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Editorial

Advanced Technology and Data Analysis of Monitoring Observations in Seismology

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Over more than a century of systematic observational seismology, the instrumental capabilities to detect, record, and analyze elastic waves and other physical variables associated with the source, medium, and recording site of earthquakes have evolved substantially. In fact, during the last two decades, technologies have frequently emerged to facilitate real-time monitoring processes or to complement early warning systems. Several emerging and cutting-edge technologies are being explored and implemented for monitoring seismicity and volcanic activity. Some of the leading technologies for monitoring these natural phenomena include:

- Fiber Optic Sensors: Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS) using fiber optic cables are increasingly being utilized for seismic monitoring. These sensors can detect ground motion and temperature changes along the entire length of the cable, providing evolutive and high-resolution data [1–3].
- Magnetotelluric deployments (MT): Time-frequency MT techniques can be integrated into permanent monitoring systems. Surficial or even at depths near earthquake or volcanic sources, changes in electrical resistivity may serve to identify transient or precursor signals [4–6]. Including MT data in a comprehensive monitoring system can improve the accuracy of early warnings. An appropriate example of this approach is being developed by the Geophysical Network of the National University of Colombia (RGUNAL), where complementing MT analysis with light gases suggests the migration of fluids and possible gradients in pore pressure in the phase before earthquakes and/or volcanic eruptions (Figure 1).
- Quantum Sensors: Quantum gravimeters and quantum magnetometers can enhance our ability to detect subtle changes in the Earth's gravitational and magnetic fields associated with seismic activity and bulk changes in magmatic and hydrothermal systems [7–9].
- Satellite-based Radar Interferometry (InSAR): InSAR measures ground deformation caused by seismic and volcanic activity. It involves comparing radar images of the same area at different times to detect even small ground movements. Improving the resolution could provide more detailed deformation during the evolution of a region's seismic or volcanic cycle [10–12].
- GNSS (Global Navigation Satellite System): GNSS technology, including GPS, monitors crustal movements. It helps track the slow buildup of tectonic stress that can lead to earthquakes and volcanic eruptions [13–15].
- Drone Technology: Drones with various sensors, including LiDAR and photogrammetry, can quickly assess earthquake or volcanic evolution and damage in hard-to-reach or dangerous areas, aiding disaster response and recovery efforts [16–18].
- Low-Cost Seismic Sensors: Miniaturized and low-cost seismic sensors are being developed, making deploying large sensor networks in earthquake-prone or active volcanic regions easier. These sensors can be used for early warning systems and volcano–tectonic research [19–21].

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- Next-Generation Seismometers: Advancements in seismometer technology continue to improve the sensitivity and accuracy of ground motion detection, enabling better earthquake characterization [22–24].

In addition, data analysis for these purposes is improving rapidly. Some of the most representative approaches for evaluating advanced technologies in seismic and volcanic monitoring are covering some of these topics:

- Machine Learning and AI: Advanced machine learning and artificial intelligence techniques are employed to process and analyze vast amounts of seismic data. These technologies can identify patterns, predict seismic events, and enhance early warning systems [25–27].
- Advanced Data Visualization: Data visualization tools, including virtual reality (VR) and augmented reality (AR), create immersive experiences for researchers and emergency responders, allowing them to explore seismic data in three dimensions [28–30].
- Crowdsourced Data: Mobile apps and citizen science initiatives enable seismic data collection from smartphones. These crowdsourced data streams can supplement traditional monitoring networks and provide real-time information [31–33].
- Real-time Data Streaming: High-speed, real-time data streaming and cloud computing are essential for quickly processing and analyzing seismic data, facilitating rapid earthquake alerts and early warning systems [34–36].
- Blockchain for Data Security: Blockchain technology is being explored to ensure seismic data security and integrity, especially in critical applications such as early warning systems [37–39].

When integrated and combined, these technologies offer a comprehensive approach to seismic monitoring, enabling better earthquake forecasting, early warning, and post-event assessment. Some of these technologies may vary depending on the region's seismic or volcanic activity and the available resources.

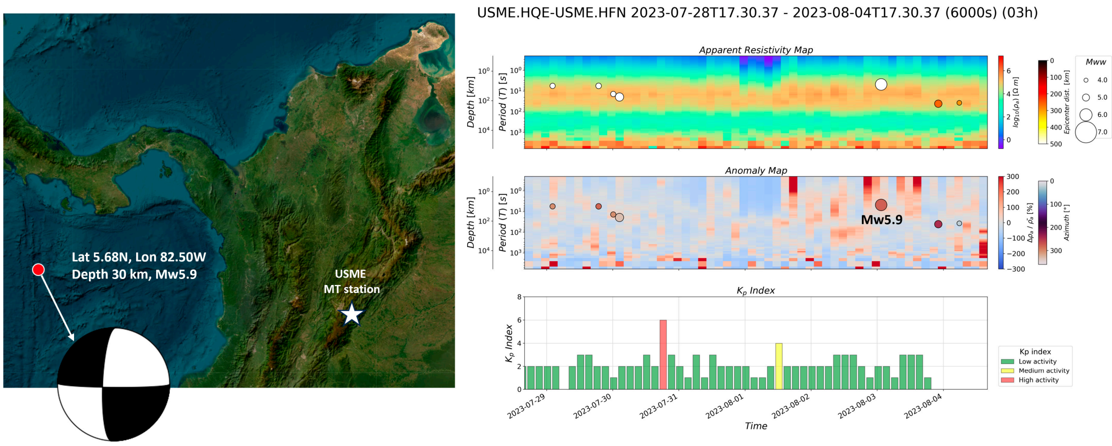

Figure 1. Time–frequency record of apparent resistivity calculated at the USME station of the Geophysical Network of the National University of Colombia. On the left is the location map of the Mw5.9 earthquake that occurred on 28 August 2023, in the Panama Fracture Zone (as suggested by the focal mechanism), which has been linked to apparent resistivity anomalies generated by fluid mobility under pore pressure gradients from the seismic source. On the right, the temporal variation in apparent resistivity with the location of the earthquakes at depth is observed (upper panel). The middle panel represents the resistivity anomaly for the average at each depth. The lower panel shows the variations in the Kp solar index, ruling out possible anomalies induced by solar activity. The hypocentral solution has been provided by the USGS [40].

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References

1. Sun, Q.; Zhang, H.; Huang, S.; You, Z. Distributed Fiber Optic Sensing for Seismic Monitoring: A Comprehensive Review. *Sensors* **2020**, *20*, 3753.
2. Lindsey, N.J.; Chalari, A.; Martin, E.R.; Lindsey, C.G. Distributed Acoustic Sensing (DAS) of Microseismicity at Brady Hot Springs, Nevada: Quantifying Fiber-Optic Cable Attributes for Seismic Monitoring. *Geophysics* **2019**, *84*, 1–23.
3. Wada, T.; Ide, S.; Shiomi, K. Real-time monitoring of microseismicity using a dense array of fiber optic cables. *Geophys. Res. Lett.* **2018**, *45*, 2255–2262.
4. Vargas, C.A.; Caneva, A.; Solano, J.M.; Gulisano, A.M.; Villalobos, J. Evidencing Fluid Migration of the Crust during the Seismic Swarm by Using 1D Magnetotelluric Monitoring. *Appl. Sci.* **2023**, *13*, 2683. [CrossRef]
5. Vargas, C.A.; Gomez, J.S.; Gome, J.J.; Solano, J.M.; Caneva, A. Space–Time Variations of the Apparent Resistivity Associated with Seismic Activity by Using 1D-Magnetotelluric (MT) Data in the Central Part of Colombia (South America). *Appl. Sci.* **2023**, *13*, 1737. [CrossRef]
6. Yohannes, L.D.; Heinson, G.; Thiel, S.; Krieger, L. Magnetotelluric monitoring of permeability enhancement at enhanced geothermal system project. *Geothermics* **2017**, *66*, 23–38. [CrossRef]
7. Giovannetti, V.; Lloyd, S.; Maccone, L. Quantum-enhanced measurements: Beating the standard quantum limit. *Science* **2004**, *306*, 1330–1336. [CrossRef]
8. Kasevich, M.A.; Chu, S. Measurement of the gravitational acceleration of an atom with a light-pulse atom interferometer. *Appl. Phys. Lett.* **1991**, *69*, 2259–2261. [CrossRef]
9. Ménoret, V.; Vermeulen, P.; Le Moigne, N.; Bonvalot, S.; Bouyer, P.; Landragin, A.; Desruelle, B. Gravity measurements below 10−9g with a transportable absolute quantum gravimeter. *Sci Rep* **2018**, *8*, 12300. [CrossRef]
10. Fielding, E.J.; Winberry, J.P. Synthetic Aperture Radar Interferometry. *Annu. Rev. Earth Planet. Sci.* **2020**, *48*, 419–447.
11. Berardino, P.; Fornaro, G.; Lanari, R.; Sansosti, E. A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Trans. Geosci. Remote Sens.* **2002**, *40*, 2375–2383. [CrossRef]
12. Zebker, H.A.; Villasenor, J. Decorrelation in interferometric radar echoes. *IEEE Trans. Geosci. Remote Sens.* **1992**, *30*, 950–959. [CrossRef]
13. Blewitt, G.; Kreemer, C. *Harnessing the GPS Data Explosion for Interdisciplinary Science*; Eos, Transactions American Geophysical Union: Washington, DC, USA, 2016; Volume 97.
14. Bock, Y.; Melgar, D.; Crowell, B.W. Real-time strong-motion Broadband GPS: Network-based monitoring of co-seismic deformation. *Seismol. Res. Lett.* **2011**, *82*, 383–394.
15. Fialko, Y.; Simons, M.; Agnew, D.C. The complete (3-D) surface displacement field in the epicentral area of the 1999 Mw 7.1 Hector Mine earthquake, California, from space geodetic observations. *Geophys. Res. Lett.* **2001**, *28*, 3063–3066. [CrossRef]
16. Shiro, B.; Deitchman, R.S. *Unmanned Aerial Systems for Volcano Observations*; Eos, Transactions American Geophysical Union: Washington, DC, USA, 2019; Volume 100.
17. Kerle, N.; Nex, F.; Gerke, M.; Vosselman, G. Guest Editorial: UAV-based remote sensing for applications in geology: Introduction to the Special Issue. *Int. J. Appl. Earth Obs. Geoinf.* **2017**, *60*, 1–4.
18. Lin, G.; Raskin, G. *The Contribution of UAVs to Earthquake Disaster Management*; Eos, Transactions American Geophysical Union: Washington, DC, USA, 2018; Volume 99.
19. Lindsey, E.O.; Lindsey, C.G. Low-Cost Seismometers: Advances and Opportunities. *Seismol. Res. Lett.* **2021**, *92*, 3255–3263.
20. Haas, J.S.; Henrys, S.; Horleston, A.; Beavan, J. Citizen Seismology for Subduction Zone Monitoring: A Volunteer Network in New Zealand. *Seismol. Res. Lett.* **2019**, *90*, 367–378.
21. Shrivastava, A.; Mohanty, W.K. Design and Evaluation of a Low-Cost MEMS Seismometer for Earthquake Monitoring Applications. *IEEE Sens. J.* **2021**, *21*, 5700–5707.
22. Bensen, G.D.; Ritzwoller, M.H.; Barmin, M.P.; Levshin, A.L.; Lin, F.; Moschetti, M.P.; Shapiro, N.M.; Yang, Y. Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements. *Geophys. J. Int.* **2007**, *169*, 1239–1260. [CrossRef]
23. Lecointre, A.; Brenguier, F.; Shapiro, N.M.; Campillo, M. Surface wave array tomography in SE Tibet from ambient seismic noise and two-station analysis I. Phase velocity maps. *Geophys. J. Int.* **2012**, *190*, 173–187.
24. Yudistira, T.; Nakano, M.; Kundu, B.; Yamanaka, H.; Kim, Y.S. On the noise-reducing performance of a helical-like seismic noise sensor. *Sensors* **2016**, *16*, 974.
25. Yoon, C.E.; O'Reilly, O.J. Machine Learning in Earthquake Seismology: Recent Advances and Future Directions. *Rev. Geophys.* **2020**, *58*, e2019RG000672.

26. Ross, Z.E.; Yue, Y.; Meier, M.A.; Hauksson, E.; Heaton, T.H. PhaseNet: A Deep-Neural-Network-Based Seismic Phase Picker for Local, Regional, and Teleseismic Data. *Seismol. Res. Lett.* **2018**, *89*, 2080–2090.
27. Wang, D.; Chen, J.; Wang, W.; Wu, W.; Wu, F. A Deep Learning Approach for Seismic Signal Detection. *Geophys. J. Int.* **2019**, *218*, 1265–1280.
28. Djamel, B.; Afonso, C.; Navas-Traver, I. A framework for immersive geospatial visualization using virtual reality devices. *ISPRS J. Photogramm. Remote Sens.* **2015**, *105*, 38–49.
29. Hu, H.; Qian, Y.; Lu, Y.; Zhang, J. A novel framework for 3D visualization of geological structure based on virtual reality. *Comput. Geosci.* **2019**, *124*, 104–115.
30. Liu, Z.; Luo, L.; Shi, X.; Wu, W. Virtual Reality-based Visualization and Exploration of Geospatial Data. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 411.
31. Böse, M.; Dannemann, F.; Husen, S.; Tilmann, F. MyShake: A smartphone seismic network for earthquake early warning and beyond. *Sci. Adv.* **2015**, *1*, e1501055.
32. Allen, R.M.; Cochran, E.S. *Seismic Network Transforms Earthquake Detection*; Eos, Transactions American Geophysical Union: Washington, DC, USA, 2011; Volume 92, pp. 277–278.
33. Kong, Q.; Allen, R.M.; Schreier, L.; Kwon, Y.W. MyShake Early Warning Smartphone App. *IASPEI Newsl.* **2019**, *57*, 37–40.
34. Newman, A.V.; Dixon, T.H.; Ofoegbu, G.; Dixon, J.E. Geodetic and seismic constraints on some seismogenic and non-seismogenic processes associated with the 2001 Bhuj earthquake. *Bull. Seismol. Soc. Am.* **2006**, *96*, 1910–1927.
35. Uchida, N.; Matsubara, M.; Ellsworth, W.L. Rapid fault-type discrimination using real-time GPS and seismic data: The 2018 Palu, Sulawesi earthquake case study. *Geophys. Res. Lett.* **2019**, *46*, 1921–1928.
36. Geng, J.; Ding, J.; Yin, X. A real-time dynamic GPS deformation monitoring system for landslides. *Landslides* **2018**, *15*, 1213–1225.
37. Fan, K.; Ren, Y.; Li, H.; Yang, Y.; Yang, Z. Blockchain-based secure firmware update for Internet of Things devices. *IEEE Trans. Ind. Inform.* **2018**, *15*, 410–418.
38. Zheng, Z.; Xie, S.; Dai, H.N.; Chen, X.; Wang, H. An overview of blockchain technology: Architecture, consensus, and future trends. In Proceedings of the 2017 IEEE International Congress on Big Data (BigData Congress), Honolulu, HI, USA, 25–30 June 2017; pp. 557–564.
39. Kalra, A.; Goel, S. Bitcoin: A comprehensive survey. *IEEE Trans. Emerg. Top. Comput.* **2017**, *6*, 384–402.
40. USGS Search Earthquake Catalog. Available online: https://earthquake.usgs.gov/earthquakes/search/ (accessed on 19 September 2023).