

Question1:

The occurrence of the perchlorate ion ClO_4 in groundwater presents a great risk to human health since perchlorate has long been known to inhibit proper functioning of the thyroid. Beneath the Naval Weapons Industrial Reserve Plant (NWIRP) in central Texas, significant concentrations of perchlorate ions derived from the manufacture of rocket propellant have been detected in groundwater and springs. A perchlorate contamination survey was conducted at NWIRP using a 50 MHz GPR system that was towed on a sled behind an all-terrain vehicle. The geology consists of weathered limestone bedrock below 0–3 m of clay overburden. The survey was executed over approximately 100 line-km covering a wide-area of ~ 500 ha. This GPR survey in karst terrain was done with the goal of mapping subsurface structural features that might be indicative of major pathways for subsurface transport of perchlorate ions.

Question 1:

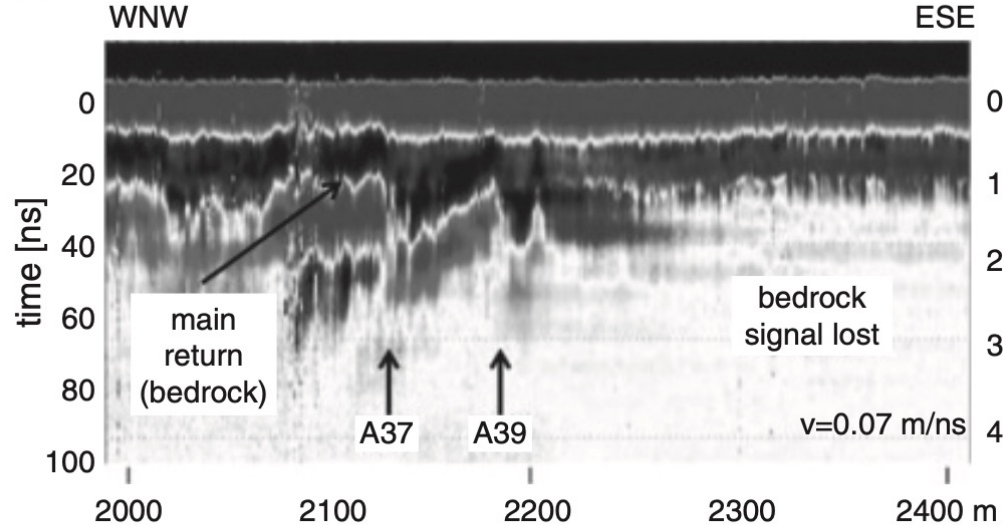
a) Lateral resolution of the GPR is about 1 m. Verify this approximately using $\epsilon_r = 9$ for weathered limestone and $f = 50$ MHz

Note: lateral resolution uses $\lambda/2$ rather than $\lambda/4$ which is used for vertical resolution.

b) Individual bedrock fractures are on the order of millimetres in width. Why can GPR not detect individual fractures?

c) Why was a low frequency of 50 MHz chosen rather than a higher frequency for this survey?

d) In the radargram, find at what time the bedrock reflection appears. Using $V = 0.07$ m/ns, calculate the depth to bedrock at this location.



Answer:

Part a) Lateral resolution verification:

$$V = c/\sqrt{\epsilon_r} = 3 \times 10^8 / \sqrt{9} = 3 \times 10^8 / 3 = 10^8 \text{ m/s} = 0.1 \text{ m/ns}$$

$$V = 0.1 \text{ m/ns} = 0.1 \times 10^9 \text{ m/s} = 10^8 \text{ m/s}$$

$$\lambda = V/f = 10^8 / (50 \times 10^6) = 10^8 / 5 \times 10^7 = \mathbf{2 \text{ m}}$$

Lateral resolution $\approx \lambda/2 = \mathbf{1 \text{ m}}$ — this matches the stated value.

Part b) Why individual fractures cannot be detected:

Individual fractures are millimetres wide. The minimum vertical resolution is $\lambda/4 = 2/4 = 0.5 \text{ m} = 50 \text{ cm}$. A fracture of millimetre width is more than 500 times thinner than the minimum resolvable feature. The fracture is completely invisible to 50 MHz GPR, the wavelength is simply too long to sense such a small feature. To resolve millimetre-scale fractures would require frequencies in the hundreds of GHz range, completely outside the GPR range and absorbed immediately by any conductive material.

Answer:

Part c) Why 50 MHz was chosen:

The survey covers ~500 hectares which is a very large area. The geology includes a clay overburden of 0–3 m with variable thickness. Clay has high conductivity, clay attenuation is 1–300 dB/m. Higher frequencies would be absorbed by the clay before reaching the bedrock surface. A low frequency of 50 MHz was needed to penetrate through variable thicknesses of clay overburden to reach the bedrock. Resolution of individual fractures was not the goal, mapping bedrock depth variations of 1–10 m was the goal, and 50 MHz is adequate for that.

Part d) Depth to bedrock:

Depth = $V \times (\text{two-way time} / 2)$

Using midpoint of the 20–40 ns range, say $t = 30$ ns:

Depth = $0.07 \times (30/2) = 0.07 \times 15 = \mathbf{1.05\ m}$

Using the extremes:

At 20 ns: depth = $0.07 \times 10 = \mathbf{0.7\ m}$

At 40 ns: depth = $0.07 \times 20 = \mathbf{1.4\ m}$

So bedrock depth on the left side of the profile ranges from approximately **0.7 to 1.4 m**, consistent with the stated geology of 0–3 m clay overburden.

Question 2:

A geologist runs a GPR survey over a site and expects to detect the boundary between two rock units. The upper unit is granite ($\epsilon_r = 6$) and the lower unit is limestone ($\epsilon_r = 6$).

- a) Calculate the reflection coefficient at this boundary
- b) The geologist sees no reflection in the radargram at the expected depth. Is this consistent with the physics?
- c) A later borehole confirms the boundary exists at 3 m depth. Why did GPR fail to detect it?
- d) What change in conditions would make this boundary detectable by GPR?

Answer:

Part a) Reflection coefficient:

$$R = (\sqrt{6} - \sqrt{6}) / (\sqrt{6} + \sqrt{6}) = 0 / (2\sqrt{6}) = 0$$

Zero reflection: no energy is reflected at this boundary.

Part b) Consistency with physics:

Yes, completely consistent! Reflection coefficient depends entirely on the contrast in dielectric permittivity across the boundary. If both materials have the same ϵ_r , the radar wave does not know it has crossed a boundary and passes straight through without reflecting. The boundary is physically real geologically but electrically invisible to GPR.

Part c) Why GPR failed:

Both granite and limestone in their dry state have similar dielectric constants which is approximately $\epsilon_r = 4-6$ for both. The boundary between two dry rocks of different mineralogy but similar water content produces essentially no permittivity contrast and therefore no GPR reflection. GPR is sensitive to electrical properties, not mineralogy or rock type per se.

Answer:

Part d) Conditions that would make the boundary detectable:

Any change that creates a permittivity contrast across the boundary:

If the granite is dry but the limestone is water-saturated! Saturated limestone would have significantly higher ϵ_r than dry granite, creating a detectable contrast

If the limestone is fractured and water-filled while the granite is unfractured: fracture porosity filled with water dramatically increases ϵ_r

If the limestone contains clay minerals that are not present in the granite because clay has highly variable ϵ_r (5–40) and high water retention

If there is a change in groundwater level that saturates one unit but not the other

Question 3:

A GPR survey is conducted over a coastal barrier island. The stratigraphy consists of aeolian sand ($\epsilon_r = 5$, dry) overlying a beach sand deposit saturated with freshwater ($\epsilon_r = 25$).

- a) Calculate the reflection coefficient at this boundary
- b) A storm causes saltwater intrusion into the lower layer (ϵ_r drops to 20 due to salinity effects on permittivity)
- c) After the storm the geologist notices that the reflection from this boundary has weakened. Calculate the new reflection coefficient and explain why
- d) If the saltwater fully replaces the freshwater ($\epsilon_r = 80$ for seawater), recalculate R and comment

Answer:

Part a) Dry aeolian sand over freshwater-saturated sand:

$$R = (\sqrt{5} - \sqrt{25}) / (\sqrt{5} + \sqrt{25}) = (2.236 - 5) / (2.236 + 5) = (-2.764) / (7.236) = \mathbf{-0.382}$$

Strong negative reflection, hence the water table boundary is clearly detectable.

Part b and c) After saltwater intrusion ($\epsilon_r = 20$):

$$R = (\sqrt{5} - \sqrt{20}) / (\sqrt{5} + \sqrt{20}) = (2.236 - 4.472) / (2.236 + 4.472) = (-2.236) / (6.708) = \mathbf{-0.333}$$

The reflection coefficient has dropped from -0.382 to -0.333 . The boundary is still detectable but the reflection is weaker. Because saltwater has lower ϵ_r than freshwater. Increased salinity reduces ϵ_r because: more salt means fewer polarisable water molecules; water molecules cannot rotate as freely when bound to Na and Cl ions; and mobile ions agitate and randomise water molecule dipole alignment. So the contrast between dry sand above and saline sand below has decreased.

Answer:

Part d) Full seawater replacement ($\epsilon_r = 80$):

$$R = (\sqrt{5} - \sqrt{80}) / (\sqrt{5} + \sqrt{80}) = (2.236 - 8.944) / (2.236 + 8.944) = (-6.708) / (11.180) = \mathbf{-0.600}$$

Paradoxically, the reflection is now stronger again. Seawater has $\epsilon_r = 80$ which is the same as freshwater, so the contrast between dry sand ($\epsilon_r = 5$) and seawater-saturated sand ($\epsilon_r = 80$) is large. However, seawater has conductivity of 1000 mS/m, so attenuation in seawater is enormous (1000 dB/m). In practice, the radar signal would be absorbed almost immediately upon entering the seawater-saturated zone and the reflection, though large in coefficient, would be accompanied by total signal loss below that boundary. This is a good example of why a high reflection coefficient does not guarantee useful GPR data and attenuation must also be considered.

Question 4:

A GPR profile over a suspected void in limestone shows a hyperbolic arrival. The wavelet at the apex of the hyperbola shows a white-black-white pattern.

- a) What does this polarity tell you about the velocity contrast at the target?
- b) Is the target consistent with a water-filled void or an air-filled void? Use ϵ_r values to justify your answer

Answer:

Part a) Velocity contrast from polarity: ϵ_2 is target

White-black-white represents a negative reflection coefficient — $R < 0$.

From $R = (\sqrt{\epsilon_1} - \sqrt{\epsilon_2}) / (\sqrt{\epsilon_1} + \sqrt{\epsilon_2})$:

R is negative when $\sqrt{\epsilon_1} < \sqrt{\epsilon_2}$, meaning $\epsilon_1 < \epsilon_2$, so the upper material has lower permittivity than the deeper material

Lower permittivity means faster radar velocity. So the radar wave is going from a **faster** material into a **slower** material.

Part b) Air-filled or water-filled void:

Limestone: $\epsilon_r = 4-8$, say 6

Air: $\epsilon_r = 1$

Freshwater: $\epsilon_r = 80$

For air-filled void: $\epsilon_{\text{target}} = 1 < \epsilon_{\text{limestone}} = 6 \rightarrow R$ is positive \rightarrow black-white-black \times

For water-filled void: $\epsilon_{\text{target}} = 80 > \epsilon_{\text{limestone}} = 6 \rightarrow R$ is negative \rightarrow white-black-white \checkmark

The black-white-black polarity is **consistent with water-filled void**; the void has lower permittivity than the surrounding limestone and the reflected wave is phase-inverted.

Question 5:

A GPR system has a transmitter-receiver separation of 0.5 m. The subsurface is wet clay ($\epsilon_r = 25$).

- a) At what time does the direct air wave arrive at the receiver?
- b) At what time does the direct ground wave arrive?
- c) A reflection from the water table arrives at 18 ns. Is this reflection obscured by the direct arrivals? Comment on the implications for shallow target detection
- d) If you move the antennas closer together to 0.1 m separation, what happens to the direct wave arrival times and the blind zone?

Answer:

Part a) Direct air wave arrival:

Air wave travels at speed of light: $c = 0.3 \text{ m/ns}$

Time = distance/velocity = $0.5/0.3 = 1.67 \text{ ns}$

Part b) Direct ground wave arrival:

V in wet clay = $c/\sqrt{\epsilon_r} = 0.3/\sqrt{25} = 0.3/5 = 0.06 \text{ m/ns}$

Time = $0.5/0.06 = 8.33 \text{ ns}$

Part c) Is the water table reflection obscured?

The water table reflection arrives at 18 ns. The direct arrivals are at 1.67 ns (air) and 8.33 ns (ground wave). The water table reflection at 18 ns arrives well after both direct arrivals, so it is **not obscured** by the direct wave arrivals. There is a clear time window between the direct ground wave (8.33 ns) and the water table reflection (18 ns) within which no direct arrivals are present.

However, the **blind zone** extends from 0 to approximately 8–10 ns and any reflector returning before the ground wave dies away cannot be detected. The depth of this blind zone is approximately:

Blind zone depth = $V \times (\text{ground wave arrival time} / 2) = 0.06 \times (8.33/2) = 0.06 \times 4.17 = 0.25 \text{ m}$

Any target shallower than about 25 cm cannot be detected with this antenna separation in wet clay.

Answer:

Part d) Closer antenna separation (0.1 m):

Air wave: $0.1/0.3 = \mathbf{0.33 \text{ ns}}$ Ground wave: $0.1/0.06 = \mathbf{1.67 \text{ ns}}$

Both arrive earlier. The blind zone depth becomes approximately: $0.06 \times (1.67/2) = \mathbf{0.05 \text{ m} = 5 \text{ cm}}$

The blind zone has shrunk from 25 cm to 5 cm. Moving antennas closer together reduces the blind zone and allows detection of shallower targets. The trade-off, as noted, is that closer antenna separation also reduces depth penetration, there is less time for the ground wave energy to penetrate before being recorded.

Question 6:

The seismic and GPR techniques are somewhat complementary in the sense that poor GPR field conditions (wet clays) are actually good seismic conditions while ideal GPR conditions (dry sands) are unfavorable for the acquisition of high-quality seismic data.

- a) Explain physically why wet clay is poor for GPR but good for seismic
- b) Explain physically why dry sand is good for GPR but poor for seismic
- c) You are asked to image a 5 m deep boundary in an unknown soil. You run a quick GPR profile and see almost no signal penetrating below 0.5 m. What does this tell you about the ground conditions and what method should you use instead?

Answer:

Part a) Wet clay: poor GPR, good seismic:

Wet clay is poor for GPR because clay has high electrical conductivity (clay conductivity as 1–300 dB/m attenuation). Radar energy is absorbed almost immediately. Clay also has high dielectric permittivity ($\epsilon_r = 5\text{--}40$) which slows the radar wave considerably. The combination of high attenuation and low velocity means radar energy is absorbed within centimetres to metres.

Wet clay is good for seismic because seismic waves are mechanical and they propagate by compression and shear of the solid matrix. Clay has moderate P-wave velocity ($\sim 1000\text{--}2000$ m/s) and when wet the acoustic impedance contrast with other materials can be significant. Seismic attenuation in clay is moderate but not catastrophic, the wave can still penetrate tens to hundreds of metres. Wet conditions also improve coupling between geophones and the ground.

Part b) Dry sand — good GPR, poor seismic:

Dry sand is good for GPR because conductivity is very low (0.01 mS/m) giving attenuation of only ~ 0.01 dB/m. Radar energy penetrates with minimal absorption. Dielectric permittivity is low ($\epsilon_r = 3\text{--}5$) giving relatively high radar velocity. Both factors make dry sand nearly transparent to radar.

Dry sand is poor for seismic because loose dry sand grains are poorly coupled to each other: P-wave velocity in dry sand can be as low as 200 m/s and the medium is highly scattering. Geophones sitting on loose dry sand have poor coupling to the ground, reducing signal quality. The low density and low elastic modulus of dry sand means seismic energy spreads rapidly and weakly.

Answer:

Part c) GPR sees no signal below 0.5 m:

Almost total signal loss within 0.5 m depth indicates very high conductivity in the shallow subsurface. This is almost certainly **wet clay** because clay can have attenuation of tens to hundreds of dB/m, giving depths of centimetres to tens of centimetres. GPR is not viable here. Switch to **DC resistivity** or **low-frequency EM induction**: both methods work well in conductive environments and are insensitive to the high conductivity that destroys GPR data.

Question 7:

A boundary exists at 3 m depth between two geological units. Unit 1 above is dry sandstone. Unit 2 below is the same sandstone but water-saturated.

Physical properties:

Dry sandstone: $V_{\text{seismic}} = 2000 \text{ m/s}$, $\rho = 2200 \text{ kg/m}^3$, $\epsilon_r = 5$

Saturated sandstone: $V_{\text{seismic}} = 3500 \text{ m/s}$, $\rho = 2350 \text{ kg/m}^3$, $\epsilon_r = 30$

- Calculate the seismic reflection coefficient: Recall that $R = (\rho_2 V_2 - \rho_1 V_1) / (\rho_2 V_2 + \rho_1 V_1)$
- Calculate the GPR reflection coefficient: $R = (\sqrt{\epsilon_1} - \sqrt{\epsilon_2}) / (\sqrt{\epsilon_1} + \sqrt{\epsilon_2})$
- Which method gives a stronger reflection at this boundary?
- What fundamental difference in physics does this illustrate?

Answer:

Part a) Seismic reflection coefficient:

Acoustic impedance $Z = \rho V$

$$Z_1 = 2200 \times 2000 = 4,400,000 \text{ kg/m}^2\text{s} = 4.4 \times 10^6 \text{ Pa}\cdot\text{s/m}$$

$$Z_2 = 2350 \times 3500 = 8,225,000 \text{ kg/m}^2\text{s} = 8.225 \times 10^6 \text{ Pa}\cdot\text{s/m}$$

$$R_{\text{seismic}} = (Z_2 - Z_1)/(Z_2 + Z_1) = (8.225 - 4.4) \times 10^6 / (8.225 + 4.4) \times 10^6 = 3.825 / 12.625 \\ = \mathbf{+0.303}$$

Moderate positive seismic reflection, the saturated rock has higher acoustic impedance.

Part b) GPR reflection coefficient:

$$R_{\text{GPR}} = (\sqrt{\epsilon_1} - \sqrt{\epsilon_2})/(\sqrt{\epsilon_1} + \sqrt{\epsilon_2}) = (\sqrt{5} - \sqrt{30})/(\sqrt{5} + \sqrt{30}) = (2.236 - 5.477)/(2.236 + 5.477) = \\ (-3.241)/(7.713) = \mathbf{-0.420}$$

Strong negative GPR reflection, the saturated rock has much higher permittivity.

Part c) Which method gives stronger reflection:

GPR: $|R| = 0.420$ — stronger Seismic: $|R| = 0.303$ — weaker

GPR gives a stronger reflection at this water saturation boundary. The dielectric permittivity changes from 5 to 30 which is a factor of 6 because water content has a dominant effect on ϵ_r .

The seismic impedance changes by a smaller relative amount, saturation increases velocity and density but not by as large a relative factor.

Answer:

Part d) Fundamental physics difference:

This illustrates that GPR and seismic respond to fundamentally different physical properties:

Seismic responds to **mechanical properties**: density and elastic modulus (which determines velocity). Water saturation does increase both density and bulk modulus, but the effect is moderate

GPR responds to **electrical properties**: specifically dielectric permittivity, which is dominated by water content. The dielectric permittivity of water ($\epsilon_r = 80$) is so much higher than dry minerals ($\epsilon_r = 3-8$) that even partial saturation causes enormous changes in bulk permittivity

This explains why GPR is particularly sensitive to water table boundaries, zones of changing saturation, and fluid-filled fractures. Seismic is better suited to detecting boundaries defined by changes in rock stiffness or density, lithological contacts, faults, and deep structural features.