Integrated Seismic Refraction and GPR Survey for Subsurface Characterization at an Ecological Research Site

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ABSTRACT:

This study presents an integrated geophysical approach for shallow subsurface characterization using seismic refraction and Ground Penetrating Radar (GPR) at the Florida Atlantic University Boca Preserve. A 240 m transect was surveyed using 48 geophones and three GPR antenna frequencies (80, 160, and 450 MHz) to capture complementary acoustic and electromagnetic responses. Seismic data were processed through first-arrival picking and layered inversion, while GPR data underwent time-zero correction, filtering, background removal, and migration. The integrated interpretation, supported by nearby borehole information, delineated four principal subsurface units: loamy soil (0–3 m), dry sand (3–8 m), saturated sand (8–30 m), and a probable limestone layer below ~30 m. Both methods independently identified a strong boundary near 7–8 m corresponding to the water table, demonstrating excellent cross-validation between seismic velocities and dielectric contrasts. The results highlight the effectiveness of combining seismic and GPR techniques for non-invasive characterization of heterogeneous coastal environments. The derived stratigraphic model provides a useful foundation for ecological restoration planning, groundwater assessment, and future geophysical studies within the preserve.

1. INTRODUCTION

Subsurface exploration involves developing a detailed representation of the physical, chemical, and structural properties beneath the Earth's surface (Tearpock & Bischke, 2002). Traditional direct methods such as drilling and borehole logging provide point-specific and highly reliable information but are limited by high operational costs, significant labour requirements, logistical constraints, and their inherently invasive nature. Moreover, the discrete nature of borehole observations restricts the ability to capture continuous lateral variation across a broader region of interest.

Geophysical techniques provide a non-invasive, indirect means of characterizing subsurface conditions by exploiting the behaviour of gravity, acoustic, or electromagnetic fields (Reynolds, 2011). Although geophysical interpretations often benefit from selective drilling for calibration, the required number of boreholes is drastically reduced. This makes geophysics an efficient and practical approach for preliminary site characterization, environmental assessment, and engineering investigations. In this study, a combination of Seismic Refraction and Ground Penetrating Radar (GPR) was employed to map near-surface subsurface conditions at the Florida Atlantic University Ecological Site.

Seismic refraction is a well-established geophysical technique that uses the propagation behaviour of acoustic waves to infer subsurface layering. Seismic energy is generated using a controlled source—commonly a sledgehammer striking a steel plate—and travels through the ground as compressional (P-waves) and shear (S-waves). P-waves propagate faster than S-waves and can travel through solids, liquids, and gases, whereas S-waves are restricted to solids. Wave velocities depend on the density, elastic moduli, and overall composition of the underlying materials. When seismic waves encounter interfaces between layers, they undergo reflection and refraction, producing travel-time patterns that can be analysed to estimate layer depths and velocities (Nadeau, 2005). This study focuses on first-arrival P-waves, which form the basis of refraction analysis.

Ground Penetrating Radar (GPR) is another widely used geophysical method for near-surface imaging. Instead of acoustic waves, GPR transmits high-frequency electromagnetic pulses into the subsurface using antennas of various operating frequencies. When these waves encounter contrasts in dielectric permittivity or electrical conductivity, part of the signal is reflected back to the receiving antenna while the remainder continues downward. The recorded travel times and amplitudes of these reflections enable interpretation of subsurface structures, buried objects, moisture boundaries, and stratigraphy (Wang & Birken, 2022). GPR provides high-resolution images of the shallow subsurface, complementing the greater penetration depth typically achieved by seismic refraction.

A wide range of applications demonstrates the value of both techniques. Viengthong et al. (2020) applied seismic refraction to assess groundwater potential zones using a 12-channel SmartSeis ST system and successfully identified aquifers at depths of 18–25 m through first-arrival analysis and tomographic inversion. Similarly, Serma and Setan (2009) used a 250 MHz RAMAC GPR system to delineate underground pipelines, demonstrating GPR's ability to detect buried utilities at varying depths, while also highlighting its limitations in resolving closely spaced or very small-diameter pipes. These examples illustrate the complementary strengths and practical constraints associated with each method.

Building on the demonstrated success of seismic and GPR surveys in shallow subsurface investigations, this study integrates both techniques to characterize subsurface features at the FAU Boca Preserve Ecological Site. The combined approach aims to improve confidence in layer identification, detect variations in material composition, and enhance understanding of near-surface geological structure within a heterogeneous ecological site.

2. STUDY AREA

The study was conducted at the Boca Preserve Ecological Site, located within the Florida Atlantic University (FAU) Boca Raton campus and adjacent to the Boca Raton Airport (26.376875° N,

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80.105358° W). The preserve encompasses approximately 60 acres of protected natural landscape and represents one of the few remaining patches of native south-Florida habitat within an otherwise urbanized setting. The site contains a diverse mosaic of ecological communities, including upland scrub, pine flatwoods, wet prairies, and hardwood hammocks, each characterized by unique vegetation structure, soil composition, and hydrologic behavior.

From an environmental standpoint, the preserve supports several keystone and protected species such as gopher tortoises (Gopherus polyphemus), burrowing owls (Athene cunicularia), and a wide range of native flora adapted to coastal sandy environments. These species depend on specific subsurface conditions such as soil compaction, moisture distribution, and burrow-supporting stratigraphy reinforcing the relevance of subsurface characterization for ecological monitoring and habitat management.

Geologically, the site is underlain by quartz-rich coastal sands overlying the Miami Limestone formation, typical of southeast Florida's Atlantic coastal ridge. These materials exhibit sharp lateral variability in density, porosity, and moisture content due to seasonal wet–dry cycles and fluctuating groundwater levels. The region also features a shallow water table, often within a few meters of the surface, which can strongly influence both seismic velocities and GPR signal penetration.

The combination of sandy sediments, moisture variability, and subtle stratigraphic layering makes the Boca Preserve well suited for the application of seismic refraction and Ground Penetrating Radar (GPR) to characterize shallow subsurface layering, material contrasts, and moisture-related variations across the site. The spatial extent and layout of the study area, including the geophysical survey line, are shown in Figure 1.

Figure 1. Study area

3. METHODS

A combined seismic refraction and Ground Penetrating Radar (GPR) survey was conducted along a 240 m survey line positioned in the northeastern portion of the Boca Preserve Ecological Site (Figure 2). The objective of the survey was to characterize shallow subsurface stratigraphy, material variability, and potential depth to the water table across a representative transect of the study area.

3.1 Seismic Data Acquisition

The seismic survey was carried out using a 48-channel system with 4.5 Hz vertical geophones deployed at 5 m spacing, resulting in a total spread length of 240 m. The acquisition geometry followed a conventional end-on refraction layout, with geophones aligned linearly along the prepared survey line. Seismic energy was generated using a sledgehammer striking a steel plate, providing a repeatable impulsive source suitable for shallow investigations.

Figure 2. Survey line

Shots were performed at 10 m intervals (every second geophone), producing a series of forward and reverse shot gathers to improve subsurface coverage. The field computer was positioned near the midpoint of the spread, allowing real-time quality control of waveform amplitudes, noise levels, and first-arrival clarity. To enhance the signal-to-noise ratio, each shot was stacked five times, and the resulting records were averaged.

Environmental factors such as uneven ground, surface vegetation, and varying soil compaction required careful planting of geophones to maximize ground coupling. Figure 3 shows the field survey setup.

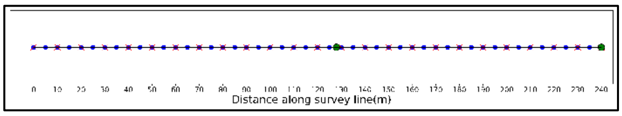

Figure 3. Seismic survey – Sketch

3.2 Seismic Data Processing

Seismic data processing was carried out using the Pickwin module of the SeisImager software package. The raw shot gathers were first imported and corrected for survey geometry and trace header information. Basic pre-processing steps were then applied, including:

- Dewow filtering to remove low-frequency instrument drift,
- Band-pass filtering to suppress high-frequency cultural noise caused by aircraft and traffic near the Boca Raton Airport,
- Amplitude scaling to improve the visibility of first arrivals.

Following pre-processing, the cleaned records were loaded into Pickwin, where Automatic First-Break Picking (AFBP) was performed and subsequently refined through manual corrections to ensure accurate first-arrival identification. The picked travel times were plotted to generate distance–time (x–t) curves, from which linear segments were analyzed to estimate layer slopes and assign preliminary refractors.

An initial layered model was constructed using intercept-time analysis, which provided first-order estimates of layer velocities and depths. This model was then refined using iterative forward modeling, where predicted ray paths were compared with observed travel times. Adjustments were made until the misfit between modeled and observed data was minimized.

The final output of this workflow is a two-dimensional velocity–depth section, representing the seismic refraction structure along the survey line. A conceptual workflow of the seismic processing steps is shown in Figure 4.

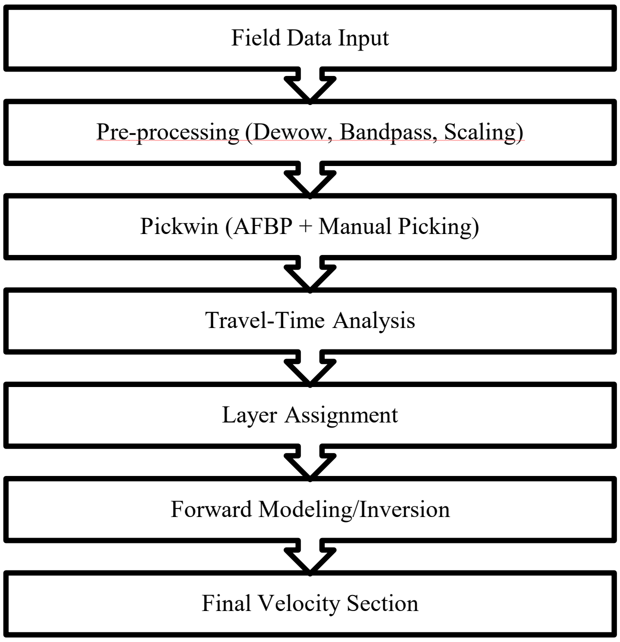

Figure 4 Seismic data processing

3.3 Ground Penetrating Radar (GPR) Data Acquisition

The GPR survey was carried out along the same 240 m transect to enable direct comparison with seismic results. Three antennas were used:

- 80 MHz (deep penetration, coarse resolution)
- 160 MHz (intermediate resolution and penetration)
- 450 MHz (high-resolution, shallow penetration)

The 160 MHz and 450 MHz antennas were mounted on a GPR cart equipped with a calibrated odometer to ensure accurate trace spacing. The 80 MHz antenna was operated using a hand-towed sled system due to its size and lower operational frequency. For each antenna, data were acquired at approximately 200 traces per second, providing dense spatial coverage along the survey line.

3.4 GPR Data Processing

GPR data were processed following a standard near-surface geophysical workflow to enhance reflector continuity and suppress noise. Raw radargrams were first imported into the processing environment and subjected to time-zero correction to align the direct airwave and ensure consistent start times across traces. This was followed by dewow filtering and background (DC) removal, which effectively reduced low-frequency instrument drift and horizontally coherent noise.

To improve the visibility of deeper reflectors, gain functions—including Automatic Gain Control (AGC) and Spreading/Exponential Compensation (SEC)—were applied. A band-pass filter was then used to isolate the dominant frequency content associated with each antenna (80, 160, and 450 MHz) and suppress out-of-band noise.

Subsequently, velocity estimation was performed using hyperbola fitting on diffractions, supported by dielectric constant ranges reported in the literature for sandy and moisture-variable environments. These velocities were applied for time–depth conversion, enabling geological interpretation in real-world depth units. The overall processing sequence is summarized in Figure 5.

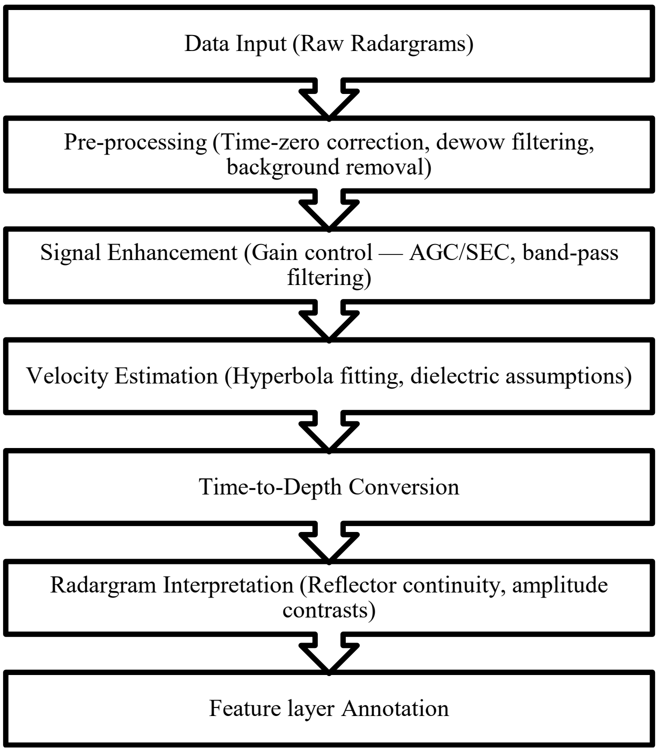

Figure 5. GPR data processing

Processed radargrams were analyzed for reflector continuity, amplitude contrasts, and boundary geometries. Among the three datasets, the 160 MHz profile offered the optimal balance between penetration depth and resolution, and was therefore selected as the primary GPR dataset for subsurface interpretation.

4. RESULTS AND DISCUSSION

4.1 Seismic Survey

Figure 6 shows the first-arrival travel-time picks and the layer assignment derived from slope changes in the distance–time curves. Three linear segments were observed, indicating three primary refractors. These refractors correspond to substantial increases in P-wave velocity with depth.

The final tomographic velocity section (Figure 7) shows a layered structure extending to approximately 50 m depth. When interpreted jointly with the available borehole record (Figure 8), and using reference velocity catalogs (Kearey et al., 2002; Geophysics for Practicing Geoscientists, 2017), the subsurface can be divided into three main units as presented in table 1.

4.2 GPR Survey

Figure 9 illustrates radargrams acquired using the 80, 160, and 450 MHz antennas. As expected, each antenna demonstrates a characteristic tradeoff between resolution and penetration depth:

- 80 MHz: Provided the deepest penetration (>20 m) but produced diffuse reflectors and limited ability to resolve thin layers.

- 450 MHz: Delivered excellent near-surface resolution but attenuated rapidly, limiting penetration to only a few meters.

- 160 MHz: Offered a balanced compromise between resolution and depth, achieving sufficient penetration (≈15–20 m) while maintaining reflector continuity and clear stratigraphic boundaries.

Because the objective of this study required both adequate depth imaging and interpretable reflector geometry, the 160 MHz profile (Figure 10) was selected for detailed interpretation. It provided the most coherent reflections across the full line and resolved boundaries consistent with the seismic model.

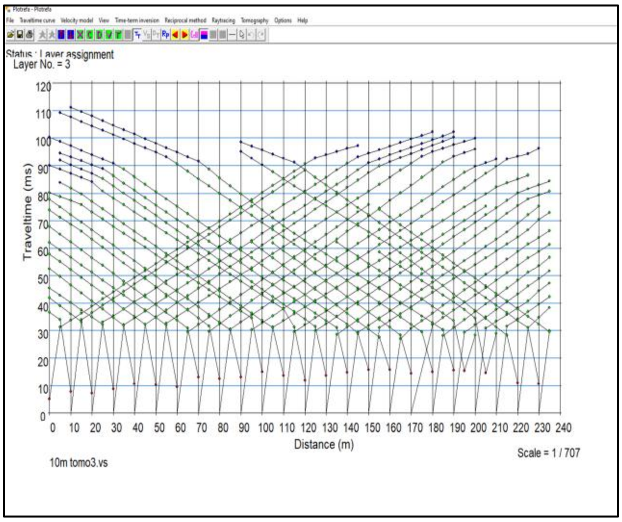

Figure 6. Layer assignment

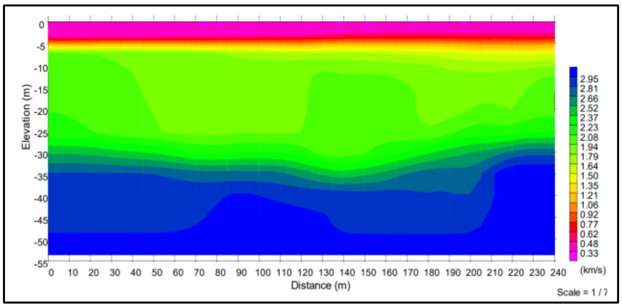

Figure 7. Velocity section profile

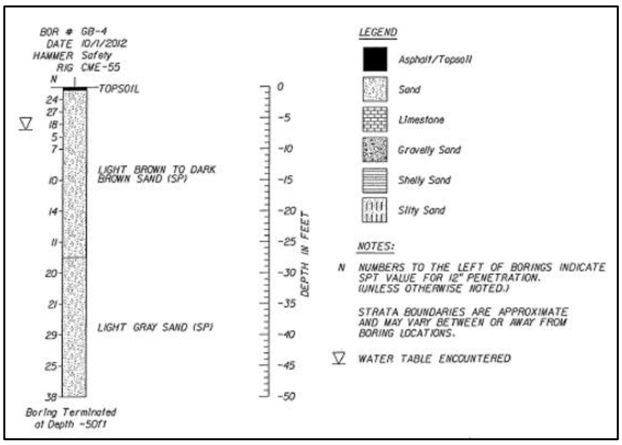

Figure 8. Bore hole information

Reference: Drill/ Literatures			Velocity Model Results		
Reference	*Depth (m)*	*Stratigraphy*	*Depth (m)*	*Velocity range (km/s)*	*Stratigraphy*
Drill	0-8	Topsoil: Light brown to Dark brown	0-7	0.3 – 1.5	Brown Soil
Drill	8-15	Gray Sand	7-30	1.5 – 2.5	Wet Sand
[1]	8-30	Wet Sand			
[2] [1]	30-50	Limestone Marls	30 - 50	2.5 – 3.5	Limestone/ Marls

Table 1. Seismic interpretation

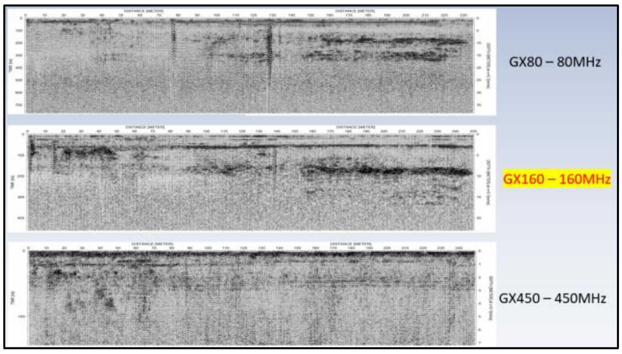

Figure 9. GPR ray diagram

Two prominent reflectors appear consistently in the 160 MHz radargram:

- A shallow reflector at ~3 m depth, marking a dielectric contrast likely associated with the transition from loamy soil to more compact dry sand.

- A deeper reflector at ~8 m depth, representing a major change in moisture content and dielectric permittivity, interpreted as the water table or onset of saturated sand. This aligns closely with the seismic velocity transition

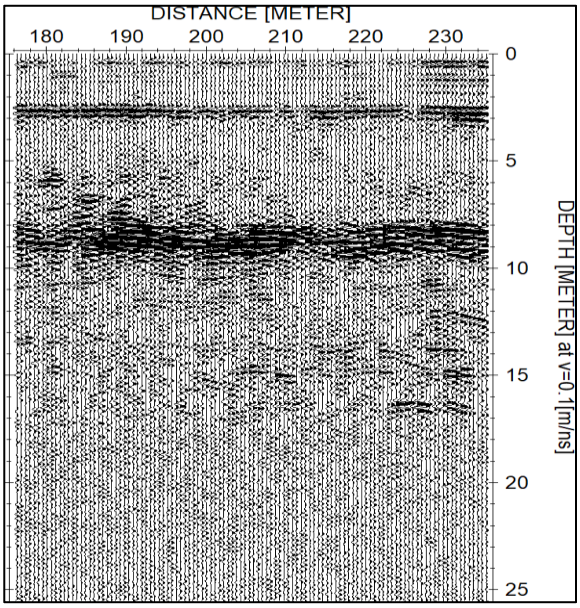

Figure 10. GX 160 MHz

With reference to Geophysics for Practicing Geoscientists (2017), the subsurface layers were characterized as summarized in Table 2. Although the processed radargrams do not provide explicit dielectric permittivity values, the interpretation was supported by integrating the seismic velocity model with the strength and continuity of GPR reflections, allowing material boundaries to be inferred more reliably.

Depth (m)	ε_r	*Stratigraphy*
0 - 3	4-6 (dry) 10-20 (Wet)	Loamy Soil
3 – 8	3 - 6	Dry Sand
>8	10 - 30	Wet Sand

Table 2: GPR interpretation

4.3 Integrated Interpretation

Figure 11 presents a 1-D stratigraphic model synthesizing seismic, GPR, and borehole observations.

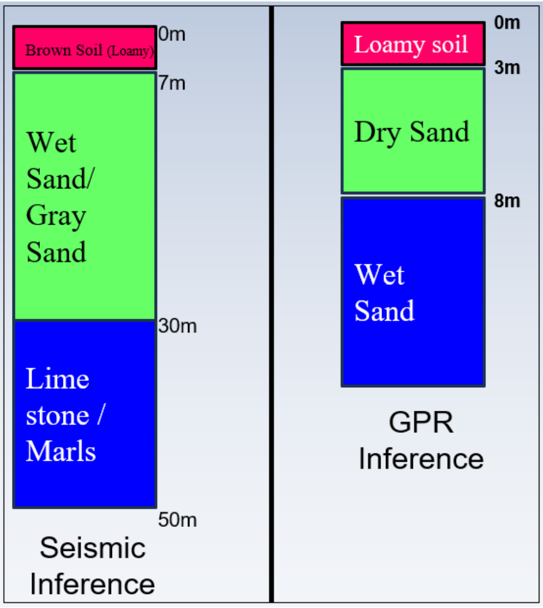

Figure 11. 1D stratigraphic column

Across both seismic and GPR datasets:

Layer 1: 0–3 m — Loamy soil / topsoil

- Low seismic velocity
- High GPR reflectivity contrast at 3 m
- Matches borehole “topsoil → light brown sand”

Layer 2: 3–8 m — Dry sand

- Moderate seismic velocity increases
- GPR reflector marking the boundary at ~3 m
- Dielectric values consistent with dry sand
- Increasing compaction toward 8 m

Layer 3: 8–30 m — Wet sand (saturated zone)

- Sharp seismic velocity increase
- Strong GPR reflection at 8 m
- Indicates water table at ~7–8 m
- Matches regional hydrogeological expectations

Layer 4: >30 m — Limestone

- Only resolved by seismic
- Matches Miami Limestone sequence known in South Florida

The strong correspondence between seismic and GPR interpretations increases confidence in the final integrated model.

5. CONCLUSION

This study demonstrates that integrating seismic refraction and Ground Penetrating Radar (GPR) provides a robust and complementary framework for shallow subsurface characterization at the Boca Preserve Ecological Site. Seismic refraction effectively resolved deeper stratigraphic boundaries and yielded reliable estimates of material velocities, while GPR provided high-resolution imaging of shallow reflectors and dielectric contrasts. Together, these methods produced a coherent geological model that is well supported by available borehole information.

The integrated interpretation identifies four primary subsurface units: (i) loamy surface soil from 0–3 m, (ii) dry sand from 3–8 m, (iii) saturated or wet sand extending to approximately 30 m, and (iv) a transition to limestone below ~30 m. Both methods independently detected a strong boundary at around 7–8 m depth—interpreted as the water table—indicating strong agreement among seismic velocities, GPR reflectors, and drill data. The consistency across methods confirms the value of using multi-parametric geophysical indicators for stratigraphic delineation in moisture-variable coastal settings.

While the results present a clear subsurface profile along the surveyed line, some limitations remain. The interpretation is based on a single 240 m transect, which restricts insights into lateral heterogeneity that may arise from vegetation rooting, moisture gradients, or anthropogenic disturbance across the preserve. Additional survey lines, especially those oriented perpendicular to the existing profile, would help resolve geometric ambiguities and improve confidence in layer continuity. Likewise, the boreholes used for validation were located approximately 350 m from the geophysical transect (figure 12) and were not deep enough to verify the full stratigraphy inferred from geophysical data. Future work should incorporate boreholes positioned directly on or near the geophysical lines, with depths extending beyond the expected water table and into the limestone horizon.

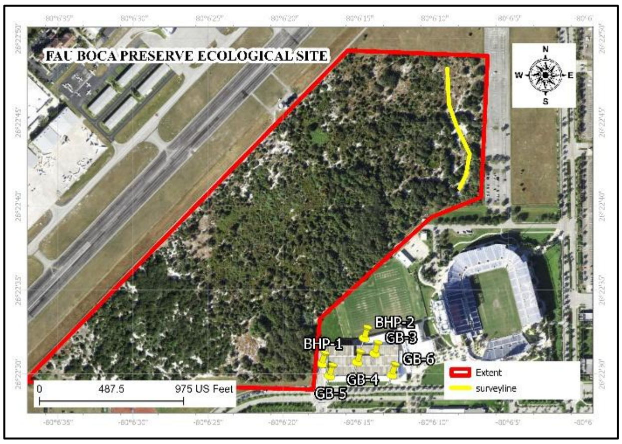

Figure 12. Drill locations

Beyond improving data constraints, multi-method surveys such as the one presented here offer tangible benefits for ecological, hydrological, and geological assessments in coastal preserves. The Boca Preserve, with its heterogeneous soils and fluctuating moisture regimes, represents an environment where single-method approaches often struggle to produce unambiguous interpretations. The complementary strengths of seismic refraction and GPR reduce uncertainty, enhance boundary detection, and provide a transferable subsurface framework that can support habitat restoration, groundwater monitoring, and environmental management. Overall, this study highlights the practical value of integrated geophysical methods for non-invasive subsurface characterization and sets a foundation for more comprehensive, spatially distributed investigations in the future.

REFERENCES

Geophysics for Practicing Geoscientists. (2017). Retrieved from https://gpg.geosci.xyz/index.html

Kearey, P., Brooks, M., & Hill, I. (2002). An introduction to geophysical exploration (Vol. 4). John Wiley & Sons.

Nadeau, J. C. (2005). Geophysical imaging of a river valley aquifer. Unpublished MSc thesis, University of New Brunswick, Fredericton, New Brunswick, Canada.

Reynolds, J. M. (2011). An introduction to applied and environmental geophysics. John Wiley & Sons.

Serma, A. I. A., & Setan, H. (2009). Ground penetrating radar (GPR) for subsurface mapping: Preliminary result. Geoinf Sci J, 9, 45-62.

Tearpock, D. J., & Bischke, R. E. (2002). Applied subsurface geological mapping with structural methods. Pearson Education.

Viengthong, X., Vu, D. M., Nguyen, A. D., & Vu, M. T. (2020). Seismic refraction exploration for groundwater potential evaluations: A case study of Vientiane Province, Laos. VNU Journal of Science: Earth and Environmental Sciences, 36(4).

Wang, M. L., & Birken, R. (2022). Ground-penetrating radar. In Sensor technologies for civil infrastructures (2nd ed., Chapter 9, Section 9.2.2). Elsevier.

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