

SEISMIC METHODS INVENTORY

A - INTRODUCTION

Environmental movements strongly oppose onshore 3D seismic campaigns by explosion, denouncing the direct impact of detonations on wildlife and ecosystems, the destruction of soils and vegetation caused by heavy machinery passage, and the risks of groundwater contamination. They primarily criticize this method as a tool that excessively facilitates the expansion of fossil fuels.

The general public is largely unfamiliar with recent technological developments in seismic exploration techniques and remains unaware of the diversity of existing seismic methods. In the public mind, exploration methods are generally boiled down to seismic surveys by explosions and by Vibroseis.

The main environmental and societal arguments raised against traditional seismic surveys revolve around several major axes:

1. Impact of Shock Waves and Explosives on Fauna and Flora

- **Ecosystem Disruption:** Explosive charges, placed in small pre-drilled boreholes, generate high-intensity seismic waves. These severely disrupt terrestrial and underground animals, causing acute stress, long-lasting behavioral changes, or even the complete desertion of breeding or wintering areas.
- **Habitat Destruction:** To deploy the physical lines of geophones and sources (whether explosives or shaker trucks), it is often necessary to clear land and create straight access tracks through fragile natural areas or forests, leading to severe habitat fragmentation and accelerated soil erosion.

2. Risks Associated with Boreholes for Explosives

- **Aquifer Pollution:** The explosion method requires drilling shot holes ranging from a few meters to several dozen meters deep. Experts point out the major risk of shallow and deep aquifer contamination, either through the accidental mixing of water from different layers or via the infiltration of chemical residues from explosives.
- **Geological Degradation:** Repeated dynamite use can cause micro-fracturing within the underlying rock matrix, permanently altering groundwater flow paths and irreversibly weakening the mechanical stability of soils.

3. Disturbances to Local Communities

- **Vibrations and Noise Pollution:** Successive explosions and the continuous passage of heavy trucks generate high-amplitude acoustic waves and ground vibrations that

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inconvenience local populations and can cause structural micro-cracks in adjacent building foundations.

4. Global Climate Critique

- **Prolonging the Fossil Fuel Era:** Beyond the direct physical damage visible on the ground, the central argument of non-governmental organizations (NGOs) is that 3D seismic is merely a preparatory phase for costly industrial exploration. Its ultimate goal remains the discovery of new oil, conventional gas, or shale gas reservoirs. Environmental movements argue that investing heavily in this technology directly contradicts international decarbonization targets and the fight against global warming.

Note on the Fundamental Difference:

The fundamental difference between the two major traditional methods lies in the precise control of energy: seismic by explosion releases a violent, destructive, and instantaneous acoustic impulse, whereas the shaker truck (Vibroseis) injects a continuous, progressive, and modulated frequency wave into the ground.

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5. Detailed Impact Comparison (Energy Control)

Impact Category	Explosive Seismic (Dynamite)	Shaker Truck Seismic (Vibroseis)
a- Environmental and Ecological Impacts	High risk of deterioration and trauma to local fauna due to the startle effect of sudden noise. Potential long-term underground pollution from chemical residues of the charges post-detonation.	Continuous but progressive noise pollution (frequency sweep), allowing animals to flee preventively. Pollution risk is strictly limited to accidental hydraulic fluid leaks from vehicles.
b- Structural and Infrastructure Impacts	Generation of strong surface vibrations that can crack nearby buildings. Usage is strictly prohibited or heavily regulated near urban centers.	Utilization of modulated and programmed frequencies to avoid reaching the resonance frequency of adjacent structures. Safe, proven, and highly frequent deployment in urban or industrial environments.
c- Geophysical Impacts and Data Quality	High-frequency signal ideal for imaging very deep geological structures. However, the immediate impact zone undergoes structural modification (plastic zone), which alters the baseline signal.	Perfectly repeatable and adjustable signal (precise choice of frequency ranges) to target specific geological layers. However, penetration is weaker in highly dense sediments or at extreme depths.
d- Logistical and Field Impacts	Mandatorily requires pre-drilling deep shot holes. Involves heavy logistics tied to regulatory safety, storage, and the transport of hazardous materials.	Causes visible surface compaction due to the extreme weight of the trucks (typically 20 to 30 tons). Consequently, usage is restricted to trafficable terrain or areas accessible by road tracks.

6. Investigation Depths According to Targets

The choice of exploration or drilling method directly depends on the depth of the geological target:

- Very Shallow Depth (0 to 50 meters): Geotechnics
 - This zone relates to infrastructure construction, foundations, and mechanical soil studies.
 - Tools: Standard Penetration Test/Cone Penetration Test (SPT/CPT), Auger drilling, Conventional coring, Electrical Resistivity Tomography (ERT).
- Shallow to Medium Depth (50 to 500 meters): Heavy Geotechnics & Surface Geothermal
 - This segment targets major civil engineering works (tunnels) and borehole heat exchangers (heat pumps).

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- Tools: Rotary drilling (direct circulation), Down-the-Hole (DTH) hammer drilling, Seismic refraction.
- Deep Depth (500 to 3,000 meters): Deep Geothermal (Hydrothermal)
 - This depth aims at capturing hot aquifers for district heating networks or electricity production.
 - Tools: Heavy Rotary drilling (with high-performance mud motors for directional drilling), 2D/3D reflection seismic, Wireline logging (gamma-ray, neutron).
- Ultra-Deep Depth (Beyond 3,000 to 7,000 meters): Oil, Gas & Enhanced Geothermal Systems (EGS)
 - This extreme depth domain requires cutting-edge technologies to withstand intense pressures and temperatures.
 - Tools: RSS-NMR satellite technology (the entirety of data recovery is performed from space via dedicated satellites), 3D/4D reflection seismic (dynamic monitoring of fluid displacement over time).

B - VIBROSEIS VERSUS EXPLOSION

The environmental, logistical, and technical impact of the Vibroseis method (vibrating trucks) and explosive seismic (dynamite) varies radically depending on the topographical nature of the terrain.

Generally, Vibroseis is preferred in urban and desert environments due to its operational safety and execution speed. Conversely, explosive seismic remains technically indispensable in dense forests because of geographical accessibility constraints and to maintain geophysical data quality under the canopy.

Detailed Analysis by Intervention Environment

1. Impact in Forest Environments

- **Vibroseis - Flora Destruction:** Trucks weighing several dozen tons require clearing straight tracks 3 to 5 meters wide, causing significant local deforestation.
- **Vibroseis - Habitat Fragmentation:** Opening these wide pathways lastingly disrupts wildlife and breaches ecological corridors.
- **Vibroseis - Soil Compaction:** The extreme weight of the machinery irreversibly destroys the superficial structure and porosity of forest soil.
- **Explosive Seismic - Canopy Preservation:** The transport of lightweight drilling equipment requires only narrow pathways under 1.5 meters wide.
- **Explosive Seismic - Ephemeral Nuisance:** Underground detonations cause an instantaneous noise that temporarily startles wildlife, but the physical impact on the habitat remains minimal in the long term.

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2. Impact in Desert Environments

- **Vibroseis - Ideal Logistics:** Large flat spaces allow truck convoys to progress at record speeds.
- **Vibroseis - Zero Waste:** This method leaves no chemical residues in the ground and does not require water use.
- **Vibroseis - Superficial Imprints:** Passage leaves tire tracks in the sand, which are rapidly erased by natural wind action.
- **Explosive Seismic - Drilling Difficulties:** Drilling shot holes in unstable sand dunes systematically requires hole casing, which slows down operation rates.
- **Explosive Seismic - Resource Consumption:** The drilling process consumes large volumes of water, a critical and scarce resource in desert environments.

3. Impact in Urban and Peri-Urban Environments

- **Vibroseis - Infrastructure Safety:** The emitted vibrations are electronically programmed (sweep curves). They adhere to strict standards to avoid damaging building foundations or buried pipelines.
- **Vibroseis - Moderate Noise Disturbance:** The noise emitted is comparable to a large industrial truck engine operating for a few seconds.
- **Explosive Seismic - Critical Danger:** Shock waves from an uncontrolled underground explosion can crack buildings, shatter windows, and rupture sensitive utility networks (gas, water).
- **Explosive Seismic - Legal Ban:** In almost all countries, dynamite use is completely banned near inhabited areas for obvious public safety reasons.

Terrain Evaluation Conclusion:

The choice of technology relies on a fine arbitrage between geographical accessibility and environmental preservation. Vibroseis is a must wherever vehicles can operate without destroying nature (cities, deserts, plains). Conversely, explosive seismic remains the only viable method to image the subsurface of topographically complex zones (dense forests). However, it is now clear that neither conventional technique can be responsibly used inside a national park due to collateral damage.

C - NEW EXPLORATION TECHNOLOGIES: RSS-NMR AND LOW-IMPACT SEISMIC

The use of RSS-NMR (Remote Sensing Survey - Nuclear Magnetic Resonance) technology represents one of the most innovative and respectful solutions to study the subsurface of a natural park or an ecologically protected area. Unlike conventional 3D seismic, which requires heavy physical interventions, RSS-NMR is a strictly passive and non-intrusive method.



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1. Shortcomings of Classical Seismic in Sensitive Areas

- **Flora Destruction:** Compulsion to cut straight lines (layons) through vegetation.
- **Wildlife Disturbance:** Explosions or strong vibrations induce continuous noise pollution and ongoing micro-seisms that drive away wild animals.
- **Blocking Administrative Hurdles:** Securing environmental exploration permits in these protected areas often takes years or proves legally impossible.

2. Core Principles of the Passive RSS-NMR Alternative

- **Remote Sensing Survey (RSS):** Satellite sensors conduct advanced spectral analyses from a distance to identify geological anomalies and map structures of interest without physical soil contact.
- **Nuclear Magnetic Resonance (NMR):** It utilizes Earth's natural magnetic field variations combined with microwaves to excite the protons of fluids (water, hydrocarbons) present in the subsurface. Each fluid returns a unique electromagnetic signature, forming a molecular 'fingerprint' for precise identification.

3. Concrete Applications for Natural Park Conservation

- **Hydrogeology and Water Management:** Accurately mapping aquifers, assessing soil porosity, and securing drinking water supplies without altering surface ecosystems.
- **Structural Studies and Hazard Prevention:** Detecting geological faults or fracture zones to prevent landslides or natural seismic hazards.
- **Energy Transition:** Assessing the geothermal potential of a zone.

D - TRIPARTITE COMPARATIVE ANALYSIS OF EXPLORATION TECHNOLOGIES

These three techniques exhibit major differences in environmental, operational, and technical impacts. The first two methods are 'active' geophysical techniques, whereas RSS-NMR is a passive, non-destructive method relying on satellite imagery and atomic magnetic resonance.

1. Detailed Impact Evaluation by Technology

Explosive Seismic (Dynamite)

- **Environmental Impact: High.** It requires drilling shot holes, perturbs local wildlife, and damages flora during line clearing.
- **Vibrational and Structural Impact: High.** Explosions generate brief but violent shock waves. Real risk to soil stability and nearby infrastructure.
- **Acoustic Impact: High.** Massive aerial and underground noise nuisances for fauna.

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**GEO-NMR.NET**
Exploration by satellite

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- **Logistical Impact:** High critical risk tied to handling, storing, and transporting hazardous materials.

Shaker Truck Seismic (Vibroseis)

- **Environmental Impact: Moderate.** No explosives are used. Main impact stems from mechanical soil compaction and minimal land clearing.
- **Vibrational and Structural Impact: Low to Controlled.** Vibrations are injected continuously and progressively (frequency sweep), complying with strict regulatory standards.
- **Acoustic Impact: Moderate.** Noise originates primarily from truck internal combustion engines pushed to high RPMs.

RSS-NMR Exploration (Remote Sensing & NMR)

- **Environmental, Vibrational, and Acoustic Impact: Strictly ZERO.** This is the main competitive advantage. Since acquisition takes place from space, it emits no shock waves, requires no heavy vehicles, no drilling, and generates zero nuisance.
- **Regulatory and Societal Impact: Very Low.** It eliminates the need to obtain burdensome environmental permits or negotiate lengthy rights-of-way.

2. Strategic Decision-Making Process and Sweet Point Marking

RSS-NMR technology maps and precisely targets 'Sweet points' (optimal fluid accumulation zones) across the explored block. At this stage, block owners must conduct an in-depth internal strategic review to decide whether to launch the subsequent phase of exploratory test wells.

Although the RSS-NMR method provides full coordinates to directly locate a well (longitude, latitude, depth, pressure), owners frequently wish to validate and refine the data using a localized seismic method focused on these Sweet points. We then recommend using modern wireless nodal seismic systems (notably Low-Impact Seismic (LIS)), which prove to be the best option over highly restricted and targeted surfaces.

E - LOW-IMPACT SEISMIC OR HAND-CARRIED NODAL SEISMIC

Low-Impact Seismic (LIS) and hand-carried nodal seismic represent a major technological revolution, enabling ultra-high-resolution subsurface imaging while drastically reducing the environmental footprint.

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1. The Pillars of Low-Impact Seismic (LIS)

- **Reduced and Sinuous Exploration Lines:** Physical transit lines are reduced to minimal widths (under 2 meters) and manually detour around large trees (doglegs), preserving the canopy and masking lines of sight to protect wildlife from predators.
- **Miniaturized Energy Sources:** Using significantly lighter wave sources (small charges buried at shallow depths, portable mini weight-drops, or light vibrating sources).
- **Passive Seismic:** Increasingly utilizing Earth's natural ambient noise (oceanic vibrations, wind, human activity) as a continuous wave source, eliminating the need to generate artificial explosions or vibrations.

2. Operation of Cable-Free Nodal Systems (Hand-Carried Nodes)

This is the key technology that makes low-impact seismic logistically viable in sensitive environments. Nodal seismic replaces thousands of kilometers of heavy copper cables with autonomous, miniaturized, and completely wireless units.

- **The 'Node' Concept:** A node is a small, all-in-one waterproof electronic box integrating a geophone sensor or accelerometer, a high-capacity internal battery, a GPS chip for synchronization, and internal Flash memory.
- **Hand-Carried aspect (Manual Deployment):** Lightweight teams on foot carry simple backpacks containing dozens of nodes (such as LOW-IMPACT SEISMIC (LIS)) and plant them directly into the ground densely without major excavation.
- **Continuous Recording:** Nodes record ground vibrations continuously for several weeks. At the end of the mission, they are retrieved on foot and plugged into a mobile data center (Nest) to harvest the measurements.

F - CONCLUSIONS AND STRATEGIC RECOMMENDATIONS

The optimal method to explore potential oil reserves within a highly protected area like A National Park is the LOW-IMPACT method combined with NMR (RSS-NMR). It offers the perfect compromise between deep geological imaging and minimal surface environmental footprint, effectively excluding the destructive use of explosions.

1. Benefits of the RSS-NMR + LOW-IMPACT SEISMIC (LIS) Technological Alliance

Maximum Cost-Effectiveness and Operational Efficiency

- **Block Screening via RSS-NMR:** Exploration is planned in two phases. The core value of RSS-NMR is its ability to analyze vast surface areas rapidly from space without drawing speculative attention or alerts on the ground (Spy mode). This drastically narrows down the geographic scope and costs of phase two.

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- **Drastic Field Cost Reduction:** The exclusive use of LOW-IMPACT SEISMIC (LIS) miniature nodes cuts field operational costs by up to 50% compared to classical land seismic.
- **Complementarity of Measurement Scales:** RSS-NMR provides remote macro-mapping. This targets specific areas of interest before deploying nodal seismic on the ground for high-fidelity imaging of geological structures.
- **Processing Speed:** The ultra-fast deployment of lightweight nodes (150 grams each) combined with satellite data accelerates the overall cycle, cutting final data processing times by 30% to 50%.

Virtually Zero Environmental Footprint (Low Impact)

- **Zero Deforestation:** LOW-IMPACT SEISMIC (LIS) nodes are transported manually on foot by operators. There is no longer any need to clear trees or destroy brush to establish baseline transit paths (no line clearing).
- **Soil and Ecosystem Preservation:** The total absence of heavy shaker trucks eliminates soil compaction risks and preserves native flora and fauna. RSS-NMR, being a remote passive method, generates absolutely zero field disturbance.
- **Carbon Footprint Reduction:** Lightening field logistics and removing heavy transport vehicles massively reduces the project's associated CO₂ emissions.

Unrivalled Precision and Image Resolution

- **Direct vs. Indirect Detection:** Classical seismic images geological structures indirectly. Coupling it with NMR directly detects the specific signature of fluid hydrogen atoms, providing immediate estimates of porosity, permeability, and exact fluid nature (water vs. hydrocarbons).
- **Ultra-High Data Density:** The low unit cost and miniaturization allow the deployment of tens of thousands of ground sensors. This density delivers 3D/4D image resolution of unprecedented clarity.

Flexibility Across All Terrains and Safety (HSE)

- **Complex Terrain Access:** This technology combination allows exploration in environments previously deemed inaccessible: dense forests, protected parks, steep mountain terrains, or sand deserts.
- **Team Safety:** The manual transport of ultra-light loads drastically decreases occupational hazards linked to heavy cable handling or off-road driving.

2. Roadmap and Arbitrages for the Paraguayan Chaco Ecosystem

To conduct this prospecting survey in strict compliance with the environmental standards of a protected area, a detailed technical analysis dictates the following trade-offs:

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- **Vibroseis:** Yields sharp 2D/3D subsurface structural images, but trucks are too heavy and the mandatory track opening would severely fragment the Chaco forest ecosystem.
- **Explosion:** To be absolutely proscribed. Detonations cause irreversible damage to local soil structure, threaten aquifers, and generate extreme acoustic stress on protected species (jaguar, Chacoan peccary). Furthermore, Paraguayan environmental regulations strictly prohibit explosive usage in these zones.
- **Surface RSS-NMR:** An excellent ecological method to estimate porosity, but its depth of investigation is insufficient on its own for classical petroleum exploration (Chaco reservoirs lie thousands of meters deep, whereas surface NMR alone only penetrates a few dozen meters). It acts as a complementary calibration tool.

Final Operational Recommendation:

1. Definitively and completely eliminate the use of dynamite explosions.
2. Utilize space-borne RSS-NMR technology in Phase 1 as the primary global screening tool of the concession to precisely map 'Sweet points' (zones of major interest containing fluids).
3. Deploy cable-free nodal seismic (LOW-IMPACT SEISMIC (LIS) type) in Phase 2 exclusively over the highlighted Sweet point zones. Operators will move strictly on foot to plant and retrieve miniature recorders, eliminating the need to clear paths for heavy machinery.
4. Integrate downhole NMR logging directly during subsequent exploratory drilling phases to analyze oil and water saturation within deep reservoir rocks, without any footprint on the surface ecosystem.

General Conclusion: Within the ultra-sensitive framework of a natural park, the sequential combination of RSS-NMR (for non-invasive Sweet point targeting) followed by LOW-IMPACT NODAL SEISMIC stands as the only viable, high-performance, and eco-responsible approach to map deep reserves. Explosive techniques must be rejected for obvious ecological reasons, and the Vibroseis technique must be discarded as it proves technically too risky due to the heavy truck track-clearing requirements.