\mathbf{G}(\mathbf{m}) \approx \mathbf{d}$

This is **almost always non-unique** — many models fit the same data within measurement uncertainty.

Gravity example:

- Deeper, denser body
  ↔️
  shallower, less-dense body → identical surface g
- Solution requires additional constraints: drill data, geological knowledge, density bounds

Tomography example:

- Velocity anomalies smear along ray paths
- Resolution uneven where earthquakes or stations are sparse

Non-uniqueness is **not a failure** — it is a statement about what the data actually constrain

Three Pillars of Geophysical Science

Theory & Computation

- Derive governing equations
- Solve numerically for realistic geometries
- SPECFEM3D, ASPECT (open source)

Field Observations

- Deploy instruments, collect data
- CASIE21: active airguns + passive OBS on Cascadia margin
- PNSN: continuous Pacific Northwest monitoring

Laboratory Experiments

- Measure rock properties under pressure and temperature
- Diamond-anvil cells → lower mantle pressures
- Links tomographic images to real mineralogy

No pillar is sufficient alone. Theory without observation is speculation. Observation without theory is cataloguing. Lab data without field context is unanchored.

Key point: Geophysics advances through integration of all three modes — each constrains the others.

Concept Check

1. A seismic reflection survey images a bright flat reflector at 2-second two-way travel time. What assumptions are embedded in concluding this is a sedimentary layer boundary? Name two that could be tested.

2. GPS stations on the Washington coast move eastward at ~10 mm/yr. Write out the forward problem: what is $\mathbf{m}$, what is $\mathbf{d}$, and what is $\mathbf{G}$?

3. A gravity survey shows a negative anomaly over a known salt dome (salt is less dense than surrounding sediment). Why cannot the gravity anomaly alone uniquely determine the dome's depth?

Discuss in pairs — 5 minutes

Summary: Lecture 2 Key Takeaways

- The Kola Borehole (12 km) penetrated 0.19% of Earth's radius — everything deeper is from geophysical inference
- **Scale determines method**: no single technique spans 10–15 orders of magnitude in space and time
- The same material (mantle) is elastic on seismic timescales and viscous on convection timescales
- Five instruments: seismometer (ground motion), gravimeter (g), magnetometer (**B**), GPS/InSAR (displacement), heat flow probe ($q = -k\,dT/dz$)
- **Forward problem** $\mathbf{d} = \mathbf{G}(\mathbf{m})$: well-posed, unique; it is computation
- **Inverse problem** — almost always non-unique; requires additional constraints; characterizing non-uniqueness is a scientific obligation

Further Reading

- Lowrie & Fichtner (2020) Ch. 1–2 — **free via UW Libraries**
- MIT OCW 12.201: ocw.mit.edu/courses/12-201
- Lehmann et al. (2024) Neural operators for seismic FWI: doi.org/10.1029/2023JB027856
- SPECFEM3D open source: github.com/geodynamics/specfem3d
- CASIE21 experiment: casie21.weebly.com
- IRIS data services: ds.iris.edu

Lab 1 (Friday): Fetch PNSN seismogram · Plot P and S arrivals · Compute source distance from $t_S - t_P = \Delta(1/\beta - 1/\alpha)$