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# Data and service management of the EPOS Volcano Observations Thematic Core Service by the European volcanological community

Letizia Spampinato<sup>1</sup> · Enrico Indovina<sup>1</sup> · Adelina Geyer<sup>2</sup> · Rikey Júlíusdóttir<sup>3</sup> · Danilo Reitano<sup>1</sup> · Giuseppe Puglisi<sup>1</sup> · Rosella Nave<sup>4</sup> · Ileana Santangelo<sup>4</sup> · Kristín Vogfjörð<sup>3</sup> · Philippe Labazuy<sup>5</sup> · Lucia Cacciola<sup>1</sup> · Itahiza Domínguez-Cerdeña<sup>6</sup> · Yannick Guehenneux<sup>5</sup> · Jean-Christophe Komorowski<sup>7</sup> · Jean-Marie Saurel<sup>7</sup>

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## Abstract

The Volcano Observations Thematic Core Service (VOLC-TCS) is one of ten core services forming the European Research Infrastructure Consortium for the European Plate Observing System (EPOS ERIC). The main objective of the VOLC-TCS is the implementation of a technical, financial, and legal framework compliant with EPOS ERIC to (i) strengthen the European volcanology community represented by Volcano Observatories (VOs) and Volcanological Research Institutions (VRIs), and (ii) provide virtual access to the community's data, data products software and services (DDSSs) from volcanoes in Europe and European overseas territories. The efforts of the VOLC-TCS community began prior to the appointment of EPOS as an ERIC and have followed a long-term work plan that started in 2002. One of the main challenges for the management of volcanological data has consisted in their great heterogeneity regarding technical characteristics and also legal aspects (e.g. different data policies among the data providers, different purposes for the use of data, ranging from science to monitoring, early-warning and crisis response, and communication and outreach). Another challenge has derived from the consistency of the VOLC-TCS' products with the overall service provision of EPOS, which merges services from different Earth Science communities (seismology, GNSS, geomagnetic, geochemistry, geology, etc.). Some of the services used in volcanology are in common with the other communities, thus the implementation work was also devoted to harmonising the data and products with standards defined by other TCSs. Yet another important task has been the implementation of the community Gateway to expose and enable access to services not fully compliant with EPOS, or to services implemented by institutions outside the EPOS perimeter, as well as to create a platform that can act as an interface between the VOLC-TCS and data infrastructures operating at a global level (e.g. WOVodat). Based on the experience gained and the results achieved, we report here on the state of the art of the VOLC-TCS implementation since 2018 and propose future actions to address some of the main technical challenges and measures to ensure mid-to-long term sustainability of the services.

**Keywords** Open Science · Data management · EPOS Research Infrastructure · Volcano community building

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✉ Letizia Spampinato  
letizia.spampinato@ingv.it

<sup>1</sup> Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo-sezione di Catania, Piazza Roma 2, 95125 Catania, Italy

<sup>2</sup> Geosciences Barcelona, CSIC, Lluís Solé Sabaris S/N, 08028 Barcelona, Spain

<sup>3</sup> Icelandic Meteorological Office, Bústaðavegur 9, 150 Reykjavík, Iceland

<sup>4</sup> Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Via Diocleziano 328, 80124 Naples, Italy

<sup>5</sup> Laboratoire Magmas Et Volcans, Université Clermont Auvergne, CNRS, IRD, OPGC, 63000 Clermont-Ferrand, France

<sup>6</sup> Instituto Geográfico Nacional, C/La Marina 20, -2, 38003 Santa Cruz de Tenerife, Spain

<sup>7</sup> Institut de Physique du Globe, Université Paris Cité, CNRS, 75005 Paris, France

## Acronyms

DDSS	Data, Data products, Services, Software
DP	Data Provider
EPOS	European Plate Observing System
EPOS-IP	European Plate Observing System-Implementation Phase
EPOS-PP	European Plate Observing System-Preparatory Phase
ERIC	European Research Infrastructure Consortium
ESFRI	European STRategy Forum on Research Infrastructures
GLASS	Geodetic Linkage Advance Software System
GNSS	Global Navigation Satellite Systems
ICS	Integrated Core Services
JRU	Joint Research Unit
NRI	National Research Infrastructure
RI	Research Infrastructure
SP	Service Provider
TCS	Thematic Core Services
TNA	TransNational Access
VA	Virtual access
VO	Volcano Observatories
VOLC-TCS	VOLCano Observations-Thematic Core Service
VRI	Volcanology Research Institutions

## Introduction

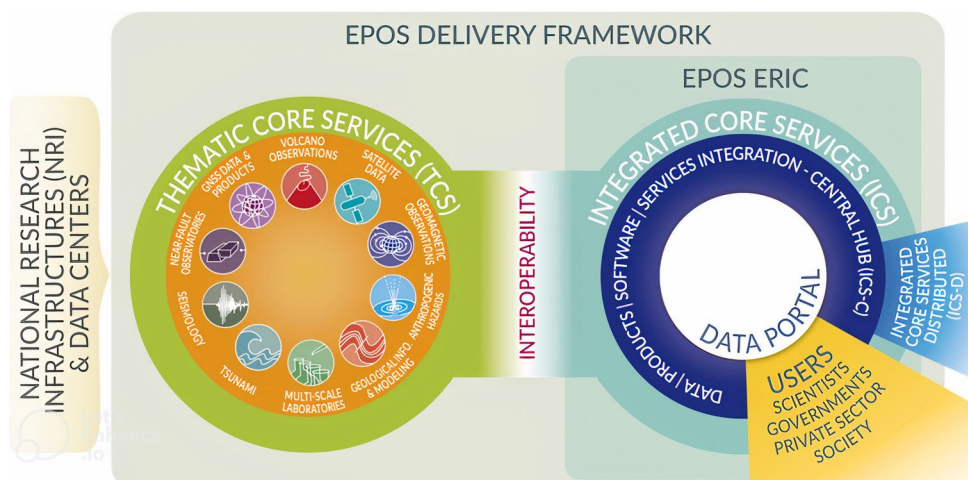
The VOLC-TCS is one of ten thematic core services of the distributed research infrastructure EPOS ([e-pos.eu.org](http://e-pos.eu.org)). The aim of EPOS is to provide access to DDSSs, entailing creation of new e-science tools to unravel the dynamics and complexity of the Earth system. The scientific scope of EPOS is to advance the Earth Science community toward

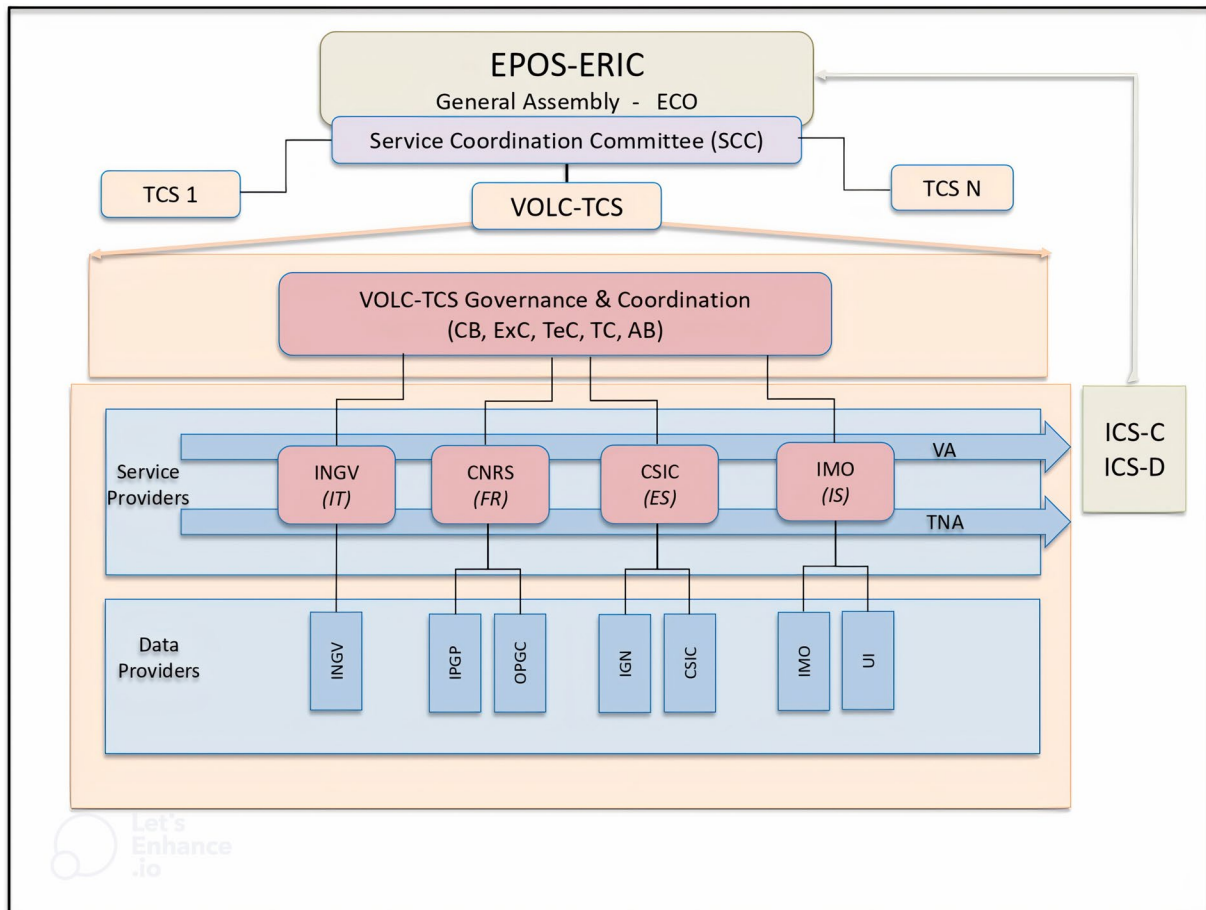
more multidisciplinary research of frontiers and development of new models that are crucial for answering scientific and socio-economic questions concerning geo-hazards and geo-resources by applying the paradigm of Open Science. Figure 1 shows the EPOS architecture in which the main connected technical and structural elements are identified, i.e. National Research Infrastructures (NRIs), Thematic Core Services (TCSs), and Integrated Core Service (ICS) (see Puglisi et al. 2022 and [e-pos.eu.org](http://e-pos.eu.org) for details). EPOS became an ERIC late in 2018; however, the community has been working on this long-term project since 2002 within four main phases: the EPOS Conception Phase (2002–2008), EPOS Preparatory Phase (2010–2014), EPOS Implementation Phase (2015–2019), and EPOS Sustainability Phase (2019–2022). Each of these phases was funded by a European Strategic Forum for Research Infrastructure (ESFRI) project (Puglisi et al. 2022).

The VOLC-TCS aims to promote volcanology research in Europe by fostering knowledge sharing and scientific collaboration through provision of long-term sustainable access to the DDSSs of European Volcano Observatories (VOs) and Volcanological Research Institutions (VRIs). Thus, VOLC-TCS is working to support the European VOs and VRI's community; implement interoperable services to ensure long-term and sustainable access to its DDSSs; and promote good practices within the volcanology community through EPOS (Puglisi et al. 2022; Wessels et al. 2022).

The VOLC-TCS technical architecture is organised in a layered structure and connected to the EPOS infrastructure as shown in Fig. 2. The main role in the VOLC-TCS is played by the VOs and VRIs, which are the service providers (SPs) for the TCS. The lowermost layer of the structure includes the data providers (DPs; other national RIs) that give access to their DDSSs through the VOLC-TCS' SPs, whereas the uppermost layer consists of the Governance and Coordination bodies of the TCS (Puglisi et al. 2022). At the beginning of 2024, the VOLC-TCS' SPs are Istituto

**Fig. 1** Key elements of the EPOS Functional Architecture. From left to right: The National Research Infrastructures (NRIs) provide data and services to the Thematic Core Services (TCSs) that in turn give access to users through the Integrated Core Service – Distributed (ICS-D) takes data from ICS-C to produce higher-level data and provide visualization services or high-performance computing (taken from [e-pos.eu.org/](http://e-pos.eu.org/))





**Fig. 2** General architecture of the VOLC-TCS and its position in the overall EPOS framework. The lower level refers to the source of the VOLC-DDSSs available through the DPs and SPs and coordinated by National Consortia (if they exist). The medium level refers to the technical management of the services (Virtual and Transnational Access; VA and TNA) services; all managed by SPs and the third overarching level refers to the management of the governance,

legal and financial issues of the TCS and the coordination activity of the community. The figure shows the SPs already activated in 2023. CB, Consortium Board; ExC, Executive Committee; TeC, Technical Board; TC, Transnational Access Committee; AB, Advisory Board; ICS-C, Integrated Core Services Central Hub system; ICS-S, Integrated Core Services Central Distributed

Nazionale di Geofisica e Vulcanologia (INGV, Italy), which is also the VOLC-TCS coordinator, Icelandic Meteorological Office (IMO, Iceland), Agencia Estatal Consejo Superior de Investigaciones Científicas (CSIC, Spain), and Centre National de la Recherche Scientifique (CNRS, France). The SPs are committed to the VOLC-TCS via a Consortium Agreement in which different governance bodies with diverse roles are identified (Puglisi et al. 2022).

The VOLC-TCS' DDSSs are intrinsically heterogeneous in nature, and their characteristics have significantly impacted on the service implementation and provision. In fact, the management of such heterogeneity has represented one of the main challenges for the VOLC-TCS, although unquestionably such a peculiarity does represent a great resource for users in terms of the variety of available information. Currently available DDSSs are of geophysical, geochemical, geological, and volcanological kinds and

include data collected by both in situ and remote instruments (ground- and satellite-based) (Table 1 in the Appendix). Moreover, the DDSSs are of diverse processing levels spanning from automatically acquired data (level 0, e.g. seismic waveforms) to more elaborated/integrated data products (level 3, e.g. hazard maps). Indeed, given the location of the VOs and VRIs, the DDSSs also differ geographically, including European volcanoes and volcanoes in overseas European territories (Table 1 in the Appendix).

To successfully provide virtual access (VA) to the VOLC-TCS' DDSSs through the EPOS Data Portal, the main effort has been in defining the metadata according to the standards of the EPOS ICS (<https://epos-eu.github.io/EPOS-DCAT-AP/v3/>). Thus, as the first step, a metadata definition process was carried out associating a conceptual model used to create a database structure, in which the information is stored, managed, and updated. During this phase, a catalogue for

VOLC-TCS' facility discovery available for physical or remote access was also implemented based on what was learnt from the ENVRI PLUS (2015–2019; envriplus.eu) and EUROVOLC (2018–2021; eurovolc.eu) EU projects (Puglisi et al. 2022; Wessels et al. 2022). Concerning the legal aspects related to DDSS provision, VOLC-TCS adopts the Open Access criteria and the Licences defined in the EPOS Data Policy (epos-eu.org/data-policy-2018). At the time of writing, the VOLC-TCS has already exposed part of its services via the EPOS Data Portal (epos-eu.org/data-portal), officially launched in Spring 2023. The EPOS Data Portal enables users to discover, visualise, and download Earth Science data in an integrated way. The portal is the result of collective work by an international team of about 600 experts working in synergy on the integration and harmonisation of over 60 different kinds of data and metadata from various disciplines, made available as EPOS data and services to the users (Bailo et al. 2023).

In addition, the VOLC-TCS is developing the Volcano Observations Gateway (/vo-tcs.ct.ingv.it/gateway/), which aims to overcome the fragmentation of the volcanology community and the widely distributed infrastructures by developing dynamic connections and collaborations within the community and between the community and its stakeholders. The VOLC-TCS envisages implementation of other services in order to offer a wider portfolio of volcanological DDSSs. Thus the Gateway (whose final name will be EUROVOLC, as an acronym for EUROpean VOLcanological Community) deals with European Volcanoes and proposes a unique access point for volcanological DDSSs both for the EPOS compliant services and for those services that are not fully compliant with EPOS standards but are of significant importance for the volcano community.

Following this brief introduction, we aim to provide an update of the VOLC-TCS activities in terms of governance and coordination, data provision and technical service implementation, as well as in terms of dissemination and outreach activities carried out to better engage and enlarge the identified stakeholder community.

## Technical aspects

### Implementation of the EPOS Data Portal

The implementation of the VOLC-TCS services in the EPOS Data Portal was carried out in cooperation with, and under the overarching guide, of the EPOS ICS team (Puglisi et al. 2022). At the time of writing the implemented services have been classified into two categories. The first includes those DDSSs, which are in common with other EPOS communities, such as the Seismology-TCS or the GNSS-TCS. The second category includes all the DDSSs specific to the

volcanology community, such as volcano activity reports, volcanic rock samples, and volcano hazard maps.

For services included in the first category, the VOLC-TCS community adopted the standards defined by the other communities to share the information. This was relatively simple, for example, for the seismological services, because the adopted data and metadata models are well established and have long been used to manage seismological data and products (Haslinger et al. 2022), so results can be easily included in the VOLC-TCS roadmap as “achieved.” However, in the case of GNSS data, products, and services, EPOS has implemented a specific standard, named GLASS (Fernandes et al. 2022). This standard is not always compliant with the technical solutions adopted by VOs managing GNSS networks; solutions which might be sensible for surveillance purposes. Thus, in some cases, these institutions had to define specific work plans to share GNSS data in accordance with the EPOS standards. For this reason and with the goal to be operational before the end of the year, the VOLC-TCS is still working to solve this issue to provide GNSS services in the required standard.

A further case of a service, in common with other EPOS TCSs, is the provision of Transnational Access (TNA, e.g. Wessels et al. 2022) currently under implementation, which provides either physical or remote access to facilities, resources, and services available among the participating institutions.

The second service category shows how the harmonisation of the heterogeneous volcanological data and products is complex, either among the volcanological institutions or across the VOLC-TCS community and other EPOS communities. The adopted strategy was to define specific needs to overcome the gaps for specific types of data or products. Defining proper data and/or metadata models to adapt the current services to EPOS is an achieved result. In particular, for some domains the developers started from scratch: it is the case of the GeoChem database under development, which is a comprehensive conceptual framework for a geochemical database compatible with the wide range of fluid and rock geochemical data, obtained through in situ measurements and/or laboratory analysis.

Currently, the ICS and TCSs are working together on solving technical issues related to the data and metadata harmonisation by using a collaborative method based on the “GitLab” environment shared among the ICS-TCS IT team. It allows, at the same time, a work programme and a workflow on specific service issues, containing details on each problem to be solved.

### The VOLC-TCS Gateway: conceptual model

To provide access to DDSSs produced by either institutions outside the EPOS perimeter (the VOLC-TCS does not include all European institutions dealing with volcanology) or to

DDSSs not yet compliant with EPOS belonging to the VOLC-TCS' DPs and SPs, a proper Gateway has been implemented. The Gateway is thus complementary to the EPOS Data Portal as it allows for discovery of new not yet EPOS compliant services. In developing the Gateway, and in order to improve its usefulness to the users of the Data Portal, the VOLC-TCS decided to follow the same data and metadata model adopted within EPOS. The strategy includes the following: (i) collecting datasets from different domains (e.g. geochemistry, rock samples, volcanic numerical models, hazard maps) and characterised by heterogeneous fields of applications, (ii) evaluating their level of maturity (i.e. their level of compliance with the EPOS standards), and (iii) connecting them to the wider environment of existing e-infrastructures and RIs. This solution to managing non-EPOS compliant DDSSs has also been successfully adopted by other TCSs.

To guarantee the long-term sustainability of a service, EPOS needs a specific and mandatory work plan to develop and/or adapt a generic DDSS into an EPOS service (technical, governance, legal, and financial issues must be defined). The VOLC-TCS' Gateway, on the other hand, can be independent from the EPOS implementation strategy and defines its own strategies. In fact, although the Gateway cannot guarantee long-term sustainability, it allows increased access to the data or information and testing of their suitability for the volcanology community. The Gateway can therefore be used to test the usefulness or importance of a specific service and then to evaluate the possibility of upgrading it into a proper EPOS compliant DDSS.

### The VOLC-TCS Gateway: state of the art

At the time of writing, the beta version of the VOLC-TCS Gateway, planned and developed within the EU project EUROVOLC, is up and running ([vo-tcs.ct.ingv.it/gateway/](http://vo-tcs.ct.ingv.it/gateway/)). The Gateway is organised into three sections, internally connected (Figs. 3 and 4):

- Service List, a detailed list of services in the form of a table, describing all the EPOS VOLC-TCS' DDSSs, both EPOS compliant and non-compliant. Each of these services can be easily accessed by using a dedicated landing page.
- EduBoX, representing research outputs, references, tutorials (i.e. videos, summer school reports, outreach material, references with DOI, and link to specific repositories).
- TNA list, a list of TNA projects providing access to volcanological RIs executed in the EUROVOLC project.

Behind the website a server-side development software (the back-end side) ensures that the website performs correctly; it uses a relational database (e.g. MySQL), back-end logic, application programming interfaces (APIs), and in terms of hardware development, server architecture, and security. The front-end solution is a data portal, able to expose web services (in the form of machine-readable tools like API RESTful services) that allow a generic user to move between main data categories (i.e. satellite

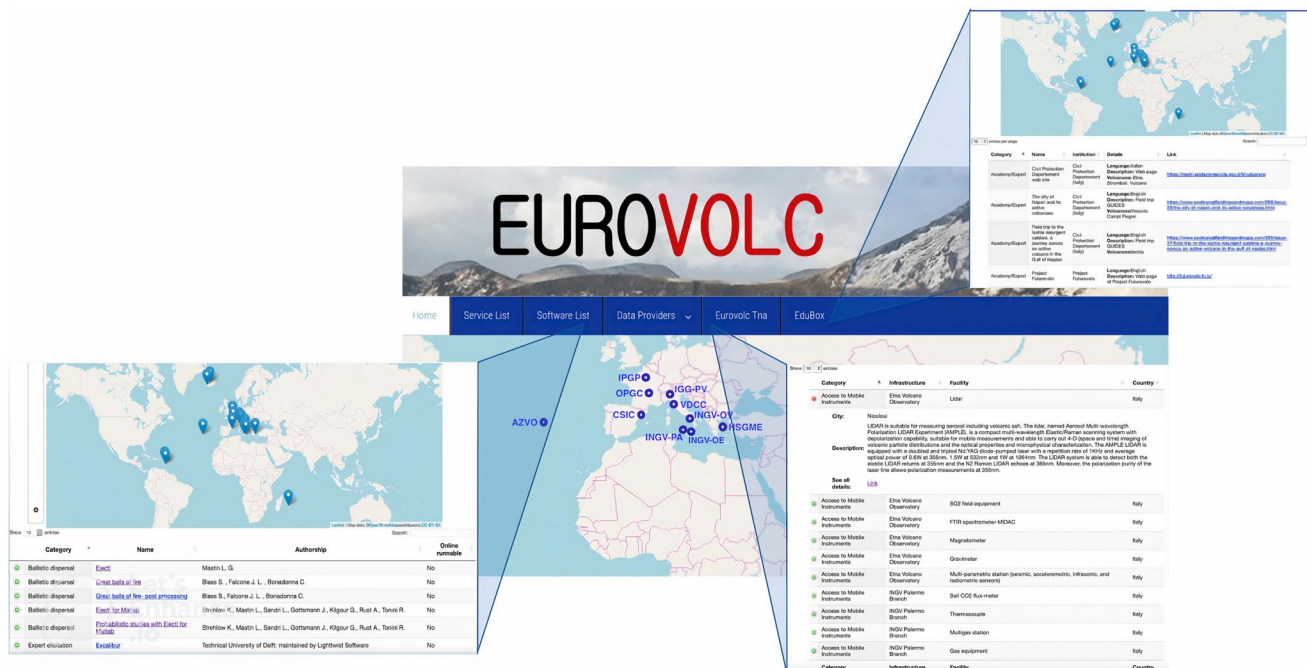


Fig. 3 Actual version of the VOLC-TCS Gateway showing the three layers, i.e. the Service list, EduBoX, and the TNA list

The screenshot displays the VOLC-TCS 'Gateway service list web page'. On the left, a world map shows three location pins in Europe. Below the map is a search bar and a table of services. The table has columns for Category, Name, Institution, and Landing page. The services are grouped into categories like Data services, Geodetic data, and Geohazard. On the right, a detailed landing page for the 'Software catalogue for petrological to geophysical modelling' is shown, featuring a 3D model of a volcano, a description, additional information, and available URLs.

Category	Name	Institution	Landing page
Data services	Software catalogue for petrological to geophysical modelling	Istituto Nazionale di Geofisica e Vulcanologia - Sezione di Pisa	<a href="#">link</a>
Geodetic data	Meta-data and waveforms of the tilt-meters stations of the French Volcanoes Observatories	Institut de Physique du Globe de Paris	<a href="#">link</a>
Geodetic data	Meta-data and waveforms of the tide-gauge stations of the Guadeloupe	Institut de Physique du Globe de Paris	<a href="#">link</a>
Geodetic data	GNSS raw data Iceland	Icelandic Met Office (IMC)	<a href="#">link</a>
Geodetic data	GNSS station list Iceland	Icelandic Met Office (IMC)	<a href="#">link</a>
Geodetic data	GNSS Site Logs in Iceland	Icelandic Met Office (IMC)	<a href="#">link</a>
Geodetic data	GPS data survey 1994- 2013 (Pangaea dataset)	Etna Volcano Observatory	<a href="#">link</a>
Geohazard	Tephra fallout hazard maps Iceland	Icelandic Met Office (IMC)	<a href="#">link</a>
Geohazard	Guideline on SO2 exposure	Icelandic Met Office (IMC)	<a href="#">link</a>
Geohazard	Spatial probability analysis/maps - Susceptibility Maps	Agencia Estatal Consejo Superior de Investigaciones Cientificas	<a href="#">link</a>

**Fig. 4** Here, the VOLC-TCS 'Gateway service list web page, which is actually in development, is shown. Services are grouped into different categories and for each service, a link leads the user to a proper

landing page (right panel) that reports details in terms of description, usage of the available queries, and other useful information

data and geodetic data), and filter the datasets by using advanced discovery features. The details of a single service are presented in the form of a landing page, which provides general information, the web service URLs, and relevant guidelines (Fig. 4).

At the end of the EUROVOLC project, a decision was made to put the whole Gateway structure under an extensive renewal action since it would be used for more than just the project purposes. A new website version is under development and new tools have been planned and proposed (Fig. 5). Starting from the lesson learnt during the EUROVOLC project, the new version of the Gateway (now in an advanced stage of development) contains the following:

- All the general information about the VOLC-TCS community.
- A data provider's section.
- The EduBox that will be organised as a service by using a structured database, integrating outreach material as data services. Moreover, it will be connected with an e-learning platform in order to propose tutorials for stu-

dents and young scientists and/or be used by a single DP to promote new research related to volcano observation matters.

- The European Catalogue of Volcanoes (volcanoes.eurovolc.eu/), an interactive website containing detailed information on key volcanoes and their associated hazards, in both English and the local language (i.e. French, Italian, Spanish, Icelandic, Norwegian, Greek, and Portuguese). Additionally, the Catalogue also shows the location of over 70 active volcanoes within the monitoring territories of Iceland, France, Spain, United Kingdom, Italy, Netherlands, Portugal, Greece, and Norway. The Catalogue is suitable for a wide range of audience.

### Open Science linked to science communication and outreach activities

Open Science is one of the EPOS pillars, aiming to foster collaboration through an open platform where researchers share data, methodologies, and preliminary findings.



**Fig. 5** The new prototype of the VOLC-TCS 'Gateway Home page'. In the foreground, users can find the list of the projects in which the VOLC-TCS community is or has been involved

Combining Open Science with science communication and outreach efforts can play a crucial role in making science more accessible, transparent, and impactful. This approach not only benefits the researchers themselves, but also contributes to the broader goal of engaging the public and encouraging a culture of collaboration and openness in

the scientific community. In this context, the VOLC-TCS Communication team is responsible for disseminating and promoting the activities and services of the TCS, as well as their implementation, to both the reference community and a broader «external» multi-stakeholder target audience (e.g. PhD, graduate and master students, and local stakeholders).



The team works in close collaboration with the EPOS ERIC Communication team, following the communication plan of EPOS.

As part of the overarching communication goal of EPOS to engage a broader scientific community and encourage greater participation in dissemination efforts within the TCS community, a long-term Communication and Outreach Strategy has been defined. The strategy foresees ten Operational Objectives devoted to:

1. Reinforcement of the EPOS branding and its implementation across each TCS group and NRIs
2. Evolve the EPOS website and increase its visibility
3. Provide a variety of informative materials on EPOS and its activities as standardised text resources (e.g. articles and calls for applications) to offer ready to use communication materials
4. Offer engaging video contents about EPOS, its activities and users
5. Increase and differentiate social media contents and grow EPOS' social media organic followers
6. Organise EPOS community meetings to illustrate the status of the services and their implementation to the community, as well as specific meetings/events with selected stakeholders to show the VOLC-TCS' services and infrastructures
7. Train and engage potential users in using the EPOS Data Portal, with particular attention to PhD students and early career researchers
8. Approach young talents and encourage them to join EPOS through several initiatives (e.g. internships, mentoring programs, summer schools, travel grants, and exchange programs)
9. Position the EPOS Open Source code to promote its reuse, tracking and showcasing relevant use cases
10. Enhance the communication flow with different target audiences, both internal and external to the scientific reference community.

To meet the ten Operational Objectives, the planned VOLC-TCS outreach and communication activities include the following:

- Active participation in training activities, identifying trainer contacts within the VOLC-TCS group for the preparation of training activities (e.g. collection and production of training materials, and design of training paths) in collaboration with the EPOS ERIC Communication team and the provision of resources to train on services and tools
- Making available, and sharing existing informative materials (e.g. photos, videos, articles, quotes, pres-

entations, flyers, and new items), the production of reusable short video presentations about EPOS, EPOS Data Portal, and its specific services, as well as the release of video contents focusing on volcanological testimonials to be promoted through cross-media campaigns

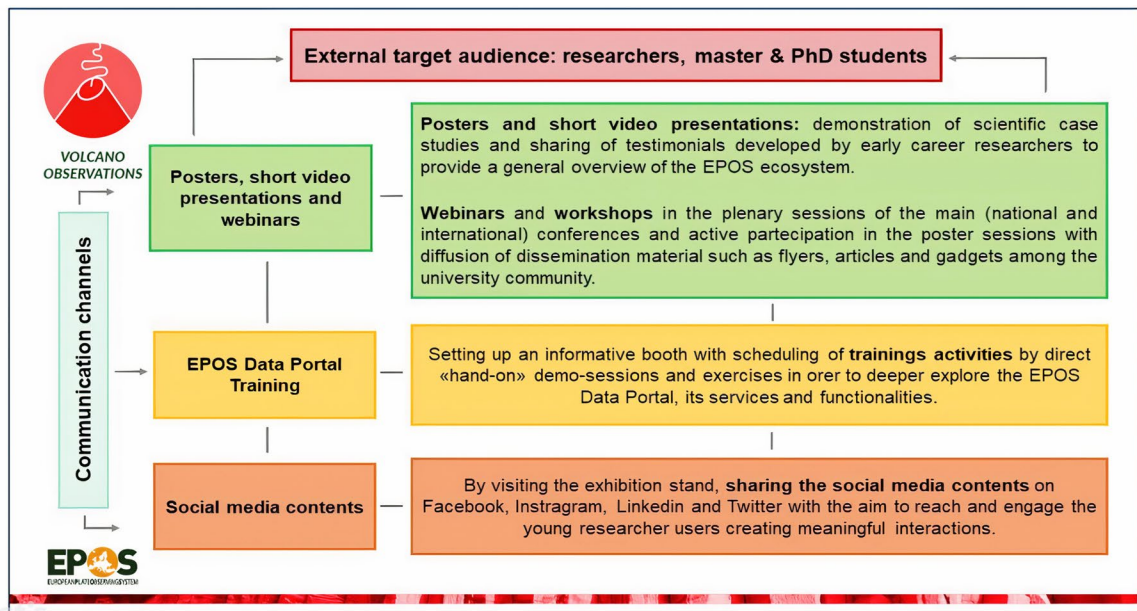
- Updating and integrating the EPOS website (according to the guidelines proposed from the EPOS ERIC Communication team), producing outreach material about tools and services offered by the VOLC-TCS community
- The implementation, revision, updating, and management of the EduBox tool, aimed to become an outreach resources database suitable for multi-query searches
- To structure a custom sub-site in the Gateway allowing sharing outreach and training materials.

Beside this regular communication engagement, notably after the launch of the EPOS Data Portal in April 2023, the VOLC-TCS communication effort was particularly focused on university students and early career researchers. As a first test of this approach, the VOLC-TCS and EPOS Communication teams joined the Italian conference “BeGEO scientists 2023- sustainability and risk: be Geo scientists on the road to the future “ held in Naples in October 2023. The meeting, attended by early career researchers and university students, represented a unique opportunity at national level to present the EPOS Data Portal. Overall, the conference represented an opportunity to test the VOLC-TCS communication strategy.

Following the BeGEO conference, a preliminary list of the main communication channels and tools has been suggested to enhance effective communication practices. The tools are primarily intended for early career researchers attending upcoming national and international conferences (Fig. 6).

### State of the art in VOLC-TCS sustainability

The financial, governance, and technical aspects together ensure the sustainability of the provision of the EPOS services (Puglisi et al. 2022). The SPs and DPs, together with the EPOS ERIC play a fundamental role in guaranteeing the sustainability of the DDSSs. SPs and DPs guarantee the continuous upgrade and update of the techniques and methodologies to collect the data and generate the products, and the SPs also the proper management of the data and facilities according to the EPOS guidelines, including their long term funding and the adoption of proper strategies and technical solutions to access the DDSSs.



**Fig. 6** Schematic roadmap summarising the main communication and outreach activities to be addressed mainly to early career researchers in future national and international conferences

EPOS ERIC partially funds the provision of the DDSSs. In particular, it supports the alignment of the provision with the EPOS guidelines as well as the governance, coordination, and outreach activities via formal agreements with the TCSs. The Coordinating institution for the TCS, which is the interface between the TCS and EPOS ERIC, is responsible for managing the funds received and distributing as necessary to the other members of the TCS. Overall, the sustainability of the services of the TCS differs whether dealing with service provision by VA and TNA. In the case of VA, the process from data generation to data provision is mostly supported by the SPs and DPs themselves, as data results from instrumentation already belonging to and maintained by the providers, and the human resources dedicated to data acquisition and analysis are already supported by the institutions. Hence, the phase of data generation is already guaranteed as part of the institutional duties/mission of the individual provider. Over time, the contribution of EPOS has consisted, in fact, in the financial support devoted exclusively to the implementation of the TCSs' services to make them interoperable with its standards. The case of TNAs is quite different from VA services. Obviously, as in the previous case, the SPs play the main role as they institutionally develop and

maintain the infrastructures and facilities to be offered for TNA activities; however, the operational phase of TNAs, i.e. the effective access of the users, is still in charge of the single researchers that can only sustain such activity through external funds (i.e. national and mainly EU projects). This last issue represents a critical point as, while VA services are mostly guaranteed in the long-term, the TNA services are subject to the capability of the providers to get funds. Consequently, the TNAs have quite weak sustainability especially in the long term.

At a national level, the European membership countries of EPOS ERIC are managing the contribution to the implementation of services through the establishment of Joint Research Units (JRUs), National Nodes or National Consortia focused on build-up of Research Infrastructures (EPOS Italy—[epos-italia.it/](http://epos-italia.it/), EPOS Spain—[epos-es.org/](http://epos-es.org/), EPOS France—[epos-france.fr/](http://epos-france.fr/), and EPOS Iceland—[epos-iceland.is/](http://epos-iceland.is/)). Some of these national initiatives can also include institutions external to the VOLC-TCS that however provide services through the SPs (Fig. 2). The JRUs, National Nodes, and National Consortia are receiving national funds for coordination and networking, and some also to implement new services as well as to support further development of already existing services.

## The Italian national node

The Italian contribution within EPOS is managed and coordinated by the JRU EPOS-Italy. It is a partnership of Public Research Institutions, Universities, and Consortia established through an agreement signed by ten partners in June 2016. INGV coordinates the Italian participation in EPOS through a formal collaboration agreement between the ten JRU institutions. The EPOS-Italy partners provide EPOS data, services, and products from their infrastructures not only for the Italian territory. The data access services provided by the local thematic portals have been standardised and are made available via the EPOS Data Portal. EPOS-Italy organises its activities through a four-year activity plan and annual executive plans. Within the current activity plan, the JRU EPOS-Italy has identified three main activities, strategic for EPOS, to be carried out under three different strategic objectives: (i) support to the National Nodes recognised in EPOS; (ii) data sharing and development of declared services in TCS with recognised Italian participation; (iii) contribution to international scientific cooperation for the development of strategic infrastructures for EPOS. All activities carried out under the activity plan are proposed by the partners, approved by the General Assembly, and co-funded by the Ministry of Universities and Research (MUR) (up to 50%) through a portion of the annual funding for EPOS European infrastructure activities. For the financing of the activities, the JRU can also use resources from project proposals made directly by the JRU partners. In particular, the current activity plan for 2021–2024 includes within the Strategic Objective 1, a project aimed at supporting the activities of the VOLC-TCS, which scope is the generation of new services to be implemented in the EPOS Data Portal and the harmonisation of existing services that are not EPOS compliant.

## The Spanish national node

In Spain, the VOLC-TCS community at national level started to meet and coordinate in March 2016, within the EPOS-IP project. Several meetings took place during the duration of this European project aimed at identifying those research groups interested in using and/or contributing to EPOS' DDSSs, in general, and the VOLC-TCS' DDSSs, in particular. The meetings continued until the end of 2019, supported by national funding (Red temática CGL2016-81965-REDT), but were interrupted during 2020–2022 due to the COVID-19 pandemic and the lack of financial endorsement. The activities

of EPOS Spain (<https://epos-es.org/>) resumed in 2023 thanks to the financial support of CSIC (INFRA20005) and national funding addressed to coordinate the participation of Spain in large European Infrastructures (Red temática RED2022-134516-E). Since then, the different TCSs, including the VOLC-TCS, have been coordinating at national level to identify the research groups interested in providing DDSSs into EPOS and to establish a roadmap for 2024–2025 to enhance the Spanish contribution to the EPOS Data Portal. At the time of writing, EPOS Spain is coordinated by CSIC, together with a Steering Board and a Scientific Committee. The Steering Board is composed of one representative of each of the institutions signing the agreement for the payment of fees and the participation of Spain in the ESFRI EPOS-ERIC. These are the following: Ministry of Science, Innovation and Universities, CSIC, Centro Nacional de Información Geográfica (CNIG)—Instituto Geográfico Nacional (IGN), University of Granada, University of Alicante, University of Salamanca, and the University of Barcelona (UB). The Scientific committee also consists of a spokesperson of the listed institutions in addition to representatives of Observatorio del Ebro, Complutense University of Madrid, and the Polytechnic Universities of Madrid and Valencia. All the institutions with representation in the EPOS Spain Scientific Committee have signed a General Action Protocol to prove their commitment to establish a stable framework for collaboration that provides coherence and continuity to the initiatives, actions, programs, and activities carried out to develop and implement the Spanish node of EPOS. Currently, Spain is providing 28 DDSSs to EPOS distributed in five different TCSs which include the following: seismology, GNSS, geological information and modelling, tsunamis and volcano observations. DDSSs' providers are research institutions (e.g. CSIC) and universities (e.g. UB, Universidad de Málaga), distributed across Spain.

## The Icelandic national node

Iceland has participated in the build-up of EPOS since 2010 and has been a member of the EPOS ERIC since 2021. From the beginning, the national node has been led by IMO, which operates the main national observation networks monitoring all natural hazards in Iceland. During the first decade, 2010–2022 the focus was on opening access to quality checked and standardised multidisciplinary Earth Science data from Iceland, including GNSS, seismic and geochemical data, and products like volcanic reports, hazard maps, and simulations of

atmospheric dispersion of volcanic ash. The access was enabled through API services on IMO's website. Funding was mainly provided by the EU, through the three EPOS ESFRI projects and the IMO. Additionally, during this period significant support to the build-up of the national volcanological research infrastructure and community came through two successive EU research and infrastructure projects, FUTUREVOLC and EUROVOLC, in which the University of Iceland (UI) was also a major participant. National funding for research infrastructures in Iceland is on a competitive basis and from 2020 the RI roadmap is defined in periods of 5 years. To be included on the roadmap, project proposals must be submitted to the Icelandic Infrastructure fund, which selects a handful of proposals prioritised for funding over the following 5 years. Roadmap projects then need to submit yearly proposals during this period. The EPOS Iceland project entered the first periodic RI roadmap from 2021 to 2025, with a total prospective budget of ~1.2 million Euro. The project is backed by a consortium of five institutions led by IMO, including UI, the National Land Survey, the Institute of Natural History and the Iceland Geosurvey. At the onset, the consortium formalised the collaboration with a signed memorandum of understanding. All institutions are DPs to the Icelandic EPOS node, while IMO is the SP for all. The national funding supports quality checking and standardization of data and products, update of older services and development of new API services. Moreover, the national funding also supports the required hardware for embedding the necessary servers within the IMO IT environment to guarantee long-term, sustained interoperability with the EPOS Data Portal and to meet the EPOS operational requirements. In this period access is opened to more kinds of data and products, including InSAR, earthquake bulletin, shake-maps, geological maps, borehole data, volcanic photographs, tephra isopach maps, and rock samples. In addition to the national funds, the contracts between EPOS ERIC and the VOLC-TCS have provided partial support for the service operation (~10% of the national funding in 2023). Partial support (~7% of the 5-year national funding) is also provided by the EU Geo-INQUIRE project to implement standardised, EPOS compliant seismic, and GNSS nodes for Iceland. The first roadmap period is providing most of the funding required to guarantee construction of the foundation for the Icelandic EPOS node, but for long-term sustainability, it is vital for the EPOS Iceland project to succeed in entering the next 5-year roadmap, after which open access should have been achieved to the main data archives and most services

should be operational. Costs should then be mainly due to operation and maintenance.

### The French national node

Epos-France is a national research infrastructure listed in the roadmap of research infrastructures published by the French Ministry of Higher Education and Research (MESR). CNRS coordinates the Epos-France consortium, which comprises the majority of French universities and organisations involved in geosciences research (<https://www.epos-france.fr/en/about-epos-france/organization/>). Epos-France followed the path of the French seismological and geodetic network Résif-EPOS, which it succeeded in October 2023. Résif-EPOS was integrated into EPOS and played an active role in its development and evolution. This is why, in Autumn 2023, Résif-EPOS was replaced by Epos-France, to create a new research infrastructure with a broader thematic scope in line with that of its European counterpart, promoting the advancement of knowledge of the Earth system in all its diversity and complexity. Like the former Résif-EPOS infrastructure, Epos-France makes geophysical, geochemical and geological data, as well as associated products and tools, freely available, both through its own national distribution channels and via the EPOS Data Portal. Epos-France partners, through their own funding, contribute to the construction and operation of Epos-France. Funds are allocated by MESR and Ecological Transition (MECT) to support (i) the French environmental science strategy, (ii) the construction of the data archiving and distribution system for certain instrumental networks, such as the Permanent Accelerometer Network (RAP), the National Geodesy and Gravimetry Network and the Permanent Seismic Broadband Network, and (iii) the maintenance of the RAP equipment, to data enhancement and knowledge dissemination initiatives, and to the activities of the transverse thematic action seismicity. Additional services such as the National Service for Volcanological Observation (SNOV), the Global Seismology Service (GEOSCOPE), the Geomagnetism Observatories, and In-situ Fault Observatories, are currently in the process of being integrated into Epos-France as of 2024.

Certainly, aside from the EPOS and national contributions to the implementation and maintenance of the VOLC-TCS' services, given the dynamic nature of the overall service and the broad spectrum of the DDSSs offered, and that might be offered, further financial support is needed. In the next future, focusing on the sustainability of the aspects that are not supported at the national level and for which may be more difficult to find

funding for sure the main challenge is represented by the harmonisation of high-level products (e.g. models, software, and tools) with the EPOS standards. Such products result from the need at first and the collaboration after, of all the EU volcanology community. Undeniably, the broadening of the service portfolio will require further financial support. For this reason, the VOLC-TCS consortium has extensively worked to establish a strong and cohesive community able to propose activities and attract external funds. Over more than 10 years the VOLC-TCS has coordinated and/or has been involved in several European and national projects under which some SPs have implemented services to be ingested in the VOLC-TCS list of DDSSs (FUTUREVOLC-cordis.europa.eu/project/id/308377/it; MED-SUV-cordis.europa.eu/project/id/308665; EUROVOLC -eurovolc.eu/; Geo-INQUIRE-geo-inquire.eu/; DT-Geo-dtgeo.eu//; PON-GRINT-rogetti.ingv.it/en/pongrint; MEET-meet.ingv.it/). Indeed, the participation of the VOLC-TCS in several external projects and initiatives has also significantly contributed to reinforcing the community, and networking a number of European VOs and VRIs, which also have granted access to their facilities through TNA calls (Wessels et al. 2022).

### What has the VOLC-TCS community learnt since 2018 and future perspectives

The official establishment of EPOS as an ERIC in 2018 represented the starting point for the implementation of the operational services in 2023. During this period, the VOLC-TCS worked hard on adapting the services to meet the EPOS requirements. The experience gained during this period allowed identification of working procedures to improve existing DDSSs, develop new ones, and guarantee the long-term sustainability of the VOLC-TCS activities. It is noteworthy that the overarching objective of VOLC-TCS is to provide the final users (researchers, students, public authorities, etc.) high-quality data, products and services suitable for generating new knowledge; thus, besides the technical, governance, and financial aspects discussed above, the variety of stakeholder environments should also be considered. Indeed, since 2018, the VOLC-TCS has strengthened the community by, not only, carrying out the TCS activities but also proposing, participating, and coordinating European projects and initiatives through which the TCS participants have developed and implemented some of the DDSS standards and some of the services, such as the TNAs. The opportunity to exploit TNAs, thus allowing the discovery and physical

or remote access to the VOs and VRIs' facilities has been particularly suitable to attract new users and produce new knowledge, as well as to foster collaboration, innovation, and the advancement of scientific understanding within the volcanology community. Based on lessons learnt from the TNA experience, the VOLC-TCS community will in the near future try to continue these activities through external financial support (national and international projects), focusing on the increase of quality and amount of facilities to be offered, and on the improvement of the research call management and evaluation procedures.

Regarding the VA to the VOLC-DDSSs, some preliminary evaluations on data discovery and download suggest an improvement of the capability to catch the type and quality of the information contained in the service at a first glance, in order to speed up the targeted DDSS's search process and to get quick information about it. In this regard, a simplification of the list of the offered services, e.g. in terms of number of services by merging some services and/or a new definition of categories and/or the introduction of new searching criteria, might be considered. Hence based on this experience, in the future, the VOLC-TCS will seek feedback from the users through questionnaires and workshops so as to dynamically improve the access to encourage and ease the access to the DDSSs.

At the national level, future important efforts are required from the coordinators of the different national nodes and the TCS representatives to (i) encourage the use of the EPOS Data Portal among the different communities with special focus on attracting early career scientists; (ii) provide support to the VOLC-TCS in identifying further DDSSs to be made available and to define realistic roadmaps accordingly; (iii) seek funding at national and international level to ensure the long-term sustainability of the DDSSs; (iv) foster networking activities among the VOLC-TCS community at national level; and (v) engage a larger number of VRIs and VOs to participate and contribute to the VOLC-TCS in particular, and EPOS in general.

As for a broader dimension, which can expand beyond the European framework, an important aspect is the possibility to interact with volcanology communities, initiatives and organisations outside Europe (K. Saleh Contell et al. 2022), for example the international volcanology WOVODat infrastructure (wovodat.org/). In this respect, the Gateway can play an important role in facilitating and managing any kind of data sets and might represent for the whole volcanology community, a way to access further DDSSs not only at the European level but also relevant to volcanic areas outside Europe. Hence, the Gateway might also represent a bridge between Europe and the foreign countries dealing with active volcanoes.

## Appendix

**Table 1** List of the VOLC-TCS active services in 2023. The table lists the current VOLC-TCS services. Note that the white services are those that are EPOS compliant and exposed either in the Gateway or in the EPOS Data Portal; the yellow services are those not EPOS compliant and thus, accessible only through the Gateway

Geographic area	Category	Service name	Service provider
<b>Active volcanoes between 70°-70° of latitude and longitude</b>	Satellite data	Geostationary satellite derived Volcanic Thermal Anomalies products	CNRS (OPGC)
		Geostationary satellite derived Volcanic Ash and SO2 plumes products	CNRS (OPGC)
<b>Bárðarbunga</b>	Volcanological/petrological	Volcanic eruption images from Iceland	IMO
	Geohazards	Daily ash/gas forecasting Iceland	
	Ground based remote sensing	Ground based UV spectra (DOAS) Iceland	
	Geohazards	S02 probabilistic hazard maps Iceland	
<b>Deception Island</b>	Geohazards	Susceptibility Maps Distribution	CSIC
	Geohazards	Lava flow invasion hazard maps	
	Geohazards	PDC hazard maps	
	Geohazards	Probabilistic Hazard maps	
<b>Eastern, Western, Northern Volcanic zone</b>	Volcanological/petrological	Catalogue of Icelandic volcanic eruptions	IMO
	Geodetic data	GNSS Site Logs in Iceland	
	Geodetic data	GNSS raw data Iceland	
	Geohazards	Susceptibility Maps Distribution	
	Geohazards	Lava flow invasion hazard maps	

Table 1 (continued)

<b>El Hierro Island</b>	Geohazards	PDC hazard maps	CSIC
	Geohazards	Probabilistic Hazard maps	
<b>Eyjafjallajökull</b>	Ground based remote sensing	Ground based radar data Iceland	IMO
<b>Etna</b>	Satellite data	Wrapped Differential Interferograms	INGV
	Geodetic data	Multi-parameter stations list Italy	INGV
	Geochemical data	Mt. Etna Bulk Rock Analysis	INGV
	Volcanological/petrological	Weekly Volcanic Report Italy	INGV
	Volcanological/petrological	VONA Italy	INGV
	Ground based remote sensing	Doppler radar near source eruptive parameters	CNRS (OPGC)
	Ground based remote sensing	Doppler radar raw spectra	CNRS (OPGC)
<b>Grímsvötn</b>	Geohazards	Daily ash/gas forecasting Iceland	IMO
	Ground based remote sensing	Ground based radar data Iceland	
	Ground based remote sensing	Ground based visible and thermal/IR camera Iceland	
	Volcanological/petrological	Volcanic eruption images from Iceland	
<b>Hekla</b>	Geohazards	Daily ash/gas forecasting Iceland	IMO
	Geohazards	Tephra fallout hazard maps Iceland	
	Volcanological/petrological	Volcanic eruption images from Iceland	
<b>Iceland</b>	Volcanological/petrological	Aviation color codes	IMO
	Volcanological/petrological	Weekly Volcanic Report Iceland	

Table 1 (continued)

	gical		
	Seismological data	Shakemaps Iceland	
<b>Katla</b>	Geohazards	Daily ash/gas forecasting Iceland	IMO
	Geohazards	Tephra fallout hazard maps Iceland	
	Volcanological/petrological	Volcanic eruption images from Iceland	
<b>Krysuvik</b>	Geohazards	S02 probabilistic hazard maps Iceland	IMO
<b>La Garrotxa volcanic field</b>	Geohazards	Lava flow invasion hazard maps	CSIC
	Geohazards	PDC hazard maps	
	Geohazards	Probabilistic Hazard maps	
<b>Lanzarote Island</b>	Geohazards	Lava flow invasion hazard maps	CSIC
	Geohazards	Susceptibility Maps Distribution	
	Geohazards	Probabilistic Hazard maps	
	Geohazards	Tephra fallout hazard maps for explosive volcanoes	
<b>Mayotte Island</b>	Seismological data	Velocity Seismic waveforms	CNRS (IPGP)
	Geodetic data	GNSS geodetic stations	
	Volcanological/petrological	Reports on volcanic activity	
	Geodetic data	GNSS observation data in RINEX format from	
	Geodetic data	Tiltmeter stations list	
<b>Montagne Pelee</b>	Seismological data	Catalog of Earthquake parameters	CNRS (IPGP)
	Seismological data	Seismic stations list	
	Seismological data	Velocity Seismic waveforms	
	Geodetic data	GNSS geodetic stations	



Table 1 (continued)

	Geodetic data	GNSS observation data in RINEX format from	
	Volcanological/petrological	VONA France	
	Volcanological/petrological	Reports on volcanic activity	
<b>Öræfajökull</b>	Volcanological/petrological	Volcanic eruption images from Iceland	IMO
	Geohazards	Tephra fallout hazard maps Iceland	
	Geohazards	Daily ash/gas forecasting Iceland	
<b>Piton de la Fournaise</b>	Geochemical data	Collection of Magmatic Rocks and Samples	CNRS (OPGC)
	Geodetic data	GNSS geodetic stations	CNRS (IPGP)
	Geodetic data	GNSS observation data in RINEX format	CNRS (IPGP)
	Volcanological/petrological	VONA France	CNRS (IPGP)
	Volcanological/petrological	Reports on volcanic activity	CNRS (IPGP)
	Geodetic data	Lava flow contour derived from InSAR data	CNRS (OPGC)
	Geodetic data	InSAR Wrapped Interferogram	CNRS (OPGC)
	Seismological data	Catalog of Earthquake parameters	CNRS (IPGP)
	Seismological data	Velocity Seismic waveforms	CNRS (IPGP)
	Seismological data	Seismic stations list	CNRS (IPGP)
	Geodetic data	Tiltmeter waveforms	CNRS (IPGP)
	Geodetic data	Tiltmeter station list	CNRS (IPGP)
<b>Reykjanes-</b>	Geohazards	Tephra fallout hazard maps Iceland	IMO
	Geohazards	S02 probabilistic hazard maps Iceland	

**Table 1** (continued)

<b>Svartsengi</b>	Geohazards	Daily ash/gas forecasting Iceland	
	Satellite data	Wrapped interferograms from Iceland	
<b>San Miguel volcano</b>	Geohazards	Susceptibility Maps Distribution	CSIC
<b>Snæfellsjökull</b>	Geohazards	Tephra fallout hazard maps Iceland	IMO
<b>Soufrière de Guadeloupe</b>	Geochemical data	Collection of Magmatic Rocks and Samples	CNRS (OPGC)
	Geodetic data	GNSS geodetic stations	CNRS (IPGP)
	Geodetic data	GNSS observation data in RINEX format	CNRS (IPGP)
	Geodetic data	Tide waveforms	CNRS (IPGP)
	Volcanological/petrological	VONA France	CNRS (IPGP)
	Volcanological/petrological	Reports on volcanic activity	CNRS (IPGP)
	Seismological data	Catalog of Earthquake parameters	CNRS (IPGP)
	Seismological data	Velocity Seismic waveforms	CNRS (IPGP)
	Seismological data	Seismic stations list	CNRS (IPGP)
	Geodetic data	Tiltmeter waveforms	CNRS (IPGP)
	Geodetic data	Tiltmeter station list	CNRS (IPGP)
<b>Stromboli</b>	Volcanological/petrological	Weekly Volcanic Report Italy	INGV
	Geodetic data	Multi-parameter stations list Italy	
	Volcanological/petrological	VONA Italy	
<b>Vestmannaeyjar</b>	Geohazards	Tephra fallout hazard maps Iceland	IMO

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