



HAL
open science

The catalogue of 1987–2023 earthquakes in the western (French) Alps north of 43.5°N

Mickael Langlais, Gael Janex, Philippe Guéguen, Agnès Helmstetter, Anne Paul,
Jean Virieux, Emeline Maufroy, Jean-Noël Bouvier

► **To cite this version:**

Mickael Langlais, Gael Janex, Philippe Guéguen, Agnès Helmstetter, Anne Paul, et al.. The catalogue of 1987–2023 earthquakes in the western (French) Alps north of 43.5°N. *Scientific Data*, 2024, 11 (1), pp.1290. <10.1038/s41597-024-04133-y>. <hal-04979721>

HAL Id: hal-04979721

<https://hal.science/hal-04979721v1>

Submitted on 6 Mar 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY-NC-ND 4.0 - Attribution - Non-commercial use - No
Derivative Works - International License



OPEN

DATA DESCRIPTOR

The catalogue of 1987–2023 earthquakes in the western (French) Alps north of 43.5°N

Mickael Langlais, Gael Janex, Philippe Guéguen , Agnès Helmstetter, Anne Paul , Jean Virieux, Emeline Maufray & Jean-Noël Bouvier

The western Alpine belt is the focal point of moderate but constant seismic activity. Numerous geodynamic and seismological studies underline the many scientific questions linked to Alpine dynamic processes and the associated rate of deformation resulting from late continental collision phases, and the assessment of seismic hazard and its associated risks. Seismic monitoring in the northern French Alps was launched in 1987 with the installation of the first seismological network, hosted by the Earth Science Observatory at Grenoble Alpes University. Since then, the network has been updated over the years, keeping pace with technical developments in seismic instrumentation, monitoring and data management. The homogenization of information described in this scientific data paper is motivated by the need for a single instrumental seismic catalogue, consisting in arrival times picks and hypocenters using the same velocity model. The final catalogue SISMalp-1987–2023 (CC-BY-4.0) contains 50,822 weak-to-moderate earthquakes with local magnitude between -1.8 and 5.0 ; it can serve as a basis for all general seismotectonic and risk assessment studies in the region.

Background & Summary

The European Alpine belt results from the convergence of the African and Eurasian plates, and the indentation of Eurasian lithosphere by the Adriatic promontory¹. This long-standing continental collision has led to strongly deformed lithospheric blocks, and microplate division evidenced by geological studies² and seismic tomography³. The present-day rate of crustal deformation is still high, as confirmed by Global Navigation Satellite System (GNSS) measurements^{4–6}. However, GNSS measurements show that convergence between Europe and Adria is still active in the eastern Alps, but it has stopped in the western part of the belt, where present-day kinematics is characterised by a counterclockwise rotation of the Adria microplate relative to Eurasia^{7,8}. Indeed, recent studies have revealed extensive and transcurrent horizontal strain rates in the western Alps, without measurable shortening^{7,9–13}. In spite of negligible convergence, vertical displacement rates are surprisingly high (~ 2 mm/yr) in the highest parts of the mountain belt^{14,15}. The processes invoked for this present-day uplift are either isostatic adjustment linked to surface processes (post-glacial rebound and erosion) or deep geodynamic processes (e.g., mantle upwelling), but no consensus has been reached as to their respective contributions⁶.

Moderate but constant seismic activity is associated with this deformation. Larroque *et al.*¹⁶ synthesized several relevant highlights on the seismic activity in the French Alps. As early as 1987, the SISMalp (Surveillance de la Sismicité des Alpes, <https://sismalp.osug.fr/>) network, hosted by the Earth Science Observatory (OSUG) of Grenoble Alpes University, and operated by the geophysics department of the Earth Science Institute (ISTerre), was launched in the French Alps (Fig. 1-left). The aim was to deploy a “dense” network of sensitive stations to compensate for the absence of strong-magnitude earthquakes by guaranteeing the ability to record low-to-weak magnitude earthquakes, and thus enable the study of the moderate seismicity of the Alps for seismotectonic analysis (e.g., the Belledonne border fault analysis¹⁷), regional seismic hazard^{18–20}, and tomography of the Alps²¹. The network also recorded some significant earthquakes (e.g., the local magnitude M_L 5.3 Epagny/Annecy 1996 earthquake²² and the M_L 4.5 Vallorcine/Chamonix 2005 earthquake²³) and specific seismic sequences (e.g., the Ubaye 2002–2003 seismic swarm²⁴ and the more recent Maurienne 2016–2019 seismic swarm²⁵). During the first period (1987–2013), triggered data were processed by in-house software to produce the SISMalp-1987–2013

ISTerre, Université Grenoble Alpes, USMB/CNRS/IRD/UGE, Grenoble, France. ✉e-mail: philippe.gueguen@univ-grenoble-alpes.fr

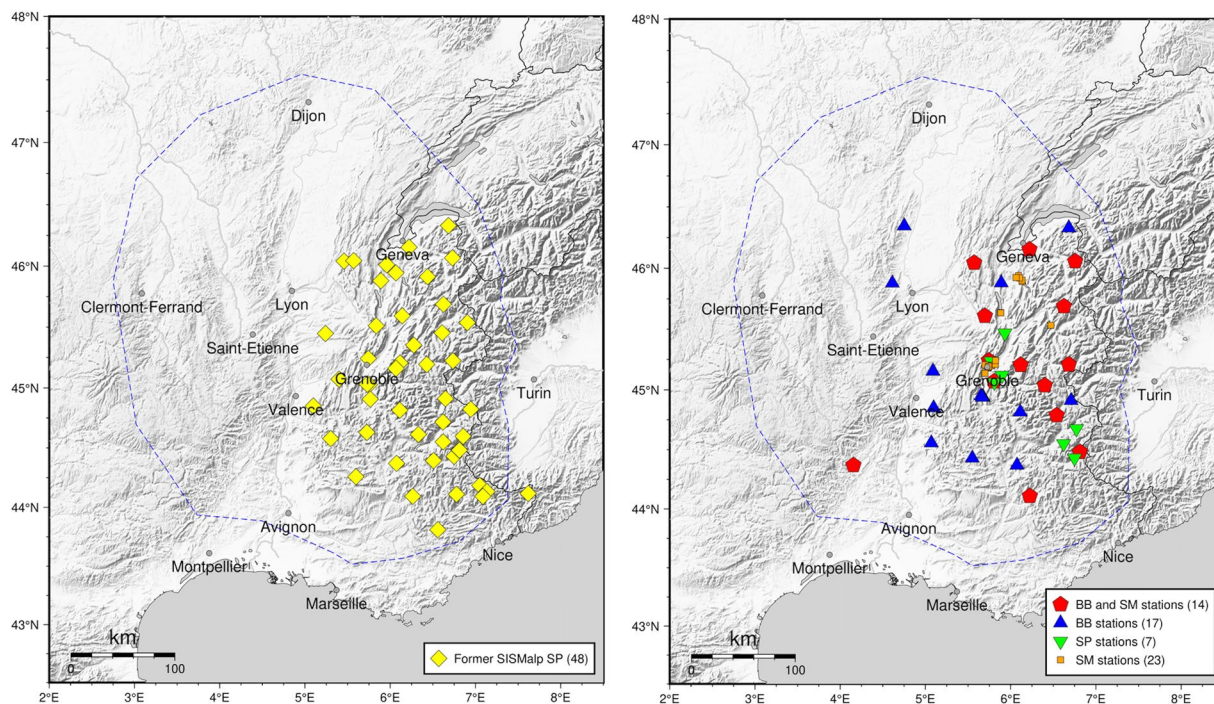


Fig. 1 SISMalp stations (left) during the period 1987–2013 and (right) today (end 2023). BB, SP and SM: broadband, short-period and strong-motion stations, respectively. The blue dashed line shows the geographic area covered by the catalogue of earthquakes published in this data paper.

catalogue. The number of present-day scientific issues yet to be explored confirm the need to maintain this observatory infrastructure, supported by research activities associated with the Alpine area.

Since the first installations in the late 80 s and early 90 s (i.e., stations in triggered mode with 1 Hz vertical seismometers), the network was rapidly upgraded thanks to major technological improvements in the areas of instrumentation, communications and earthquake monitoring developed by the seismological community over recent decades. Initially established as an independent regional network, SISMalp became part of a broader seismic monitoring effort with the creation of the national infrastructure RESIF in 2008 (recently integrated into Epos-France for alignment with the European EPOS infrastructure). This initiative facilitated the consolidation of regional seismic networks across France into a unified national infrastructure. SISMalp stations were progressively incorporated into national networks registered with the FDSN, aligning data and metadata descriptions with international FDSN standards, including site naming conventions, data and metadata description, and seismic observation tools. The French territory was divided into geographical areas, each managed by historical regional operators (i.e., universities, observatories, or research laboratories), with SISMalp being assigned the northern Alps region (Fig. 1).

In 2010, six first-period sites were upgraded with continuous, real-time 3-component broadband stations, thus anticipating the nation-wide standardisation of such equipment supported by the French seismological and geodetic network (Epos-France, formerly RESIF, <https://www.epos-france.fr/>). Between 2013 and 2015, the SeisComP²⁶ software was deployed and tested at the SISMalp operations centre, benefitting from new data management, processing and exploitation developments. In late 2015, continuous, real-time 3 C strong motion stations were incorporated in the seismic monitoring system. Since 2020, 17 3-component broadband (BB) stations (network code FR²⁷), 37 accelerometer (SM) stations (network code RA²⁸) (including 14 co-located with FR broadband stations) and 7 short-period (SP) stations (network code FR²⁷) with continuous and real-time recording have been in acquisition and are now part of the national Epos-France infrastructure (Fig. 1-right). Until 2014, seismic event localization was performed manually based on triggers. With the modernization of SISMalp, detections are now automatically generated from continuous data streams using SeiscomP, followed by manual review and validation of seismic events.

SISMalp operations centre continues its monitoring activities, providing a dynamic catalogue of earthquakes covering a large part of the French Alps and the Rhône valley (north of 43.5°N). In 2013, an in-house observatory framework for catalogue improvement was implemented at SISMalp: (1) in 2014, the SCANLOC module²⁹ improved picking of the arrival times of P and S wave phases, (2) 2016–2022 manual picking of events not automatically associated in the most active areas characterized by active seismic swarms, (3) since 2020, sharing of earthquake information (i.e., localisation, depth, local magnitude) with French RESIF partners through the QuakeLink package (<https://www.gempa.de/products/quakelink/>), and (4) since 2023, automatic day + 1 non-detected event searching with the machine-learning-based detection package EQTransformer³⁰ and the Rapid Earthquake Association and Location package (REAL³¹) before transfer to the SeisComP database for manual verification. The new generation of the SISMalp catalogue (herein referred to as SISMalp-1987-2023) is

Depth (km)	Vp (km/s)
0–3	5.30
3–27	5.92
27–35	6.60
>35	8.80

Table 1. Velocity model used by SISMalp for seismic location (considering $V_p/V_s = 1.7$).

	Number of stations	Number of picks
Primary Catalogue	415	1,137,455
...outside the SISMalp zone (see Fig. 1)	37	2,896
...net = LDG station without metadata	10	12,369
...other stations without metadata	43	4,292
XML SISMalp-1987-2013 catalogue	325	1,117,898
Ratio	78.3%	98.3%

Table 2. Number of stations and picked arrival times in the new version of the SISMalp-1987-2013 catalogue, including events outside the SISMalp zone.

constantly being improved in terms of completeness and precision. Due to the moderate seismicity in the Alpine region, the majority of events cannot be estimated using moment magnitude (M_w). Only a limited number of specific events, which have been subject to specific published analyses, have M_w evaluations. Correlations between M_L and M_w have also been established based on subsets of the catalogue data for targeted studies. To maintain consistency and homogeneity, the catalogue we produce is primarily reported in M_L .

However, these developments have made the 1987–2023 SISMalp catalogue heterogeneous in terms of epicentre and local magnitude information. Seismotectonic analysis requires homogeneous information on the hypocentres (including focal mechanisms) while seismic hazard assessment depends upon catalogue completeness and continuity in local magnitude assessment¹⁸. This paper therefore aims to present the work done on the whole 1987–2023 SISMalp catalogue (“SISMalp-1987–2023”) to share a reference catalogue for the French Alps area covered by SISMalp (see Fig. 1).

Methods

To build the SISMalp-1987-2023 catalogue, we used seismology community standards, specifically the QuakeML format³², to structure the event catalogue. QuakeML is an XML-based data exchange standard for seismology. It describes the properties of seismic events in a hierarchical manner, as well as the resources identified for enriching seismic information. It complies with the standards of the international Federation of Digital Seismograph Networks (FDSN³³) for defining the names of networks, stations, channels, etc.

Takeover from the primary catalogue, SISMalp-1987-2013. The first step was to extract the data from the primary catalogue, SISMalp-1987-2013, which included picking arrival times for the period 1987-2013. The polarities and errors associated with each pick were included in the extracted data. Local magnitudes were also extracted when available (e.g., no magnitude is available for 1987 and 1988, during the construction phase of the SISMalp network). Hypocentre locations had been calculated using a P- and S-wave velocity model (V_p , V_s) that has evolved over the years.

The locations were therefore recalculated a posteriori using the velocity model, described in Table 1, and now currently used by SISMalp. Velocity models from the SISMalp-1987-2023 catalogue were tested a posteriori by Virieux *et al.*²¹ and the SISMalp-1987-2023 catalogue has homogenous hypocentres. With the new velocity profile, most of the picks were kept as reliable (Table 2).

The metadata for the stations associated with the selected picks were then generated/created. This was a somewhat laborious task that involved digging up hard copies (records were not digitised at the time) archived at SISMalp and contacting the datacentres that distributed the data used for location. It is important to note that during the period covered by the catalogue, stations not managed by SISMalp were also used to locate events in the Alps. Picks belonging to stations in the Geoscope (code G), LDG (code RD), Genova university (code GU), INGV (codes IV and MN), and ETHZ (code CH) networks were used to improve the quality of monitoring system detection and location. The picked arrival times of stations with some missing metadata (e.g., network code, location, or channel) have been kept in the final version of the XML catalogue but with generic network/location/channel codes (net=XX, location=“00”, channel=“XXZ”). This metadata library recalculates the epicentres using the latest SISMalp velocity model (Table 1) to build the catalogue in the first Hypo71 format³⁴ before conversion into XML: QuakeML (version 1.2) for the catalogue of events with seismological information, and SC3ML (version 0.12) for the catalogue of picked arrival times used to locate/relocate events via the seismicity monitoring system implemented at SISMalp (SeisComp²⁶).

This enables each preserved picked arrival time to be associated with a station with, for the most part, known coordinates and other metadata (network and channel code, sometimes even instrumental response).

	NoLoc	Loc	Total
Number of events	78,520 (69.6%)	34,357 (30.4%)	112,877
Number of picked arrival times	173,030 (15.5%)	944,868 (84.5%)	1,117,898
Mean number of picked arrival times per event	2.2	27.5	

Table 3. Earthquake number in the SISMalp-1987-2013 xml catalogue, located (Loc) or unlocated (NoLoc) in the primary catalogue.

Re-formatting the primary catalogue, SISMalp-1987-2013. The primary catalogue in Hypo71 format was converted to SC3ML / QuakeML formats, including all parameters available for transfer to the SeisComP database, in order to build the complete catalogue for the period 1987–2023. It should be noted that a significant proportion of the detected events (Table 3) have a low number of picked arrival times and were therefore not located in the primary catalogue. These events were converted anyway, using the coordinates of the station of the first pick (earliest pick time) as their artificial origin.

All located events were converted to XML format and named as follows: ISTerre-SISMALP-Year-EvIndex.xml, where Year is replaced by the year, and EvIndex is a 6-digit index starting with 000001. Table 3 shows the number of events included in the primary catalogue.

Fusion of catalogues for 1987–2013 and 2013–2023. After conversion to the SC3ML format, all the hypocentre information (origin, picks, magnitudes, errors, polarities, etc.) was imported into the SeisComP/SISMalp database. The area of the original SISMalp catalogue was larger than the area concerned by the new catalogue since 2013. This is due to a refocusing of SISMalp observation activities on the northern western Alps (north of 43.5°N), due to the operational organisation of seismic monitoring in collaboration with the other French observatories in the context of the Epos-France nation-wide infrastructure.

After transferring the SISMalp-1987-2013 catalogue into SeisComP, the database was sorted and classified. All events from SISMalp-1987-2013 located outside the new zone were classified as “Outside-of-Interest” but not deleted. The classification of events used in SISMalp-1987-2013 was carried over to the completed SeisComP database covering the period 1987–2023. The “earthquake” type was maintained, while “explosion” and “quarry blast” were merged into a single “quarry blast” category for homogeneity.

The final version of the earthquake hypocentre catalogue 1987–2023 is shown in the map of Fig. 2. The SISMalp network coverage is limited to its defined area of interest as specified in Epos-France. For integration with other national catalogues or those of European partners, such as Switzerland or Italy, data merging should be done using the arrival time picks provided in QuakeML format rather than the hypocentre catalogue.

Validity and Quality of the data. Events occurring during the 2013–2019 period of the SISMalp-2013-2023 catalogue were validated and rigorously classified in 2020 according to (1) the SISMalp geographical area (event outside -> “Outside-of-Interest”), (2) event type (quarry blast/earthquake) based on location criteria (using QGIS software to compare the type, time and position of “suspicious” events), time, waveform and magnitude, and (3) work on earthquake depths (no surface earthquakes, relocation/re-picking work).

In the 1987–2023 events database integrated into SeisComP, 1987–2013 events are distinguished by agency name (ISTerre-SISMalp) and the event identifier (ISTerre-SISMALP-YEAR-idnumber, and events from 2013–2023 by ISTerre and ISTerreYEARalphabeticalcode).

In addition to converting, merging and classifying the events from the SISMalp-1987-2013 catalogue, we have also compiled a database of seismological waveforms from historical SISMalp stations over the period 1987–2013. The trigger-mode data were archived in an “outdated” data format. This conversion work was carried out in best-effort mode, in the sense that results that could not be exploited (e.g., loss of information due to naming of the stations/sites that produced these recordings) were not converted into the current standard mseed format supported by SeisComP. This conservation effort will enable us to make this discontinuous archive available to the community. However, the quality of the converted data will not be guaranteed and a significant number of records will include conversion errors (unreadable signals) or dating errors (problem of triggered stations using a radio time stamp system which limits the correction of time).

This data conversion was carried out in the same spirit of safeguarding and preserving instrumental seismicity in the Alps, which was the motivation for the SISMalp-1987-2023 catalogue.

Since 2020, these criteria have been systematically applied for manual relocation steps to maintain the homogeneity of the catalogue.

The evaluation of M_L in SISMalp-1987-2013 and SISMalp-2013-2023 is computed based on amplitudes measured from waveform. For the first period, the original SISMalp magnitude is kept, as defined in Thouvenot *et al.*³⁵. For the second period, the magnitude is computed according to the SeiscomP attenuation model described on the user manual (<https://docs.gempa.de/seiscomp/current/base/glossary.html#term-magnitude-local-ML>), without adapting the parameters to the area of interest. Both magnitudes are not calibrated to the same attenuation model. This is a strong limitation of the produced catalogue, particularly concerning discussions on the completeness and seismic hazard assessment. Recalculating the magnitude in SISMalp-1987-2013 is not feasible due to missing data and information (related to instrumental response and triggering mode of recording). A correlation relationship over a common year is currently being studied, with the aim of generalizing it to the entire period.

Concerning M_L calculated in SISMalp-2013-2023, a bias for low-magnitude earthquakes ($M_L < 1.0$) was identified, mainly due to the fact that most of the SISMalp stations are broadband. The long-period wave due to macroseismic noise outweighs the seismic signal produced by the event, even in the near-field. Although

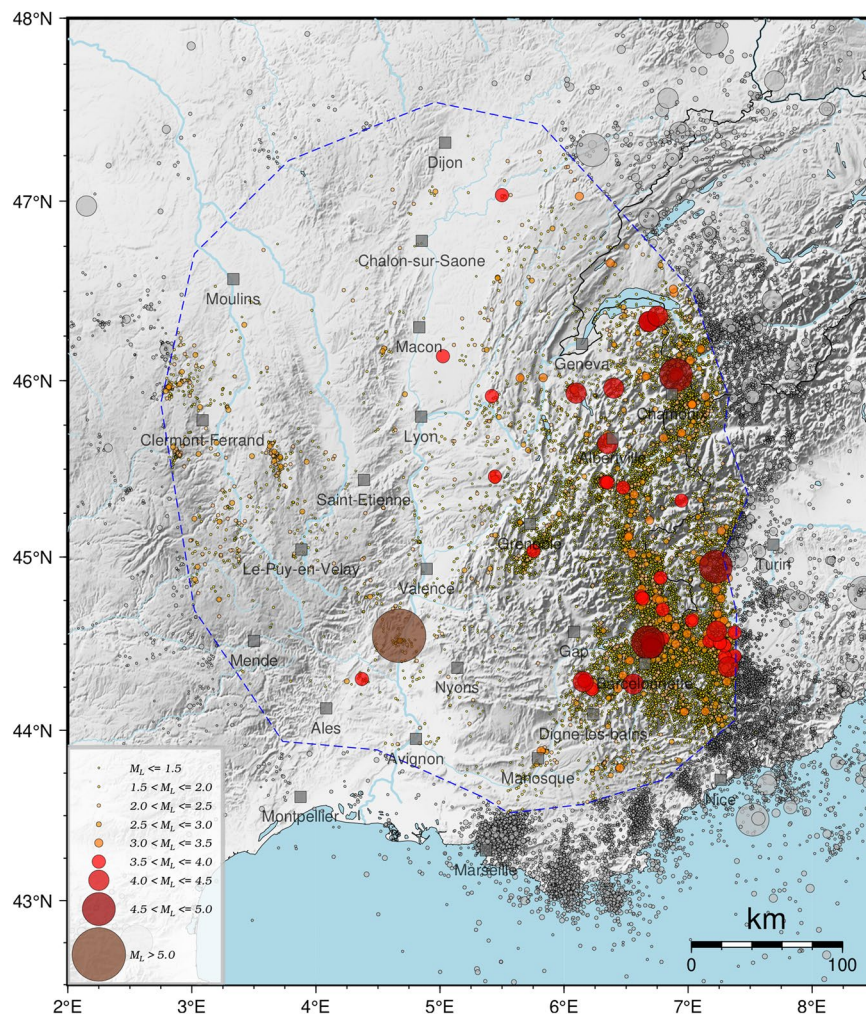


Fig. 2 Map of earthquake epicentres from the SISMalp-1987-2023 catalogue. The blue dashed line shows the geographic area covered by the catalogue. The outer grey circles are epicentres detected by the SISMalp network but not distributed by SISMalp.

the signal is filtered for detection, this was not always done correctly in the SeisComP system implemented at SISMalp for the magnitude calculation. This issue was corrected in 2022, but a major overhaul is necessary to recalculate all the magnitudes of $M_L < 1.0$ events in previous years and will be scheduled in the near future. The differences observed when setting up this filter might be significant (of the order of one magnitude).

Other data identified by an ISTerreEQT1696407633662489496-type ID correspond to events automatically located by the EQTransformer + REAL process added to our SISMalp SeisComP instance and triggered, for example, during swarm-type seismic sequences for better spatiotemporal resolution.

Data Records

The SISMalp-1987-2023 catalogue³⁶ is hosted by the Data Terra repository, the French infrastructure designed to facilitate access to solid earth data acquired and managed by research laboratories and observatory services³⁶. The catalogue contains only earthquakes, i.e. non-localized earthquakes and others event (e.g., blasts) are removed for this repository.

The data repository contains the following:

1. **Earthquake Catalog:** The complete catalog of earthquakes is available in QuakeML (QUAKEML.atr.gz) and SC3 (SC3ML.tar.gz) formats. These files include hypocentral information related to each earthquake, such as the geographical location of the epicenter (latitude, longitude, depth), local magnitude, and arrival times of seismic phases (e.g., Pg and Sg waves) picked with SeisComP. Each pick includes associated timing errors based on the velocity model (Table 1). Additional metadata include station and network details, recording channel information relative to instrument type and orientation, and observatory agency identification. The file also includes additional details for the largest events, such as focal mechanisms and P and S wave polarities, where these assessments are feasible. These files provide a comprehensive set of information in a standard expert format that can be utilized by observatory agencies or expert seismologists looking to integrate this data into a broader activity of research or observation.

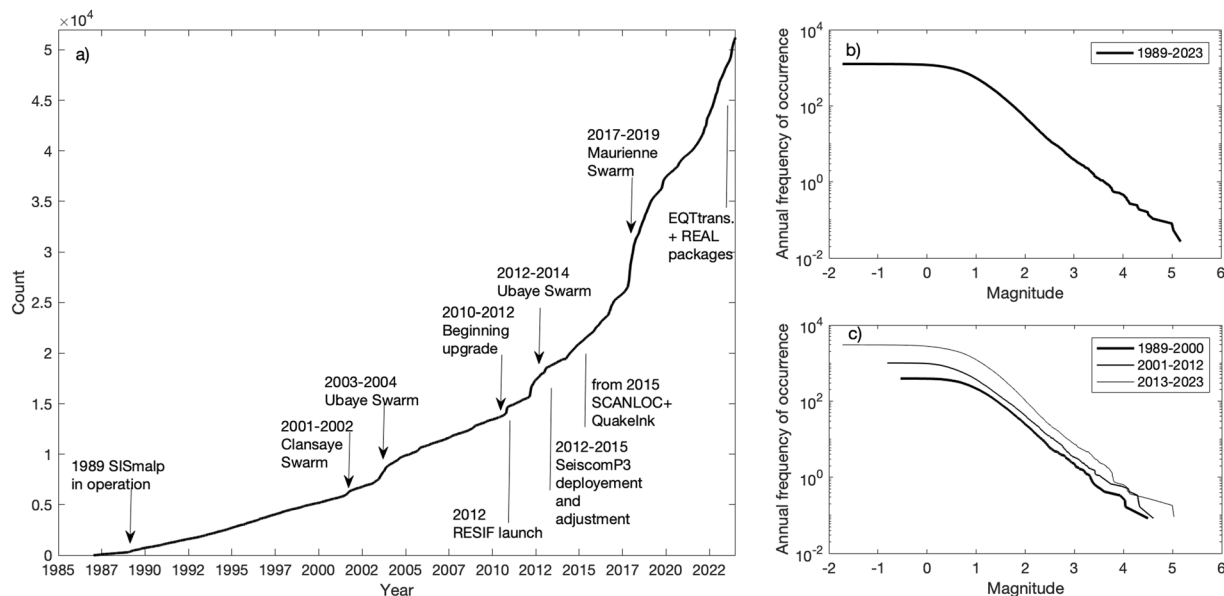


Fig. 3 The SISMalp 1987–2023 catalogue. **(a)** Cumulative number of earthquakes per year with significant seismic sequences that temporally modify background seismicity and network upgrade that improves detection. **(b)** Annual frequency of occurrence by magnitude for the 1989–2023 catalogue. **(c)** Evolution of the annual frequency of occurrence according to the main upgrade periods (1989–2000, 2001–2012 and 2013–2023), showing the improvement in detection.

- Event List:** A CSV file (EQ-SISMALP-1987-2023.csv) containing a list of events with key details such as the event time, hypocentral parameters (latitude, longitude, depth), and local magnitude for expert or non-expert seismologists.
- Station Metadata:** A text file (Station_info_final.csv) containing basic station metadata since 1987. This includes the network and station names, channel names in FDSN format (instrument type and orientation), operational periods (opening and closing dates), and station locations (latitude, longitude, elevation).
- README File:** A README.txt file providing descriptions of the contents of each file, including naming conventions and data structure details.

Earthquakes outside the SISMalp zone are available via Epos-France web services (<https://www.epos-france.fr/>). Lastly, time series (seismograms) are available for visualization exclusively for earthquakes recorded between 2013 and 2023 in the SISMalp dataset via the Epos-France time_series_plot web service. (<https://ws.resif.fr/resifws/timeseriesplot/1/local=en>).

To cite the dataset: Janex, G., Langlais, & Guéguen, P. SISMalp-1987-2023: The catalogue of 1987–2023 earthquakes in the western (French) Alps north of 43.5°N. <https://doi.org/10.57932/bba3b3a3-e92e-4d90-92db-9b045684ed5d> (2024).

Technical Validation

Recent ambient noise tomography of W-Europe³⁷ and receiver function cross-sections of seismic experiments in the Western Alps³⁸ contributed to new evidences on the crustal-scale geometry and European Moho attitude of Western Alps. In addition, the SISMalp-1987-2023 comprehensive database for the French Alps enables in-depth study of the influence of the parameters and choices involved in a Local Earthquake Tomography (LET) application, which inverts local-regional earthquake arrival time selections for P- and S-wave velocities jointly with hypocentre parameters.

Virieux *et al.*²¹ used the SISMalp-1987-2023 catalogue to test picking and location quality, and the velocity model via LET. Based on the 1987–2013 events (implemented in SISMalp-1987-2023), which had already been the subject of specific work on arrival times and seismic imaging of the Alps³⁹, several spatially and temporally distributed data subsets confirmed the reliability of the fusion of the two observation periods. The merging of temporal selection databases must be carried out with care, as data quality can be highly variable due to differences between acquisition systems and selection strategies, whether manual or automatic. For example, by examining the residuals between observed arrival times and synthetic arrival times, Virieux *et al.*²¹ have shown that strict examination of the new database is unnecessary, as the 3D velocity models obtained from the 1987–2013 database are accurate enough to enable good quality prediction of synthetic times compared with picked times. Furthermore, the initial hypocentre locations obtained by hypo71 are sufficiently reliable to allow data selection based on the comparison of observed and synthetic times. In conclusion, Virieux *et al.*²¹ demonstrated, using LET as an integral part of the fusion strategy, that the SISMalp-1987-2023 database is of similar quality to the earlier SISMalp-1987-2013 database, but with a much larger number of selections from more stations, thus improving spatial coverage.

The characteristics of the SISMalp-1987–2023 catalogue are described in Fig. 3. Observed seismicity has increased due to the deployment of new stations (Fig. 3a) and optimization of the detection and location system. The cumulative number of seismic events detected by SISMalp highlights the significant contribution of the most significant swarms in the SISMalp-monitored area, i.e. the Ubaye 2002–2003 seismic swarm²⁴ and the more recent Maurienne 2016–2019 seismic swarm²⁵. The overall increase in the seismic event localization rate (Fig. 3a) translates into a more complete catalogue since 1987 ($M_c < 1$), refining the spatiotemporal resolution of Alpine seismicity and confirming a constant seismicity rate (i.e., b-value of the annual frequency of the occurrence model defined as the slope of the rate) (Fig. 3b).

Code availability

SeisComP package. <https://www.gempa.de/>.

No custom code was used during this study for the curation and/or validation of the dataset.

Received: 23 January 2024; Accepted: 13 November 2024;

Published online: 26 November 2024

References

- Coward, M. & Dietrich, D. Alpine tectonics—an overview. *Geological Society, London, Special Publications* **45**(1), 1–29 (1989).
- Handy, M. R., Schmid, S. M., Bousquet, R., Kissling, E. & Bernoulli, D. Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps. *Earth-Science Reviews* **102**(3–4), 121–158 (2010).
- Malusà, M. G. *et al.* The deep structure of the Alps based on the CIfALPS seismic experiment: A synthesis. *Geochemistry, Geophysics, Geosystems* **22**(3), e2020GC009466 (2021).
- Nocquet, J. M. & Calais, E. Geodetic measurements of crustal deformation in the Western Mediterranean and Europe. *Pure and applied geophysics* **161**, 661–681 (2004).
- Walpersdorf, A. *et al.* Does long-term GPS in the Western Alps finally confirm earthquake mechanisms? *Tectonics* **37**(10), 3721–3737 (2018).
- Sternai, P. *et al.* Present-day uplift of the European Alps: Evaluating mechanisms and models of their relative contributions. *Earth-Science Reviews* **190**, 589–604 (2019).
- Calais, E., Nocquet, J. M., Jouanne, F. & Tardy, M. Current strain regime in the Western Alps from continuous Global Positioning System measurements, 1996–2001. *Geology* **30**(7), 651–654 (2002).
- Collombet, M. *et al.* Counterclockwise rotation of the western Alps since the Oligocene: New insights from paleomagnetic data. *Tectonics* **21**(4), 14–1 (2002).
- Delacou, B., Sue, C., Champagnac, J. D. & Burkhard, M. Present-day geodynamics in the bend of the western and central Alps as constrained by earthquake analysis. *Geophysical Journal International* **158**(2), 753–774 (2004).
- Heidbach, O. *et al.* The World Stress Map database release 2016: Crustal stress pattern across scales. *Tectonophysics* **744**, 484–498 (2018).
- Mathey, M., Walpersdorf, A., Sue, C., Baize, S. & Déprez, A. Seismogenic potential of the High Durance Fault constrained by 20 yr of GNSS measurements in the Western European Alps. *Geophysical Journal International* **222**(3), 2136–2146 (2020).
- Serpelloni, E., Vannucci, G., Anderlini, L. & Bennett, R. A. Kinematics, seismotectonics and seismic potential of the eastern sector of the European Alps from GPS and seismic deformation data. *Tectonophysics* **688**, 157–181 (2016).
- Serpelloni, E. *et al.* Hydrologically induced karst deformation: Insights from GPS measurements in the Adria-Eurasia plate boundary zone. *Journal of Geophysical Research: Solid Earth* **123**(5), 4413–4430 (2018).
- Serpelloni, E., Faccenna, C., Spada, G., Dong, D. & Williams, S. D. Vertical GPS ground motion rates in the Euro-Mediterranean region: New evidence of velocity gradients at different spatial scales along the Nubia-Eurasia plate boundary. *Journal of Geophysical Research: Solid Earth* **118**(11), 6003–6024 (2013).
- Nocquet, J. M. *et al.* Present-day uplift of the western Alps. *Scientific reports* **6**(1), 28404 (2016).
- Larroque, C. *et al.* Seismotectonics of southeast France: from the Jura mountains to Corsica. *Comptes Rendus. Géoscience* **353**(S1), 105–151 (2021).
- Thouvenot, F., Fréchet, J., Jenatton, L. & Gamond, J. F. The Belledonne Border Fault: identification of an active seismic strike-slip fault in the western Alps. *Geophysical Journal International* **155**(1), 174–192 (2003).
- Beauval, C. & Scotti, O. Quantifying sensitivities of PSHA for France to earthquake catalog uncertainties, truncation of ground-motion variability, and magnitude limits. *Bulletin of the Seismological Society of America* **94**(5), 1579–1594 (2004).
- Tasan, H., Beauval, C., Helmstetter, A., Sandikkaya, A. & Guéguen, P. Testing probabilistic seismic hazard estimates against accelerometric data in two countries: France and Turkey. *Geophysical Journal International* **198**(3), 1554–1571 (2014).
- Beauval, C. & Bard, P. Y. History of probabilistic seismic hazard assessment studies and seismic zonation in mainland France. *Comptes Rendus. Géoscience* **353**(S1), 413–440 (2021).
- Virieux, J. *et al.* Assessing the reliability of local earthquake tomography for crustal imaging: 30 years of records in the Western Alps as a case study. *Geophysical Journal International* **236**(1), 99–118 (2023).
- Thouvenot, F. *et al.* The ML 5.3 Epagny (French Alps) earthquake of 1996 July 15: a long-awaited event on the Vuache Fault. *Geophysical Journal International* **135**(3), 876–892 (1998).
- Fréchet, J., Thouvenot, F., Frogneux, M., Deichmann, N. & Cara, M. The Mw 4.5 Vallorcine (French Alps) earthquake of 8 September 2005 and its complex aftershock sequence. *Journal of Seismology* **15**, 43–58 (2011).
- Jenatton, L., Guiguet, R., Thouvenot, F., & Daix, N. The 16,000-event 2003–2004 earthquake swarm in Ubaye (French Alps). *Journal of Geophysical Research: Solid Earth* **112**(B11) (2007).
- Guéguen, P. *et al.* Unprecedented seismic swarm in the Maurienne valley (2017–2019) observed by the SISMalp Alpine seismic network: operational monitoring and management. *Comptes Rendus. Géoscience* **353**(S1), 517–534 (2021).
- Weber, B. *et al.* SeisComP3—Automatic and interactive real time data processing. *In Geophys. Res. Abstr.* **9**(09), 219 (2007).
- RESIF. RESIF-RLBP French Broad-band network, RESIF-RAP strong motion network and other seismic stations in metropolitan France. RESIF – Réseau Sismologique et géodésique Français <https://doi.org/10.15778/resif.fr> (1995a).
- RESIF. RESIF-RAP French Accelerometric Network, RESIF – Réseau Sismologique et géodésique Français <https://doi.org/10.15778/resif.ra> (1995b).
- Röföler, D. *et al.* Cluster-search based monitoring of local earthquakes in SeisComP3. In *AGU Fall Meeting Abstracts* **2016**, S31E–06 (2016).
- Mousavi, S. M., Ellsworth, W. L., Zhu, W., Chuang, L. Y. & Beroza, G. C. Earthquake transformer—an attentive deep-learning model for simultaneous earthquake detection and phase picking. *Nature communications* **11**(1), 3952 (2020).
- Zhang, M., Ellsworth, W. L. & Beroza, G. C. Rapid earthquake association and location. *Seismol. Res. Lett.* **90**(6), 2276–2284 (2019).

32. Schorlemmer, D., Euchner, F., Kästli, P., Saul, J. & Quake, ML Working Group. QuakeML: status of the XML-based seismological data exchange format. *Annals of Geophysics* **54**(1) (2011).
33. Suárez, G. *et al.* The international federation of digital seismograph networks (FDSN): An integrated system of seismological observatories. *IEEE Systems Journal* **2**(3), 431–438 (2008).
34. Lee, W. H. K., & Lahr, J. C. HYPO71: A computer program for determining hypocenter, magnitude, and first motion pattern of local earthquakes. *US Department of the Interior, Geological Survey, National Center for Earthquake Research* (1972).
35. Thouvenot, F., Fréchet, J., Guyoton, F., Guiguet, R. & Jenatton, L. Sismalp: an automatic phone-interrogated seismic network for the western Alps. *Cahiers du Centre européen de géodynamique et de sismologie* **1**(1), 10 (1990).
36. Janex, G., Langlais, & Guéguen, P. SISMalp-1987-2023: The catalogue of 1987-2023 earthquakes in the western (French) Alps north of 43.5°N, <https://doi.org/10.57932/bba3b3a3-e92e-4d90-92db-9b045684ed5d> (2024).
37. Nouibat, A. *et al.* Lithospheric transdimensional ambient-noise tomography of W-Europe: implications for crustal-scale geometry of the W-Alps. *Geophysical Journal International* **229**(2), 862–879 (2022).
38. Paul, A. *et al.* Along-strike variations in the fossil subduction zone of the Western Alps revealed by the CIFALPS seismic experiments and their implications for exhumation of (ultra-) high-pressure rocks. *Earth and Planetary Science Letters* **598**, 117843 (2022).
39. Potin, B. Les Alpes occidentales: tomographie, localisation de séismes et topographie du Moho. PhD thesis, Université Grenoble Alpes <https://theses.hal.science/tel-01539221v1> (2016).

Acknowledgements

This study was supported by LabEx OSUG@2020 (Investissements d’avenir-ANR10LABX56). Part of the study was funded by the SISM@LP-Swarm (POIA-FEDER Grant, financed by Région Sud and Agence Nationale de la Cohésion des Territoires). SISMalp is part of the Epos-France national infrastructure recognised as such by the French Ministry of Higher Education and Research. Epos-France is managed by the Epos-France consortium, composed of 18 research institutions and universities in France. Résif-Epos is also supported by a public grant overseen by the French National Research Agency (ANR) as part of the “Investissements d’Avenir” programme (reference: ANR-11-EQPX-0040) and the French Ministry of Ecology, Sustainable Development and Energy. The authors would like to thank all the SIG (Geophysical Instrumentation) group members at ISTerre who actively maintain and manage the stations in the field (see list of members: <https://www.isterre.fr/french/services-plateformes/gis-geophysical-instrumentations/membres-du-service/>).

Author contributions

Mickael Langlais was involved in the picking of arrival times, implementation of the SeisComp package codes in SISMalp, maintenance of the SISMalp catalogues; he also contributed to the writing of this paper and its revision. Gael Janex was responsible for merging the catalogues, exporting them in XML format, uploading them to the DataTerra national datacentre; he also helped to write and revise this paper. Philippe Guéguen was responsible for the scientific coordination and supervision of the project, writing the first version of the article and coordinating with the co-authors. Anne Paul co-led the validation phase of the SISMalp catalogue via the Local Earthquake Tomography (LET) application and helped to write and revise the paper. Jean Virieux co-led the validation phase of the SISMalp catalogue via the Local Earthquake Tomography (LET) application and helped to write and revise the paper. Emeline Maufroy has contributed to the writing of the paper and its revision as head of the permanent National strong-motion network (RAP-RESIF @ Epos-France) involved in the Alps seismic monitoring. Agnès Helmstetter was involved in the picking of arrival times and has contributed to the writing of the paper and its revision. Jean-Noel Bouvier is the IT supervisor who maintains the IT system for the SISMalp Network.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to P.G.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2024