Advances in Geo-Energy Research

Vol. 18, No. 1, p. 1-6, 2025

Perspective

Repurposing deep closed mines as seismic forecasting research platforms

Peng Li[1], Chenyu Tang[1], Yatao Li[1,2]*, Yuezheng Zhang[1], Mostafa Gorjian[3], Meifeng Cai[1]*

[1]*Key Laboratory of Ministry of Education for Efficient Mining and Safety of Metal Mines, University of Science and Technology Beijing, Beijing 100083, P. R. China*

[2]*Department of Civil and Earth Resources Engineering, Kyoto University, Kyoto 615-8530, Japan*

[3]*Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, BC V6T 1Z4, Canada*

Keywords:
Deep closed mines
seismic forecasting
earthquake prediction
multi-physics monitoring
underground space reuse

Cited as:
Li, P., Tang, C., Li, Y., Zhang, Y., Gorjian, M., Cai, M. Repurposing deep closed mines as seismic forecasting research platforms. Advances in Geo-Energy Research, 2025, 18(1): 1-6.
https://doi.org/10.46690/ager.2025.10.01

Abstract:
Seismic forecasting remains constrained by surface noise and low spatial resolution, limiting reproducible predictions. Although deep borehole stations and underground laboratories improve conditions, they face high costs, sparse coverage, and narrow disciplinary scope. In this work, the strategic reuse of deep closed mines as seismic forecasting laboratories was evaluated. Closed mines, abundant and deep with extensive tunnels and reusable infrastructure, provide ideal low-noise, near-source environments for scalable observation networks. They can lower construction costs, enable simultaneous monitoring of natural and induced earthquakes, and support comparative studies of source mechanisms and forecasting methods. Key challenges include processing massive data volumes, integrating multi-source information, and ensuring equipment reliability in harsh environments. Future directions emphasize building three-dimensional, multi-physics monitoring networks, advancing interdisciplinary and international collaboration, and developing an integrated "observation–warning–prevention" platform. Repurposing closed mines not only expands underground space utilization but also offers a potential paradigm shift in seismic monitoring, providing a novel pathway to overcome longstanding forecasting bottlenecks.

1. Introduction

Seismic events are natural processes in which rocks in the earth crust or mantle fracture and fault movements release energy, typically occurring at depths ranging from several km to tens of km beneath the surface. Due to the inaccessibility of the earth interior, current technological methods are insufficient to directly observe the seismic processes at the source. Consequently, reliance is placed on indirect signals observed at the surface or shallow depths. However, these signals inevitably undergo attenuation and are subject to noise interference during transmission, significantly diminishing their reliability and interpretability. As a result, seismic forecasting has long been considered the long-standing goal of earth sciences, with the primary challenge being the weak and complex nature of precursory signals (Mastella et al., 2022). These signals may manifest as crustal deformations, electromagnetic anomalies, or changes in seismic wave characteristics, yet they are often extremely subtle and influenced by a multitude of coupled physical and chemical effects, making them difficult to consistently capture and identify with current techniques (Freund et al., 2021; Gusman et al., 2025; Milliner et al., 2025). As shown in Figs. 1 and 2, the dilatancy diffusion model predicts a variety of precursory phenomena and a scaling between precursor duration and earthquake magnitude. While this represents an important theoretical advance, its practical

*Corresponding author.
E-mail address: pengli@ustb.edu.cn (P. Li); tangchenyu0423@163.com (C. Tang); liyatao@ustb.edu.cn (Y. Li); zhangyuezheng@ustb.edu.cn (Y. Zhang); mgorjian@eoas.ubc.ca (M. Gorjian); caimeifeng@ustb.edu.cn (M. Cai).

Received August 16, 2025; revised August 29, 2025; accepted September 7, 2025; available online September 10, 2025.

Yandy Scientific Press

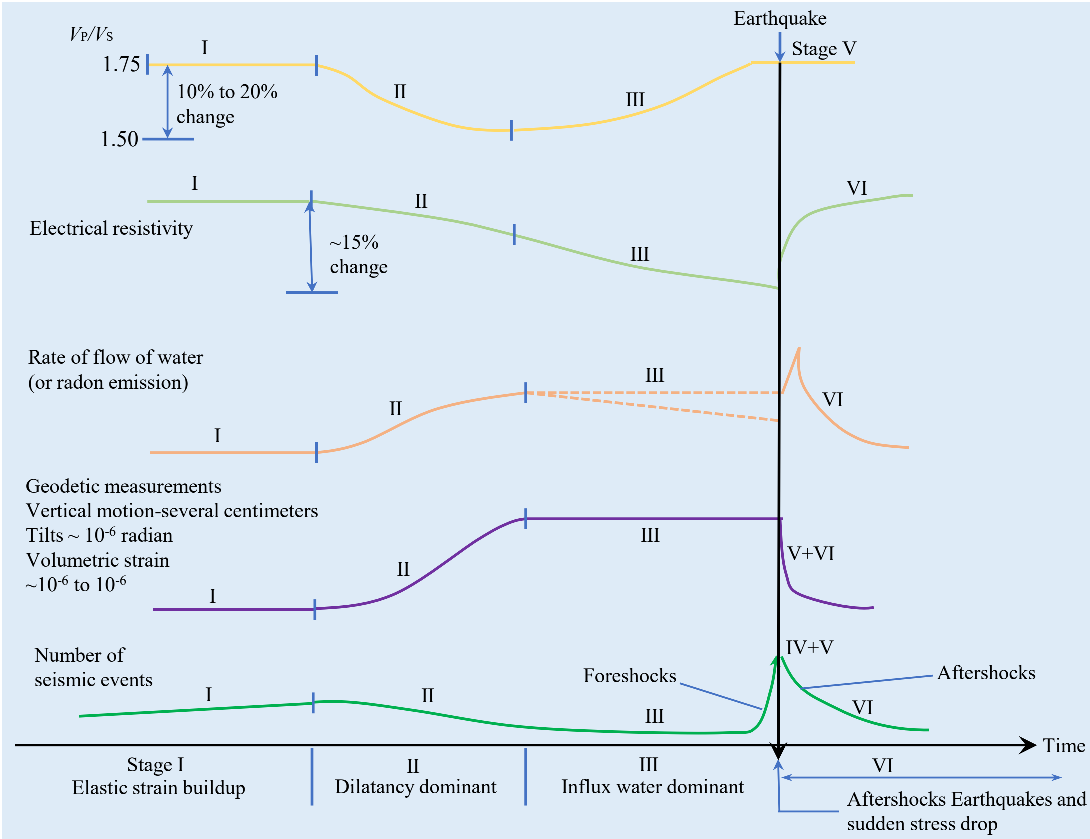

Fig. 1. Various precursory phenomena predicted by the dilatancy diffusion model (after Scholz et al. (1973)).

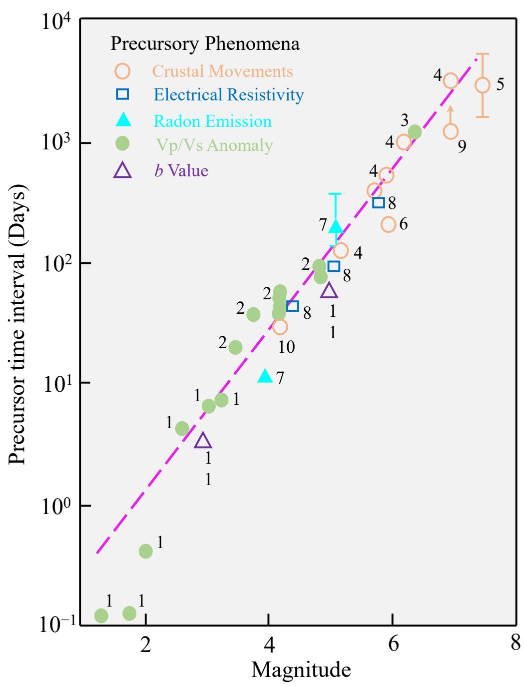

Fig. 2. An empirical relation between precursor time and earthquake magnitude (after Scholz et al. (1973)).

use remains constrained by high noise levels and the enormous data requirements.

Fundamentally, the difficulty of seismic forecasting stems from the conflict between "insufficient human understanding of deep earth dynamics" and "the inherent complexity of seismic systems". As such, current research has largely shifted focus towards seismic hazard assessment and early warning systems rather than achieving precise predictions. While advancements in deep earth exploration, big data, and artificial intelligence offer the potential to gradually overcome some of these technological barriers, the reliable identification of precursory signals remains a substantial challenge.

Meanwhile, the deep subsurface environment is increasingly recognized by researchers as a critical breakthrough for improving forecasting accuracy due to its advantages, such as low noise, high stability, and proximity to seismic sources. International efforts have explored deep borehole observatories and underground experimental sites. For example, the km scale deep borehole station near the active fault of the Kii Peninsula in Japan, and deep experimental sites in Europe, have demonstrated an improvement in observational accuracy by 1–2 orders of magnitude. However, these efforts face common challenges: first, the construction and maintenance costs are prohibitively high, leading to limited deployment and sparse distribution; second, most experimental sites focus on single-disciplinary monitoring, lacking coupled observations of stress, seismic waves, fluid, and electromagnetic fields, which hinders a comprehensive understanding of the complex seismic source processes and their evolution.

In this context, the potential value of closed mines as deep observation sites becomes increasingly evident. Globally, the number of closed mines exceeds one million, with 12,000 such mines in China (Foulger et al., 2018 ; He et al., 2023; Ma et al., 2024; Zhang et al., 2025), of which approximately 60% are coal mines and 40% are metal and non-metal mines. With the ongoing energy restructuring and capacity reduction policies, it is projected that by 2030, the number of closed mines in China will reach 15,000, with more than 60% located at depths ranging from 100 to 800 m, and some extending beyond 800 m, even reaching 1,200 m. Of particular significance is the high spatial overlap between closed mines and seismic activity zones. For instance, the Huainan and Huaibei mining areas in Anhui Province are located near the Tanlu Fault Zone, which has historically experienced multiple strong earthquakes of *Mw* 6.0 or higher; the mining areas of Datong and Yangquan in Shanxi Province are situated within the Fenwei Earthquake belt, a major seismic zone in North China; the Southwest seismic zone, located within the Mediterranean-Himalayan tectonic belt, is the largest and most seismically active region in China, having experienced significant earthquakes such as the 1950 *Mw* 8.5 earthquake in Tibet, the 2008 *Mw* 8.0 Wenchuan earthquake, and the 2014 *Mw* 6.5 Ludian earthquake. The spatial overlap of closed mines with high-magnitude seismic belts provides a unique opportunity for near-source deep seismic observation.

In conclusion, the long-standing challenges in seismic forecasting arise from the limitations of surface-based observations and the complexity of deep earth processes. Existing deep borehole and experimental site approaches still fall short in terms of scalability and multi-physics coupling. In stark contrast, deep closed mines offer numerous advantages, including their large numbers, suitable depths, strong spatial connectivity, and reusable infrastructure, yet they have long been underutilized. This oversight has resulted in the wasted potential of valuable underground space and hindered the development of low-noise, near-source, and scalable observation systems. By strategically repurposing deep closed mines into seismic forecasting research laboratories, not only could observational conditions be significantly improved, but this approach could also pave the way for novel technical pathways to overcome the bottlenecks in seismic forecasting.

2. Deep mine closure transformed for seismic forecasting

2.1 Deep subsurface environment merits

The precursory signals released during the seismic generation process are typically very weak, requiring high-sensitivity and high-precision observational equipment to detect these signals. However, strong background noise from urban development and industrial activities often severely interferes with observational results, masking potential seismic anomalies. For example, during the *Mw* 7.2 Kobe earthquake in Japan in 1995, despite the establishment of a well-developed seismic observation network, the mixed high noise levels in the urban environment made it difficult to effectively identify weak precursor signals. Such cases highlight the inherent limitations of surface-based observations in terms of signal-to-noise ratio.

In contrast, the deep subsurface environment offers a natural "noise shield", significantly reducing the impact of surface disturbances and providing a low-noise operational environment for high-precision instruments. In recent years, researchers both domestically and internationally have gradually extended seismic observation stations into deeper subsurface spaces. For example, Japan has established a deep borehole observation system at a depth of approximately 1,020 m near the active fault of the Kii Peninsula, which has demonstrated an improvement in observational accuracy by 1–2 orders of magnitude compared to surface measurements. Similarly, studies at the -848 m deep test site in Huainan region, China, show that the noise level in the deep subsurface environment is reduced by about two orders of magnitude compared to surface observations. Furthermore, the deep subsurface environment is minimally affected by climatic and seasonal fluctuations, with relatively stable temperature, humidity, and pressure conditions. This significantly reduces instrument drift and environmental noise interference, thereby extending the lifespan of the equipment and ensuring long-term, stable, and continuous observational records.

Moreover, deep subsurface observations not only mitigate environmental noise but also offer a geometric advantage by being in close proximity to potential seismic source regions, enabling near-source monitoring. For example, in the Tanlu fault zone, the tunnels of the Longkou coal mine in Shandong Province are located just 3–5 km from the main fault, providing a unique opportunity for setting up near-fault observations. Through long-term monitoring in the deep subsurface environment, in-situ multi-physics data can be obtained from locations closer to the seismic source region, including key parameters such as stress, strain, seismic wave characteristics, and fluid evolution. This not only overcomes the depth limitations of traditional surface-based monitoring but also contributes to a deeper understanding of the dynamic evolution of the seismic source region, providing scientific insights for advancing the study of seismic source mechanisms and forecasting methods.

2.2 Benefits of repurposing closed mines

The existing tunnel networks in closed mines provide unique conditions for the construction of seismic monitoring systems. These spatial corridors not only significantly reduce the construction difficulty and economic costs associated with deploying deep subsurface monitoring instruments but also enable efficient coverage of the mine's space. At the same time, the mine's original power supply and communication infrastructure often still possess substantial potential for reuse, allowing for the rapid establishment of data acquisition and transmission networks, thus greatly shortening the deployment timeline of the observation system. With the ongoing advancements in artificial intelligence, big data analytics, and sensor technologies, the repurposing of closed mines is now underpinned by solid technological support, laying the foundation for the integrated reuse of underground space and the development of a three-dimensional deep seismic monitoring network.

Additionally, deep closed mines offer a unique opportunity for the simultaneous observation and comparative study of

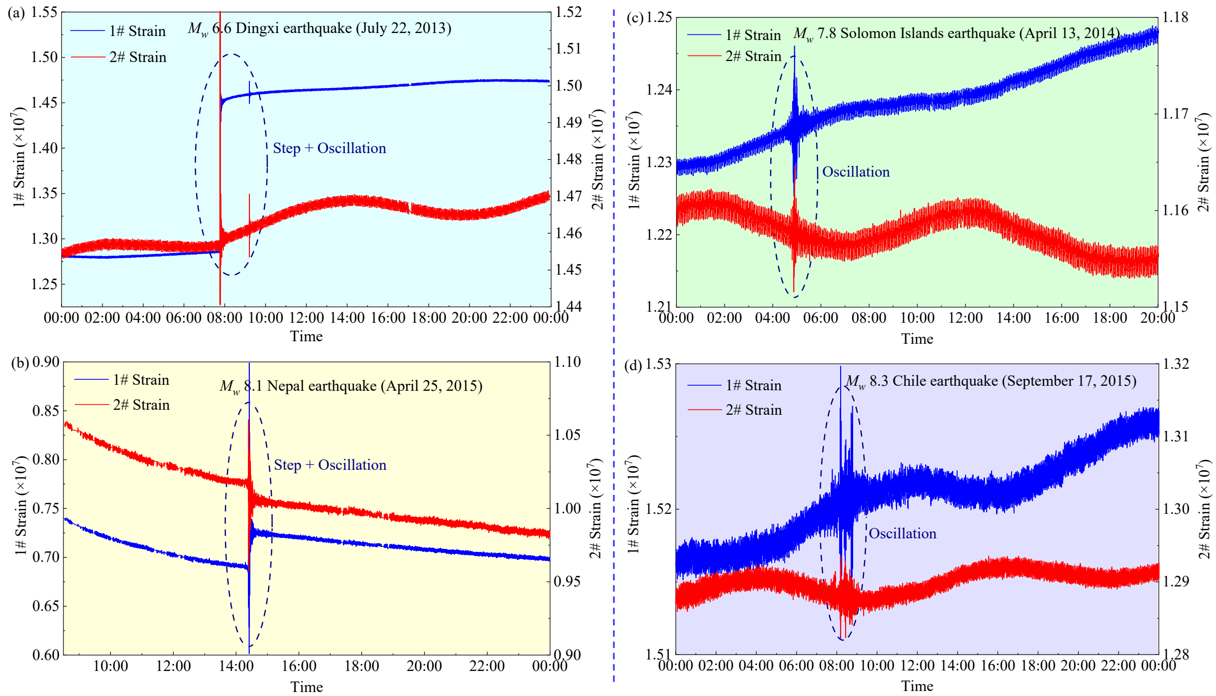

Fig. 3. Coseismic responses (step + oscillation) induced by nearby and distant natural earthquakes observed using a high-precision four-component borehole strain monitoring system at the Huating coal field in Gansu Province, China: (a) *Mw* 6.6 Dingxi earthquake, (b) *Mw* 8.1 Nepal earthquake, (c) *Mw* 7.8 Solomon Islands earthquake and (d) *Mw* 8.3 Chile earthquake.

natural and induced earthquakes. While these two types of earthquakes differ in origin, both are fundamentally driven by the long-term accumulation of elastic energy and the gradual evolution of stress and strain. Studies on the Lao Hutai coal mine in Fushun, Liaoning, have shown that the occurrence of induced earthquakes is not only related to mining activities but is also closely linked to regional geological structure and the stress field distribution. Hence, recording both natural and induced seismic events within the mine and analyzing their source mechanisms, waveform characteristics, and spatiotemporal distribution differences will not only help clarify the seismic occurrence patterns but also provide solid data support for the development of innovative seismic forecasting theories and methods.

Empirical observations at the Huating coal field in Gansu Province, China, further validate this potential. The high-precision four-component borehole strain monitoring system deployed at this mining area successfully tracked coal pressure-induced seismic activities while also capturing strain responses from both near-source and distant natural earthquakes. The monitoring results indicate that the *Mw* 6.6 Dingxi earthquake and the *Mw* 8.1 Nepal earthquake exhibited typical characteristics of strain steps and oscillations, while more distant events, such as the *Mw* 7.8 Solomon Islands earthquake and the *Mw* 8.3 Chile earthquake, primarily showed oscillatory responses Fig. 3. These observations suggest that long-term monitoring within the mine not only enables the differentiation of regional strain features across various seismic source processes but also provides insights into the dynamic evolution of seismic triggering mechanisms and their precursor information.

To sum up, transforming deep closed mines into seismic forecasting research laboratories not only maximizes their reuse value in engineering construction and infrastructure but also provides unprecedented experimental conditions for the systematic comparative study of natural and induced earthquakes (Xiong et al., 2022; Li et al., 2025). This strategic transformation is expected to advance the fundamental research in earth sciences and open new research directions to address the long-standing challenges in seismic forecasting that have long plagued humanity.

3. Major challenges

Although deep closed mines offer significant advantages for seismic forecasting research, their transformation into research laboratories still faces numerous challenges. The primary issue lies in the efficient processing of massive amounts of data and the extraction of precursory information. Deep mine monitoring often relies on high-density sensor arrays, with each device capable of generating tens of kilobytes of raw data per second. If the monitoring network consists of hundreds of devices, the annual data volume can easily exceed the petabyte scale, far surpassing the data volume of traditional surface-based networks. This magnitude not only places extreme demands on data transmission cables and storage media but also presents significant challenges to real-time processing capabilities and storage architecture. More complex is the fact that seismic monitoring data exhibit strong temporal dependencies and contextual relevance, meaning that isolated data points often lack independent significance. As a result, once the monitoring system is initiated, it must maintain a high level of continuity and integrity; any interruptions could lead to the loss of precursory information. Additionally, over long-term operation, issues such as data loss and inconsistent formats may arise, further complicating the management and utilization of the data.

Furthermore, the complexity of the deep mine environment means that a single sensor is insufficient to fully characterize the seismic generation process. Precursory signals often manifest as coupled effects from multiple physical fields, requiring the integration of multi-source data such as seismic waves, stress-strain measurements, fluid pressure, and electromagnetic radiation. Achieving efficient integration and coordination among different types of sensors, ensuring consistency in both spatial-temporal resolution and physical coherence, is a complex system engineering challenge. In addition, as the density of the monitoring network and the variety of equipment increase, issues related to system interoperability, real-time performance, and fault tolerance emerge as critical technical bottlenecks that must be addressed.

Finally, the reliability of equipment operation and maintenance cannot be overlooked. Deep mines typically present extreme conditions, such as high pressure, high humidity, and high temperature, which can lead to significant wear on sensors and communication systems, making maintenance difficult and costly. This necessitates that monitoring equipment not only possess high environmental adaptability and long-term stability but also incorporate self-diagnosis and fault-tolerant capabilities to minimize the need for manual intervention.

In summary, the transformation of deep closed mines into seismic forecasting research laboratories must overcome three core challenges: first, the development of an efficient information processing platform capable of supporting petabyte-scale data transmission and storage; second, the advancement of multi-source data fusion and intelligent analysis techniques to achieve integrated recognition across multiple physical fields; and third, the design of specialized monitoring equipment with high reliability and autonomous operation capabilities. Only with the dual support of engineering and information technology can the deep closed mine observation system fully realize its strategic value in seismic forecasting research.

4. Future development directions

The unique value of deep closed mines in seismic forecasting research lies not only in their low-noise environment and proximity to seismic sources but also in their ability to capture comprehensive data from both natural and induced earthquakes. Existing studies have shown that both types of earthquakes exhibit components of a double-couple source and follow a similar scale invariance relationship between seismic moment and stress drop. This similarity provides a crucial opportunity for seismic research: by using high-precision monitoring of “small-scale” induced earthquakes as a “window” for observing natural earthquakes, we can deepen our understanding of the source’s generation, rupture, and energy release processes, thus providing new perspectives for breakthroughs in future seismic forecasting theories and methods (Kaushal et al., 2025). Future development can proceed along the following three strategic directions:

(1) Construction of a three-dimensional, multi-physics integrated observation network. Leveraging the existing tunnels and shafts in closed mines, high-density sensor arrays should be deployed across different horizontal layers and vertical shafts, combined with emerging technologies such as distributed acoustic sensing to construct a three-dimensional monitoring network covering fault zones. Simultaneously, various data types, including seismic waves, stress-strain measurements, fluid pressure, and electromagnetic anomalies, should be integrated for synchronized multi-physics monitoring. Using deep learning and intelligent algorithms, the vast microseismic data can be analyzed for feature extraction and pattern recognition, allowing the identification of abnormal signals related to rock mass fracture and seismic source processes. By coupling deep mine data with surface Global Positioning System and Interferometric Synthetic Aperture Radar remote sensing information, a “deep-to-surface” linked seismic precursor model can gradually be established.

(2) Interdisciplinary integration and engineering collaborative innovation. The repurposing of deep closed mines involves multiple disciplines, including geophysics, geology, mining engineering, materials science, and computer science, necessitating the creation of an interdisciplinary collaborative research platform. The “deep earth space development + smart construction” model, as exemplified by the Yunlong Lake Laboratory, can be adopted, integrating seismic monitoring with carbon sequestration, geothermal development, and other deep earth engineering practices, to form a “monitoring-energy storage-warning” integrated platform. This model will not only enhance the effectiveness of seismic observation systems but also promote the integrated use of underground space, contributing to energy transition and sustainable development.

(3) International cooperation and the establishment of a global monitoring alliance. Seismic activity has a trans-regional characteristic, and the observation network of a single country often cannot provide comprehensive coverage. Drawing on the international cooperation experience from Switzerland’s Grimsel Test Site, a cross-border monitoring alliance can be established to facilitate data and technology sharing. For example, China can collaborate with countries along the Pacific Ring of Fire under the “Belt and Road” initiative, deploying joint monitoring systems in areas where closed mines are distributed, thus building a cross-regional collaborative seismic observation and early warning network.

The ultimate goal is to establish an accurate and efficient seismic early warning and emergency response system based on three-dimensional monitoring of deep closed mines and international cooperation, minimizing earthquake disaster risks. Through continuous technological evolution and interdisciplinary integration, deep closed mines are expected to become a strategic platform to break through seismic forecasting bottlenecks, providing solid support for both earth science research and global disaster reduction efforts.

5. Conclusions

Repurposing closed deep mines as seismic forecasting facilities provides three distinct advantages: low noise levels, proximity to seismic sources, and reusable infrastructure that enables rapid network deployment. Such sites facilitate the recording of both natural and induced seismic events, providing critical data for advancing source physics understanding and forecasting techniques. However, the major challenges include managing petabyte-scale data streams, integrating multi-physics observations, and ensuring long-term equipment reliability under extreme conditions such as high pressure, humidity, and temperature. Addressing these issues depends on developing three-dimensional integrated monitoring systems, fostering interdisciplinary collaboration (particularly toward integrated monitoring, energy storage, and early warning capabilities) and establishing international partnerships to enable cross-regional data and technology exchange. Overall, the adaptive reuse of closed mines presents a transformative opportunity for post-mining regions and could emerge as a critical catalyst for progress in seismic forecasting research, thereby contributing a new scientific pathway to global disaster mitigation efforts.

Acknowledgements

This work was financially supported by the the National Natural Science Foundation of China (Nos. 52474091 and 52504076).

Conflict of interest

The authors declare no conflicts of interest.

References

Bantidi, T. M., Nishimura, T., Ishibe, T., et al. Variability of ETAS parameters and their relationship with physical processes for earthquake forecasting in Africa. Earth, Planets, and Space, 2025, 77: 29.

Foulger, G. R., Wilson, M. P., Gluyas, J. G., et al. Global review of human-induced earthquakes. Earth-Science Reviews, 2018, 178: 438-514.

Freund, F., Ouillon, G., Scoville, J., et al. Earthquake precursors in the light of peroxy defects theory: Critical review of systematic observations. The European Physical Journal Special Topics, 2021, 230: 7-46.

Gusman, A. R., Tanioka, Y. Atmospheric lamb wave inversion from the 2022 Hunga Tonga–Hunga Ha'apai eruption for tsunami prediction. Geoscience Letters, 2025, 12: 32.

He, M. C., Cheng, T., Qiao, Y. F., et al. A review of rockburst: Experiments, theories, and simulations. Journal of Rock Mechanics and Geotechnical Engineering, 2023, 15(5): 1312-1353.

Kaushal, A., Gupta, A. K., Sehgal, V. K. Earthquake prediction optimization using deep learning hybrid RNN-LSTM model for seismicity analysis. Soil Dynamics and Earthquake Engineering, 2025, 195: 109432.

Li, Y. Spatial distribution of strain energy changes due to mining-induced fault coseismic slip: Insights from a rockburst at the yuejin coal mine, China. Rock Mechanics and Rock Engineering, 2025, 58: 1693-1706.

Ma, R., Gao, J., Guan, C., et al. Coal mine closure substantially increases terrestrial water storage in China. Communications Earth & Environment, 2024, 5: 418.

Mastella, G., Corbi, F., Bedford, J., et al. Forecasting surface velocity fields associated with laboratory seismic cycles using deep learning. Geophysical Research Letters, 2022, 49: e2022GL099632.

Milliner, C., Avouac, J. P., Dolan, J. F., et al. Localization of inelastic strain with fault maturity and effects on earthquake characteristics. Nature Geoscience, 2025, 18: 793-800.

Scholz, C. H., Sykes, L. R., Aggarwal, Y. P. Earthquake prediction: A physical basis. Science, 1973, 181(4102): 803-810.

Xiong, W., Chen, W., Wang, D., et al. Coseismic slip and early afterslip of the 2021 Mw 7.4 Maduo, China earthquake constrained by GPS and InSAR data. Tectonophysics, 2022, 840: 229558.

Zhang, V. Embodying industrial transitions: Melancholy loss, interrupted habit and transitional memory after the end of a coal mine. Transactions of the Institute of British Geographers, 2025, 50: e12672.