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Research article
Volcanology

Scientific response to the 2021–2022 seismic swarm in the Monts Dore volcanic province (France): dynamic insights from temporal surveys (2/2)

Guillaume Boudoire[*,a,b,c], **Lydie Gailler**[*,a,b], **Jean Battaglia**[*,a,b], **Aude Beauger**[d], **Martial Bontemps**[b], **Valérie Bosse**[a], **Vincent Breton**[e], **Danielle Briot**[a], **Philippe Cacault**[b], **Valérie Cayol**[a], **Nicolas Cluzel**[a], **Emmanuel Delage**[b], **Géraldine Del Campo**[b], **Catherine Deniel**[a], **Jean-Luc Devidal**[a], **Jean-Michel Douchain**[b], **Alexandre Faissal**[b], **Patrick Freville**[b], **Francesco Frondini**[f], **Pierre-Jean Gauthier**[a], **Nicola Genzano**[g], **Clément Grace**[a], **Fausto Grassa**[c], **Marc Grunberg**[h], **Yannick Guéhenneux**[b], **Lucia Gurioli**[a,b], **Andrew Harris**[a], **Philippe Labazuy**[a,b], **Didier Laporte**[a], **Manfredi Longo**[c], **Francesco Marchese**[i], **Gilles Mazet-Roux**[j], **Etienne Médard**[a], **Charley Merciecca**[a], **Marianne Métois**[k], **Nicola Pergola**[i], **Manon Pouget**[a], **Victoria Rafflin**[a,l], **Edouard Regis**[b], **Lisa Ricci**[f,m], **Andrea Luca Rizzo**[n,o], **Thierry Souriot**[a], **Luca Terray**[e], **Valerio Tramutoli**[p], **Cristina Trull-Hernandis**[q], **Benjamin van Wyk de Vries**[a], **Olivier Voldoire**[d] and **Erwan Thebault**[a,b]

[a] Université Clermont Auvergne, CNRS, IRD, OPGC, Laboratoire Magmas et Volcans, 6 avenue Blaise Pascal, 63178 Aubière, France

[b] Université Clermont Auvergne, CNRS, Observatoire de Physique du Globe de Clermont-Ferrand, 4 avenue Blaise Pascal, 63178 Aubière, France

[c] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Palermo, Italy

[d] Université Clermont Auvergne, CNRS, GEOLAB, F-63000 Clermont-Ferrand, France

[e] Université Clermont Auvergne, CNRS, LPC, F-63000 Clermont-Ferrand, France

[f] Department of Physics and Geology, University of Perugia, piazza Università, 06100 Perugia, Italy

[g] Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Via Ponzio 31, 20133 Milan, Italy

[h] EOST, UAR 830, Université de Strasbourg, CNRS, 5 rue René Descartes, 67084 Strasbourg Cedex, France

[i] National Research Council, Institute of Methodologies of Environmental Analysis, C.da S. Loja, Tito Scalo, Potenza 85050, Italy

[j] CEA, DAM, DIF, Arpajon, France

[k] Université Claude Bernard Lyon 1, CNRS, ENS de Lyon, Université Jean Monnet, LGL-TPE UMR5276, Villeurbanne, France

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[*] Corresponding authors

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[l] Department of Earth Sciences, Royal Holloway, University of London, Egham, TW20 0EX, UK

[m] Geosciences and Earth Resources (IGG) – National Research Council of Italy (CNR), 56124 Pisa, Italy

[n] Dipartimento di Scienze dell'Ambiente e della Terra, Università degli Studi di Milano-Bicocca, Piazza della Scienza 4, 20126 Milano, Italy

[o] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Milano, Italy

[p] School of Engineering, University of Basilicata, 85100 Potenza, Italy

[q] Universitat Politècnica de València, Instituto Universitario de Seguridad Industrial, Radiofisica y Medioambiental, Spain

Current address: Laboratoire Magmas et Volcans, Campus universitaire des Cézeaux, 6 Avenue Blaise Pascal, 63170 Aubière, France (G. Boudoire, L. Gailler, J. Battaglia)

E-mails: guillaume.boudoire@uca.fr (G. Boudoire), lydie.gailler@uca.fr (L. Gailler), jean.battaglia@uca.fr (J. Battaglia), aude.beauger@uca.fr (A. Beauger), martial.bontemps@uca.fr (M. Bontemps), valerie.bosse@uca.fr (V. Bosse), Vincent.BRETON@uca.fr (V. Breton), Danielle.BRIOT@uca.fr (D. Briot), Philippe.CACAULT@uca.fr (P. Cacault), valerie.cayol@uca.fr (V. Cayol), nicolas.cluzel@uca.fr (N. Cluzel), emmanuel.delage@uca.fr (E. Delage), g.delcampo@opgc.fr (G. Del Campo), Catherine.DENIEL@uca.fr (C. Deniel), j-luc.devidal@uca.fr (J.-L. Devidal), J-Michel.DOUCHAIN@uca.fr (J.-M. Douchain), A.Faissal@opgc.fr (A. Faissal), patrick.freville@uca.fr (P. Freville), francesco.frondini@unipg.it (F. Frondini), Pierre-Jean.GAUTHIER@uca.fr (P.-J. Gauthier), nicola.genzano@unibas.it (N. Genzano), Clement.GRACE@uca.fr (C. Grace), fausto.grassa@ingv.it (F. Grassa), marc.grunberg@unistra.fr (M. Grunberg), Yannick.GUEHENNEUX@uca.fr (Y. Guéhenneux), lucia.gurioli@uca.fr (L. Gurioli), Andrew.HARRIS@uca.fr (A. Harris), Philippe.LABAZUY@uca.fr (P. Labazuy), didier.laporte@uca.fr (D. Laporte), manfredi.longo@ingv.it (M. Longo), francesco.marchese@cnr.it (F. Marchese), Gilles.MAZET-ROUX@cea.fr (G. Mazet-Roux), etienne.medard@uca.fr (E. Médard), Charley.MERCIECCA@uca.fr (C. Merciecca), marianne.metois@univ-lyon1.fr (M. Métois), nicola.pergola@cnr.it (N. Pergola), Manon.POUGET@uca.fr (M. Pouget), victoria.rafflin@uca.fr (V. Rafflin), edouard.regis@uca.fr (E. Regis), lisa.ricci58@gmail.com (L. Ricci), andrealuca.rizzo@unimib.it (A. L. Rizzo), thierry.souriot@uca.fr (T. Souriot), luca.terray@uca.fr (L. Terray), valerio.tramutoli@unibas.it (V. Tramutoli), critruhe@upv.es (C. Trull-Hernandis), Ben.VANWYK@uca.fr (B. van Wyk de Vries), Olivier.VOLDOIRE@uca.fr (O. Voldoire), erwan.thebault@uca.fr (E. Thebault)

Abstract. During years 2021–2022, an unusual seismic swarm was recorded at crustal level beneath the Monts Dore volcanic province (France). Complementary field and remote measurements were performed. Together with the time series recorded on the seismological and GNSS national networks, these measurements were fundamental for monitoring the evolution of the seismic swarm and deciphering its origin. Although a potential vertical migration of the seismic events is suggested, the complementary measurements presumably discard the hypothesis of magma intrusion at shallow crustal level. The ascent of a CO_2-rich fluid originating from the mantle might instead have reacted with the hydrothermal system beneath the Monts-Dore since at least the summer 2021 leading to the reactivation of pre-existing tectonic structures with known associated seismicity. Feedback on the management of the 2021–2022 seismic swarm prompts for several recommendations that should be considered in future to better face and address at the national level the issues raised at long-dormant volcanic provinces in mainland France.

Keywords. Seismic swarms, Monitoring, Volcanic provinces, Risk mitigation, ECRS.

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1. Introduction

Seismic swarms are “localized surges of earthquakes, with no one shock being conspicuously larger than all other shocks of the swarm” (Govoni et al., 2013). They are often considered as a mechanical response to stress history of the geological structures where fluid-driven mechanisms (Hill, 1977; Miller, 2013) and/or fault-creep or slow-slip (Okutani and Ide, 2011; Roland and McGuire, 2009) mechanisms are involved. The question of seismic swarms trigger becomes even more critical when they occur in volcanic context. There, seismic swarms induced by dyke propagation or by the pressurization of magmatic reservoirs are frequent and may be precursors of potential subsequent volcanic eruptions (Acocella et al., 2024; Passarelli et al., 2018; Roman and Cashman, 2018). In long-dormant volcanic provinces, such as in the Monts Dore, monitoring networks can be sparse and generally not designed for local and multidisciplinary analyses. In such a context, detecting volcano-tectonic activity and deciphering its causes are challenging tasks. For such a reason, seismic swarms in long-dormant volcanic provinces are often a major source of concern for both scientists, authorities, and local population as recently evidenced in the West Halmahera (Indonesia) in 2015, in the Campi Flegrei (Italy) since 2005, or in Mayotte (France) in 2018 (Astort et al., 2024; Chiodini, Vandemeulebrouck, et al., 2015; Fallou et al., 2020; Passarelli et al., 2018).

The European Cenozoic Volcanic Province (ECVP) that accommodates the European Cenozoic Rift System (ECRS) extends from Spain, France, Germany, Czech Republic, to Poland over more than 1500 km (Martí et al., 2017; Merle and Michon, 2001). Related volcanism is mainly confined to four volcanic regions which are the Bohemian Massif, the Rhenish Massif, the French Massif Central, and the Valencia Trough (Martí et al., 2017; Ulrych et al., 2011) (Figure 1a). In the Bohemian Massif, the last known eruptive activity dates back to about 290,000 years (Ulrych et al., 2011) but a repeated occurrence of seismic swarms characterized the Novy Kostel focal zone. The hypocentres of these seismic swarms (6–15 km-depth) indicate a west-dipping fault plane 70–80° in accordance with regional tectonics (Bankwitz et al., 2003; Tanner et al., 2020). These seismic swarms are considered as a shallow response (fluid circulation and hydraulic fracturing) to the ascent of magma from the deeper lithospheric mantle reservoir (Bräuer, Kämpf, Koch, et al., 2011; Špičák et al., 1999). In the Rhenish Massif, the last eruption occurred about 11,000 years ago in the Eifel Volcanic Field. Seismic swarms were recently documented beneath the Laacher See volcano. They cluster along an 80° dipping line between 10 and 40 km-depth that suggested interactions between shear cracks and fluids potentially coming from magmatic reservoirs (Bräuer, Kämpf, Niedermann and Strauch, 2013; Hensch et al., 2019). In the French Massif Central, the last known eruption occurred about 7000 years ago (i.e., the most recent eruptive activity of the ECVP) at the Pavin maar-crater (Juvigné and Miallier, 2016). The volcanic edifice, now filled with a lake, is located at the southern extremity of an alignment of about 80 monogenetic volcanoes along a N–S orientation forming the Chaîne des Puys volcanic chain. Geographically, the eruptive site is set on the slope of the Monts Dore stratovolcano (last eruptive phase about 200,000 years ago) (Nomade et al., 2014) (Figure 1b,c). At the end of 2021, a seismic swarm started beneath the Monts Dore stratovolcano raising some concerns about the origin of this unusual seismicity (Figure 1d). The scientific response to this event provided on the field by the local scientific and technical staff of the Observatoire de Physique du Globe de Clermont-Ferrand (OPGC) and the Laboratoire Magmas et Volcans (LMV) in collaboration with the Bureau Central Sismologique Français–Réseau National de Surveillance Sismique (BCSF-RéNaSS https://renass.unistra.fr; https://doi.org/10.17616/R31NJNC4) allowed a detailed spatial characterization of the seismic swarm (Gailler et al., 2025). The seismic swarm clustered between 3 and 7 km-depth along two fault planes-oriented N173-85W and N13-68W in accordance with the regional tectonic setting (Figure 1e). Although the spatial definition of the seismic swarm and its link with the reactivation of pre-existing tectonic structures are now constrained, the origin of this reactivation is still subject of debate.

In this study, we evaluate the time series of monitoring records from both permanent and temporary networks and surveys in order to better decipher the processes involved in such a seismic activity beneath the most recent stratovolcano of the French Massif Central. In Section 2, we summarize the geological context of the Monts Dore volcanic

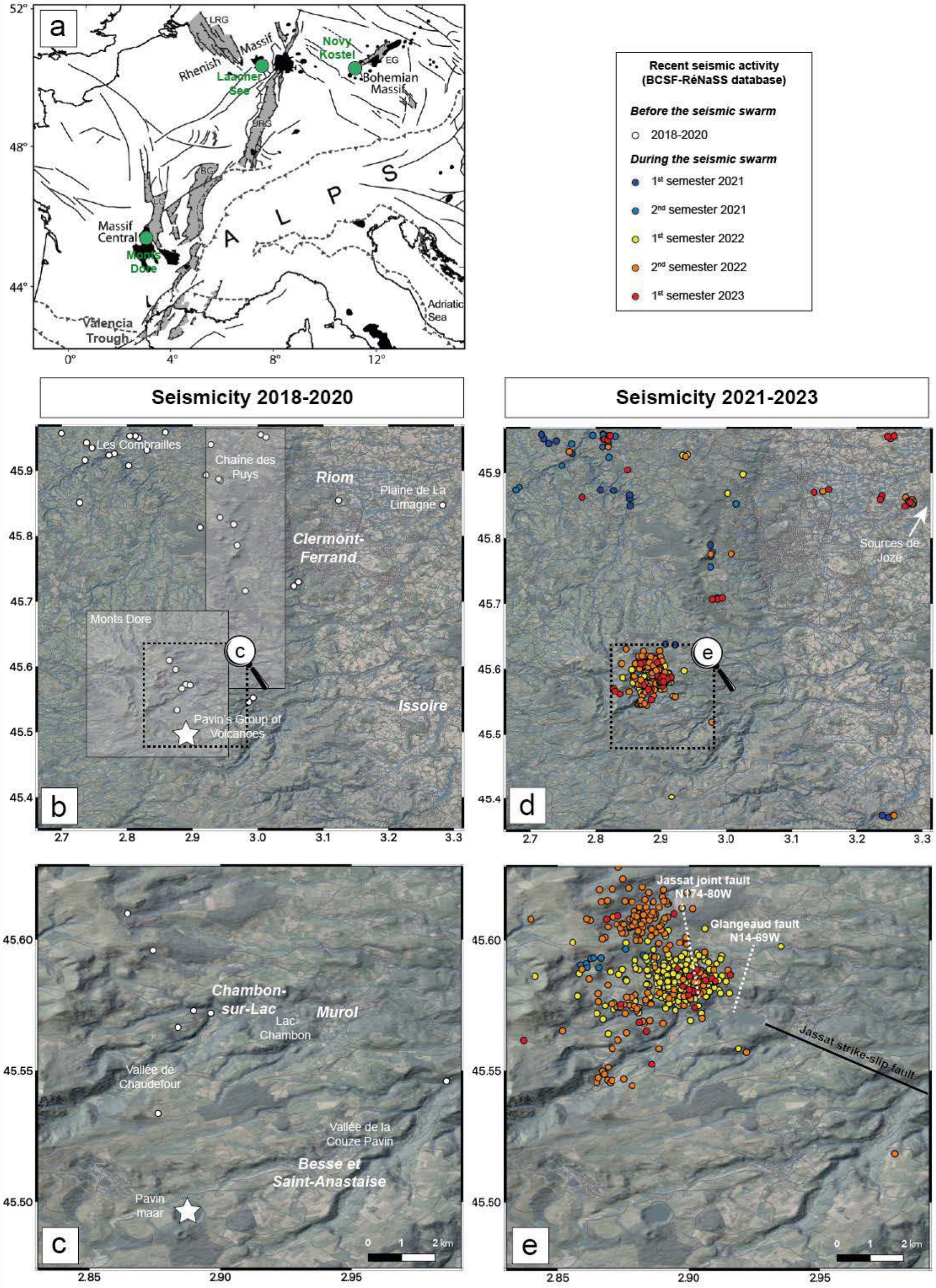


Figure 1. Caption continued on next page.

Figure 1. (**cont.**) (a) Map of the European Cenozoic Rift System (ECRS) showing the main Cenozoic faults (black lines), rift-related sedimentary basins (light gray: BG, Bresse Graben; EG, Eger Graben; LG, Limagne Graben; LRG, Lower Rhine Graben; URG, Upper Rhine Graben), volcanic fields (black), and the recent seismic swarms (green) within the European Cenozoic Volcanic Province (ECVP). Modified from Dèzes et al. (2004). Epicenters of the seismic events detected and localized by the BCSF-RéNaSS (b,c) between January 1, 2018 and December 31, 2020 and (d,e) between January 1, 2021 and June 30, 2023 (https://api.franceseisme.fr/fr/search). The main urban areas (white bold italic), places of interest discussed in this study (white), the most recent eruptive site (white star), the Jassat strike-slip fault (black line), and the surface projection of the fault planes accommodating the seismic swarm (dashed white lines) are shown. Source data from QGIS (IGN-Géoportail, BD Carthage, ASTER DEM).

province. In Section 3, we present some details about the seismic, remote satellite and geochemical data that were collected and on the data processing applied for the global analysis of this seismic swarm. Additional local measurements and analyses based on dedicated geophysical campaign surveys are compiled and analysed in the companion paper (Gailler et al., 2025). In Section 4, we present the results and discuss them in Section 5, with a special focus on the chronology of the seismic swarm and on lessons learned from the scientific and operational management at the national level. We finally conclude in Section 6.

2. Context of the study

The Monts Dore volcanic province spreads on about 600 km^2 and is located immediately South of the Chaîne des Puys volcanic chain, the most recent volcanic field in mainland France (Boivin and Thouret, 2014). Its eruptive activity spans a period ranging from 3 Myr to 0.2 Myr (Nomade et al., 2014) and its current morphology was acquired through successive glacial erosion periods. However, several recent (<15 kyr) eruptive cones and maars (cf. Tartaret, Montcineyre, Montchal, Pavin) were identified on the slope of the stratovolcano (Juvigné and Miallier, 2016). While their ages are contemporaneous of the last eruptive phase of activity in the Chaîne des Puys, their location as well as the chemical fingerprint of the eruptive products (Boudoire, Pasdeloup, et al., 2023; Villemant et al., 2016) still raises debates about their affiliation.

Current evidence of a potential reminiscent magmatic activity in the mantle beneath the Monts Dore include the presence of numerous springwaters (bicarbonate, bicarbonate-chloride, and acid-sulfate) that contain partly mantle-derived CO_2 and noble gases (Boudoire, Pasdeloup, et al., 2023; Bräuer, Kämpf, Niedermann and Wetzel, 2017; Pauwels et al., 1997; Ricci et al., 2024). Bräuer, Kämpf, Niedermann and Wetzel (2017) noted that the fingerprint of “fluid transport in deep reaching faults from the magmatic reservoir to the surface” is more marked for the Monts Dore volcanic province than anywhere else in the French Massif Central. The area is also characterized by soil CO_2 emissions (Boudoire, Pasdeloup, et al., 2023; Gal, Leconte, et al., 2018; Gal and Gadalia, 2011). Finally, high average heat flux (Lucazeau and Vasseur, 1989), high electrical conductivity body identified by magnetotellurics at depth greater than 8 km (Dupis et al., 1980; Gailler et al., 2025), and the water chemistry and thermometry support the presence of a hydrothermal system beneath the Monts Dore volcanic province (Bosch et al., 1980).

In the French Massif Central, about 5000 earthquakes were recorded since 1962, i.e., 110 earthquakes per year, on average (Battaglia and Douchain, 2016). The depth of hypocentres usually does not exceed 11 km. With the exception of few historical high magnitude earthquakes ($M > 4.5$), like those of the fifteenth century (1450, 1477, 1490) that generated major damages, earthquakes are mostly unfelt by the population (Dorel et al., 1995). The seismicity mostly clusters at the Northwest of Clermont-Ferrand (cf. “Combrailles” on Figure 1), in the vicinity of Saint-Flour and Ambert (out of the map on Figure 1), and in the Monts Dore (cf. “Monts Dore” on Figure 1).

Between 1962 and 2017, just over 290 earthquakes were localized in the Monts Dore with only five of magnitude (ML) higher than 3. This seismic activity mostly occurred on restricted time intervals (Battaglia and Douchain, 2016): (1) 10 earthquakes in June 1979, (2) 79 earthquakes in March–April 1980, (3) 7 earthquakes in January 1983, (4) 37 earthquakes in April 1984, (5) 6 and 16 earthquakes in April and September 2008, respectively, and (6) 14 earthquakes in June 2013. To date (before the 2021–2022 seismic swarm), the main period of seismic activity in the Monts Dore refers to 1979–1980 (89 earthquakes, some of which were close to magnitude of 3) and 1982–1983 (44 earthquakes, 37 of which were recorded within 4 days). These earthquakes mostly occurred on the North-eastern rim of the caldera that is the place of the 2021–2022 seismic swarm too. Battaglia and Douchain (2016) reported that these previous seismic swarms do not present the usual appearance of a main earthquake followed by aftershocks, which generally characterizes tectonic earthquakes occurring on a well-defined fault system. However, we note that these previous seismic swarms were recorded by a monitoring network that was probably too sparse at that time to detect and locate all events.

The BCSF-RéNaSS catalogue of seismic events detected by the RAP (Réseau Accélérométrique Permanent) and RLBP (Réseau Large Bande Permanent) national seismic networks (integrated in the EPOS-France research infrastructure; https://www.epos-france.fr/en/about-epos-france/epos/) listed 8 earthquakes in the Monts Dore between 2018 and 2020 (Figure 1b,c). Following this period, the first earthquake in the area in 2021 was detected on November 16 and marked the beginning of the 2021–2022 seismic swarm characterized by more than 400 earthquakes catalogued listed by the BSCF-RéNaSS catalogue. All are located at the Northwest of the town of Chambon-sur-Lac within a 3–7 km depth range above a high electrical conductivity body identified at depth by magnetotellurics (Gailler et al., 2025) (Figure 1d,e). Hypocentres clustered along two fault planes N173-85W and N13-68W linked to regional structures (Jassat joint fault and Glangeaud fault). These fault directions are reminiscent of those of the two main Variscan crustal faults families cutting the Plateau des Dômes (i.e., the basement of the Chaîne des Puys volcanic chain) (Merle, Aumar, et al., 2023): the Villefort fault family (N160-170E) and the Sillon Houiller fault family (N20E).

3. Data and methods

Time series of monitoring signals were obtained by merging data available from (1) national permanent networks (seismology, ground deformation), (2) remote sensing (ground deformation, thermal imagery), and (3) specific measurements and temporary networks (fluid geochemistry, seismology, ground deformation) deployed during the seismic swarm event (Figure 2). The main objective was to compare time series of these physical quantities measured before, during, and after the seismic swarm in order to better understand the chronology and then to constrain involved processes.

3.1. *Seismology*

The BCSF-RéNaSS, from which the seismic data for this study are processed (https://renass.unistra.fr), integrates seismic signals from permanent velocimetric (RLBP) and accelerometric (RAP) national networks, which are part of the national EPOS-France research infrastructure (so-called Résif before 2023 according to the FDSN nomenclature). Seismic events are detected and localized at the national level in near-real time, first using Seiscomp's automatic pick detection (Weber et al., 2007), then refined, completed, and validated manually by human operators. Locations are obtained using the LocSAT earthquake location program (Bratt and Nagy, 1991) with a five-layer 1D regional velocity model well suited for the French Massif Central (Mazabraud et al., 2005). In addition, the BCSF-RéNaSS catalogue provides the local magnitude (MLv) of each event (Figure 3) and a preprocessing tool designed to discriminate between earthquakes and quarry blasts (Grunberg et al., 2023; Renouard et al., 2021), the latter representing a significant amount of recorded seismic events.

At local scale (i.e., within and in the vicinity of the Monts Dore), the seismic monitoring network includes 8 accelerometers (RAP) and 14 broadband velocimeters (RLBP) maintained by the Observatoire de Physique du Globe de Clermont-Ferrand (OPGC). Accelerometric stations are equipped with Nanometrics Centaur digitizers and Kinemetrics Episensor FBA ES-T accelerometers. All the closest velocimetric stations are equipped with Nanometrics Centaur digitizers and Trillium 120PH sensors installed in 5- to 10-m-deep boreholes. In March 2022, these stations, and the ones belonging to the CEA seismic network identified a long-lasting seismic swarm beneath the Monts Dore volcanic province. The nearest permanent stations, however, are an accelerometer (OCMD

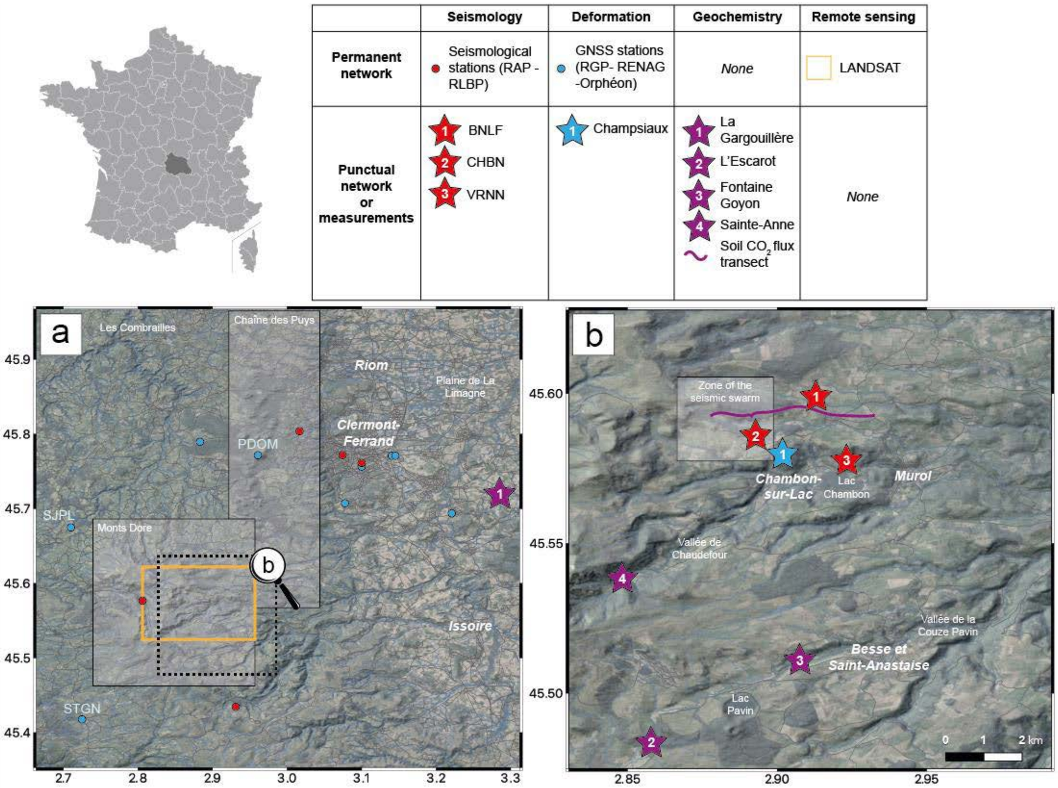


Figure 2. Map of the national permanent seismic (RAP, RLBP) and GNSS networks (RENAG, RGP, Orphéon) and punctual network/survey deployed during the seismic swarm. Source data from QGIS (IGN-Géoportail, BD Carthage, ASTER DEM). The orange square delimits the geographical extent of the areas covered for thermal imagery (LANDSAT) investigations.

from the RAP network) and a velocimeter (CMPS from the RLBP network) located around 6.5 km and 17 km from the swarm, respectively. As the average distance between stations in the region is around 30–40 km, a first temporary velocimetric station (CHBN) was installed right above the swarm on April 4, 2022, to improve the detection threshold for monitoring small seismic events. It is equipped with a Kinemetrics Q330 digitizer and a Nanometrics Trillium 120PA sensor buried. Given the persistence of the seismic swarm, two additional stations (BNLF and VRNN) were installed on June 15 and 20, 2022. These are equipped with Centaur digitizers and Nanometrics Trillium Compact 120s sensors. As data from the CHBN and BNLF stations are transmitted in real time, they are used by BCSF-RéNaSS to monitor seismicity in real time, unlike VRNN, whose data are only available once they have been collected in the field. VRNN data are therefore only used to complete data on events that have already been previously identified by BCSF-RéNaSS.

For a more comprehensive view of the number of events, particularly those with magnitudes too low to be detected automatically by the BCSF-RéNaSS, we apply the PhaseNet algorithm (Zhu and Beroza, 2019) to the continuous recordings of the CHBN station. The algorithm identifies potential P and S phases and provides associated probabilities. We used a version of the program trained with the Californian data set with no preliminary filtering. We then consider that the station detects a local event if it shows a P phase with a probability greater than 0.90, an S phase with a probability greater than 0.50 and a difference in arrival times $t_S - t_P$ less than 2 s (Figure 3). All detected events forming the seismic swarm had P and S waves (see Supplementary Material for an example of the typical seismic waveform detected) and no tremors or Long Period events have been identified until now.

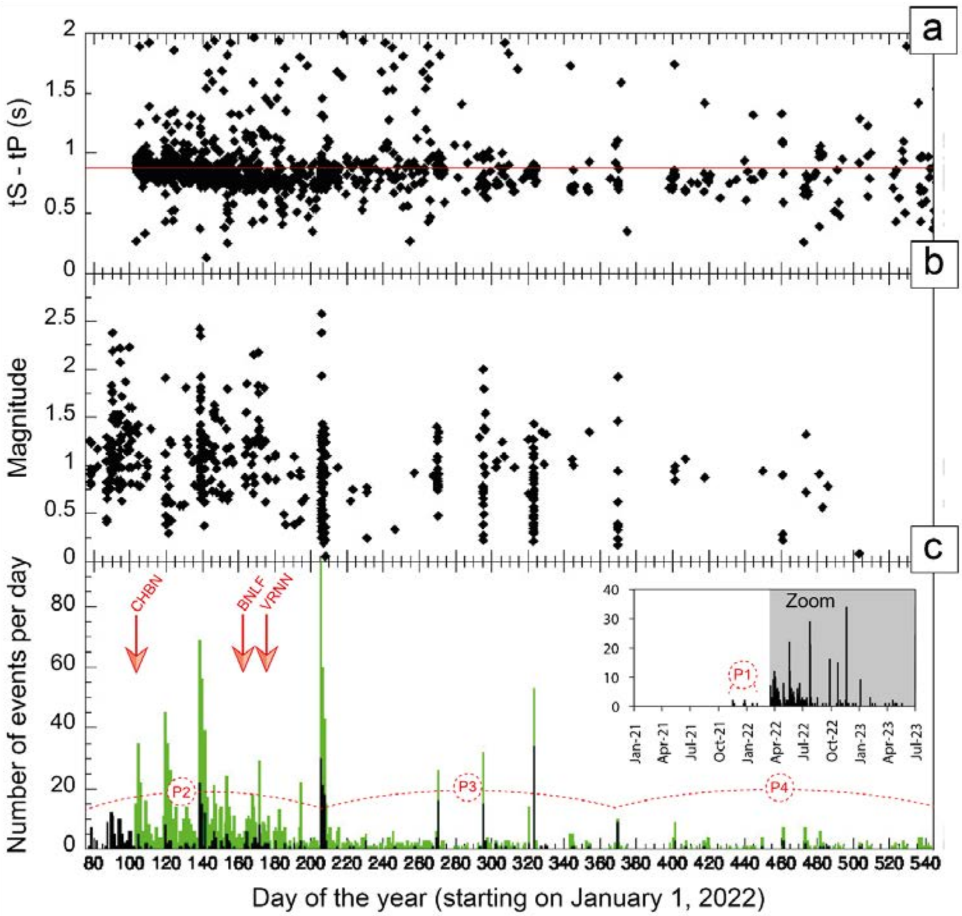


Figure 3. Time evolution of the seismic swarm beneath March 2022 and July 2023 (cf. zoom on the January 2021–July 2023 period): (a) Time difference of arrival between the S- and P-waves, $t_S - t_P$, at CHBN (PhaseNet algorithm; the horizontal red line highlights the average time). (b) Magnitude of the seismic events reported in the BSCF-RéNaSS catalogue. (c) Number of seismic events per day: in black, the counting from the BCSF-RéNaSS catalogue (automatic detection system computed by the BCSF-RéNaSS including over time the three temporary seismic stations whose installation dates are indicated by the red arrows); in green, the number of detections on the CBHN temporary seismic station, only (automatic detection on Phasenet of seismic events with both P- and S-waves separated by less than 2 s). P1, P2, P3, P4 highlight the 4 periods of seismic activity described in the main text.

3.2. *Ground deformation*

In order to seek for large-scale deformation of the Monts Dore area that could have occurred together with the seismic swarm, we compute baseline time-series of open-access daily GNSS data ("daily-rapid" Rinex) from three geodetic quality continuous stations of the national RGP (Réseau GNSS Permanent) and RENAG (https://renag.resif.fr/fr/) networks that both contribute to the national EPOS-France research infrastructure. The closest stations (PDOM, SJPL, STGN) from the area marked by the seismic activity (Figure 2) that have a good data availability over the period of interest (2021–2023) are located more than 20 km from the seismic swarm location. "Daily-rapid" Rinex were processed for these three stations with the IGN PPP calculation service (https://rgp.ign.fr/SERVICES/ppp_online.php) by using the default parameters of the BERNESE 5.2 software. 3D distances between each station

(PDOM-SJPL, PDOM-STGN and SJPL-STGN) were then computed.

One temporary GNSS station made of a TOPCON GB1000 receptor with a PG-A1 antenna (equipped with a one-meter steel mast sunk in the soil to a depth of 70 cm) available at the Laboratoire Magmas et Volcans (LMV) was deployed in a pasture from July 6 to November 2, 2022. The pasture is in the area marked by the seismic activity and was targeted due to geological evidence of past landslide above the D996 road (Figure 2). Data were recorded at 30 s intervals and converted in daily Rinex. Two post-processing methods were tested. The first post-processing method (so-called "BERNESE" in Supplementary Material) was carried out online on the IGN website (https://rgp.ign.fr/SERVICES/calcul_online.php), by using the default parameters of the BERNESE 5.2 software. For the second post-processing method (so-called "GIPSYX" in Supplementary Material), Rinex were reduced to daily static positions using the GIPSYX software (Bertiger, Bar-Sever, et al., 2020) in a precise point positioning mode applied to ionospheric-free carrier phase and pseudorange data (Zumberge et al., 1997) and using JPL's final no-net-rotation GPS orbit products. We use the Vienna Mapping Function to estimate tropospheric gradients and delays every 5 min, and compute ocean loading from the FES2012 tidal model (http://holt.oso.chalmers.se/loading). Ambiguities were fixed using wide lane and phase bias method (Bertiger, Desai, et al., 2010). Finally, we convert our coordinates in IGS2014 reference frame using the daily parameters provided by the JPL. No significant difference between the time series obtained by the BERNESE and GIPSYX softwares was observed (Supplementary Material).

The data used in this study are published by the RENAG network (Epos-France, 2023). ORPHEON GNSS data were provided to the authors for a scientific use in the framework of the GEODATA-INSU-CNRS convention. They are distributed by the RENAG data center (re3data.org, 2022).

3.3. *Geochemistry*

A quadrimestrial sampling of four thermo-mineral bubbling springs and mofettes was performed since April 2021 in the Plaine de la Limagne and Monts Dore volcanic province (Figure 2) (Supplementary Material). Springs and mofettes were firstly targeted for gas chemistry (since April 2021) for the purpose of local research projects focused on the degassing mechanisms in continental rifting, then applied progressively for characterizing the water chemistry (since February 2022) in response to this unprecedented seismic activity.

Bubbling gaseous samples were collected by accumulation in a funnel and pumped into a 100 cm^3 syringe. By using three-ways valves, gas was then injected into a two-ways stainless steel tube with Swagelok valves at both ends for noble gases analysis. Air was purged away from containers by means of several cycles of pumping and injection. Analyses were made at the Istituto Nazionale di Geofisica e Vulcanologia–Sezione di Palermo (INGV Palermo). The abundance and isotope composition (^{3}He, ^{4}He) of helium (He) were determined by a split flight tube mass spectrometer (Helix SFT-GVI). Neon (Ne) abundance and isotope composition (^{20}Ne) were determined by a Helix MC Plus Thermo. Argon (Ar) abundance and isotope composition (^{40}Ar, ^{38}Ar, ^{36}Ar) were measured in a multicollector mass spectrometer (Helix MC-GVI). The analytical errors of the He, Ne, and Ar isotopes were less than 1.4%, 0.13%, and 0.8%, respectively. The analytical procedure and correction for air-contamination of noble gases are the same as the ones described in Boudoire, Rizzo, et al. (2020).

Temperature, conductivity, and pH measurements of the water were obtained by using a multiparameter WTW probe FC Multi 340i. Water samples were collected for analysis in major ions. Concentrations (mg/L) of various anions and cations (lithium, sodium, ammonium, potassium, magnesium, calcium, fluoride, chloride, nitrite, nitrate, phosphate, and sulphate) were analyzed using high-pressure ion chromatography. For cations, a Thermo Scientific Dionex ICS1100 system was used, and for anions, a Thermo Scientific Dionex Aquion system (Thermo Fisher Scientific) was used. The uncertainty is lower than 5% for all anions and cations. Water total alkalinity was measured onsite by using a HI3811 HANNA alkalinity test kit (0–300 mg/L). The Total Dissolved Inorganic Carbon (TDIC) of water was calculated from pH, temperature, and total alkalinity by assuming that the total alkalinity was equivalent to the carbonate alkalinity (phosphate, borate, silicate, and hydroxide ions contribution being negligeable).

The maximum uncertainty (2σ) on the calculation of the TDIC is 6 mmol/L.

Additionally, the 100 m-spacing soil CO_2 transect measurements crossing the seismic swarm described in (Gailler et al., 2025) was reiterated 5 times between May 2021 and June 2023 to study the time evolution of diffusive degassing in the area (Supplementary Material). Measurements were performed by combining a West Systems C-type accumulation chamber and a PP Systems EGM-5 NDIR gas analyzer device (with temperature and pressure compensation). The EGM-5 device may measure CO_2 content up to 50,000 ppm with an uncertainty lower than 1% over the calibrated range. Soil CO_2 gas was also collected in glass vials by using a similar three-ways valves procedure as described above. In this case a probe was inserted in the soil at 50 cm-depth on 5 sites along the whole profile. Gas samples from soil were successively analysed for carbon isotopes ($^{13}C/^{12}C$) of CO_2 by using a Thermo (Finnigan) Delta Plus XP CFIRMS connected to a Trace GC gas chromatograph and a Thermo (Finnigan) GC/C III interface installed at INGV-Palermo (Supplementary Material). The absolute $\delta^{13}C$ analytical error is <0.15‰ (1σ).

3.4. *Thermal imagery*

Thermal imagery from Landsat 8 and 9 satellite platforms (courtesy of the U.S. Geological Survey). was obtained on a well-defined area covering the major part of the Monts Dore (Figure 2). Images from Landsat 8 (Collection 2 Tier 1 and 2) and Landsat 9 (Collection 2 Tier 1) were collected, analysed, and processed with Google Earth Engine (GEE) through online JavaScript algorithms. In the absence of high temperature hotspot in the area, the spectral band 13 of the OLI and OLI-2 (TIR; 10.60–11.19 μm) was considered to explore possible faint temperature variations (Harris, 2013).

The Robust Satellite Technique (RST) (Genzano et al., 2021; Tramutoli, 1998) is based on a multitemporal approach that identifies statistically significant variations, considered as anomalies, in the signal at pixel level. In this work, the RST was applied on two thermal indices: ALICE (Tramutoli, 1998; Tramutoli, 2007) and RETIRA (Eleftheriou et al., 2016; Tramutoli et al., 2005) (Supplementary Material). The anomalous pixels are highlighted once the baseline signal and its statistical variability are identified. For this purpose, the mean (μ) and standard deviation (σ) of each pixel were computed from a series of thermal images covering every month since 2013. The images were sorted according to the month of year and time of day after careful removal of cloudy pixels. This provided us with reference field images (μ,σ) for each date (t) from which the ALICE values for each pixel (x, y) were computed through Equation (1):

$$\text{ALICE}(x, y, t) = \frac{T(x, y, t) - \mu(x, y)}{\sigma(x, y)} \tag{1}$$

where $T(x, y, t)$ is the brightness obtained for each pixel (x, y) of the thermal image available at a date (t). RETIRA values were computed in a similar way but now considering the brightness variation $\Delta T(x, y, t)$ defined as (Equation (2)):

$$\Delta T(x, y, t) = T(x, y, t) - T_{\text{average}}(t) \tag{2}$$

where $T_{\text{average}}(t)$ is the mean value of $T(x, y, t)$ over all pixels for a given date (t). This index is useful to mitigate the effect of occasional large scale warming on generating false positives. Equation (1) relies on the Gaussian statistic hypothesis from which we identify the anomalous pixels as those corresponding to ALICE or RETIRA values larger than +2.5; i.e., thus corresponding to positive brightness values and variations outside the 99.5% confidence interval around the means.

4. Results

4.1. *Time series of the seismicity*

The BCSF-RéNaSS catalogue shows that the first seismic events in this study were detected in the area on November 16, 2021 (Figure 3). This was followed by an almost continuous series of daily seismic events (up to 22 events on May 18, 2022) from March 18, 2022, to July 15, 2022 (aseismic periods not exceeding 5 days). From then, the seismic activity concentrated on narrower time windows: (i) 68 seismic events on July 24–26, 2022, (ii) 16 events on September 27, 2022, (iii) 15 events on October 22, 2022, and (iv) 34 events on November 19, 2022. From January 5, 2023, the seismic activity becomes anecdotal with 13 seismic events detected up to July 1, 2023. The magnitude of the seismic events ($M < 2.5$) seems to decrease in time.

However, it is worth noting that there is a bias in the time evolution of the seismic swarm extracted from the BCSF-RéNaSS catalogue. In fact, the algorithm of automatic detection is not based on a fixed network of seismic stations but includes also progressively the signals obtained from the temporary stations (CHBN, BNLF, VRNN) set in the seismic area (see Methods). It means that the ability to detect the lowest magnitude seismic events increased in time. Consequently, a better fit is obtained between the BCSF-RéNaSS catalogue and the CHBN catalogue in time, i.e., when all three stations are included in the BCSF-RéNaSS detection algorithm (Figure 3). It is important to keep this bias in mind as it suggests that the number of daily seismic events detected at the beginning of the seismic swarm (prior to installing the CHBN station in April 2022 and the BNLF-VRNN stations in June 2022) is a lower limit of the real number of seismic events. Consequently, the most intense seismic activity cannot be excluded to have happened prior April 2022.

The time difference of arrival between the S- and P-waves on the CHBN temporary station remained mostly stable since the station was installed in April 2022 (Figure 3) suggesting at first order an absence of large-scale (i.e. from mantle to crustal depths) vertical migration of the seismic swarm. A similar conclusion was preliminary reached when looking at the hypocenters of the seismic events automatically detected from the BSCF-RéNaSS catalogue that are randomly distributed between 2 and 9 km-depth. Further investigations based on the deployment of seismic nodes in the area (not considered in the BCSF-RéNaSS catalogue) allowed a posteriori relocation of the seismic events (methods and dataset available in Gailler et al. (2025)). Results highlight a preferential clustering of the seismic events between 3 and 7 km-depth along two preferential directions (Figure 1e) (ibid.). This clustering is characterized by a slight and non-linear decrease of the depth of the hypocenters until June 2022. Similarly, the time difference of arrival between the S- and P-waves on the CHBN temporary station slightly decreases between April and June 2022 (Figure 3).

Considering these analytical limits, we distinguish 4 periods of seismic activity making up the swarm:

(1) November 16, 2021–February 3, 2022 (P1 on Figure 3) marked by the first casual detections of seismic events (11 days with no more than 2 events per day on the BCSF-RéNaSS catalogue).

(2) March 18–July 15, 2022 (P2 on Figure 3) characterized by an almost daily detection of seismic events (262 seismic events on the BCSF-RéNaSS catalogue). The seismic activity apparently culminated on May 18–21, 2022, but we cannot exclude that the peak of seismic activity was reached on March 28–April 5, 2022. A slight non-linear decrease of the depth of the hypocenters seems specific to this period (ibid.) with the shallowest seismic events (3.5–5.5 km-depth) clustering along the N13-68W structure and the deepest ones (5–6.5 km-depth) along the N173-85W structure.

(3) July 24, 2022–January 4, 2023 (P3 on Figure 3) characterized by 4 narrow time windows of seismic activity not exceeding 3 days and counting for 133 seismic events of the 175 ones detected on the full P3 period. Over this period, seismic detection on CHBN with Phasenet is still almost continuous.

(4) January 5, 2023 (P4 on Figure 3)–July 1, 2023 (P4 on Figure 3) characterized by only punctual seismic detections on both the BCSF-RéNaSS catalogue (13 seismic events) and on CHBN with Phasenet.

4.2. *Time series of ground deformation*

Daily baselines time series (from 25 to 43 km of distance) between the three closest GNSS stations from the RGP and RENAG networks (PDOM, SJPL, STGN on Figure 2a) show variations of several millimeters on a daily, monthly or even multiannual basis. It is therefore impossible to detect any significant ground deformation of the Monts Dore volcanic province on the period 2021–2023 (Figure 4a–c). Because of the large distance between the permanent GNSS stations and the heart of the volcanic province, this kind of baseline calculation cannot detect localized and/or low amplitude deformation and is rather prescribed to retrieve large deformation of the entire massif. Therefore, we cannot totally discard that very localized surface deformation occurred before, during, or after the swarm based on the GNSS data.

Meanwhile, during the management of the seismic swarm (see below), the ISDeform national service provided InSAR time series to the LMV-OPGC that also concluded in an absence of detectable

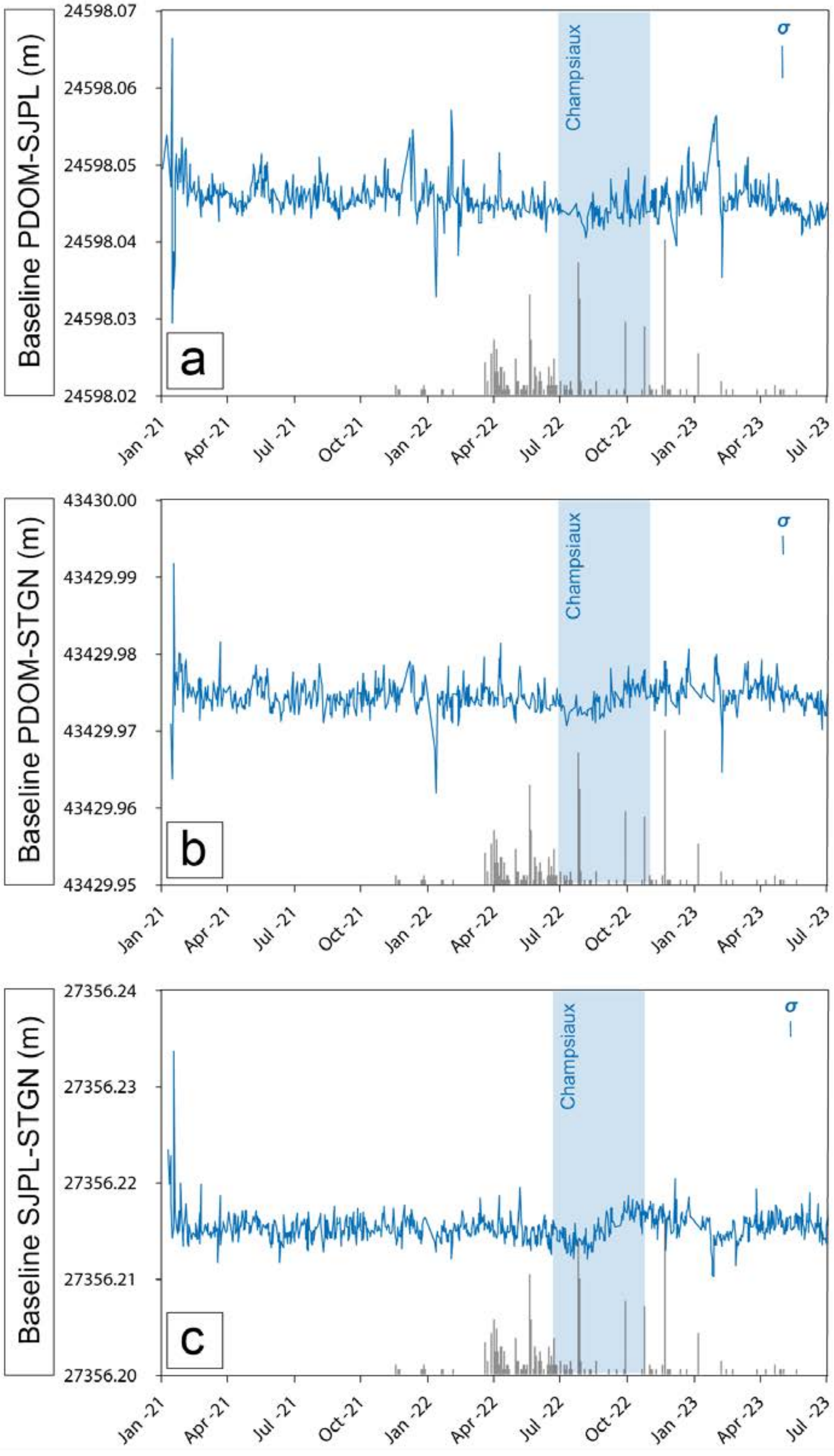


Figure 4. Caption continued on next page.

Figure 4. (**cont.**) Baselines of ground deformation obtained from (a) PDOM-SJPL, (b) PDOM-STGN, and (c) SJPL-STGN GNSS stations. The period of deployment of the temporary GNSS station at Champsiaux is marked by the shaded blue area. The general trend of evolution of the seismic swarm (Figure 3; BCSF-RéNaSS) is reported for comparison. The daily position (with uncertainty) of each station is available in Supplementary Material.

deformation when the seismic swarm occurred (unpublished data from internal PROVA[2] technical report on July 4, 2022). Additionally, the GNSS station temporary deployed between July and November 2022 at the Champsiaux site, i.e., in the zone of the seismic swarm (Figure 2b), did not reveal significant position changes (Supplementary Material).

4.3. *Time series of geochemical data*

The isotope chemistry of the fluids released by bubbling springwaters and the Escarot mofettes is variable on the 2021–2022 period (Figure 5). Maximum ^{3}He/^{4}He values in the CO_2-rich gas (Bräuer, Kämpf, Niedermann and Wetzel, 2017) are reached in September 2021 (Figure 5a), i.e., before the seismic swarm. At the Escarot mofettes, the ^{3}He/^{4}He value (up to 6.54 Ra) is even greater than the ones measured by Bräuer, Kämpf, Niedermann and Wetzel (ibid.) in 2011–2015 (up to 6.38 Ra). On the course of 2022, ^{3}He/^{4}He decreased towards minimum values in May–June (during the seismic swarm). This evolution is mirrored by a slight decrease of the ^{4}He/^{40}Ar* (Figure 5b) from 2.49 to 2.35 at the Escarot mofettes.

The chemistry of the associated waters presents maximum TDIC (Total Dissolved Inorganic Carbon) values in February 2022 (Figure 5c), i.e., at the beginning of the main seismic period (P2 on Figure 3): up to 127 and 99 mmol/L at Fontaine Goyon and La Gargouillère, respectively. These values are two- to three-times greater than past measurements performed in 2015–2018 and in July 2021 (Ricci et al., 2024). They highlight a process of carbon-enrichment in the springwaters since at least the beginning of 2022. Over the course of 2022 (during the seismic swarm), TDIC values decrease to reach values similar to the ones measured in 2015–2018. Similarly, the composition in other chemical elements (e.g., SO_4^{2-}, Cl^-, F^-) and physical parameters (e.g., pH, conductivity) is the same in 2022–2023 than in 2015–2018 for the springwaters in the Monts Dore (Sainte-Anne, Fontaine Goyon).

Along the transect of soil CO_2 flux crossing the area of the seismic swarm, δ^{13}C values of soil CO_2 are in the range −19.9/−22.1‰ in May 2022 and −20.3/−23.2‰ in June 2023. At the first order, these values are close to the mixing line between air and organic endmembers. No significant variation is observed between Zone 1 (medium- to- high flux) and Zone 2 (low flux), neither in time (during and after the seismic swarm) (Figure 6a,b).

The average of raw soil CO_2 flux reached a maximum (25.4 $gm^{-2}\cdot d^{-1}$) in July 2022 and decreased in the following months to reach a minimum (6.6 $gm^{-2}\cdot d^{-1}$) in November 2022 (Figure 6c). Another high average of raw soil CO_2 flux is measured in June 2023. Even if only 5 reiteration surveys were performed between May 2022 and June 2023, this time evolution (with maximum flux during the summer) seems mirroring a seasonal effect (Boudoire, Di Muro, et al., 2017; Viveiros et al., 2008). To investigate this effect, we applied a correction (Equation (3)) to each measurement of raw soil CO_2 flux ($\phi_{CO_2\mathrm{raw}}(t)$):

$$\phi_{CO_2\mathrm{corrected}}(t) = \frac{\mu_{CO_2\mathrm{raw}}(t)}{\mu_{CO_2\mathrm{raw}}\ (\text{May } 2022)} \times \phi_{CO_2\mathrm{raw}}(t) \quad (3)$$

where $\mu_{CO_2\mathrm{raw}}(t)$ is the average of the soil CO_2 flux obtained from the 9 sites of measurement located in Zone 2 (i.e., the area of low soil CO_2 flux more prone to be affected by seasonal variations) and $\mu_{CO_2\mathrm{raw}}$ (May 2022) is the average obtained from the Zone 2 in May 2022. This corrective model highlights a maximum average of corrected soil CO_2 flux reached in May 2022 followed by a continuous decrease until the last survey in June 2023 (Figure 6c).

4.4. *Times series from remote thermal imagery*

Thermal satellite imagery on the period 2015–2023 highlights a peak of anomalous pixels on August 2015 for ALICE (15,823 anomalous pixels in the area of interest; Figure 7a) and July 2019 for RETIRA (1891; Figure 7b). Anomalous pixels are also detected in May–July 2020 for ALICE (up to 2838

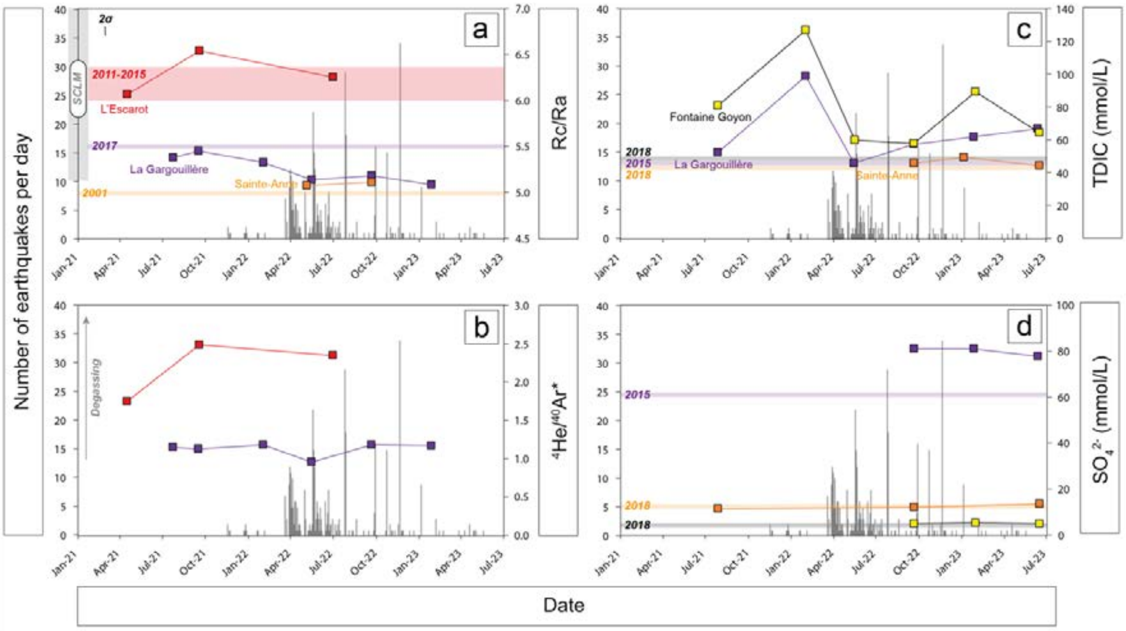


Figure 5. Time evolution of (a) ^{3}He/^{4}He (expressed as Rc/Ra where Rc is the ^{3}He/^{4}He corrected from atmospheric contamination and Ra the ratio in the air; the range of values from a Sub-Continental Lithospheric Mantle (SCLM) source is highlighted) (Gautheron and Moreira, 2002) and (b) ^{4}He/^{40}Ar* in the gas and of (c) TDIC and (d) SO_4^{2-} content in the water related to bubbling springwaters. Shaded horizontal bars highlight the range of values before 2021 in literature at Escarot (in red; Bräuer, Kämpf, Niedermann and Wetzel, 2017), La Gargouillère (in purple) (Moreira et al., 2018; Ricci et al., 2024; unpublished data GEOLAB), Sainte-Anne (in orange) (Bräuer, Kämpf, Niedermann and Wetzel, 2017; unpublished data GEOLAB), and Fontaine Goyon (in grey) (Bräuer, Kämpf, Niedermann and Wetzel, 2017; unpublished data GEOLAB). The uncertainty on the measurements (2σ) is smaller than the size of the square symbols.

anomalous pixels) but unmatched for RETIRA that is less sensitive to weather conditions and in particular to anomalous thermal pixels during the summer (see Methods).

During the seismic swarm, no significative thermal anomalies are detected, even less in the zone immediately above it. A detailed analysis of a clear weather satellite image obtained on July 13, 2022, reveals 5 anomalous pixels for RETIRA, only (areas R1 and R2 on Figure 7c). They belong essentially to areas marked by a contrast of vegetation. For instance, the geographical extension of A1/R1 overlaps the area where trees have recently been pruned for commercial purposes. It argues in favour of developing indices taking into account the influence of vegetation and soil heterogeneity on the detection of thermal anomalies. Considering the reference field images (i.e., μ and σ) used to compute the RETIRA index (see Methods), one can argue with 99.5% of confidence (2.5σ) that no anomalous temperature greater than 5 °C were detected in the area during the seismic swarm.

5. Discussion

5.1. *Seismic activity triggered by fluid circulation*

The comparison of the distinct physico-chemical signals and/or measurements performed over the 2021–2023 period is fundamental to investigate the processes linked to the seismic swarm (Figure 8).

The chemistry of the gas phase released by bubbling springwaters spread in the Monts Dore volcanic province and its vicinity changed at the end of the summer 2021. In particular, an increase of the ^{3}He/^{4}He was measured together with a potential

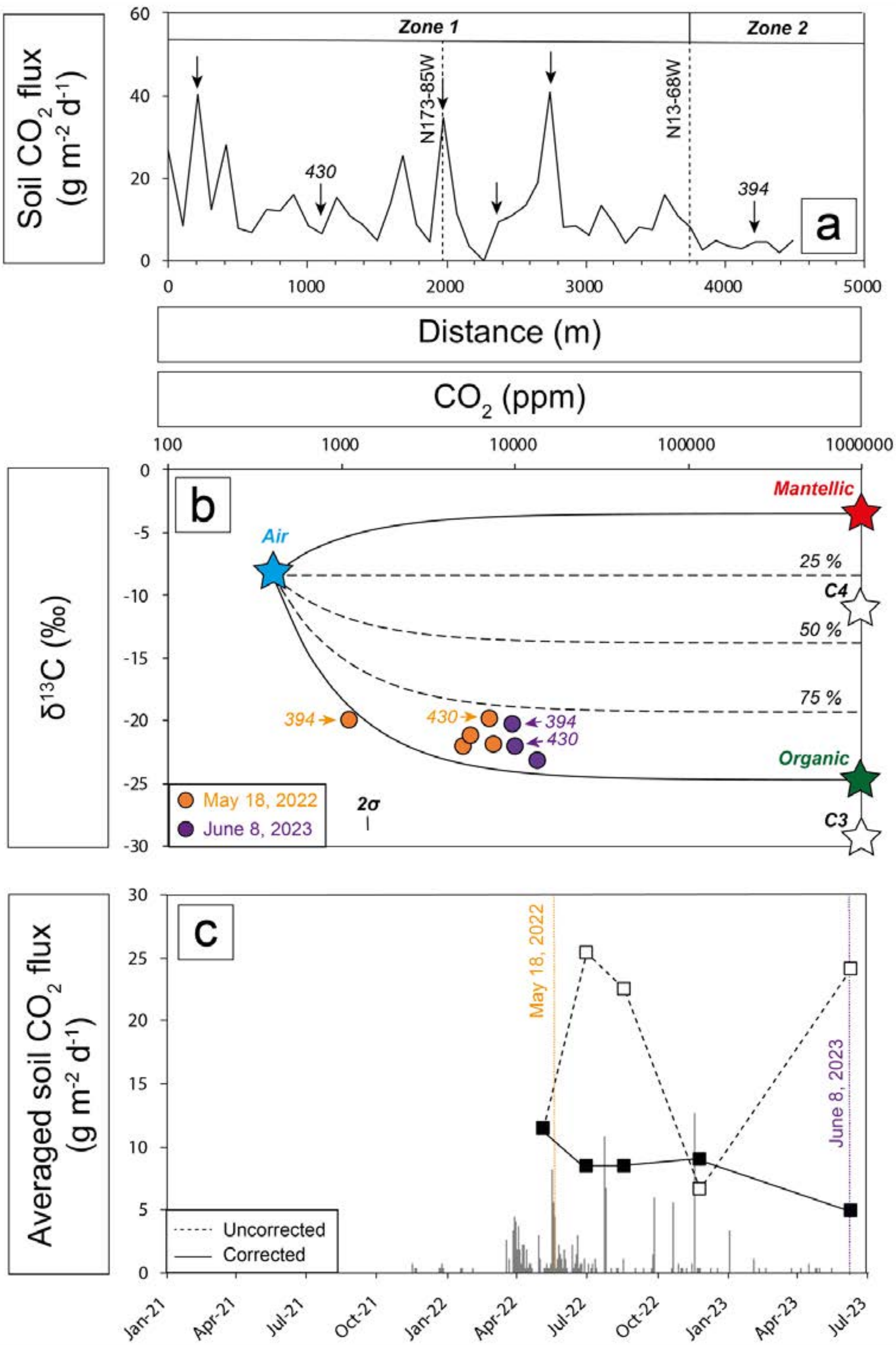


Figure 6. Caption continued on next page.

Figure 6. (**cont.**) (a) Transect of soil CO_2 flux (May 6, 2022) with a 100 m-spacing crossing the area of the seismic swarm (Gailler et al., 2025) (Figure 2b). Vertical dashed lines highlight the theoretical projection of the fault planes at the surface. The black arrows highlight the sample sites for the analysis of the $\delta^{13}C$ of soil CO_2 (from which the two sites 394 and 430 reiterated in time). Zones 1 and 2 delimit the areas characterized by medium- to- high flux and low flux, respectively. (b) Mixing plot of the $\delta^{13}C$ of soil CO_2 between three endmembers: atmospheric (Graven et al., 2020), organic (Morandi et al., 2016), and mantellic (Boudoire, Pasdeloup, et al., 2023). CO_2 content from GC analysis of the gas sampled in glass vials (see Methods). Averaged $\delta^{13}C$ values of soil CO_2 from C3–C4 plants are also shown (Staddon, 2004). The numbering highlights the two sample sites reiterated in time (cf. (a)). (c) Time evolution of the averaged soil CO_2 flux along the transect (calculated from the 48 sites of measurements). The vertical dotted lines highlight the date of the gas sampling for the analysis of the $\delta^{13}C$ of soil CO_2. The general trend of evolution of the seismic swarm (Figure 3; BCSF-RéNaSS) is reported for comparison. The uncertainty on the measurements (2σ) is smaller than the size of the square and circle symbols.

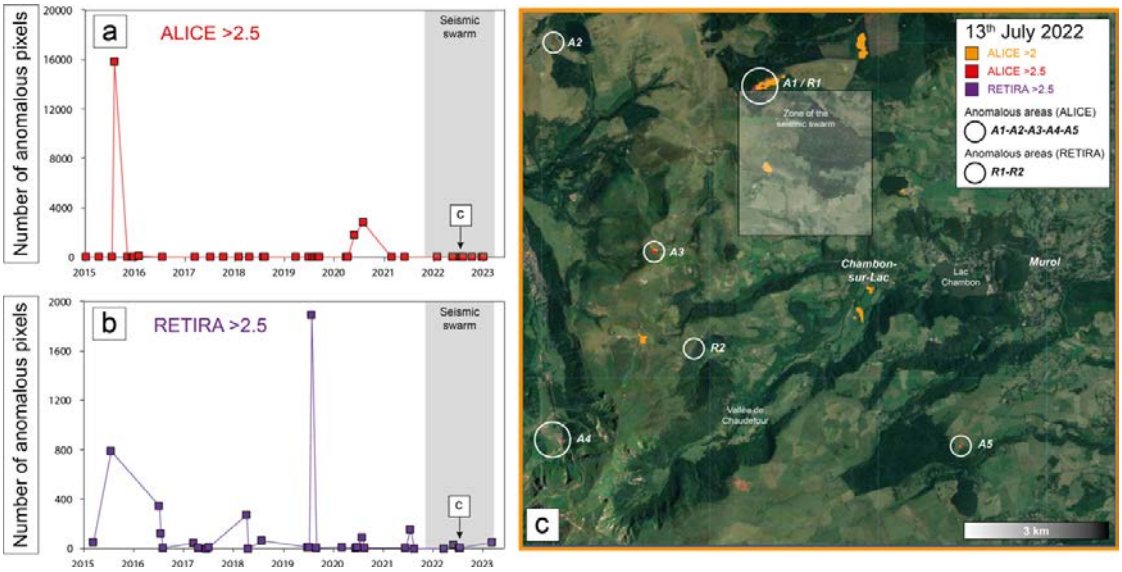
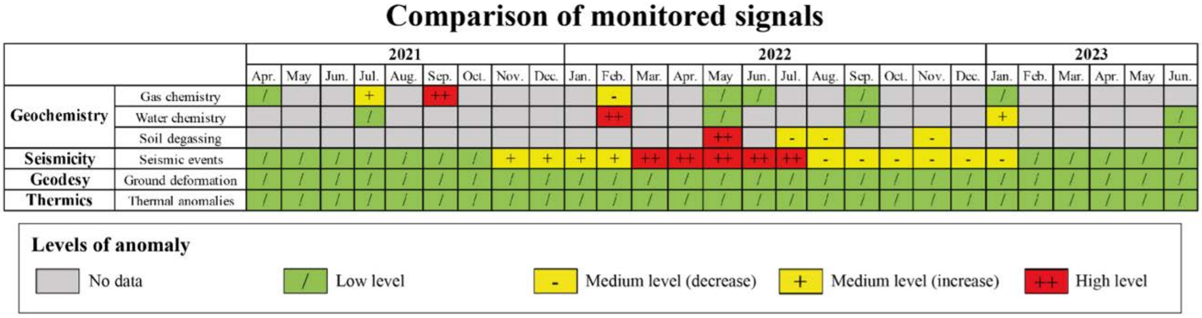


Figure 7. Time evolution of thermally anomalous pixels (spatial resolution is 30 × 30 m in Google Earth Engine) identified with (a) ALICE and (b) RETIRA indices (see Methods) with 99.5% of confidence (2.5σ). The period of seismic activity is highlighted with the grey shaded square. (c) Location of anomalous hotspots from satellite imagery (LANDSAT) on July 13, 2022, in the area of interest.

slight increase of the $^4He/^{40}Ar^*$. At the end of the autumn 2021, the first seismic events are detected (P1 period on Figure 3). While the gas chemistry came back to more classical values during the winter 2021–2022, the water chemistry of the bubbling springwaters became marked by a clear increase of the dissolved carbon without significant evolution of other species such as SO_4^{2-}, Cl^-, F^-. The most intense seismic activity (P2 period on Figure 3) is not associated with any anomalous values of physico-chemical parameters monitored in the bubbling springwaters. However, we note that this period is characterized by the highest soil CO_2 flux measured above the seismic swarm. In parallel, local testimonies reported the occurrence of new degassing areas (bubbling) on some hiking paths of the Vallée de Chaudefour (Figure 2), close to the Sainte-Anne springwater. Soil CO_2 flux progressively decreased during the summer 2022 in parallel to the decrease of the seismic activity (P3 period on Figure 3). No global ground deformation of the volcanic massif was detectable on GNSS baselines during the whole period. From the beginning



Comparison of monitored signals

		2021								
		Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Geochemistry	Gas chemistry	/			+		++			
	Water chemistry				/					
	Soil degassing									
Seismicity	Seismic events	/	/	/	/	/	/	/	+	+
Geodesy	Ground deformation	/	/	/	/	/	/	/	/	/
Thermics	Thermal anomalies	/	/	/	/	/	/	/	/	/

		2022											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Geochemistry	Gas chemistry		-			/	/			/			
	Water chemistry		++			/				/			
	Soil degassing					++		-	-			-	
Seismicity	Seismic events	+	+	++	++	++	++	++	-	-	-	-	-
Geodesy	Ground deformation	/	/	/	/	/	/	/	/	/	/	/	/
Thermics	Thermal anomalies	/	/	/	/	/	/	/	/	/	/	/	/

		2023					
		Jan.	Feb.	Mar.	Apr.	May	Jun.
Geochemistry	Gas chemistry	/					
	Water chemistry	+					/
	Soil degassing						/
Seismicity	Seismic events	-	/	/	/	/	/
Geodesy	Ground deformation	/	/	/	/	/	/
Thermics	Thermal anomalies	/	/	/	/	/	/

Levels of anomaly

⬜	No data
/	Low level
-	Medium level (decrease)
+	Medium level (increase)
++	High level

Figure 8. Comparison between the evolution of the distinct time series of physico-chemical signals acquired in the frame of this study. No data for the absence of measurements. Low (/) and high (++) levels highlight qualitatively, during the considered period, steady-state background conditions and maximum amplitude of identified anomalies described in the text, respectively. Medium levels highlight either the increase of the monitored signals from background conditions to maximum amplitude identified anomalies (+) or its decrease (−).

of 2023, the seismic activity became only residual (P4 period on Figure 3) with no significant variations of the other physico-chemical parameters monitored. Interestingly, some seismic events were also detected in the area of the Joze springwaters, more than 40 km far from the area of the seismic swarm (Figure 1). This observation supports the idea of a close relation between fluid circulation and seismicity, not only within the Monts Dore volcanic province but rather at regional scale.

The absence of notable ground deformation, of enrichment in S–Cl–F-bearing species in springwaters, and of more enriched δ^{13}C signature of the CO_2 release from the soil tend to discard the hypothesis of magma intrusion at crustal level. Constraining the expected ground deformation induced by magma injection is challenging due to several unknown input parameters (magma volume and pressure, crustal rheology, … (Townsend, 2022) for a review) required to build thermo-mechanical models. If we recognize that future work is needed to model such expected changes, it is worth noting that dyke propagation or magma refilling of crustal reservoirs at this depth range (3–7 km) generally trigger inflation/deflation processes characterized by horizontal and/or vertical plurimillimetric displacements (Beauducel et al., 2020; Sigmundsson et al., 2018; Wadge et al., 2006) that should have been detected by InSAR, and are not detected in this study, even in the epicenter zone (Champsiaux GNSS temporary station; Supplementary Material). Similarly, magma ascent towards the surface favors the degassing of gaseous species with a higher solubility in magma (i.e., SO_2, H_2S, HCl, HF) that could in turn modify the chemistry of local springwaters (Federico et al., 2023) and/or the enrichment in ^{13}C in CO_2 emissions in the epicenter zone or in its vicinity (Boudoire, Rizzo, et al., 2020). These geochemical markers are not detected in our study.

The seismic swarm clustered along tectonic structures where magnetotelluric surveys revealed relatively higher electrical resistivity values (~100 Ω·m) compared to the low electrical resistive body (<10 Ω·m) present at depth greater than 8 km (Gailler et al., 2025). This observation raises the question of what triggered the reactivation of these structures, bearing in mind that the reactivation was presumably not caused by magma injection. Considering the temporal sequence of variations reported above, we propose that this seismic swarm was induced by a perturbation of the hydrothermal system beneath the Monts Dore due to the arrival of a CO_2-rich fluid originating from the mantle. Undated magma intrusion at mantle depth (Figure 9a) could have generated the forming of a foam at the top of a magma reservoir by early degassing or second boiling (Figure 9b) where overpressure would be able to release a CO_2-rich gaseous phase. A similar process has already been proposed to explain recurrent seismic swarms in several volcano-tectonic provinces in continental rifts (Lindenfeld et al., 2012), including the ones of the European Cenozoic Rift System (Audin et al., 2002; Fischer and Horálek, 2003) as the Novy Kostel area (Eger Rift, Czech Republic; Figure 1a) (Bräuer, Kämpf, Koch, et al., 2011; Fischer, Horálek, Michálek, et al., 2010; Fischer, Horálek, Hrubcová, et al., 2014) and the Laacher See Volcano (Eifel, Germany) (Hensch et al., 2019).

In the Monts Dore volcanic province, the initial increase of the $^3He/^4He$ values in the gas phase of bubbling springwaters during the summer 2021 may track such changes in magma dynamics and degassing within the Sub-Continental Lithospheric Mantle (Boudoire, Pasdeloup, et al., 2023; Bräuer, Kämpf, Niedermann and Wetzel, 2017) (Figure 9c). The isotopy of noble gases ($^3He/^4He$; $^4He/^{40}Ar^*$) is consistent with gas ascent from mantle depth rather than from crustal reservoirs (Boudoire, Pasdeloup, et al., 2023, and this study). Gas–water reaction triggered by the arrival of mantle CO_2 at crustal level could have increased the total dissolved carbon content in the aqueous phase of the springwaters in the following months (Figure 9d). The presence of a high electrical conductivity body at depth greater than 8 km beneath the Monts Dore supports the existence of a hydrothermal system at depth that may favor fluids circulation and reaction (Gailler et al., 2025; Pauwels et al., 1997). This perturbation of the hydrothermal system may have been balanced by the seismic reactivation of pre-existing shallower structures (Figure 9d) acting as preferential fluid pathways (as suggested by self-potential and electrical resistivity tomography surveys, (Gailler et al., 2025)) and the increase of soil CO_2 flux. This synchronous response of soil degassing (without change of the $\delta^{13}C$ of CO_2; Figure 6b) to stress change at depth is perfectly compatible with a pulsating degassing mechanism (Boudoire, Finizola, et al., 2018). This process is reminiscent (on a shorter timescale and with a much smaller magnitude) of that occurring in active calderas, such as the Campi Flegrei (Italy), where seismic activity at shallow level is partly explained by a thermofluid dynamical model where deep fluid injections other than magma may be involved but with minor changes in the temperature (Chiodini, Todesco, et al., 2003; Chiodini, Caliro, et al., 2012). At the same time, the decrease of the $^3He/^4He$ during the seismic swarm may reflect a preferential release of crustal-derived components due to rupturing (Bräuer, Kämpf, Koch, et al., 2011).

5.2. *Insights for future monitoring*

The first communication about the occurrence of a seismic swarm in the Monts Dore area was made by the Commissariat à l'Energie Atomique (CEA; in charge of seismic alerting in mainland France) to the Observatoire de Physique du Globe de Clermont-Ferrand (OPGC) and the Laboratoire Magmas et Volcans (LMV) on April 12, 2022. Once the communication was received at OPGC, the first temporary seismic station (CHBN) was installed in the area of the seismic swarm to densify the national network and therefore to increase our ability to detect and localize the events at depth with more accuracy (Figure 3). A concerted effort between the OPGC and the LMV towards deploying scientific and technical human resources with instrumental and logistical supports made it possible 30 dedicated field surveys as of July 2023 (without counting the maintenance routine operations). The OPGC internal school also temporarily reorganized its practical courses in geology and instrumentations. This allowed involving some of its undergraduate and master's students, as part of their initial training, on a scientific issue requiring rapid intervention. In addition, the data center of OPGC created a dedicated catalogue to aid monitoring and planning survey missions and to share and archive the data on the long term. This action, articulated between research, technical developments, teaching, and the national facilities, allowed to collect multidisciplinary data to characterize the seismic swarm (Gailler et al., 2025, and this study).

In parallel with the scientific surveys, communication to the national authorities (Direction Générale de la Prévention des Risques: DGPR), to the regional authorities (Direction Régionale de l'Environnement, de l'Aménagement et du Logement: DREAL), and to the local authorities (Direction Départementale des Territoires: DDT) about the seismic swarm were initiated on June 13, 2022, by the OPGC and LMV managers and their representatives. This was made under the umbrella of the Centre National de la Recherche Scientifique (CNRS). Public communications to the regional press were also organized to minimize the propagation of fake news among local inhabitants about a potential renewal of the eruptive activity in the Monts Dore. Additional meetings with public authorities were organized to raise awareness about the necessity

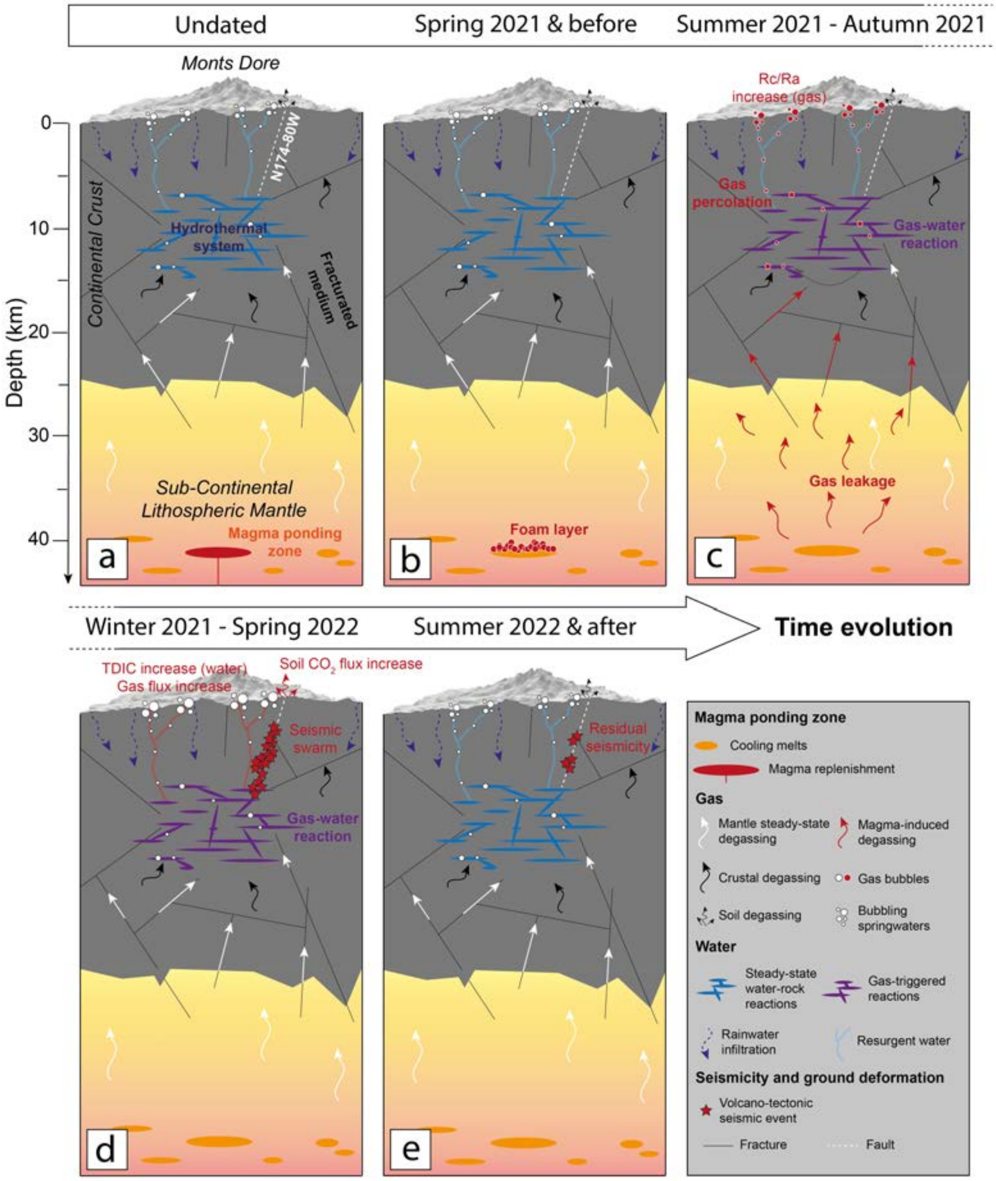


Figure 9. Model of the time evolution of the processes (a–e) involved in the 2021–2022 seismic swarm in the Monts Dore volcanic province and described in the main text (modified from Boudoire, Pasdeloup, et al., 2023).

to reinforce the national monitoring networks in the Monts Dore, and more generally in the volcanic provinces in mainland France. These efforts led to the signing of a 5-year agreement (ReODORE) between the Université Clermont Auvergne (UCA) and the Direction Départementale des Territoires (DDT) in order to strengthen the national observation networks in the Monts Dore and to facilitate in turn the delivery of reports to the local authorities. The DDT through this agreement provided funding for one permanent seismic station, two permanent GNSS stations, one permanent soil CO_2 flux station, and for regular sampling and analysis of five springwaters (Figure 10a).

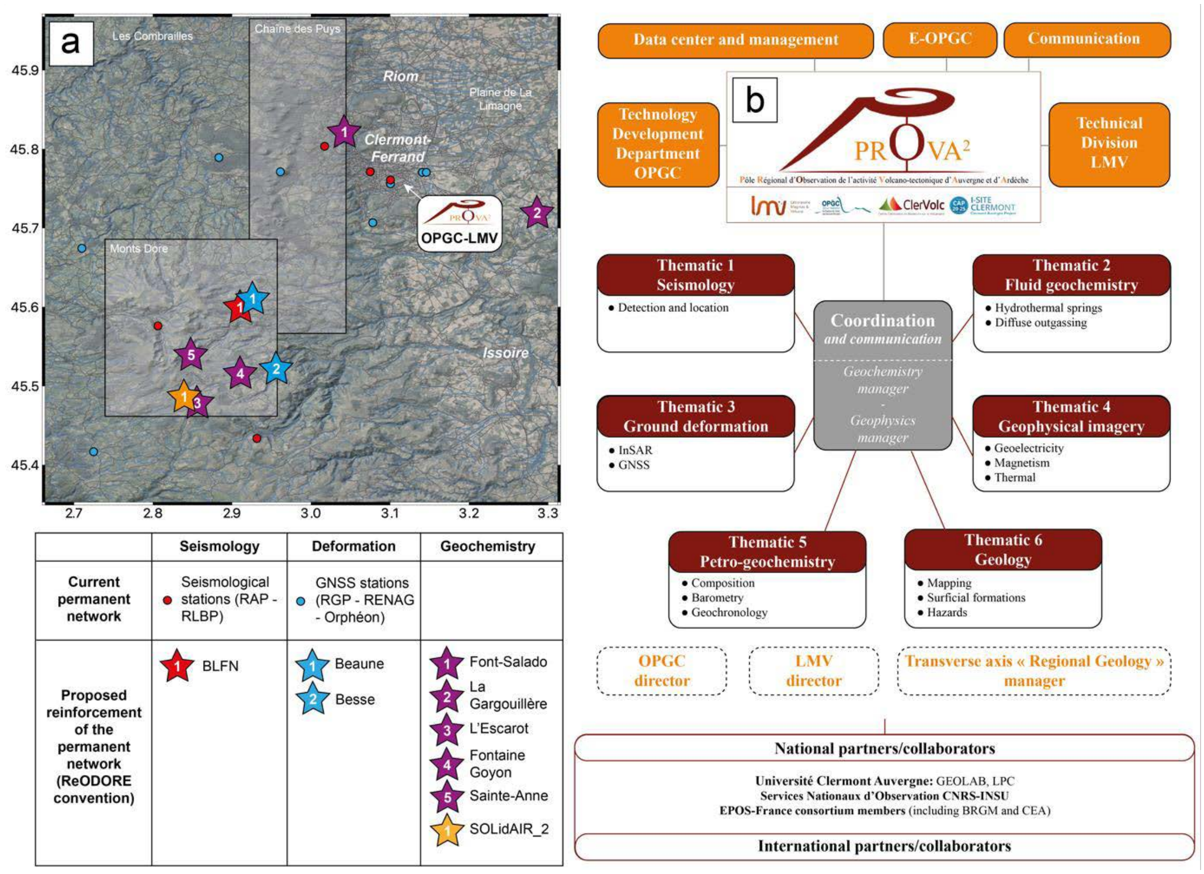


Figure 10. (a) Reinforcement of the monitoring network (seismology, geodesy, geochemistry) in the Monts Dore planned in the frame of the ReODORE agreement between the UCA and the DDT. (b) Organisation chart of the PROVA^2 consortium led by the OPGC-LMV.

On August 29, 2022, this collaborative experience led to the creation by the OPGC and the LMV of a local initiative, the Pôle Régional d'Observation de l'Activité Volcano-tectonique d'Auvergne et d'Ardèche (PROVA^2) led by scientists at LMV in which, the scientific long-term questions, the operational resources engaged to address them, and the communication channels to local authorities are now structured in working groups (Figure 10b). This consortium includes the support of national and international collaborators and is designed to address five objectives: (1) to promote programs strengthening the observation of local volcano-tectonic activity, (2) to support the structuration of field measurements and monitoring signals into database and metadata, (3) to deploy a scientific response in the event of significant variations in activity, (4) to promote research and student formation based on the geological wealth in the local territory, (5) to strengthen the communication mission of the OPGC towards the regional authorities and populations, and (6) to address specific information requests from local authorities. Furthermore, the new French national research infrastructure EPOS-France created in November 2023 represents an opportunity to bring together and federate the scientific communities responsible for monitoring the French territory (mainland and overseas), to strengthen links of solidarity and instrumental pooling, and to establish multidisciplinary actions in solid earth sciences with broad thematic contours. The PROVA^2 initiative is in line with this effort and supports the consideration of volcanic provinces in mainland France as main subjects of scientific interest for the EPOS-France community.

5.3. *Insights for risk mitigation strategies*

Two main recommendations emerge from the management of the 2021–2022 seismic swarm in the Monts Dore volcanic province. Firstly, a concerted protocol at the national level regarding the detection and the rapid reporting of seismic swarms on mainland France could be consolidated in favor of quick scientific and operational responses. In a similar way, an emergency response strategy with the various Services Nationaux d'Observation (SNO), EPOS-France and international partners would enable rapid access to complementary information that appeared crucial during this seismic swarm, such as satellite imagery. For instance, an effort should be made to extract multi-year InSAR time series of ground deformation at the scale of the entire massif to identify potential displacements over the long term and not only during seismic swarms (as documented in this study). In parallel, a scientific effort should be also led to develop physics-based models of expected change in monitoring geodetic signals in case of volcano unrest (Acocella et al., 2024). This is particularly important for the geographical area covered by long-quiescent volcanic provinces and where in-situ monitoring networks are sparse. Secondly, we support initiatives for the elaboration of a general transverse management protocol between the academic and societal worlds regarding unusual volcano-tectonic activity in mainland France. In France, the ORSEC plans (Organisation de la Réponse de SEcurité Civile) define the general organization of civil protection to cope with natural or industrial disasters. Plans to trigger a rapid and appropriate response to volcano-tectonic activity exist in the French overseas departments but not, to our knowledge, for mainland France. We recognize that the probability of an eruption in mainland France may appear low but we also note the presence of several basanitic and basaltic eruptive cones within or close to the seismic area with ages more recent than the end of the Monts Dore stratovolcano's activity (Boivin, Besson, et al., 2017). Following the definition of the French Ministry of Ecological Transition (in charge of preparing and implementing the government's policy regarding environmental questions) a major risk "is characterized by its low frequency and its enormous severity". As such, discussions regarding the relevance of including volcano-tectonic activity as a potential risk for the volcanic provinces of the French Massif Central could be at least conducted with the civil protection.

6. Conclusion

The evolution of the 2021–2022 seismic swarm in the Monts Dore volcanic province was monitored by coupling (1) time series from permanent stations of the seismic and GNSS national networks, (2) time series from temporary seismic and GNSS stations deployed by the OPGC-LMV, (3) field measurements of the physico-chemical parameters of local springwaters and soil CO_2 flux transect, and (4) remote sensing based on thermal imagery. Results indicate an absence of global ground deformation during the seismic swarm. No anomaly in the content of S–Cl–F-bearing species in springwaters, and no thermal anomaly before, during, and after the seismic swarm was identified. Therefore, there is so far no evidence supporting the direct causal link between the seismic swarm and magma intrusion at shallow crustal level.

However, ^{3}He-enrichment in the gaseous phase of local springwaters at the end of the summer 2021 followed by an increase of the Total Dissolved Inorganic Carbon (TDIC) in the aqueous phase during the winter 2021–2022, preceded the most intense period of seismic activity in March–July 2022. During this period, soil CO_2 flux was at its highest. Based on these results, we proposed a model in which a CO_2-rich fluid ascending from the mantle reacted in a hydrothermal system beneath the Monts Dore at crustal level. Fluid circulation and change in the fluid composition in this mixing zone would have triggered the seismic activity and the increase of soil CO_2 flux along pre-existing tectonic structures. Note that when finalizing this article (in May–June 2024), new seismic events were detected in the same area.

The management of this unusual seismic activity in the Monts Dore volcanic province raises several recommendations about the monitoring of long-dormant volcanic provinces on mainland France, among which (1) the development of a national protocol of detection and rapid reporting of seismic swarms in mainland France, especially in active volcano-tectonic areas, (2) the creation of an operational protocol for the management and the communication of any unusual activity in long-dormant volcanic provinces, and (3) the promotion of joint research initiatives to better investigate expected change in monitoring signals as well as hazard assessment related to potential eruptive scenario. Similar seismic swarms detected in other volcanic provinces of the European Cenozoic Rift System (Novy Kostel, Laacher See) as well as inferences about the presence of a persistent magmatic activity at mantle depth beneath these provinces should especially simulate joint research and civil protection European initiatives.

Data availability

Supplementary Material related to the manuscript is available through a .zip file the OPGC data center PROVA^2 (Observatoire de Physique du Globe de Clermont-Ferrand, 2021). The Supplementary Material is an Excel file with seven sheets: "Seismic database" compiles the daily seismic number of events from the BCSF-RéNaSS catalogue in the area of interest; "Seismic waveform" show typical waveform of volcano-tectonic events forming the seismic swarm; "GNSS permanent stations" compiles the data from the PDOM, SJPL, and STGN stations of the RENAG and RGP networks used to calculate the baselines; "GNSS temporary station" compiles the East, North and vertical component of the Champsiaux station; "Bubbling springwaters" compiled the chemical dataset used in this study for the four monitored sites; "Soil degassing" related to the soil CO_2 flux measurements and related carbon isotopy made along the transect; "Thermal imagery" compiles the time series of anomalous pixels in the area of interest by using both ALICE and RETIRA indexes.

Declaration of interests

The authors do not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and have declared no affiliations other than their research organizations.

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Supplementary data

Supporting information for this article is available on the journal's website under https://doi.org/10.5802/crgeos.285 or from the author.

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