Remittances Review
September 2024,
Volume: 9, No: S 4, pp. 1159-1180
ISSN: 2059-6588(Print) | ISSN 2059-6596(Online)
Received : 25 July 2024, Accepted: 18 September 2024
DOI: https://doi.org/10.33282/rr.vx9i2.65

Frontier in Geophysical Exploration: Emerging Technologies & Application

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Abstract

Geophysical exploration has played a key role in scientific discoveries and industrial applications, such as resource extraction, environmental monitoring, and subsurface imaging. Conventional techniques, including seismic surveys, electromagnetic (EM) methods, and gravity measurements, have been commonly applied for subsurface investigations. Technological, analytical, and computational power have significantly improved exploration efficiency, accuracy, and sustainability. Emerging technologies–Artificial intelligence (AI), machine learning (ML), distributed acoustic sensing (DAS), quantum sensors, unmanned aerial vehicles (UAVs), full-waveform inversion (FWI), and satellite-based remote sensing–are transforming geophysical exploration. The innovations bring higher subsurface imaging resolution, lower operational cost, and reduced environmental impact. DAS allows for real-time monitoring of seismic activity, and AI and ML are used to automate seismic interpretation and anomaly detection. Improved gravity and magnetic surveys — Quantum sensors make this possible with improved precision for mineral and hydrocarbon exploration. UAVs allow for cheap, high-resolution aerial geophysical surveys, and FWI can provide the best seismic images. Such satellite-based remote sensing techniques as synthetic aperture radar (SAR) and hyperspectral imaging enable large-scale geophysical property assessments. These technologies can also be applied to mineral and hydrocarbon exploration, geothermal energy assessment, environmental monitoring, and infrastructure evaluation. Nonetheless, issues like data integration difficulties, expensive implementations, and ecological implications persist. Future research endeavors can thus work towards streamlining AI intelligence analytics, Real-time monitoring, and sustainable exploration methodologies. This review discusses new developments in geophysical exploration and illustrates the positive influence of emerging technologies on the solution of present-day resource and environmental problems.

Keywords: Geophysical exploration, Artificial Intelligence (AI), Machine Learning (ML), Distributed Acoustic Sensing (DAS), Quantum Sensors, Full-Waveform Inversion (FWI),

Introduction

Geophysical exploration has been a key component of all scientific discovery and industrial evolution, including global resource extractives, environmental monitoring, and subsurface imagery. This increase in demand for natural resources (Ghasemi et al., 2024), like hydrocarbons, minerals, and groundwater, demands more effective, precise, and sustainable exploration methods to be developed. The subsurface structure is traditionally explored by geophysical methods, i.e., seismic survey (Qiao et al., 2021), electromagnetic, and gravity measurement. However, However, recent technological, computational, and data analytic advances have transformed the field, enabling more accurate, higher-resolution, and cheaper exploration. (Argyrou et al., 2022) Everything from (Argyrou et al., 2022) to artificial intelligence (AI), machine learning (ML), distributed sensing, and satellite-based remote sensing is at the cutting edge of what exploration geophysicists can do these days. Not only have these innovations enhanced the precision of subsurface imaging, but they have also notably minimized the environmental footprint as well as the operational expenses inherent in conventional approaches.

Various developments have been made to (Guoqiang et al., 2024) geophysical exploration techniques, driven by introducing of (Yu et al., 2021) sensor technologies, computational power,

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and the need for more sustainable management of resources. Conventional systems used in the early days of geophysical exploration include refraction and reflection seismology (Tsai et al., 2022), electrical resistivity surveys, and magnetic prospecting were utilized for subsurface structure mapping (Buddo et al., 2022). Although these methods have given relevant indications, they were often restricted due to low resolution, data acquisition challenges, and interpretation complexities (Mou et al., 2023). Sensitive monitoring systems with low time constants and high electronic noise are used for data acquisition. This synergy between AI and big data enables the detection of small subsurface anomalies, the automation of interpretation, and the refinement of the exploration procedure (Epelle et al., 2020; Manaviriyaphap et al., 2024).

High-resolution (Okada et al., 2022) sensing technologies represent recent geophysical exploration advancements. In the past decade, new technologies, including full-waveform inversion (FWI), distributed acoustic sensing (DAS), and quantum gravity sensors, have revolutionized geophysical data quality. These technologies enable detailed real-time monitoring, enhanced subsurface imaging, and improved depth penetration through complex geological formations (Daramola et al., 2024). Moreover, satellite remote sensing (Jafarzadeh et al., 2021), synthetic aperture radar (SAR), and hyperspectral imaging have allowed geophysical exploration to stretch out the mainstream ground-based techniques. This enables them to obtain high-resolution data remotely, thus a valuable tool for detecting minerals and hydrocarbons and monitoring the environment (Dada A. et al.,2024).

In addition, advances in sensing technologies may be integrated with geo-transformative global technologies, such as AI and machine learning, which are arising in geophysical exploration (Muir, J. et al., 2024). Using these technologies, data can be processed, patterns identified, and modeled, making the explanation easier and faster and taking up fewer resources. For example, AI-enabled seismic interpretation has higher acuity than ever in mapping fault organization, stratigraphic features, and hydrocarbons. Geophysical inversion processes can also benefit from machine learning techniques that optimize resolution and uncertainty quantification in subsurface models. The innovative nature of AI (Dada, M. A. et al.,2024) and its combination with big data analytics has presented a considerable change to geophysical decision-making paths along with the active interpretation of data and episodic exploration strategies.

Another significant advancement in geophysical exploration is autonomous and robotic technologies. (Sangeetha, A. et al.,2023) Robotic systems have dramatically improved the specific acquisition of data in complex environments with uncrewed aerial vehicles (UAVs), autonomous underwater vehicles (AUVs), and robotic borehole logging systems. (Parshin, A et al.,2021) The launch of geophysical UAVs that enable rapid, affordable surveys over multiple hectares of land offers a way forward, making them applicable across various sectors, from mineral exploration and environmental research to infrastructure management. Alternatively, autonomous undersea vehicles, or AUVs, are pivotal to marine geophysics, gathering seabed data that can be used for underwater mapping, pipeline inspections, and offshore resource exploration. * Remote-Controlled Borehole Logging in Hazardous Environments: Mobile Platform Technologies for Enhanced Efficiency and Safety in Subterranean Exploration74

Sustainable development has led to the emergence of a significant factor in any modern geophysical exploration (green technologies). Passive seismic methods are one example, which utilizes naturally occurring seismic waves for subsurface imaging and does not require active sources (such as explosives or vibroseis trucks). This process enhances effective environmental management, along with the extraction of further new valuable geophysical information (Capello M. A. et al.,2021). In exploration, geophysical techniques have improved the detection of geothermal energy hot spots at lower ecological costs. Integrating geophysical data with geological and hydrological models helps create sustainable resource management and long-term strategies that balance costs against preserving environmental and ecological systems.

One of the key aspects of this mission is the adoption of multiphysics approaches (Panzera, M et al., 2022) co-applying multiple geophysical methods in modern geophysical exploration practice in a unified manner enables an integrated perception of subsurface materials. The approach allows for joint inversion of seismic, electromagnetic, and gravity data, enhancing the subsurface models' robustness. In multi-facies formations, results from single-technique surveys may not accurately indicate the formation's seismic strength, which can be particularly helpful. By providing a more detailed picture of the subsurface causal processes, integrating multiple geophysical responses (e.g., Xu, 2023) improves exploration success (Yoo et al., 2016). Thus, one of the principal aims of exploring 3D image modeling is to integrate geophysical, geological, and geochemical data

(Cao X et al.,2024). In case studies from the oil, gas, mining, and environmental geophysics industries, multiphysics approaches reduce exploration uncertainty, guiding the extraction rationale.

However, geophysical exploration has challenges, ranging from technological limitations to high costs and data interpretation issues. Emerging technologies to be implemented come at a high cost in terms of infrastructure, capable personnel, and computation. Additionally, as geophysical data explodes, new data management and processing techniques must be developed for meaningful interpretation. Moreover, the development of beyond AI algorithms will drive future times, for example, shadowing ability algorithms for mineral detection, and quantum sensors which have the potential to deliver high sensitivity magnetic field measurement, and massive real-time data researched ability systems to address the issue of offline and offline processes in geophysical exploration. While remaining forward-looking, geophysicists must be aware of and respond to technology adoption's social, environmental, and commercial implications as the industry evolves toward a more sustainable future.

This comprehensive review summarizes and highlights the advances in geophysical exploration using these new technologies and applications. In particular, this article explores how these developments in sensing technologies, AI-based analytics, autonomous exploration, and sustainable practices mark a significant paradigm shift in geophysics today. It will also explore the challenges faced and opportunities for the future of geophysical exploration, with insights on how such practices are evolving to meet the demands of the 21st century (Yijun, L et al.,2023). With the ever-expanding frontiers of geophysical exploration, incorporating novel technologies will be instrumental in unveiling discoveries and advancing the sustainable management of resources.

Classical Geophysical Surveying Techniques

We use different (Revuelta et al., 2017), known as Non-destructive geophysical exploration techniques. Seismic exploration, electromagnetic (EM) and electrical resistivity surveys, and gravity and magnetic surveys are traditional methods that have played a key role in exploring minerals, hydrocarbons, and groundwater. Though helpful, they have limited natively resolution,

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depth penetration, and data interpretation, so the development of technology for better accuracy and efficiency.

Seismic Exploration

Seismic exploration is extensively applied to hydrocarbon and mineral exploration and geotechnical and earthquake studies. It creates seismic waves from controlled sources (e.g., explosions or vibroseis (Arrowsmith, S. J et al.,2022) trucks), which travel through the subsurface and reflect or refract at geological boundaries. These returning waves are recorded by geophones or hydrophones, enabling geophysicists to produce images of the subsurface.

Seismic methods: Reflection seismology provides high-resolution imaging for oil and gas exploration, while refraction seismology is used in engineering and environmental studies. While accurate, this technology is expensive, environmentally intrusive, and requires sophisticated computational methods for data processing. As environmentally friendly alternatives, passive seismic techniques have been explored.

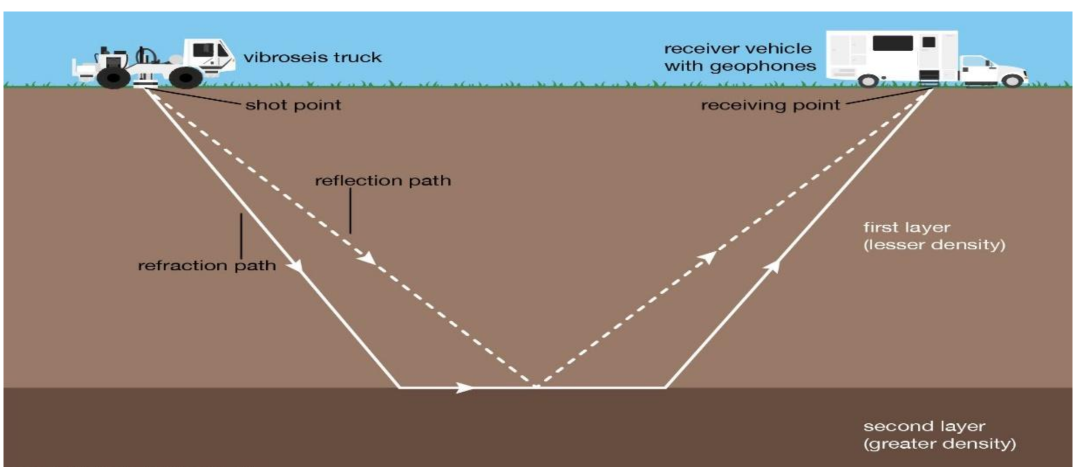

Figure 1: Seismic Exploration

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Figure 1 shows an example of a seismic survey technique used extensively for geological formation studies beneath the surface. Seismic waves are created when a vibroseis truck vibrates at a specific location or shot point. These waves then propagate in one of two directions: reflection or refraction. When we look at the reflection path, the seismic waves are reflected at the boundary of the first layer (less density) and the second layer (greater density) and then come back to the surface, which is detected by the receiver vehicle with geophones at the receiving point. Analyzing the time it takes for those waves to return allows the mapping of structures underground. Some waves head deeper into the second layer in the refraction path, causing an angle of refraction as their density changes, and they rise to the surface again. Geophysicists can infer subsurface formations' depth, composition, and structure by analyzing wave velocities and refraction angles. It is extensively applied to oil and gas exploration, geological mapping, and resource detection.

Electromagnetic (EM) and Electrical Resistivity Methods

Electromagnetic (EM) and electrical resistivity methods (Martinho E et al.,2023) measure subsurface conductivity variations and are helpful for groundwater detection, mineral exploration, and environmental studies. EM surveys propagate an electromagnetic field into the ground, resulting in secondary currents detected by receivers. These currents can be used to discern the presence of ore bodies or conductive materials such as groundwater, with their strength being directly related to the conductivity of the surrounding materials. Electrical resistivity surveys like Electrical Resistivity Tomography (ERT) (Kumari A. et al.,2021) use direct currents to establish differences in resistivity of multiple layers, making it possible to distinguish different types of rock and soil.

They are inexpensive, less invasive methods but have limited depth penetration and are extremely sensitive to ambient noise from the power grid or infrastructure. Progress in inversion algorithms and sensor technology have increasingly expanded their diagnostic capability.

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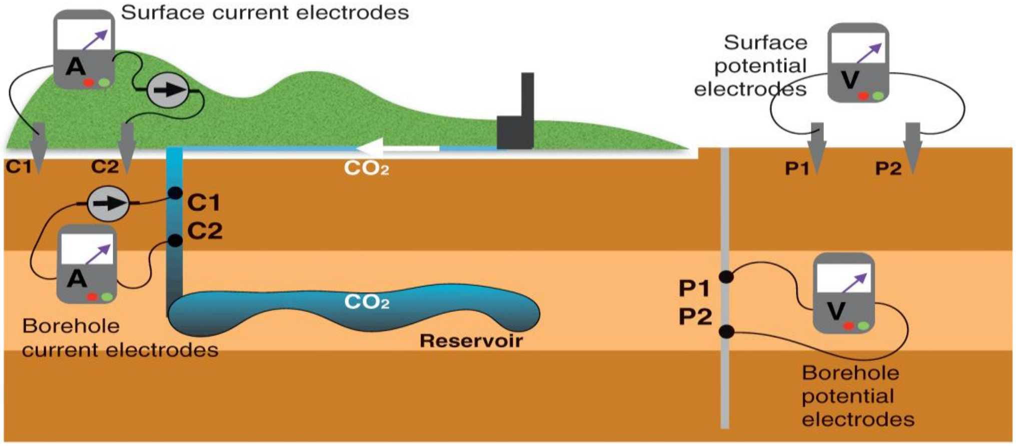

Fig 2: Electromagnetic (EM) and Electrical Resistivity Methods

Example 2: Electrical Resistivity or Self-Potential Geophysical Survey for Monitoring CO_2 Injection into Subsurface Reservoir (Figure 2) The configuration involves surface and borehole current electrodes (C1 and C2) injecting electrical current to the ground. Surface and borehole potential electrodes (P1 and P2) also measure voltage differences induced by the injected current. The blue area is a subsurface CO_2 reservoir, which might be for a geological storage or enhanced oil recovery (EOR) process. Geophysicists can also monitor CO_2 migration and underground fluid movement through analysis of electrical resistivity changes. This method has applications in environmental monitoring, groundwater studies, and carbon capture and storage (CCS) applications, as the combination of surface and borehole measurements gives a more complimentary subsurface picture.

Gravity and Magnetic Surveys

Passive geophysical methods include gravity and magnetic surveys, which detect density and magnetic variations in the subsurface (Reynolds, 2011 Refs M). Gravity: It is used with gravimeters to survey density changes (Shettell, N. et al.,2021) of the earth in order to identify dense ore bodies, salt domes, and geological structures, which are associated with hydrocarbons. The magnetic survey detects variations in the earth`s magnetic field, forming when igneous and metamorphic rock and mineral deposits containing metallic minerals such as magnetite are deposited. These techniques perform well during large-scale surveys but must be adjusted to account for environmental factors such as terrain and structures. Airborne and satellite-based

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survey techniques have seen rapid development in the modern era, with improving spatial resolution and coverage leading to their integration for regional geological mapping.

Geophysical exploration is changing the game with better performance on all accounts (Li, J et al.,2020). New technologies like artificial intelligence (AI), distributed acoustic sensing (DAS), quantum sensors, unmanned aerial vehicles (UAVs), full-waveform inversion (FWI), and satellite-based remote sensing are revolutionizing the acquisition and analysis of subsurface data. Registered users will be directed to an external site. These innovations help reduce environmental impact and operational costs while enhancing resource exploration.

Machine Learning (ML) and Artificial Intelligence (AI)

AI and ML are automating geophysical data interpretation and speeding up and improving anomaly detection accuracy in seismic, gravity, and electromagnetic data. ML models utilize extensive datasets to predict mineral and hydrocarbon deposits, minimizing dependence on manual interpretation. Seismic Imaging and Fault Identification: Deep learning methods (like CNNs (Convolution Neural Networks) (Abdel-Baset A. et al.,2024) improve the quality of seismic images and help detect faults, thus making exploration more efficient and cost-effective.

Distributed acoustic sensing (DAS)

DAS uses fiber optic cables as dense arrays of seismic sensors, enabling continuous, real-time monitoring of seismic activity, oil reservoirs, and structural integrity. For instance, Chen P et al.2023 highlighted this technology being adopted for statewide pipeline monitoring, hydrocarbon exploration, and earthquake detection, demonstrating a cost-effective high-resolution collection of x-line seismic data across large areas without using traditional geophones.

The use of quantum sensors for high-sensitivity measurements

Quantum gravimeters and quantum magnetometers enable us to measure eight orders of magnitude more sensitivity than classical gravimeters, a game-changer for oil and gas exploration.

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With extreme accuracy, these sensors detect minute changes in magnetic and gravitational fields (Liu, H et al., 2022), assisting in mineral exploration, groundwater detection, and fault zone delineation. Their survival in hostile environments makes them an excellent tool for geophysical applications.

Use of UAV in Geophysical Surveys

Drones or Unmanned Aerial Vehicles (UAVs) with geophysical sensors (Hussain, Y et al.,2022), such as magnetometers, LiDAR, and ground-penetrating radar (GPR), offer rapid and cost-effective data acquisition, particularly where remote or risky topography is concerned. They provide relatively low logistical hurdles and high-resolution aerial geophysical surveys to facilitate mineral exploration, environmental assessment (Usman M et al.,2024), and infrastructure evaluation.

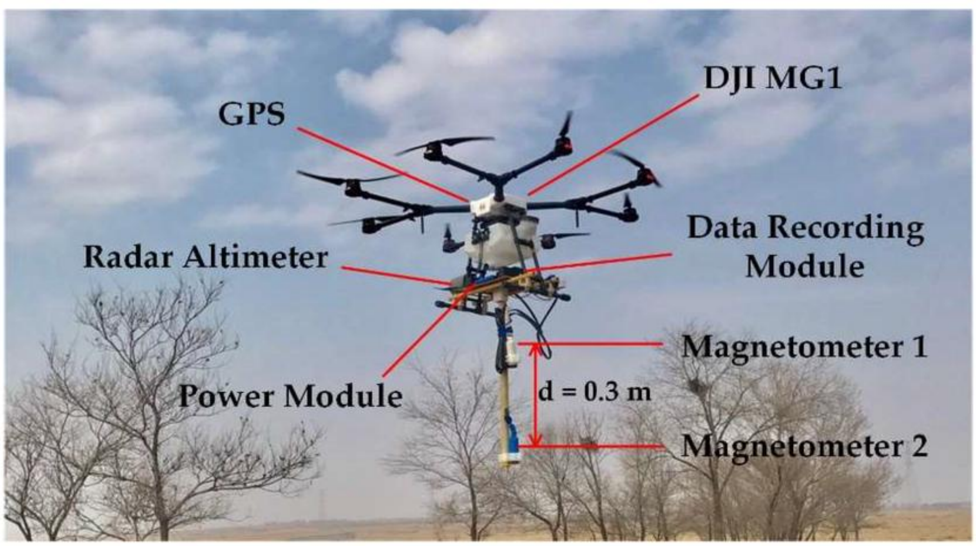

Figure 3: Unmanned Aerial Vehicles (UAVs) in Geophysical Surveys

Figure 3, DJI MG1 drone with scientific instruments for geophysical mapping. The drone also includes a GPS module for accurate positioning and a radar altimeter for measuring the elevation above ground. A power module provides power to the onboard sensors and instruments. Attached is a data recording module to store the collected geophysical data. Two magnetometers dangle 0.3 meters below the drone and are probably used to measure the Earth's magnetic field for geological

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or mineral exploration. This supports aerial magnetic surveys, which map underground geological structures, identify potential mineral deposits, and perform environmental studies. The mobility and the sensors allow this system to be easily used for remote sensing.

FWI — High-Resolution Imaging

Full Waveform Inversion (FWI) is a cutting-edge approach to seismic imaging that uses the complete wave field to construct high-resolution models of the subsurface (Huang, R et al.,2021). It does so more accurately than before, leading to better resolution in areas like the characterization of oil and gas reservoirs, geothermal exploration, and fault detection. Compared to conventional seismic inversion methods, FWI provides higher exploration precision for disposition with data-intensive properties.

Satellites for Remote Sensing

Satellite remote sensing techniques are capable of enabling the collection of geophysical data over large areas, relevant to the detection of minerals (Sikakwe, G. U et al.,2023), hydrocarbon searching, and environmental monitoring (synthetic aperture radar (SAR) and hyperspectral data). They enable the global mapping of resources and monitoring the environment and stimulate climate science, which is vital for modern geophysical exploration.

Novel Geophysics Technologies: Using them

While geophysical technologies have existed for decades, recent developments (Ofubu E et al., 2024) transform exploration and monitoring across sectors such as mineral and hydrocarbon exploration, groundwater management, and environmental monitoring. Such techniques have been applied in mineral and hydrocarbon exploration, geothermal energy assessment (Rohit, R. Vet al., 2023), environmental monitoring, infrastructure assessment, etc. Recent advances in reducing the environmental footprint and cost of data collection when using geophysical methods are among the newest technologies that have opened a new chapter in data acquisition principles in a multiplied form of power and capability, confirming one of the most successful techniques ever developed for Earth analysis.

Mining, Hydrocarbon Exploration and Exploitation

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Revolutionizing the global hunt for mineral and hydrocarbon resources are advanced geophysical technologies. AI-enabled data analysis further improves seismic imaging, allowing geoscientists to identify subsurface formations (Singh R. K et al.,2024). Drone-mounted magnetometer and hyperspectral sensor data enable fast, high spatial resolution mapping over large areas, thus significantly reducing exploration costs and the time to identify the site of potential economic interest. Quantum sensors enhance gravity and magnetic surveys for better ore body and petroleum reservoir identification (Kantsepolsky, B. et. al, 2023). In addition, real-time monitoring of hydrocarbon reservoirs with Distributed Acoustic Sensing (DAS) for optimized production strategies. These technologies can make exploration more effective while eliminating the need for invasive drilling.

Geothermal Energy Exploration

Geothermal energy (Memon, A.R et al. 2024) and emerging geophysical tools are essential for detecting potential geothermal reservoirs. In a seismic inversion, the resolution of an image is proportional to the number of input data. Full-waveform inversion (FWI) is a novel computational seismic processing method with two key features: FWI considerably improves the quality of seismic reflection images, and it also maps smeared sub-scale structural characteristics of geothermal reservoirs and allows for reservoir characterization via cross-correlating the subsurface heat flow and fault systems. Satellite remote sensing of various forms—specifically synthetic aperture radar (SAR)—has been widely used in mapping surface deformations associated with geothermal activity globally. Geochemistry26-based UAV surveys detect geothermal anomalies at locations with less human access and rugged terrain. They vowed to bring precision to exploration, lower the risks of projects, and help the world transition to renewable energy.

Environmental and Geohazard Monitoring

New geophysical technologies are key to evaluating environmental changes and monitoring geohazards like earthquakes, landslides, or aquifer contamination. DAS can also be used for earthquake detection and early warning by allowing real-time seismic monitoring (Zhu H. H et al., 2022). Geophysical anomalies based on AI metadata analysis allow potential hazards to be determined. At the same time, quantum sensors have been proven to provide ultimately sensitive gravity measures to discover underground cavities or unstable slopes. Real-time land subsidence, pollution dispersion, and climatic shifts (Bayomi N et al.,2023) monitoring is carried out using

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UAV and remote sensing-based satellites for timely intervention and avoidance of disasters. These innovations are key to safeguarding communities and ecosystems against environmental perils.

Urban Geophysics and Infrastructure

The importance of geophysical technologies in urban planning, infrastructure development, and structural health monitoring cannot be overstated, as there is growing concern about modern disasters and the consequences they bring. (Wen, C et al.,2024) DAS monitors underground pipelines and detects leaks or stress points before failures occur. One such technology is UAV-mounted sensors , which provide 3D mapping of utility pipes in GPR, thus enabling contractors to reduce the risk of excavation damages. Seismic imaging powered by AI assesses if bridges, tunnels, and dams remain stable over time. Remote sensing methods are also used to track urban subsidence and ground motion, avoiding potential damage to construction and transport networks. These technologies improve the resilience of urban systems and infrastructure sustainability.

Table 1: Applications of Emerging Geophysical Technologies

Technology	Application Areas
AI & ML	Seismic data interpretation, fault detection
UAVs	Aerial magnetic surveys, environmental monitoring
Distributed Acoustic Sensing (DAS)	Pipeline integrity monitoring, earthquake detection
Quantum Sensors	High-resolution gravity/magnetic field mapping
FWI (Full-Waveform Inversion)	Advanced subsurface imaging in oil & gas exploration
Satellite Remote Sensing	Large-scale mineral/hydrocarbon exploration

Table 1 Emerging geophysical technologies and their use cases. 1. Lowering Costs and Automating the Interpretation of Seismic Data: AI and ML automate the interpretation of seismic data, creating a faster discovery of faults while increasing accuracy. As UAVs are inexpensive surveying tools, they are good options for mineral exploration surveys and environmental monitoring. Through MINECRAFT, LGB in DAS, quantum sensors, FWI, and satellite remote sensing, enabling high-resolution imaging, real-time monitoring, and large-scale resource characterizations, ultimately through advanced data acquisition, making geophysical exploration come true.

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Launch and Prospect of New Generation

While these emerging geophysical technologies have yielded significant advancements in subsurface exploration when employed in diverse implementations within the geophysical community, numerous impediments remain to broader adoption. Issues surrounding data, expenses, environment, and the need for further study all pose obstacles that require innovative solutions. However, tackling these problems will ultimately allow geophysical exploration to move in a direction that is accurate, cost-effective, and sustainable (Mensah, V et al., 2024).

Table 2: Comparison of Traditional vs. Emerging Geophysical Methods

Parameter	Traditional Methods (Seismic, EM, Gravity)	Emerging Methods (AI, UAVs, Quantum Sensors)
Resolution	Moderate to high	Very high due to AI-driven analytics
Operational Cost	High	Reduced due to automation & UAVs
Environmental Impact	Can be intrusive	Lower impact (passive methods, UAVs)
Data Processing Speed	Slower, manual interpretation	Fast, AI-enhanced real-time processing
Depth Penetration	Varies (seismic: deep, EM: shallow)	Quantum sensors enable deeper scans

As shown in Table 2, classical geophysical methods such as seismic, electromagnetic (EM), and gravity surveys typically deliver moderate to high resolution. In contrast, innovative technologies, including AI, UAVs, and quantum sensors, can achieve dramatically higher resolution using sophisticated data analytics. Traditional methods are expensive and disruptive to the environment, but through automated methods, UAV-based surveys have reduced costs and the impact on the environment. Traditional data processing is manually intensive and slow; AI-driven analysis allows for real-time, high-speed interpretation. Furthermore, although traditional methods have different penetration depths, they become less effective the deeper any subsurface component exists, while quantum sensors enable more profound and more accurate subsurface detection.

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Integration and Interpretation

Managing and integrating big data collected from various sources is one of the most foreboding challenges in contemporary geophysics (Yu, S et al.,2021). New tools for solving this are courtesy of the latest technologies, including artificial intelligence (AI), quantum sensors, and satellite remote sensing. These produce large volumes of data amenable to processing by high-performance computing and advanced algorithms. For example, consistent data fusion among multiple datasets (seismic, electromagnetic, gravity, and remote sensing) is complex and needs improvement. Besides, AI models require thorough training on vast amounts of quality data to spec with low error rates and guarantees concerning their interpretations. Given this, we may need either innovating machine learning algorithms or cloud-based high throughput computing platforms to handle multi-source geophysical data in real-time for the future of geophysical exploration (Saremi et al., 2024).

Cost, Technological Barriers

Despite their many advantages (Banso, A. A. et al. 2023), many cutting-edge geophysical technologies are still expensive to develop, deploy, and maintain. Quantum sensors, for instance, need calibration down to the quantum level and expensive materials, making them less likely to be used broadly. Likewise, the long-term costs of operating powerful AI models and high-performance computing infrastructures can be prohibitive. Though UAV-based surveys are more cost-effective in specific instances, the survey still requires specialized equipment and well-trained personnel. This leads to several hurdles, specifically concerning geophysical exploration, as most developed countries are already at the forefront regarding technological advancements.

In contrast, many developing countries are still not yet in the race for such sophisticated machinery. As these technologies continue to develop and save on costs with miniaturization, automation, and open-access geophysical data platforms (McKinney et al., 2023), worldwide implementations become more accessible. They could shortly mitigate global consequences (Mehan et al., 2023).

Environmental and Ethical Considerations

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Geophysical exploration with earth-friendly and sustainable practices Manufacturers of traditional geophysical methods — seismic surveys that use explosives or vibroseis trucks — have been criticized for impacting the environment, particularly in sensitive ecosystems and marine environments. Although airborne surveys based on passive seismic methods and UAV (Javan, F. D et al.,2024) have been introduced to limit environmental disturbances, these approaches still incur other challenges. The ethics of using AI to enhance decision-making, maintain data privacy during large-scale remote sensing, and manage the ecological consequences of resource extraction must be addressed for future exploration endeavors. As technology advances, regulations and guidance must also develop to provide a framework for sustainable and responsible geophysical exploration.

Future Research Directions

The future of geophysical exploration lies in conducting real-time monitoring, transitioning toward fully integrated AI, exploring a multi-physics approach, and moving toward AI-driven methodologies. However, that research is now working to develop quantum-enhanced geophysical instruments, improve AI-based predictive modeling, and expand satellite-based geophysics—all at a much larger scale. Integrated systems for real-time geophysical data acquisition leveraging DAS and UAV-based surveys will become more widely adopted, significantly reducing exploration costs with more accurate data. Moreover, interdisciplinary strategies merging geophysics with geochemistry, hydrology, and environmental science (Alao, J et al., 2024) will further enhance our ability to monitor and responsibly manage Earth's subsurface resources. As more research and studies are conducted, geophysicists are responsible for innovating technology with careful consideration of the ethics of technology and geophysics to ethical and environmental sustainability.

Conclusion

Data science and machine learning advancements have transformed geophysical exploration, enhancing subsurface investigation methods' precision, effectiveness, and sustainability. Although traditional techniques like seismic, EM, and gravity surveys have yielded valuable geological information, new technologies are transforming the discipline. Automated data analysis powered by AI and ML can improve anomaly detection and predictive modeling. DAS converts fiber optic infrastructure into highly dense arrays of seismic sensors for real-time monitoring of geophysical activity. Ultra-sensitive gravity and magnetic measurements have recently been developed through quantum sensors, and UAV-based geophysical surveys address limited data acquisition in remote and hazardous environments. FWI provides unique seismic imaging that, combined with satellite-based remote sensing, enables geophysical exploration at a worldwide level. These are particularly important in mineral and hydrocarbon exploration, geothermal energy potential and risk assessment, environmental hazards monitoring, and urban infrastructure evaluation. Nonetheless, issues remain, such as more precise data integration, high technology costs, and sustainability of the environment. Until then, we can expect future geophysical research to optimize AI-driven modeling, automate operations to reduce costs and find more environmentally friendly exploration methods. The future of natural resources exploration will rely heavily on innovative methods that must be developed as the exploration industry grows. AI, quantum sensing, UAVs, and real-time data processing will all impact the future of geophysics and ensure the efficient and sustainable management of the resources of the 21st century.

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