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EDITORIAL

New perspectives and applications of gas geochemistry

Ching-Chou Fu[1] · Heiko Woith[2] · Guodong Zheng[3] · Giovanni Martinelli[3,4]

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Introduction

Gases and geofluids continuously migrate through the Earth, connecting reservoirs and processes from the mantle and deep crust to the hydrosphere, atmosphere, and biosphere. Their chemical compositions, isotopic signatures, concentrations, and fluxes are controlled by their sources as well as by fluid–rock interactions, phase separation, mixing, biological activity, and transport through permeable geological structures. Consequently, gases provide sensitive tracers of geological processes that are otherwise difficult to observe directly.

Gas geochemistry has developed substantially during the past five decades, supported particularly by advances in mass spectrometry, isotope-ratio measurements, field sampling, continuous monitoring, and numerical modelling. The analyses of major gas species such as CO_2, CH_4, N_2, H_2, and H_2S, together with stable isotopes and noble gases, have provided important constraints on volatile sources and migration in volcanic and hydrothermal systems, active faults, sedimentary basins, and other geological environments. More recently, high-frequency observations, improved gas-flux measurements, laboratory simulations, and integration with geophysical and hydrological datasets have extended gas geochemistry from source characterization toward the investigation of dynamic Earth processes.

The Collection "New Perspectives and Applications of Gas Geochemistry" was conceived to highlight these developments and the increasingly interdisciplinary applications of gas-geochemical approaches. Its original scope encompassed gases in volcanic and hydrothermal environments, tectonically and seismically active areas, hydrocarbon reservoirs, minerals, and rocks, biogeochemical systems, geological storage environments, and environmental settings. The twelve contributions assembled in this Collection illustrate this breadth, spanning processes from gas generation at molecular and reservoir scales to crustal volatile migration, surface degassing, environmental impacts, and geohazard monitoring.

The papers can broadly be grouped into five interconnected themes: (1) volcanic and hydrothermal gas geochemistry and monitoring; (2) tectonic degassing and fault-controlled volatile migration; (3) earthquake–fluid interactions; (4) gas generation and hydrocarbon evolution; and (5) gases as archives of past environmental conditions. Together, they illustrate how chemical and isotopic analyses, flux measurements, continuous observations, experiments, and numerical modelling can be combined to understand the origin, transport, evolution, and consequences of gases in the Earth system.

Volcanic and hydrothermal gas geochemistry and monitoring

Volcanic and hydrothermal systems represent natural pathways through which deep volatiles are transferred toward the surface. Gas compositions, isotopic signatures, and emission rates can, therefore, provide information on magma degassing, hydrothermal circulation, and changes within subsurface magmatic systems. Three contributions to this Collection address these processes from complementary perspectives, ranging from source characterization and continuous monitoring to numerical hazard assessment.

Hu et al. (2025) investigate CO_2, ^{222}Rn, and He degassing from the Julong and Jinjiang hydrothermal springs on the cone of Mt. Changbai. Although both systems show C–He isotopic signatures indicative of magmatic contributions, differences in gas concentrations and fluxes suggest connections to different parts of the magmatic–hydrothermal system. Excess ^{222}Rn at Julong Springs is attributed to a

✉ Ching-Chou Fu
ccfu@earth.sinica.edu.tw

1 Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan

2 GFZ Helmholtz Centre for Geosciences, Potsdam, Germany

3 School of Environmental Studies, China University of Geosciences, Wuhan, China

4 Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

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relatively shallow magma pocket, whereas magmatic CO_2 and He discharged from Jinjiang Springs are interpreted as being more closely connected to the main magma chamber. The authors propose that the two hydrothermal systems may therefore provide complementary information on magmatic processes occurring at different depths and emphasize the value of integrated gas observations for volcanic surveillance.

Moving from spatial characterization to temporal observation, Woith et al. (2026) present the first real-time fluid-monitoring network for CO_2-rich mineral waters and mofettes in the Eifel volcanic fields of Germany. Twelve stations established at CO_2 wells, mofettes, mineral springs, CO_2-rich soils, and a cold-water geyser record fluid parameter at temporal resolutions of up to 1 Hz. The multi-year observations allow environmental baseline variations to be distinguished from short-lived transients associated with rainfall, atmospheric-pressure disturbances, and earthquakes. Longer-term changes were also observed in potential magmatic indicators including helium isotope ratios, radon concentrations, and water temperature. The study demonstrates the importance of long-term, multi-parameter networks, and the joint interpretation of geochemical, meteorological, hydrogeological, geophysical, and geodetic observations.

Wang et al. (2025) extend volcanic gas studies from monitoring toward hazard assessment by modelling CO_2 dispersion at the Julong hot springs and Tianchi caldera lake of Changbaishan volcanic area. Using the DISGAS and TWODEE − 2 models, they evaluate how emission rate, topography, atmospheric conditions, and release duration influence near-surface CO_2 concentrations. The present-day emissions generally remain below hazardous levels, whereas enhanced degassing could result in potentially dangerous CO_2 accumulation, particularly in low-lying areas under stagnant atmospheric conditions. The study illustrates how gas-geochemical information can be incorporated into quantitative exposure assessment and provides a methodological basis for designing monitoring and warning strategies in volcanic tourist areas.

Tectonic degassing and fault-controlled volatile migration

Active faults and fracture systems can act as preferential pathways for gases originating in the mantle, crust, sedimentary sequences, or hydrothermal reservoirs. Spatial variations in gas flux and composition, therefore, provide information not only on volatile sources but also on crustal permeability and tectonic architecture.

Liu Y et al. (2026b) investigate hydrothermal and diffuse CO_2 emissions across the Sangri–Cona rift of the southern Tibetan Plateau using an integrated dataset of spring waters, bubbling gases, soil-gas fluxes, and carbon and helium isotopes. Their results indicate that deeply sourced CO_2 is mainly related to metamorphic decarbonation of crustal carbonaceous materials and migrates upward along active faults as dissolved inorganic carbon, bubbling gas, and diffuse soil emissions. A particularly important result is the dominance of diffuse soil degassing in the regional CO_2 budget. The study therefore shows that conspicuous hydrothermal discharges alone may provide an incomplete estimate of tectonic carbon release and highlights the importance of combining multiple pathways when evaluating volatile transfer from active continental crust.

Su et al. (2026) use a large spatial survey of soil-gas ^{222}Rn across the Miaodao Archipelago, North China, to investigate fault-controlled degassing and its relationship with regional tectonics. Measurements at 185 sites reveal pronounced radon anomalies associated with NE-, NW-, and nearly E–W-striking structures. Spatial analysis delineates fault systems linked to the Tancheng–Lujiang and Zhangjiakou–Penglai fault zones, while elevated radon release and offshore seismicity are interpreted in the context of crustal structures influenced by ongoing Pacific Plate subduction. The work demonstrates how systematic soil-gas surveys can contribute to the characterization of concealed or poorly exposed structures and provides an example of using gas emissions to investigate tectonic processes even within dormant volcanic regions.

These two studies illustrate the complementary roles of gas surveys in tectonic environments. Whereas quantitative CO_2 flux and isotope measurements constrain the magnitude and origin of deep carbon transfer, radon distributions provide a sensitive tracer of shallow fracture connectivity and fault-controlled migration. Their combination with structural and seismic information provides a means of linking surface gas emissions with deeper tectonic processes.

Earthquake–fluid interactions

The response of subsurface fluids to crustal deformation and earthquakes has long been an important application of geochemical monitoring. The changes in stress and pore pressure can modify fracture permeability, fluid mixing, water–rock interaction, and the transport of deeply sourced gases. At the same time, hydrological and meteorological processes can generate variations of similar magnitude, making long-term baseline characterization essential. Three contributions address these challenges in different tectonic and hydrogeological environments.

Fu et al. (2026) examine anomalous fluid emissions from the Chung-lun mud pool in southwestern Taiwan using continuous water-level records together with photographic

observations and regional geophysical information. Short-period fluctuations can largely be related to environmental forcing, whereas several longer-duration changes in water level and degassing behaviour cannot readily be explained by meteorological effects alone. The observations are interpreted in terms of subsurface pore-pressure perturbations and deep-fluid pressure transients migrating through a thrust fault and fracture network. Rather than requiring a direct one-to-one relationship between individual anomalies and earthquakes, the proposed model considers the mud pool as a near-surface window integrating deep fluid reservoirs, fault-controlled migration pathways, and shallow degassing processes.

Liu W et al. (2026a) investigate hydrogeochemical changes in five geothermal springs following the 2022 Ms 6.8 Luding earthquake along the Xianshuihe fault system in the eastern Tibetan Plateau. Most major ions and hydrogen and oxygen isotope compositions remained comparatively stable, suggesting that post-seismic changes mainly reflected processes within the aquifer rather than the introduction of isotopically distinct external waters. In contrast, changes in $\delta^{13}C$ of dissolved inorganic carbon indicate increased input of deep CO_2 associated with earthquake-related permeability changes and stress redistribution. Carbon mass-balance and radiocarbon constraints indicate that this deep CO_2 was predominantly derived from crustal metamorphic decarbonation. The results emphasize the sensitivity of carbon-isotope systematics to changes in deep-fluid migration within active fault systems.

Hu et al. (2026) investigate the hydrogeochemical and hydrogen–oxygen isotopic variations at seven hot springs in southern Yunnan. Their 1-year observations indicate that meteoric recharge and fault-controlled fluid mixing dominate spring chemistry, with limited seasonal influences. Quasi-synchronous δ^2H and $\delta^{18}O$ fluctuations were observed at four springs approximately three months before the 2024 Pu'er ML 5.0 earthquake, with statistically identified anomalies at two sites. Post-seismic geochemical responses were also recorded at three springs following the Ning'er ML 4.0 earthquake. These variations were attributed primarily to enhanced groundwater mixing rather than intensified water–rock interaction. The heterogeneous responses highlight the importance of local fault architecture and hydrogeological conditions, beyond earthquake magnitude and epicentral distance, in controlling geochemical sensitivity to seismic activity.

These studies highlight both the potential and challenges of geochemical monitoring in earthquake–fluid research. Reliable interpretation requires distinguishing seismic signals from environmental variability through baseline characterization and understanding of stress-driven fluid migration. Heterogeneous responses further emphasize the importance of local fault structures, hydrogeological connectivity, and appropriate indicators. Long-term, high-frequency, multi-parameter monitoring is therefore essential for identifying earthquake-related geochemical responses and understanding their underlying mechanisms.

Gas generation and hydrocarbon evolution

The chemical and isotopic characteristics of natural gases reflect not only migration and mixing but also the mechanisms by which gases are generated. Three contributions use experimental and modelling approaches to investigate radiolytic, abiogenic, and thermogenic pathways of gas formation.

Schimmelmann et al. (2026) investigate the radiolytic generation of CH_4 and CO_2 by exposing organic compounds with different molecular structures to α-, β-, and γ-radiation. Their results demonstrate a strong dependence of gas production on molecular structure and functional groups. Methane formation generally involves the production of methyl radicals followed by hydrogen acquisition, whereas oxygen-bearing and particularly carboxyl-bearing compounds favour CO_2 production. Amino acids show additional pathways associated with decarboxylation and deamination. These experiments demonstrate that natural radioactivity can contribute to gas formation at comparatively low temperatures and provide mechanistic constraints for recognizing radiolytic contributions to CH_4 and CO_2 in geological environments.

Zhao ZF et al. (2026a) investigate abiogenic hydrocarbon formation from formate through hydrothermal experiments using magnetite or olivine. Both experimental systems produce methane-dominated gaseous hydrocarbons through formate hydrogenation and methanation of decomposition products. The products show unusual molecular distributions, including enhanced C_4 hydrocarbons, together with systematic carbon- and hydrogen-isotope trends. These observations suggest possible C_2-unit coupling and kinetic isotope fractionation during hydrocarbon chain growth, although the authors appropriately note that the proposed C_2 coupling remains speculative. The experiments establish the feasibility of formate-driven hydrocarbon formation under hydrothermal conditions, while also emphasizing that quantitative extrapolation to lower-temperature natural systems requires caution.

Deng et al. (2026) address thermogenic hydrocarbon evolution in ultra-deep petroleum systems by combining closed-system gold-tube pyrolysis experiments with pressure–volume–temperature simulation for light oil from the Tarim Basin. Their results show progressive changes in phase behaviour during thermal cracking, with condensate and gas phases forming as intermediate products and the gas–oil ratio increasing with maturity. At sufficiently high maturity, the products evolve toward a single gas phase. The geological

comparison, however, indicates that the maturity of many light-oil reservoirs in the Tarim platform-basin remains below the complete-gasification threshold, helping explain their long-term preservation under ultra-deep conditions. The work demonstrates the value of integrating experimental gas generation with phase-equilibrium modelling when reconstructing the evolution of deep petroleum systems.

These studies demonstrate that superficially similar gas species may be generated through fundamentally different mechanisms. Molecular distributions and isotopic signatures therefore need to be interpreted within a framework that considers thermogenic reactions, water–rock processes, mineral catalysis, and natural radioactivity. The experimental gas geochemistry provides an essential basis for distinguishing these processes in natural systems.

Gases as archives of past environmental conditions

Gas geochemistry can also extend beyond modern dynamic processes by exploiting gases preserved within minerals as records of ancient environments.

Zhao Z et al. (2026b) examine primary fluid inclusions in Eocene–Oligocene gypsum from the Yehucheng Formation of the Lanzhou Basin. Petrographic and microthermometric observations are used to distinguish primary inclusions from material affected by dissolution–reprecipitation before gas compositions and carbon isotopes are interpreted. The primary inclusions contain CO_2, N_2, O_2, and Ar, with carbon isotopes indicating substantial microbial contributions to CO_2 and CH_4, whereas N_2, O_2, and Ar preserve an atmospheric component. After accounting for microbial influences, the authors reconstruct aspects of paleo-atmospheric composition and identify stratigraphic CO_2 variations corresponding to major late Eocene–early Oligocene climatic events.

This study expands the application of gas geochemistry from tracing active fluid systems to reconstructing paleoenvironmental conditions. It also illustrates the importance of petrographic screening and recognition of secondary alteration before interpreting gases preserved in mineral inclusions. The observed relationship between gypsum-hosted gas records and global climatic events suggests that carefully characterized evaporite inclusions may provide useful archives of atmospheric and climatic evolution.

Perspectives

The 12 contributions in this Collection illustrate how gas geochemistry is evolving from the measurement of gas concentrations and compositions toward a more integrated understanding of gas generation, sources, transport, fluxes, temporal variability, and geological consequences. This transition is particularly evident in studies combining gas chemistry and isotopes with flux measurements, hydrogeochemistry, structural geology, seismicity, meteorological observations, and numerical simulations. Rather than serving solely as indicators of gas provenance, geochemical and flux observations increasingly provide quantitative constraints on mass transport through permeable geological structures and their responses to geological processes.

A second important development is the growing emphasis on spatially and temporally resolved observations. Diffuse CO_2 measurements across active faults demonstrate that focused hydrothermal vents may represent only part of the total volatile output, while regional radon surveys reveal structures that may not be evident from surface geology alone. At the temporal scale, the Eifel, Chung-lun, Luding, and southern Yunnan studies demonstrate the importance of sustained monitoring and environmental characterization for distinguishing potential geological signals from rainfall, atmospheric pressure, groundwater recharge, and seasonal variability. Establishing site-specific baselines and identifying the environmental sensitivity of individual parameters are, therefore, essential for interpreting transient gas and fluid anomalies.

A third direction concerns the interpretation of gas origins and transformations. The experimental contributions demonstrate that CH_4 and other hydrocarbons can be generated through thermogenic cracking, mineral-catalyzed abiogenic reactions, and radiolytic processes. These processes may produce partially overlapping molecular or isotopic signatures, complicating the identification of individual gas sources. Subsequent mixing, oxidation, dissolution, fractionation, and fluid–rock interaction can further modify these signatures. Future source attribution will therefore increasingly require multi-species and multi-isotope approaches supported by laboratory experiments and quantitative models rather than reliance on individual geochemical indicators.

A related challenge is determining whether transient geochemical anomalies reflect changes in deep fluid supply or variations in subsurface transport and near-surface conditions. Similar variations in gas concentrations, isotopic compositions, and emission rates may arise from changes in permeability, fluid mixing, or environmental forcing. Distinguishing these processes requires integrated geochemical and geophysical observations, site-specific environmental corrections, and quantitative models of fluid migration.

Finally, the Collection demonstrates that gas geochemistry increasingly connects fundamental Earth science with societal and environmental applications. Volatile emissions provide information on mantle and crustal processes, active tectonics, earthquake–fluid interactions, deep carbon cycling, petroleum evolution, and ancient environments, while the same measurements can contribute to volcano

surveillance and gas-hazard assessment. Future advances in analytical sensitivity, autonomous sensors, high-frequency monitoring, experimental techniques, and integrated numerical modelling should further strengthen these connections. The studies presented in New Perspectives and Applications of Gas Geochemistry demonstrate that gases are not simply products accumulated in geological reservoirs or released at the Earth's surface; they are dynamic tracers of interactions among the deep Earth, crust, hydrosphere, atmosphere, and biosphere. We hope that this Collection will stimulate further interdisciplinary research and broaden the application of gas-geochemical approaches across the Earth and environmental sciences.

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