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The integrated multidisciplinary European volcano infrastructure: from conception to implementation

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Abstract

Recent decades have highlighted the increasing need to connect and strengthen the volcanology community at European level. Indeed, research in the volcanology field is highly qualified in Europe and the volcano monitoring infrastructures have achieved valuable know-how, becoming the state-of-the-art in the world. However, the lack of common good practices in sciences and technologies, missing standards, as well as a significant fragmentation of the community requires coordination to move forward and guarantee a trans-national harmonisation. The European Plate Observing System (EPOS) represented the first opportunity to initiate this process of coordination by encouraging the creation of a European volcanological scientific infrastructure for data and service sharing. During the preparation and the design of EPOS, the volcanology community identified the objectives and the needs of the community building, the services to be provided and the work plan to implement the infrastructure. To achieve this aim, the contribution from three European projects FUTUREVOLC, MED-SUV and EUROVOLC was essential. This paper presents the main steps performed during the last years for building the community and implementing the infrastructure. This paper also describes the strategic choices and actions taken to realise the infrastructure such as the establishment of the Volcano Observation Thematic Core Service (TCS), whose structure and activity are described.

Keywords: Volcanology; Open Access; Community building; Data; Services

1. Introduction

1.1 Background

Volcanic eruptions are relatively common natural phenomena. About 50-60 volcanoes erupt on a yearly basis (Smithsonian Institution Global Volcanism Program) and their impact on human activities and the environment may be severe [e.g., Chester et al., 2000; Self 2005; Loughlin et al., 2015; Brown et al., 2015]. Volcanology is aimed at observing, tracking, and quantifying the volcanic phenomena. It entails modelling the processes related to the magma genesis and evolution and its movement within the Earth's crust, studying eruption dynamics and their effects on the ground and in the atmosphere, and eventually estimating the hazard associated with volcanic eruptions to reduce their risk. The growth in volcanology research relies on the possibility to access active volcanic areas, collect data relevant to the volcanic activity, and share this information among the volcanology community; hence it is closely linked to direct observations and ultimately to human settlements. Europe has been the cradle of volcanology since the first "scientific" description of the 79 AD eruption of Vesuvius, provided by Pliny the Younger, in his second letter to Tacitus [Epistulae VI, 16]. Throughout the centuries, the scientific interest in volcanic phenomena increased with the number of the described eruptions, usually those with the greatest impact on human life [e.g., 1669 Etna – Italy, Branca et al, 2013; 1763 Lakagigar – Iceland, Steingrímsson and Kunz, 1998; 1783 Asama – Japan, Yasui, and Koyaguchi, 2002; 1815 Tambora – Indonesia, Oppenheimer 2003; 1902 Montagne Pelée – Martinique, France, Lacroix, 1904; Mount St Helens, 1980; Lipman and Mullineaux, 1981; 1985 Nevado del Ruiz – Colombia, Voight, 1990; 1991 Pinatubo – Philippines and Unzen, 1991, Nakada et al., 1999; Mount; and Soufrière Hills, Montserrat, 1995-on going, Druitt and Kokelaar, 2002; Wadge et al., 2014]. Until roughly the beginning of the 20th century, volcanology was mainly descriptive [Sigurdsson, 2015] with the "schools of volcanology" largely developed around the active volcanoes. The continuous improvement in technology has led volcanology to reduce its "descriptive" approach; thus, the quantification of the volcanic phenomena and effects has become ever more pervasive. The most evident effect of this evolution is the installation of monitoring networks, at the beginning predominantly seismological, but slowly incorporating over time other geophysical and geochemical parameters such as ground deformation, fluid geochemistry, gravity, or magnetic natural fields. Another, more recent, advancement in volcanology is the application of the remote sensing techniques (both ground-based and satellite-based) to volcano surveillance and monitoring activities [e.g., Brunori et al., 2013; Parks et al., 2015].

At the same time, new data opened up new research fields and spurred cooperation among research and academic centres that became more frequent and strategic, reducing the fragmentation among the volcanological centres and fostering scientific initiatives. The first worldwide initiative was probably the establishment of the Association Internationale de Volcanologie in 1930, in the framework of the International Union of Geodesy and Geophysics (IUGG), renamed International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI, https://www.iavceivolcano.org/) in 1971. More recently, IAVCEI promoted the implementation of the World Organization of Volcano Observatories (WOVO, https://www.wovodat.org). However, apart from periodic conferences or meetings, coordinated scientific programmes across different institutions and/or countries were established only towards the end of the last century, such as PIRPSEV (which led to SNOV of CNRS-INSU in the 2000s) in France, NordVulk in Iceland (still existing) or GNV in Italy (whose tasks were transferred to INGV in 1999). Thanks to these initiatives, not only are scientists in Earth Science studying volcanoes, but also researchers with backgrounds in Physics, Chemistry, Engineering, Mathematic, Computer science and social sciences. Today, volcanology has become a real multidisciplinary science and multi-faceted field [e.g., Fearnley et al., 2018].

1.2 The European framework

In recent decades, Europe has played a leading role in the evolution of volcanology. From 1992 to 1996, the European Science Foundation promoted and coordinated the European Volcanological Project (EVOP), a multidisciplinary research on six European "Laboratory Volcanoes": Etna (Italy), Teide in Canary Islands (Spain), Santorini (Greece), Krafla (Iceland), Piton de la Fournaise in La Réunion Island (France), and Furnas in Azores Islands (Portugal). This initiative included the formation of a multidisciplinary team of volcano experts for immediate response [Gasparini, 1993]. The novelty of EVOP was to work towards two parallel directions: achievement of scientific objectives (e.g., it encouraged using mathematical approaches to model volcanic processes, or introducing new monitoring techniques such as microgravity or geomagnetism) and the fostering of networking in the volcanological community through meetings and schools. Considering the activity of EVOP, it is not surprising that during the Fourth and Fifth Framework Programme of the European Community (FP4 and FP5), a significant number of projects were funded and carried out successfully (e.g., SEAVOLC, MADVIEWS, AVMS, TomoVes, TEKVOL, EMEWS, PRE-ERUPT, in FP4, and ROBOVOLC, DORSIVA, ERUPT, E-RUPTION, EXPLORIS, MULTIMO, VOLCALERT, in FP5). The long-lasting positive effect of EVOP diminished somewhat in the Sixth Framework Programme (FP6), which counts only two EC projects related to volcanoes (NOVAC and VOLUME).

During the Seventh Framework Programme (FP7) the number of volcanological projects increased again, suggesting a new interest in volcanology and an expansion of the community (MIAVITA, VUELCO, APHORISM, EVOSS, DEMONS). However, the most relevant initiatives for establishing the volcanological community were offered by the European Strategy Forum on Research Infrastructures (ESFRI) work programme: to network through the European Plate Observing Systems Preparatory Phase (EPOS-PP) project and to participate in the EC call for supporting the implementation of GEO Supersites in Europe. The EPOS-PP project allowed drafting the guidelines for building the volcanological community within the wider Earth Science community and the "Supersite call" was an opportunity to submit two proposals relevant to the Icelandic and Italian volcanoes, which were funded as the FUTUREVOLC and MED-SUV projects, respectively. The two projects reinforced European cooperation on the scientific themes related to the volcanological processes and tested operational infrastructures based on the "Open Science" (OS) paradigm. Indeed, it is worth noting that the Geohazard Supersite and Natural Laboratory GEO Initiative aims at demonstrating "how the OS approach and international collaboration can generate actionable geohazard scientific information" over selected sites. The two projects succeeded in making Iceland and Italy (Mt. Etna, Campi Flegrei and Vesuvio) part of the Permanent Supersites (http://geo-gsnl.org/supersites/permanent-supersites/). More recently, Horizon2020 (H2020) gave other opportunities for building the Volcanological community (EPOS-IP, EPOS-SP and EUROVOLC projects) that are discussed in detail in this contribution.

1.3 Open Science

The Open Science (OS) paradigm is based on a relatively simple, but fundamental concept: sharing the data and the experiences is the natural and essential prerequisite for making science and the scientific community grow. OS includes different but converging concepts and actions, including but not restricted to: Open Access to the research products, Open access to the data, Open-source software, Open reproducible research, Open Science Policy, etc. The impact of OS in volcanology has a twofold aspect. First, it helps reduce the fragmentation of the volcanology community around volcanoes, themes, techniques, tools, etc. Second, in a broad perspective, it offers the opportunity to explore new scientific frontiers in other scientific domains thanks to the intrinsic multidisciplinary set of data produced by the observational systems. An example of this impact is the growing collaboration between volcanology and atmospheric sciences. The European scientific ecosystem is particularly stimulating in this respect, considering the very important initiatives launched in the last years in the frame of ESFRI work programme (e.g., EPOS, EMSO, ENVRI, etc.) and lastly, but not less important, the European Open Science Cloud (EOSC).

1.4 Rationale

The EPOS initiative aims at constructing a pan-European infrastructure for solid Earth science by integrating the diverse and advanced European Research Infrastructures focused on the solid Earth (https://www.epos-eu.org/). To achieve this, several thematic working groups (lately established as Thematic Core Services – TCS) were created including among many others, the one for volcanology. In this sense, EPOS has offered to the volcano observatories and the research centres the natural framework for contributing to the establishment of an effective and structured volcanological community in Europe.

In this paper, we describe the conceptual design, evolution, and implementation of the Volcano Observation Thematic Core Service (VO-TCS), its current state and future perspectives. Furthermore, the contribution of the H2020 I3 EUROVOLC project to EPOS and the implementation of the effective provision of volcanological services are also presented.

2. Establishing a volcanology community within the EPOS framework

2.1 EPOS: An overview

The ultimate goal of EPOS is to provide new e-science tools and opportunities to unravel the dynamic and complex Earth System. This will be achieved through innovative multidisciplinary research for a better understanding of those physical and chemical processes controlling mineral and geothermal resources, potentially hazardous geological processes (e.g., earthquakes, volcanic eruptions, tsunami), as well as the processes driving tectonics and Earth's surface dynamics. By integrating data, models and facilities, EPOS helps the Earth Science community to move forward in the development of new concepts and tools that are paramount for solving scientific and socio-economic questions concerning geo-hazards and geo-resources. In this way, EPOS contributes to the construction of a safer and more sustainable society, with a better knowledge on how to monitor geohazards and an improvement of our ability to better manage the use of the Earth's resources.

The EPOS architecture is composed of three connected technical and structural elements (Figure 1): (i) National Research Infrastructures (NRI); (ii) Thematic Core Services (TCS); and (iii) Integrated Core Services (ICS). European NRIs for solid Earth science are responsible for the operation of instrumentation in each country and generate data and information. The TCS constitute the community-specific integration (e.g., in seismology, volcanology or geodesy) and represent a governance framework where data and services are provided to answer scientific questions and where each community discusses their specific implementation, best practices and sustainability strategies as well as legal and ethical issues. Finally, the ICS represents the novel e-infrastructure consisting of services that allow access to multidisciplinary data, data products (e.g., reports, models, simulations) to different end-users including, among others, the scientific community. The key element of the ICS in EPOS will be a central hub (ICS-C) where users (primarily scientists, researchers, and students) can discover and access data and data products available in the TCS and NRIs, as well as access a set of services for integrating and analysing multidisciplinary data. The ICSC will also provide access to distributed resources which form the distributed ICS (ICS-d) and include access to supercomputing facilities, as well as to visualisation, processing and modelling tools that need not be centralised.

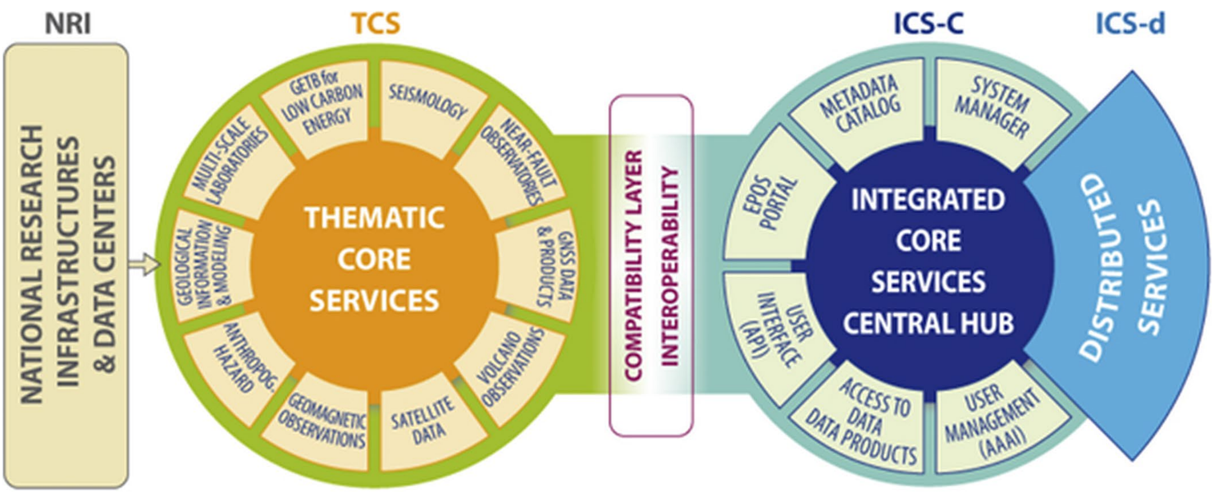

Figure 1. Key elements of the EPOS Functional Architecture. From left to right: The National Research Infrastructures (NRIs) provide data and services to the Thematic Core Services (TCSs) that in turn give access to users through the Integrated Core Service Central Hub (ICS-C). The Integrated Core Service – Distributed – (ICS-d) takes data from ICS-C to produce higher level data.

During the past two decades, EPOS has been constructed in four main phases with the respective EU funded projects: (i) EPOS Conception Phase (CP; 2002-2008), (ii) EPOS Preparatory Phase (EPOS-PP; 2010-2014), (iii) EPOS Implementation Phase (EPOS-IP; 2015-2019), and (iv) EPOS Sustainability Phase (EPOS-SP; 2019 until present). In 2008, at the end of the EPOS CP, EPOS entered into the Environmental Sciences section of the European Strategy

Forum on Research Infrastructures (ESFRI) roadmap. In 2018, during the EPOS-IP project, the EC granted the legal status of European Research Infrastructure Consortium (ERIC) to EPOS. During these four development phases, the volcanology community has worked hard to evolve from the working group created during EPOS-PP to today's fully operational Volcano Observation Thematic Core Service (VO-TCS, Figure 2).

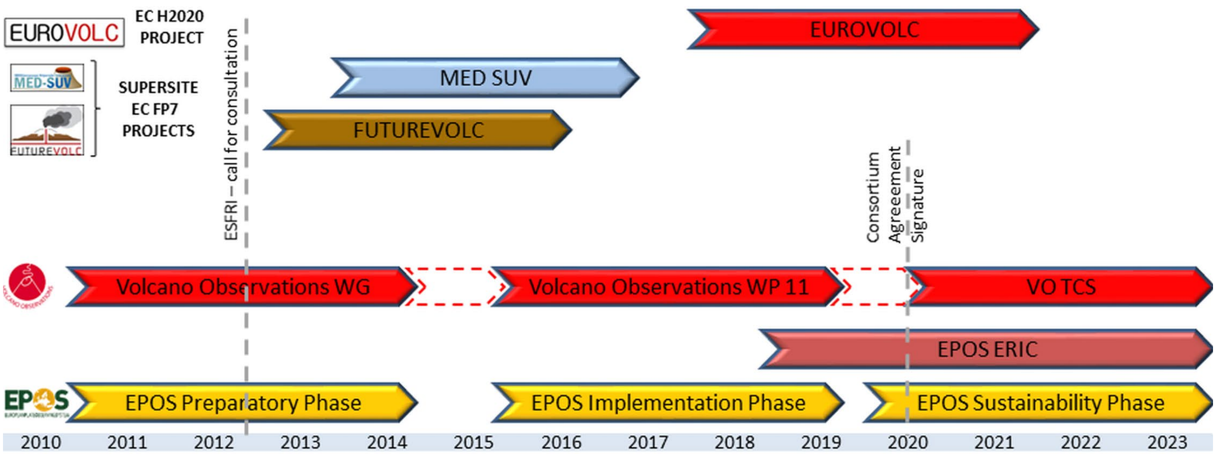

Figure 2. Timeline summarising the EU projects and the initiatives linked to the implementation of EPOS and its integration with the European volcanological community.

2.2 The EPOS-PP Project

During the EPOS-PP, the EPOS community worked to develop the architecture of the future e-infrastructure and, at the same time, to establish an efficient coordination and management structure at European level. Within the "Technical preparation" working package of EPOS-PP project (WP 5), seven thematic working groups were created: (i) Seismological data; (ii) Volcano Observatories and other Observatories; (iii) Geological and Surface Dynamics data; (iv) GNSS-GPS Geodetic data; (v) Other Geophysical data; (vi) Analytic and Experimental Rock Physics Laboratories; and (vii) e-infrastructures and virtual community (HPC and Grid). These groups were asked to provide an overview of the existing and planned infrastructures (incl. instrument networks, laboratories, observatories, etc.) and data repositories at national and European level, as well as to identify the responsible institutions, contact persons, and data policies. In addition, it was requested to define the expectations and requirements of the user community represented by the respective working groups to the EPOS e-infrastructure and to list specific software and tools to be integrated. Finally, each working group was tasked with identifying the requirements to their specific community (related to instrumentation, data sampling, data quality and availability, etc.) to develop plans for future implementation within EPOS.

During the kick-off meeting of the EPOS-PP (November 2010), the representatives of various Observatories and research institutions (INGV, IMO, IGME, UI, DIAS, OPGC, ETH, IPGP) met in the "Volcano Observatories and other Observatories" working group (WG 2) organised in the framework of EPOS-PP WP 5. Originally, the idea was to define the community of volcanic and magnetic observatories together. However, it was very soon clear that data, products and services of each kind of observatories have different characteristics mainly due to the level of processing (from raw data to high level products), the types of data and data products, the methodologies of data collection (e.g., time series from permanent stations or data from field campaigns) and the metadata formats. Therefore, the WG 2 took on the role of the working group of the volcanology community since the first months of the EPOS-PP project. Another concept raised during the first months of the WG 2 activities was that the services of the volcanology community are provided not only by the Volcano Observatories (VO) but also by some Volcanological Research Institutions (VRI; universities, research centres, etc.). This consideration led to a change in the name of WG 2 to "Volcano Observations Working Group ‘’ (VO-WG), in order to clearly indicate the inclusive approach in building this community. At the beginning of EPOS-PP the VO-WG comprised of representatives of various VOs and VRIs (INGV, IMO, IGME, UI, DIAS, OPGC, IPGP based in Italy, Iceland, Portugal, Greece, France, and Ireland). Volcanic areas monitored by respective authorities in Spain, UK, Norway, Netherland, and Turkey were not represented during the early stages of the working group. CSIC and IGN (Spain) were later incorporated and the University of Bristol and BGS joined VO-WG yet later as VRIs with deep involvement in the monitoring of the UK volcanoes.

For the VO-WG it was clear that EPOS was offering the volcanology community an exceptional opportunity to overcome existing problems of fragmentation, lack of full multidisciplinary collaboration, and data exchange as well as to improve integration. In this sense, it became evident that the integration of the volcanology community into EPOS was fundamental to give visibility and coherence to the community, making it competitive to address global challenges [Puglisi et al., 2015]. Also, it offered the possibility to implement, for the first time, trans-national access among VOs and VRIs, and potentially influence national priorities ensuring long term sustainability of the RIs.

During EPOS-PP, the VO-WG worked towards: (i) identifying further representatives to be included in the working group; (ii) list all European active volcanoes; (iii) develop and complete a template for the description of instrumentation on European volcanoes and (iv) explore the idea of having a centralised repository for volcano data and develop a plan for integration of legacy (past) data. At the same time, the VO-WG started the process of preparation of an 'Infrastructure Project' proposal aiming at a closer collaboration between volcano observatories. This idea, launched during the "ESFRI Call for consultation" in 2012, culminated successfully in 2018 with the EUROVOLC project (see section 5).

The main conclusions drawn by the VO-WG were that the community needed to establish a coordination for proposing services at European level as done in the past by the seismological community with the ORFEUS initiative (https://www.orfeus-eu.org/). Back then, only France had already taken steps towards distributing seismic and geodetic data from volcano observatories through Résif data centre (https://seismology.resif.fr/). Consequently, at the end of the EPOS-PP project, the VO-WG strongly supported the proposal to implement a TCS for Volcano Observations, adopting the concept and the implementation work plan of the TCSs defined in the frame of EPOS-PP [Puglisi et al., 2015].

2.3 The EPOS-IP Project

The EPOS-IP project was the continuation of and built on the achievements of the successful EPOS-PP. The communities that contributed to define the TCSs remained active because they represented a collaborative framework where to discuss and support the EPOS implementation and its achievements. The final overall goal was the establishment of the EPOS-ERIC and has been hosted at INGV Rome since 2018. During EPOS-IP the main tasks included: (i) establishing a governance structure to coordinate, manage and orchestrate data and community services as well as formal links to the EPOS managing bodies; (ii) find technical solutions to implement the data infrastructures and the web services into EPOS e-infrastructure; (iii) define a financial plan to guarantee the long term sustainability of involved data and e-infrastructures; and (iv) validate the TCSs suitability to enter into the EPOS Operational Phase. The Work Package 11 (WP11) of EPOS-IP was the one whose implementation led to establishing the EPOS ERIC VO-TCS.

The TCSs defined during EPOS-PP were organised in pillars in which specific services and data infrastructures were planned to be provided through single or distributed infrastructures. These services and data infrastructures could already exist and consequently, would be adapted for integration in EPOS, or may be new according to the needs identified by the community. Therefore, the main aim of WP 11 was to network the existing volcanological services for sharing data, products and tools within the European volcanology community and, through the link with the ICS, with users and stakeholders outside this community. Provided services were envisaged to be both "virtual" and "physical" and addressed to deliver volcanological data (incl. Seismic and GPS/geodetic, Volcanological / environmental data) and products (incl. products from Seismic, GPS/geodetic and Satellite data, Volcanic Reports, numerical simulations and software, and hazard assessments).

In particular, the WP 11 had to define the VO-TCS governance structure, and categorise and prioritise the services to be provided. Additionally, WP11 worked on establishing the conceptual design of the Volcano Gateway (see section 4.4). In parallel, the VO-TCS worked at the volcanology community level, to increase awareness of the impact and benefits of the EPOS new research exploitation platform, foster training, outreach, and international cooperation. The details of the structure, governance, and service provision of VO-TCS are reported in the next sections.

During the EPOS-IP, the WP11 made a profound revision of the Data, Data products, Software and Services (DDSSs). To this end, it defined a clear and verifiable roadmap to fix the main gaps for the technical implementation (revision of the DDSSs and relevant providing services, completion of the submission of the service within GitHub, a common used shared developing framework and putting the services into operational), and governmental, legal and financial aspects (finalisation of the Consortium Agreement and the Supplier Letters, implementation of the Data Management Plan and the cost book). This major effort enabled the VO-TCS to pass the validation criteria fixed by EPOS-IP to be considered as TCS, in 2019. At the end of the EPOS-IP project, the envisioned services were 41, corresponding to 29 DDSSs in total (Table 1). The service provision is a dynamic process, thus the number of services offered as well as that of the service providers will increase over time with respect to the numbers showed in Table 1. The table, in fact, represents a snapshot of what has been implemented at the time of writing.

DDSS - ID	Category	DDSS Name	CSIC	IMO	INGV	IPGP	OPGC
WP11-DDSS-001	Seismological data	Velocity seismic waveforms		Eastern, Northern and Western volcanic zones	Etna, Stromboli, Vulcano, Campi Flegrei, Vesuvio	Mayotte, Montagne Pelée, Piton de la Fournaise, Soufrière de Guadeloupe,	
WP11-DDSS-002	Seismological data	Acceleration /Accelerometer waveforms			Etna, Stromboli, Vulcano, Campi Flegrei, Vesuvio	Montagne Pelée, Soufrière de Guadeloupe,	
WP11-DDSS-003	Geodetic data	GNSS raw data (Rinex Data- 15s)		Eastern, Northern and Western volcanic zones	Etna, Stromboli, Vulcano, Campi Flegrei, Vesuvio	Mayotte, Montagne Pelée, Piton de la Fournaise, Soufrière de Guadeloupe,	
WP11-DDSS-005	Geodetic data	Tiltmeter				Mayotte, Montagne Pelée, Piton de la Fournaise, Soufrière de Guadeloupe,	
WP11-DDSS-006	Geodetic data	Tide gauge				Soufrière de Guadeloupe	
WP11-DDSS-022	Ground-based remote sensing data&products	Ground-based radar data		Grímsvötn, Eyjafjallajökull			
WP11-DDSS-023	Ground-based remote sensing data&products	Ground-based visible and thermal / IR camera		Bárðarbunga			
WP11-DDSS-024	Ground-based remote sensing data&products	Ground-based doppler radar near-source eruptive parameters					Etna
WP11-DDSS-025	Ground-based remote sensing data&products	Ground-based UV scanner spectra		Bárðarbunga			
WP11-DDSS-026	Rock sample properties	Collections of magmatic rocks					Piton de la Fournaise
WP11-DDSS-031	Volcanological /petrological	Reports on volcanic activity		All volcanoes in Iceland	Etna	Mayotte, Montagne Pelée, Piton de la Fournaise, Soufrière de Guadeloupe,	
WP11-DDSS-032	Volcanological /petrological	Aviation colour codes for volcanoes		All volcanoes in Iceland	Etna		
WP11-DDSS-033	Volcanological /petrological	Catalogue of eruptions		Bárðarbunga, Eyjafjallajökull, Grímsvötn, Hekla, Katla			
WP11-DDSS-036	Geochemical /petrological	Chemical analysis and physical properties of gas, water and rocks			Etna		Piton de la Fournaise
WP11-DDSS-047	Satellite data	Volcanic Plume (Ash + SO2)					Active volcanoes between -70° and 70° of latitude and longitude
WP11-DDSS-049	Satellite data	Thermal anomaly (lava flow)					Active volcanoes between -70° and 70° of latitude and longitude
WP11-DDSS-050	Satellite data	Wrapped Differential Interferograms (Phase and Amplitude)			Etna		Piton de la Fournaise
WP11-DDSS-051	Satellite data	InSAR lava flow maps					Piton de la Fournaise
WP11-DDSS-053	Ground-based remote sensing data&products	Ground-based Doppler radar spectra					Etna
WP11-DDSS-054	Geohazards	SO2 concentration probabilistic hazard maps		Bárðarbunga			
WP11-DDSS-056	Geohazards	Spatial probability analysis/maps	San Miguel, Lanzarote Island, El Hierro island, Deception Island, La Garrotxa Volcanic Field				
WP11-DDSS-057	Geohazards	Lava flow invasion hazard maps	Lanzarote island, El Hierro island, Deception Island, La Garrotxa Volcanic Field				
WP11-DDSS-058	Geohazards	Tephra fallout hazard maps for explosive volcanoes	Lanzarote island	Hekla, Katla			
WP11-DDSS-059	Geohazards	PDCs hazard maps	El Hierro, Deception Island, La Garrotxa Volcanic Field				
WP11-DDSS-060	Geohazards	Probabilistic volcanic hazard assessment (maps)	Lanzarote island, El Hierro island, Deception Island, La Garrotxa Volcanic Field				
WP11-DDSS-064	Geohazards	Effects on health and recommendations for response to SO2 from volcanic eruptions		All volcanoes in Iceland			
WP11-DDSS-065	Geohazards	Daily ash/gas forecasting maps		Dependent on the daily runs			
WP11-DDSS-067	Data services	Station information		Eastern, Northern and Western volcanic zones			
WP11-DDSS-070	Modelling and Computational Volcanology	Software catalogue for petrological to geophysical modelling			√		

Table 1. List of the services currently active in the EPOS ICS. Note that the DDSSs includes data collected at different volcanic areas, which might belong to different Service Providers. The table also shows the areas for which data or products are provided; DDSS 070 does not refer to a specific area, as it provides access to computational tools.

3. Volcano Observations Thematic Core Service

3.1 Objectives

Based on the efforts made in EPOS-PP and EPOS-IP, from April 2020 the VO-TCS was formally established as a component of the EPOS Delivery Framework (i.e., the technical, legal, financial and governance framework defined in the EPOS-ERIC to provide the services). In line with the outcome of the previous work, the objective of the VO-TCS is to provide long-term sustainable access to the Volcano Observatories' and Volcano Research Institutions' DDSSs by implementing facilities that allow easy access and interoperable services. The final purpose is to promote volcanology research in Europe by fostering knowledge sharing and scientific collaboration. Additionally, the VO-TCS also contributes to the activity of the EPOS-SP project designed to promote EPOS to a wider user community at European and global level.

In the framework of the VO-TCS, the Volcano Observatories (VOs) are defined as the legal entities that have the operational responsibility of monitoring volcanoes, forecasting hazards, issuing warnings and alerts to Civil Protection authorities and Volcanic Ash Advisory Centres (VAACs), and informing society when the volcanoes show signs of unrest or imminent eruption. The VOs operate multidisciplinary monitoring and surveillance systems to assess volcanic activity, support decision makers, Civil Protection, and aviation authorities at regional-, national-, or international level to achieve their operational goals, and carry out research, technological developments, modelling, and hazard evaluation in all fields of volcanology as well as communicate volcanological information to civil society. The distribution of the VOs is dictated by the location of active volcanoes (Figure 3), which within Europe are found in Italy, Iceland, Portugal, Spain, Greece and Norway. Active volcanoes also belong to European Outermost regions (ORs) in the Caribbean Sea (France, UK, and Netherlands), Indian- and Pacific oceans (France) and the South Atlantic Ocean (UK).

Volcano Research Institutions (VRIs) are defined as institutions that include universities, agencies, institutes, centres, laboratories, and groups that use and produce volcano observations, carry out experiments, modelling, and scientific studies to improve the knowledge of volcanological processes and hazards. The VRIs often utilise the monitoring data produced by the VOs and, even though they do not have formal monitoring responsibilities, and in some cases, they may also operate monitoring programs and systems and provide scientific knowledge and advice.

Considering all this, the overall mission of the VO-TCS is:

1) to provide coordination between the European VOs and VRIs;
2) to implement interoperable services;
3) to provide long-term and sustainable access to Volcanological DDSSs (VO-DDSSs) related to volcanic areas monitored and/or studied by the European VOs and VRIs;
4) to promote good practices through EPOS.

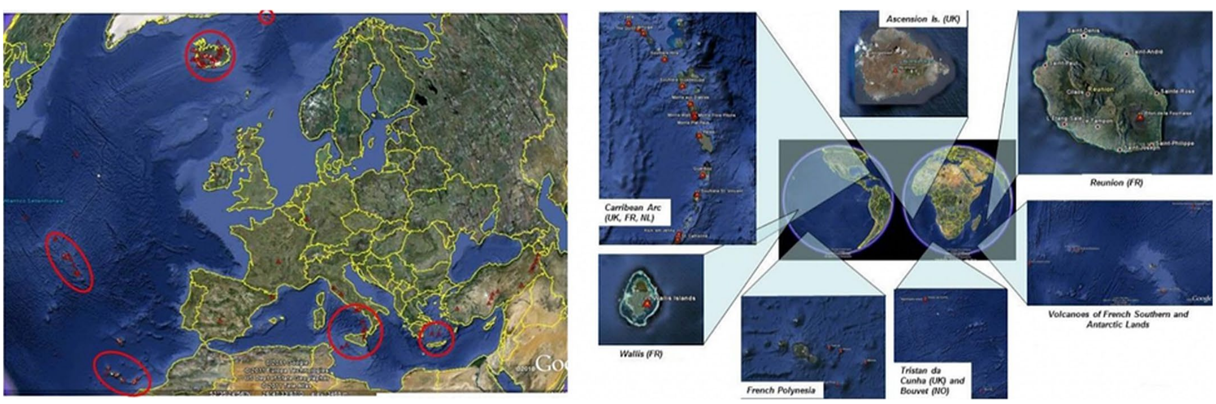

Figure 3. Geographical Distribution of European volcanic areas (red circles) and volcanoes (red triangles) included in EPOS VO-TCS: on the European continent and the Canary Islands (left) and in overseas countries (right).

In order to achieve these goals, the VO-TCS actions consist in:
1) defining the standard services and assessing their quality, as well as coordinating their implementation in accordance with EPOS policy;
2) developing a Data Management Plan;
3) providing access to Data and Data products resulting from monitoring and research activities on European volcanoes, as well as Software and Services aiming at modelling the volcanic processes and assessing the dynamics, extent and impact of volcano-related hazards through Virtual Access (VA) and Trans-national Access (TNA);
4) sharing good practices in the community of the Volcano Observatories and Volcano Research Institutions (VOs/VRIs) in terms of observational techniques, methods of analysis and modelling, service implementation and data management;
5) defining and implementing the information and dissemination outreach strategy;
6) coordinating the community for collaborative projects across VOs/VRIs.

3.2 Functional Architecture and governance bodies

3.2.1 VO-TCS architecture

The VO-TCS is organised in a layered structure (Figure 4), where the main role is played by the institutions (VOs and/or VRIs) providing DDSSs through VA and TNAs, hereafter referred to as Service Providers (SPs). The lowermost layer of the structure includes the Data Providers (other national RIs; DPs) that provide DDSSs to the TCS through the SPs to which they are linked by specific agreements; in some cases, an institution may have both the roles of Service Provider and Data Provider.

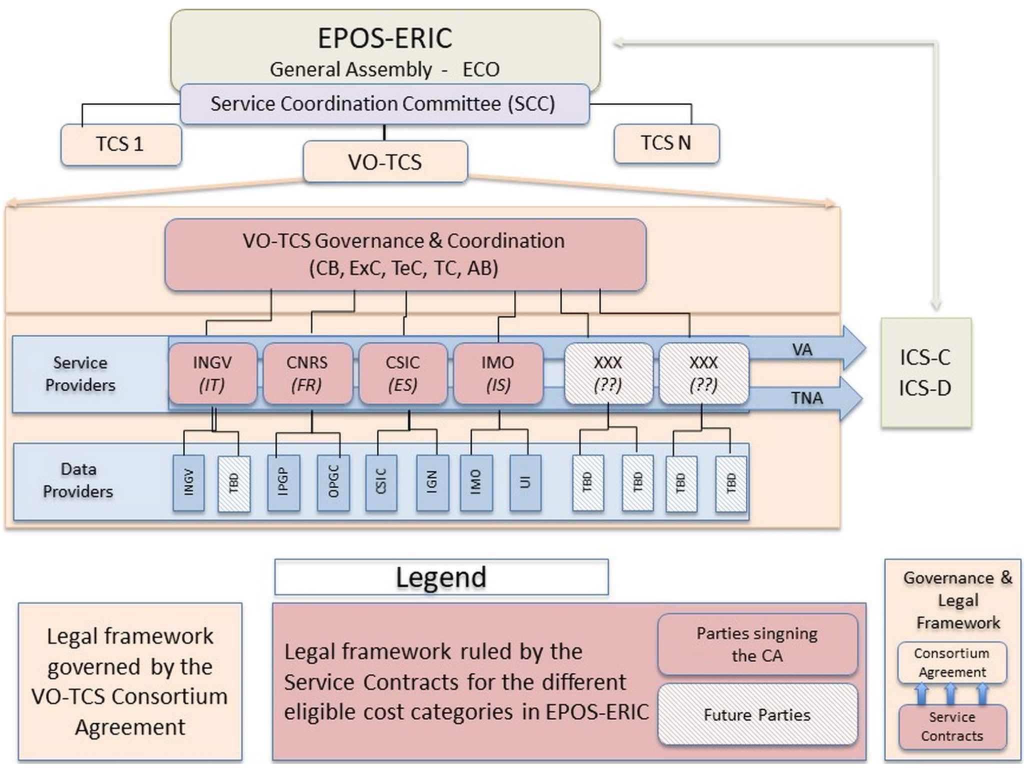

Figure 4. General architecture of the VO-TCS. The lower level refers to the source of the VO-DDSSs available through the Data providers and coordinated by National Consortia (if they exist); please note that the open fields and question marks imply the opportunity to add more Service Providers and relative Data Providers to the VO-TCS. The medium level refers to the technical management of the services (VA and TNA services; all managed by Service Providers) 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.

At the time of writing, the SPs with successfully tested and validated services are:

- *Istituto Nazionale di Geofisica e Vulcanologia (INGV, Italy):* Manages two volcano observatories (Osservatorio Vesuviano and Osservatorio Etneo at Naples and Catania, respectively), and includes several laboratories and modelling centres at INGV in Rome, Palermo, Pisa and Bologna).

- *Icelandic Meteorological Office (IMO, Iceland):* The Volcano Observatory in Iceland, which also manages the contributions of the national university (University of Iceland, UI).

- *Agencia Estatal Consejo Superior de Investigaciones Científicas (CSIC, Spain):* A research institution that also includes the data and data products provided by the monitoring system of the Canary Islands, managed by Instituto Geográfico Nacional (IGN, Spain).

- *Centre National de la Recherche Scientifique (CNRS, France):* Includes the Institut de Physique du Globe de Paris (IPGP) and the Observatoire de Physique du Globe de Clermont-Ferrand (OPGC). The IPGP manages three volcano observatories (Observatoire Volcanologique et Sismologique de la Martinique, Observatoire Volcanologique et Sismologique de la Guadeloupe, Observatoire Volcanologique du Piton de la Fournaise), and OPGC contributes (with IPGP) to the national volcano monitoring systems (SNOV). Both institutions include several laboratories and modelling centres. The newly created (2019) REVOSIMA (the Volcanological and seismological monitoring network of Mayotte) is operated by IPGP, BRGM, IFREMER and CNRS in France along with many partners of the REVOSIMA consortium including the OPGC.

Besides the above listed institutions, in the future the VO-TCS will also include the partners that participated in the EPOS-WP11 activities and other European institutions which share the mission of the VO-TCS and will aim to contribute to the VO DDSSs provision.

The uppermost layer of the TCS architecture consists in the Governance and Coordination bodies, whose roles and aims are detailed in the following section (3.2.2 VO-TCS Governance bodies). The TCS also has a Coordinator, which is selected among the SPs and represents the TCS interface with EPOS-ERIC for all the technical, legal, and financial aspects. Hence the Coordinator represents the Party who acts as the legal intermediary between EPOS-ERIC and the TCS.

3.2.2 VO-TCS Governance bodies

As for any consortium, the governance and reference terms of the VO-TCS are detailed in a Consortium Agreement (CA). This CA specifies the relationship among all participants, their rights and obligations, as well as the organisational, managerial and financial guidelines to be followed by the VO-TCS in order to cooperate with EPOS-ERIC.

The VO-TCS governance is carried out by the following bodies (Figure 5):

- **Consortium board (CB):** Decision-making body responsible for the overall performance of the VO-TCS Consortium, which provides an overall leadership for the strategic direction of the Consortium and is free to act on its own initiative to formulate proposals and take decisions in accordance with procedures set out in the CA.
- **Executive Committee (ExC):** Supervisory body for the execution and implementation of the TCS activities and of the CB decisions. The ExC has the joint overall responsibility for managing the activities decided by the CB and representing the VO-TCS Consortium, and manages the Services for Governance and community coordination. One of the ExC members is appointed as Coordinator.
- **Technical Committee (TeC):** TeC provides technical advice, harmonises and shares knowledge and solutions between Parties, advises and introduces new technology and shares ideas on how the services can develop. The TeC will monitor the performance of services and eventually plan the implementation of potential new services.
- **Transnational access Committee (TC):** TC is responsible for the financial and technical management of the transnational access (TNA) activities according to the TCS work programme and the EPOS guidelines.
- **Advisory Board (AB):** AB supports the community building, advises the CB on the development of the TCS work programme, provides users perspective on the services, advises on future development, and priorities to further extend the services. According to the role, the AB is composed of representatives of the stakeholder community.

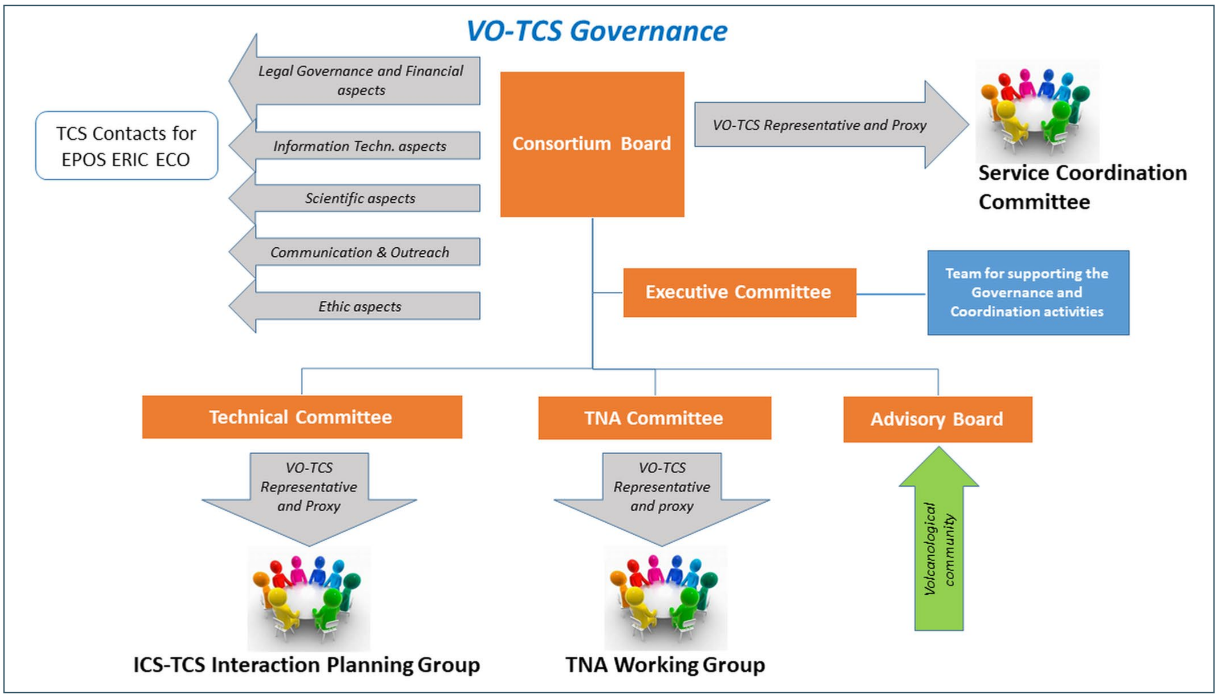

Figure 5. The structure of the governance bodies of VO-TCS (in orange); the relationships with the other components of the EPOS ERIC (grey arrows) and with the community (green arrow) are reported. A Team supporting the ExC committee (box blue) has also been appointed, although this is not foreseen by the structure of the governance.

4. The VO-TCS service provision

4.1 Kind of services and accesses

As in the other TCSs, the provision of the VO-TCS services has two aspects: the legal and financial, from one side, and the technical, from the other, which are managed by the TCS Governance according to the EPOS ERIC frame and the characteristics of each VO-TCS Service Provider. The overall aim is to provide sustainable services with clear access rules, well-defined maintenance costs and harmonised easy-to-use access. Dissemination activities are part of the service provision as they promote the discovery, encourage their use, and enlarge the stakeholder community. Volcanological DDSSs are intrinsically heterogeneous in nature, and such characteristic significantly impacts on the service provision. Indeed, some DDSSs are in partnership with other EPOS communities, such as the seismic waveforms or the GNSS raw data or the SAR Interferometric maps while other DDSSs, such as the geochemical data, are solely part of the volcanology community. The management of such heterogeneity has represented one of the main challenges of the VO-TCS service provision though at the same time, it is unquestionable that such a peculiarity does represent a great resource for users. Indeed, VO-TCS provides data, data products and services of different nature, spanning from example from the velocity seismic waveforms recorded by permanent networks to more elaborated products such as reports and modelling software (Table 1). The services are of geophysical, geochemical and volcanological nature and include data collected by both in-situ and remotely (ground- and satellite-based) (Table 1). Among the highest level of products offered, it is worth mentioning, for instance, the SO_2 concentration probabilistic hazard maps, lava flow invasion hazard maps and software catalogue for petrological to geophysical modelling. Of course, given the many service providers of the VO-TCS, the data differ also geographically – in fact, the accessible information belong to diverse European and Pan-European volcanoes, such as Mt. Etna, Stromboli, Vulcano, Campi Flegrei and Vesuvius (in Italy), Piton de La Fournaise (La Reunion Island, France), Hekla, Katla, Bárðarbunga, Grímsvötn and Eyjafjallajökull (in Iceland) or El Hierro and Lanzarote (Canary Islands) (Table 1). This huge diversity of the services does effectively represent a unique opportunity and great wealth for users such as academics and students willing to carry out research in Earth Sciences as well as in other research domains like atmosphere and climate for instance. The different nature of the data allows exploring the targeted volcanic areas from depth to the atmosphere, and thus enables studying and modelling dynamics inside the Earth as those occurring once the volcanic products interact with the atmosphere. Hazard products will also be attractive for different kinds of stakeholders including non-European volcanology observatories and decision-making agencies.

The following subsections detail the management of the DDSSs diversity, and the related issues linked to service provision and report on the technical solutions that VO-TCS adopted to access the services (i.e. the Gateway implementation).

4.2 Harmonisation and standardisation for the service provision (financial, legal, and technical aspects)

Acting under the EPOS-ERIC umbrella, in order to provide services in a harmonised framework, the VO-TCS and the other EPOS TCSs collaborate to adopt the same approach in defining the cost of the services and the legal access rules, and sharing DDSSs data and metadata standards.

Financial aspects

The assessment of the service costs has followed the funding model and the cost book scheme defined by EPOS, and aimed at estimating the financial efforts for implementing (national contribution) and maintaining (national + EC contribution) the services.

Overall, NRIs support the implementation of the services contributing with their own infrastructures, and thus with data generation, which are funded by institutional or other national funds. In particular, considering the characteristics of the volcanological observational systems, in many cases these funds have come from the Civil Protection Agencies, although recently the contribution to support the national research infrastructures has become more significant thanks to the positive influence of EPOS at a national level. Hence, while on one hand the service implementation has been supported at a national level and by the European projects in which the volcanology community has been involved (e.g., the implementation of the Gateway, see the section 4.3), on the other hand the VO-TCS service maintenance is supported from both national and EPOS-ERIC funds.

Legal aspects

Concerning the legal aspects related to DDSSs provision, VO-TCS adopts the Open Access criteria and the Licenses defined in the EPOS Policy. Of course, “open access” does not mean “free access”, in fact, VO-TCS aims at granting access to its DDSSs according to their classification. In this sense, a service is classified as “Open”, if it is freely available to users, “Restricted” if it is accessible under the condition set out by the Service Provider (e.g., data are sensitive for Civil Protection purposes, acquired in the frame of PhD activity, etc.), or “Embargoed” if the service is available after an embargo period, which is set to a maximum of 3 years. Whatever the class of the service, the metadata are “Open” to allow the data discovery. In terms of licenses, VO-TCS adopts the Creative Common 4.0 License to regulate the use and reuse of data and metadata.

Technical aspects

One of the key elements of the EPOS functional architecture is the interaction between ICS and the TCSs (the “Compatibility Layer”; Fig. 1). From the technical point of view, in the EPOS-ERIC this is managed by a group named “ICS-TCS Interactions Planning Group (IPG)” (Fig. 5). Due to the presence of heterogeneous datasets, one of the problems of the volcanology community in the frame of IPG has been the lack of a pre-defined common format for all data domains. So, at the very beginning, a survey was carried out within the VO-TCS to classify different datasets and to understand their level of compatibility with respect to the ICS requirements. The survey also helped the TeC to collect all parameters needed to describe the main metadata for each VO service.

Once the service was “up and running”, the EPOS harmonisation process started and ended only when the validation procedure, managed in cooperation with ICS, had been passed. Adopting this general procedure to provide services to ICS, the VO-TCS has managed the access to two types of services: Virtual Access and Trans-national Access to facility services.

To provide virtual access (VA) to data, products or services, the main effort has been defining the metadata standards that could have best represented the services and enabled the data dissemination. So, initially, it was necessary to carry out the metadata definition process working in closely contact with the domain experts and then, associating a conceptual model used to create the database structure, in which the information is stored, managed, and updated. In this way VO-TCS contributed to argument the EPOS metadata model by new entities – i.e. web service, volcano, web categories, staff, end point, institution, and reference.

In particular, the *web service* entity provides the specific characteristics of the service (i.e. name, description, etc.); the "volcano" entity refers to the area where the data are collected; the "web categories" relate to the type of data (i.e. seismic, geodetic, volcanological/petrological, geohazard, ground-based remote sensing, satellite data); "Staff" is the contact point information, to which the user can turn for further service details; the "end point" is the available URLs or access points, which manage the facilities made available to access, discover and download data; the "Institution" provide information related to the data provider institution; "references" are the associated scientific papers.

VO-TCS Transnational Access (TNA) provision benefitted from the experiences gained in the framework of the ENVRI PLUS (http://www.envriplus.eu) and EUROVOLC projects. In particular, in the latter an *ad hoc* software tool was implemented. This framework takes up the design scheme envisaged in EPOS, and follows the specifications required by its services. The proposed infrastructure is based on an interactive Web portal solution that uses a relational database. The infrastructure is composed of i) a back end, based on a Linux server that provides all the necessary services and controls; ii) a front end based on the relational "MySQL" database.

The main goals of the TNA portal are (i) to detail information on the opportunities provided by each research structure, thus supporting the TNA call dissemination, (ii) to manage the submission phase through the implementation of a TNA submission form and the development of a relational database for data storage and (iii) to guide the evaluation phase of the applications submitted through analysis and statistical procedures.

The volcanology community defined three main categories in which all the VO-TCS facilities can be grouped:

- Access to Volcano Observatories and Volcano Research Institutions (e.g., laboratories, observatories, etc.);
- Access to Mobile Instruments (e.g., seismometers, drones, LIDARs, gravimeters, thermal cameras, etc.);
- Provision of Rock Samples (remote access to rock samples of different volcanoes and eruptions).

The querying and population of the structure was carried out using the SQL language and implementing dedicated views.

4.3 Outreach, communication, and engagement of the community

The aim of VO-TCS communication is primarily to share and disseminate information about its activities, infrastructures, services, and related implementation steps, both inside the TCS community and toward the enlarged reference one, with the effort towards making the community wider and more easily interconnected. VO-TCS outreach and dissemination activity operates in close collaboration with the EPOS-ERIC Communication team and according to the EPOS communication Plan. In particular, the VO-TCS outreach and dissemination team collaborates with EPOS to broadcast the specific VO topics, both to the reference scientific and stakeholder community, and to a wider target audience (e.g., PhD students, University students, local stakeholder, etc.). This is mainly achieved through the EPOS website, and through EPOS presence during National and International congresses. The long-lasting Communication & Outreach contribution of the VO-TCS has been devoted (i) to the update and integration of the EPOS website, producing outreach material about tools and services offered, as well informing about specific issues, as activities carried out facing volcanic eruptions and unrest, and (ii) to the provision of resources to training on services and tools, and implementing VO topics knowledge.

To pursue and strengthen the performance of VO-TCS communication & outreach, some actions have been outlined with the primary task to reach and involve a wider reference scientific community, and also encourage a deeper participation of each TCS partner in the communication issue. The planned activities have included:

- definition of a wider target audience within both the VO scientific community and the academic field, with particular attention to PhD students and young researchers;
- organisation of the community meetings to present the status of the services and their implementation to the community, as well as meeting with selected stakeholders to show the VO-TCS services and infrastructures;
- taking into account the EduBox tool implemented in EUROVOLC (see later) as an outreach resources database suitable for multi-query searches, to structure a custom sub-site in the Gateway to able sharing of output and outreach materials (files, videos, references etc.).

4.4 The VO-TCS Gateway

4.4.1 Objectives

The idea of a *Volcano Gateway Data Portal* (currently beta version is available currently beta version is available at http://vo-tcs.ct.ingv.it/) was came about in EPOS-IP with the purpose of technically integrating access to multidisciplinary data and scientific products generated by the volcanology community. The idea was finalised while working on the EUROVOLC project proposal, as one of the main objectives was to develop an e-infrastructure (a bridge) for sharing data and services (including those from EPOS) amongst the EUROVOLC community.

Todays, the VO-TCS Gateway Data Portal provides scientists with access to a portfolio of data, data products and services to improve their knowledge of volcanic processes, as well as managing the trans-national access to VOs and VRIs. It represents a great resource to access the huge amount of geophysical, geochemical, and environmental data that the volcanology community currently holds by managing thousands of monitoring stations located around European volcanoes.

The VO-TCS Gateway takes inspiration from the experience gained in the frame of the volcano observatories/research institutions and from the results obtained in the two projects FUTUREVOLC (http://futurevolc.hi.is/ & http://futurevolc.vedur.is/) and MED-SUV (https://www.brgm.fr/en/reference-completed-project/med-suv-project-mediterranean-supersite-volcanoes).

By using the e-infrastructure of EPOS, the VO-TCS Gateway stores and provides access to existing and/or new data and services of the volcanology community also managing those services that are not ready in EPOS from the legal, governance and financial point of view. In this sense, the VO-TCS Gateway guarantees the perfect technical compliance with the standards defined in EPOS-IP and benefits from all results of the VO-TCS-ICS interaction that characterises the production phase. The "beta version" of the "Gateway" is one of the products of the EUROVOLC project and the actual VO-TCS Gateway will migrate into the *Eurovolc.eu* domain. To ensure the long-term sustainability after EUROVOLC, EPOS will guarantee sustained data access in a wide sense, while the VO-TCS Gateway will extend the practices and knowledge developed in the EUROVOLC project, thus avoiding the natural fragmentation, and providing data access to the volcanology community.

4.4.2 Architecture

The main idea for the VO-TCS Gateway Data Portal is to implement a technical solution that allows providers to efficiently manage, organise and share data on one hand and, on the other, to have a system where users can access and discover resources easily and efficiently (Figure 6).

The adopted approach is focused on the development of a conceptual model based on the volcanology community shared experience, to represent and organise heterogeneous information by using a complete metadata representation. This approach should ensure the capability of the system to associate descriptive characteristics to each resource with a proper metadata description, thus leading to the development of a metadata catalogue, which provides common and standard features needed to represent the heterogeneous resources, and which facilitates the creation of data structures for data management and storage (Figure 7). Indeed, the Gateway is compliant with the FAIR principles (findability, accessibility, interoperability, and reusability) in data discovery and access.

The Gateway internal architecture roadmap is based on four main steps (Figure 7): (i) Metadata definition, (ii) Metadata Conceptual model implementation, (iii) Data structure development, (iv) Data discovery implementation.

The first step, the *Metadata definition* process, defines a set of entities and associated properties, which identifies, in a universal and univocal way, a resource. In this sense, the defined entities are used to create a *Metadata Conceptual model*, which allows the data organisation in terms of a standard representation of assets and the relationship between them. The obtained model represents the starting point for the *Data structure implementation;* from a technical point of view, this question relates to the use of MySql as the chosen relational databases that have been created to store the different types of information. At this stage, different solutions create efficient tools for data visualisation and for the dynamic management of the resources in terms of sharing and discovering datasets. In detail, the Web Portal implements the specific web page and functionalities for different kinds of services and accesses provided by the VO-TCS community.

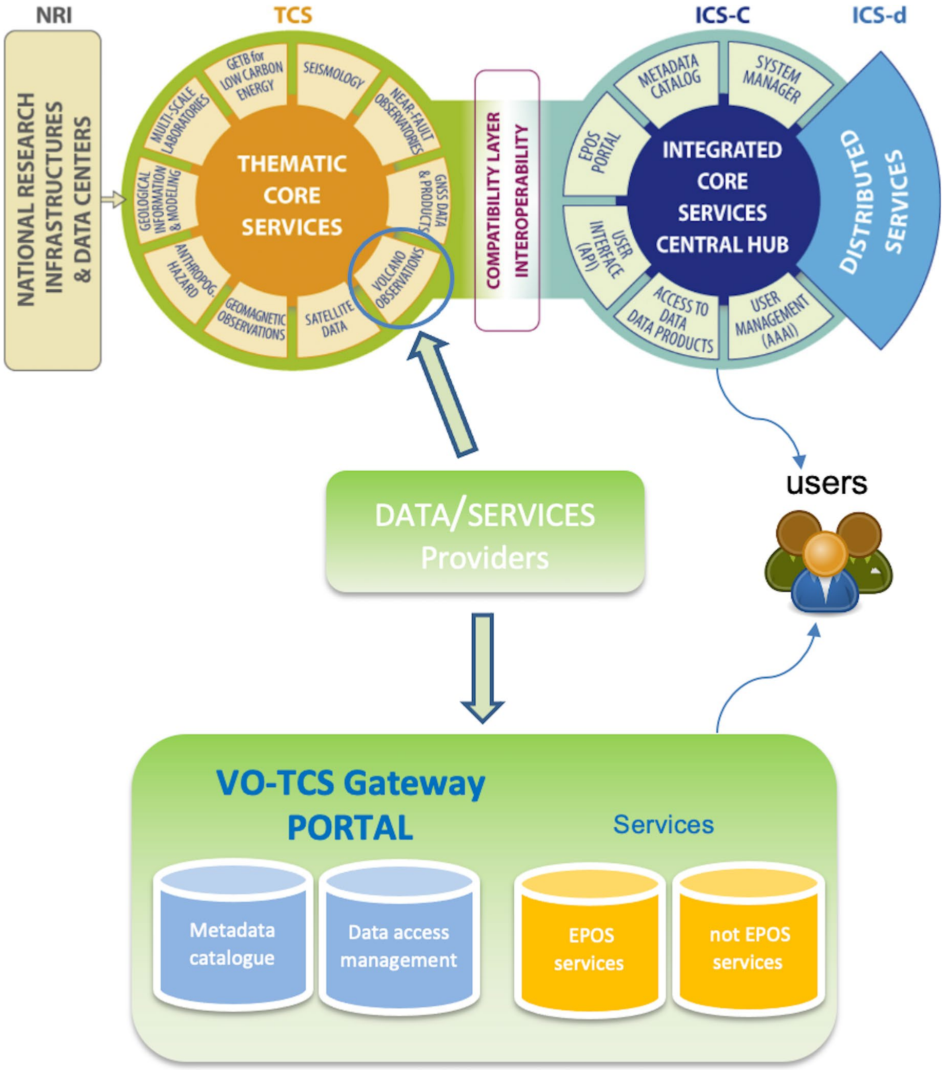

Figure 6. Conceptual model of the VO-TCS Data Portal. The VO-TCS Gateway allows the volcanological community to manage a custom data portal.

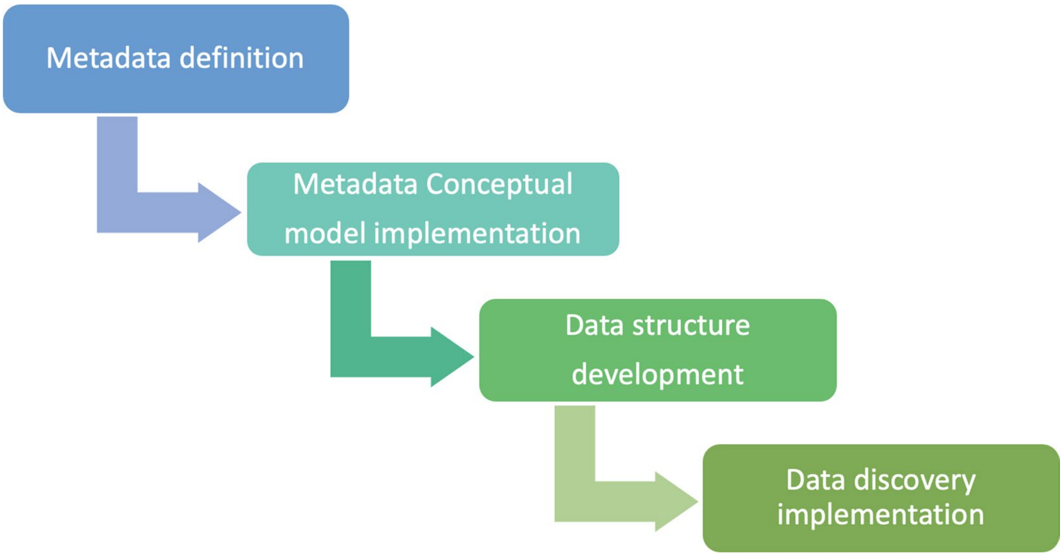

Figure 7. Gateway architecture steps.

To facilitate this process, the VO-TCS Gateway Web Portal implements a custom Graphical Interface (Figure 8) that allows discovering metadata in two different ways:

1) a first more generic approach uses datatables table view (https://datatables.net/) and provides a free text search and semantic filters (category, service name, institutions);
2) a second approach refers to a specific landing page containing all the details necessary to manage the requested service (Figure 9).

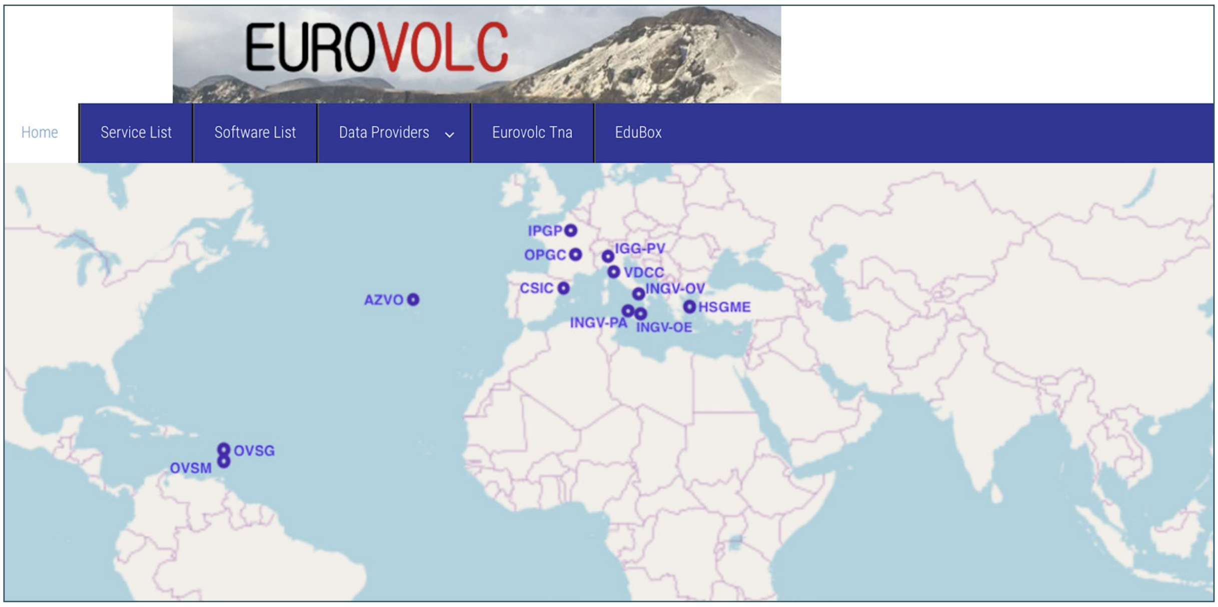

Figure 8. Home Page of the VO-TCS Gateway: it shows the main five bar functionalities: the "Service list"; the "Software List", the link to web pages of the "Data Providers"; the data portal dedicated to "Eurovolc Tna" calls; and the "EduBox" that includes the list of references and outreach material. Through the bars it is possible to recognise the services reported in the next 5.4.3 paragraph. All operational EPOS services are included into the Service List, flagged by the EPOS logo in the Service details (left sidebar of the landing page in Figure 9). The operational EUROVOLC services and products are accessible through the Software List and in the EduBox bar.

4.4.3 Examples of Gateway services

To show the opportunities offered by the VO-TCS Gateway, here we report the examples of three kinds of services: an operational EPOS service, an operational EUROVOLC service and an EUROVOLC service under implementation in the Gateway.

The operational EPOS service

Figure 9 shows an example of a landing page of an operational EPOS service. It consists of the INGV contribution to the WP11-DDSS-036 EPOS service (see Table 1) "*Chemical analysis and physical properties of gas, water and rocks" (http://193.206.223.51:8088/eurovolc/landingPage.php?ID=1))*; a set of geochemical bulk-rock and trace element compositions of Mt. Etna Volcano products. The OPGC also contributes to the WP11-DDSS-036 EPOS service by providing information on French volcanoes (Piton de La Fournaise). The service is up and running within the EPOS framework owing to the successful achievement of the whole validation process with ICS.

The operational EUROVOLC service

The "Software List" refers to the VA to a catalogue of "Existing volcanic hazard tools" and represents one of the expected EUROVOLC products. Because hazard tool software versions are continuously modified/updated, the main effort in planning the system is to develop an interactive tool, a "web catalogue", very simple to use and easy to upgrade. From a technical point of view, experts or no-expert users can find details even if they do not know appro-

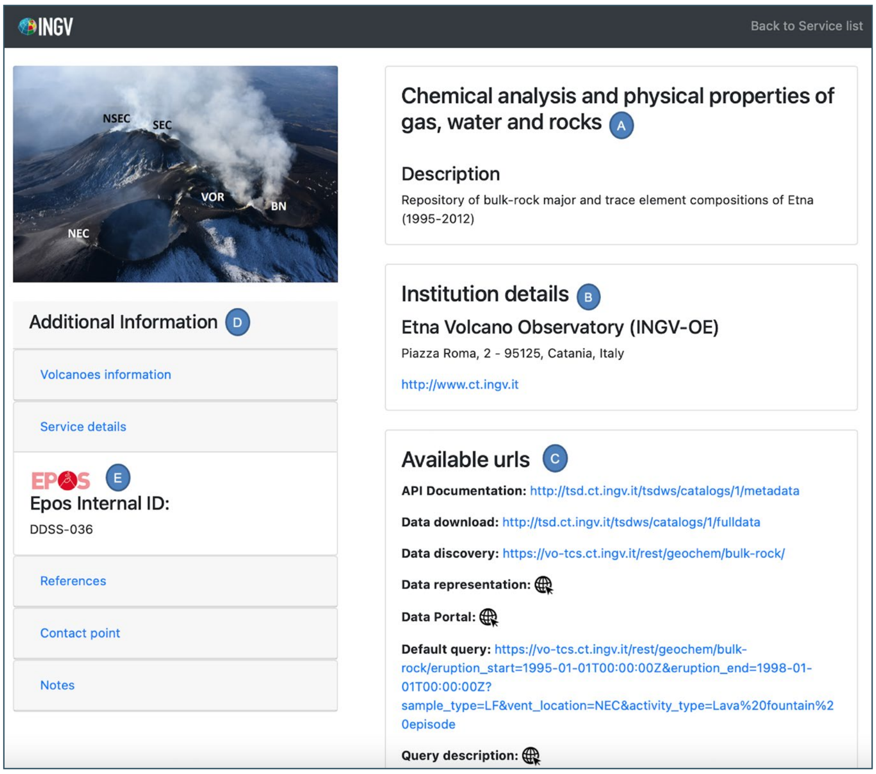

Figure 9. Example of a landing page for a specific service. The landing page represents a dashboard that helps a generic user to manage all available information related to a specific service. Moving from the top right, the page describes the generic info of the services (A) and the providing institution (B). The bottom right window contains all technicalities to access data in a manual or in an automatic way (C). The left side contains, instead, useful additional information (D), like EPOS DDSS related number (E).

priate keywords; a free search area can be used to search, filter, and also to group the needed information and allow to discover metadata in a very intuitive way. This catalogue can be considered a useful use case for developing a new EPOS service starting from an existing structured tool, but not yet compliant with EPOS requirements.

The non-operational EUROVOLC service

The VO-TCS Gateway will also be linked to the *European Catalogue of Volcanoes and Volcanic Areas* (ECV) (https://volcanoes.eurovolc.eu/) (see Section 5.2.2), one of the products of the EUROVOLC project. Indeed, a roadmap to verify the interoperability between the ECV and the VO-TCS gateway is defined, and it consists of two different steps. The first is obtained by including the ECV as an operational EUROVOLC service (see volcanoes information in the section above) within the VO-TCS Gateway with its own landing page for details. The second, that will be conducted in a parallel way, is the definition of the main ECV features, in terms of metadata descriptors, that can be used to expose a Representational State Transfer (REST) response as requested by EPOS metadata model to expose the whole set of metadata. In such a way, the ECV will be a candidate service for EPOS, and it will be included in its service portfolio in the near future.

4.5 The VO-TCS Sustainability

One of the main challenges of the service provision is their sustainability. Considering the different aspects of the service provision (i.e., technical, financial and governance), the analysis and the solutions to guarantee the sustainability of the long-term service provision are diverse. Before analysing the different aspects, we should bear in mind that each service provider of VO-TCS is an organization that manages the volcanological observational systems (either network of sensors in the field or laboratories or computational facilities) for scientific and/or social purposes (e.g., Civil Protection) and participates in EPOS in the framework of national mandates.

Technical sustainability is related to the possibility to provide data and services in compliance with the solutions and guidelines adopted by the EPOS ICS-C. In this respect, the close cooperation of the TeC with ICS-C is the needed pre-requisite to achieve this objective. In the case of services and data shared with other EPOS communities (e.g., seismic or GNSS data), the technical compliance is intrinsically guaranteed. In the case of the services specific for the volcanological community, the commitment of the organizations acting as service providers creates the optimal operational framework to guarantee the continuity of the data provision and the continuous adaptation of the observational systems to the technological evolution. For this last kind of services, the main critical issue could arise from the potential technical conflict between the data and/or metadata standards adopted in the different organizations (e.g., due to the requirements with other service provisions such as the Civil Protection Agencies) and EPOS. However, the close cooperation in the volcanological community and with ICS-C is able to manage and find the solutions to this risk.

Financial sustainability is based on the continuity of sufficient funding to maintain and upgrade the provision of the services. At the national level, the funds aim to support the maintenance and upgrading of the observational systems, and the provision of some service in the cases the participation to EPOS is included in the national research infrastructure roadmap. The risk of potential (even marginal) reduction or interruption of funding might be handled due to the long-lasting planning of the activity of the organizations that provide data and services. EPOS-ERIC will contribute to the VO-TCS service provision with their funds, provided that the VO-TCS has the needed requisites to participate to the EPOS delivery framework (the governance is implemented and operating, and the services are validated). Besides this, the participation in competitive projects is an additional source of funds, in particular for the development of new services. This is the case, for instance, of EUROVOLC project, as discussed below.

Also, the sustainability of the governance of the VO-TCS service provision can be analysed at the two levels: national and EPOS-ERIC. At national level the governance of each service is undertaken by the organizations providing the services, which in turn is guarantee by both the agreements of each institution with EPOS-ERIC and the respective institutional governance. At the EPOS-ERIC level, the governance should balance different requirements: the available resources to provide services, the relevant efforts needed to provide the services and the expectations of the community. The structure of the VO-TCS described above (section 3) is able to manage the trade-off among the different needs because all competences and stakeholders are represented in the governing boards and committees.

5. EUROVOLC project: the first pillar for EPOS service implementation, networking and community building

5.1 Project’s overview

5.1.1 Objectives and structure

In line with the mission of the VO-TCS, the overarching goal of the Horizon2020 EUROVOLC project was to strengthen volcanological research and research environment in Europe through integration and harmonisation of the fragmented European volcanological community, and by opening physical and virtual access to key, multidisciplinary research infrastructures and resources. The integration was aimed at fostering sustained, long-term collaboration and harmonisation between the widely distributed VOs and VRIs to promote multidisciplinary research and knowledge-sharing between the institutions and to facilitate uptake by the VOs of new research discoveries and methodologies for improved monitoring and management of volcanic hazard. The harmonisation was focused on long-term data curation and development of good practices in multidisciplinary volcano observations, research, and monitoring, as well as on the communication of volcanic hazard both within the community and between the community and its stakeholders (incl. the general public, public authorities, national and international civil protection agencies).

Fragmentation penetrates many levels in the volcanological community and affects and slows down progress and advances in volcanology in general. To maximise the output and success of collaborative volcanological research projects, this fragmentation needs to be addressed and overcome. The community fragmentation is governed by the distribution of volcano observatories mostly on the periphery of the European continent and in

European overseas territories (see Figure 3), sometimes limiting their connection and collaboration with other volcanological research institutions in the wider community. The limited interconnection often delays propagation and implementation of scientific advances and new methodologies achieved in the volcanological community, but also limits the VOs own sharing of know-how and good practices. The remote locations also limit the community's access to the highly valuable research infrastructures and data resources of the observatories. Research of volcanic processes and hazards is also multidisciplinary, involving a wide range of disciplines such as seismology, geodesy, rock- and fluid mechanics, petrology, rock- fluid- and gas-geochemistry, physical volcanology, probabilistic hazard assessment, computer modelling, deep-learning data analysis, remote-sensing, and meteorology, with the addition of social sciences playing a role in volcanic hazard studies and crisis response and management. This is a form of disciplinary fragmentation, and integration of these varied disciplines is a challenge for collaborative research projects, as it requires a large and varied consortium with little or no pre-existing connections. Furthermore, the lack of continuity of previous collaborative research projects is yet another form of project fragmentation. These projects have been carried out by independent research groups and time limited to a few years, with no organi-

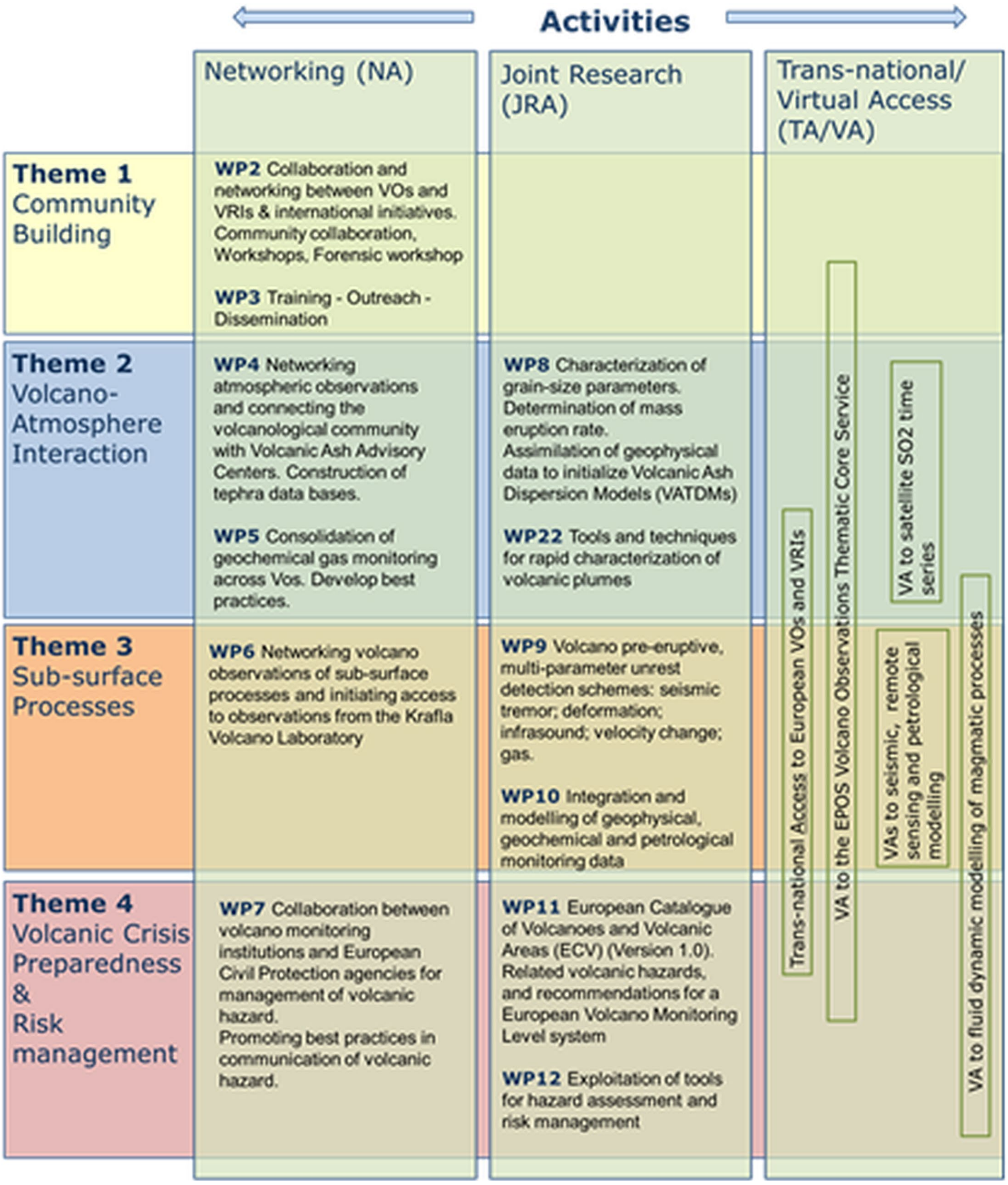

Figure 10. EUROVOLC project structure showing the organisation of activities under the four main themes and three different activity types.

sation or infrastructure in place to sustain long-term access to the data and products generated, or to facilitate transfer of the knowledge gained to the wider community.

To reach the objectives and address the broad-ranging problems of fragmentation, the activities of EUROVOLC were structured into three types of activities: Networking, Joint Research, and Transnational and Virtual Access, and focused under four main themes: Community building, volcano-atmosphere interaction, Sub-surface Processes, and Volcanic Crisis Preparedness and Risk management (see Figure 10). The project also utilised and built upon some of the outcomes of the previous European volcano supersite projects, FUTUREVOLC and MED-SUV and some of the activities were closely linked to the EPOS ERIC VO-TCS, whose services and e-infrastructure are used to provide long-term sustained FAIR access to the data and products networked in the project.

Under each theme, the activities focused on: (i) networking people, institutions and data, building connections with relevant stakeholders, developing data standards and good practices in observations and operations, disseminating project results and outreach material, and training young scientists; (ii) joint research to produce knowledge, catalogues, methodologies and tools for improved volcano monitoring and hazard assessment, real-time and near-real-time processing and modelling of pre-eruptive processes, and real-time processing eruptive processes; (iii) opening physical and virtual access for the volcanological community to research infrastructures and resources of VOs and VRIs, and to various modelling and assessment tools for responding to volcanic unrest.

5.1.2 The Consortium

The EUROVOLC consortium is composed of 19 European partners representing a diverse type of volcanological stakeholders: 7 VOs, 7 VRIs, 2 Civil Protection Agencies, a Volcanic ash advisory centre, an IT company, and a Geothermal power company. Additionally, a research institute, a university and a tech company are third parties of partners, making a total number of 21 contributing partners. Some of the VOs are also contributing as research institutions and one VO and a VAAC are also meteorological offices with responsibilities for aviation. On top of these partners, four additional participants outside contributed to some of the project activities and or provided material. They comprise two VOs, an additional VAAC, and a university.

- Volcano Observatories, each responsible for monitoring volcanic activity and volcanic hazard at a number of active volcanoes in Europe and overseas territories in the Indian Ocean, the Caribbean Sea, the South Atlantic Ocean, the Pacific Ocean ranging from a few volcanoes to over 30 are: HMSGE in Greece, IPGP in France, IMO in Iceland, INGV in Italy, CIVISA in Portugal, IGN in Spain (represented through CSIC in the CA) and BGS in the United Kingdom, KNMI in the Dutch Caribbean (see Figure 3). All the above VOs also actively carry out volcanological research and either led or contributed to most of the research activities in the project and many provided Transnational access to their Research Infrastructures. The Dutch VO (KNMI), monitoring volcanoes in the Caribbean, and the University of Bergen, monitoring Jan Mayer island in the North Atlantic, participated in a VO-VAAC meeting held within the project, and interacted with the Icelandic VO. KNMI also contributed to enlarge the number of active volcanoes listed in the ECV by adding those in the Dutch Caribbean.
- Volcano Research Institutions are: DIAS, CSIC, IPGP, INGV and the Universities of Clermont Auvergne, Florence, Geneva, Iceland, Leeds, Manchester. Many led activities or work packages in the project. Some are also involved in volcano monitoring. Third parties contributing to research activities are Sapienza University of Rome and tech company ITEM. Some partners, with the addition of third party CNR-IGG also provided Transnational or Virtual access to their RIs and resources. An additional university, the Arctic University of Norway contributed material on Jan Mayen's Beerenberg volcano in the northern Atlantic.
- Civil Protection Agencies: Two Civil protection agencies, ICP in Italy, and NCIP in Iceland, participated in networking activities focused on research and management of volcanic hazard.
- Volcanic ash advisory centres: One partner, London VAAC at the UK Metoffice, led meetings of VOs with the aviation sector. The Toulouse VAAC also participated in one VO-VAAC meeting during the extension period. Two partners, the UK Metoffice and IMO, are also meteorological offices with responsibilities in monitoring meteorological and volcanic hazard to aviation in the N-Atlantic and N-Europe.
- IT company: Terradue s.r.l. contributed to research activities.
- Geothermal power company: Landsvirkjun o.h.f. contributed to networking activities and provided access to data from the geothermal power operations at Krafla volcano, Iceland.

5.2 Project activities and achievements

In the 3rd and final year, planned EUROVOLC networking and transnational activities were adversely affected by extensive travel restrictions due to the COVID-19 pandemic, temporarily halting community meetings and field surveys, as well as activation of many TNA research projects. During a 10-month extension granted by the European Commission, the consortium activated extra measures to enable most of the project meetings and the completion of all but one TNA project.

5.2.1 Networking activities

Under the Community building theme, workshops and shorter meetings were held to establish connections and plan collaboration between partners and activities. The workshops were attached to the main Earth science conferences scheduled during the project. In the first workshop, a joint session was organised with the EPOS VO-TCS to introduce to the EUROVOLC partners the data policy, standards, and services of EPOS and to ensure alignment of the data products to be networked in EUROVOLC with the EPOS standards. The workshop also deliberated and laid out general guidelines for the development of the various planned best practice standards of EUROVOLC. A joint EUROVOLC and Volcano Best Practices Workshop held in Mexico City generated recommendations for best practices in VO operations during volcanic crises. The guidelines were summarised in a publication by Lowenstern et al. (2022). After travel restrictions started limiting the options for physical meetings, some of the planned workshop topics were attached to the yearly project meetings. A special session on technical and scientific aspects of VO monitoring infrastructures and ranking of volcano monitoring levels, followed by introductions of some of the newest instrument technologies was included in the virtual 3rd year meeting. This virtual form of the technical session turned out to attract more participation by VO technical staff, who do not normally travel to attend meetings. At the final hybrid project meeting (November 2021), the establishment of a formalised collaboration between European VO, attained through MoUs was extensively debated.

The main activities, results, and reports of EUROVOLC are disseminated through the project website (https://eurovolc.eu). A EUROVOLC Wiki (https://eurovolc.cp.dias.ie/) was also constructed to enable dissemination of information from the project to the wider volcanological community (see Fig. 11). The Wiki has been utilised to host the descriptions of the VO monitoring infrastructures. Two VOs, IMO and IPGP, have already entered their information on the Wiki and other VOs are expected to follow suit. To preserve long-term maintenance of access to the technical information the Wiki is accessible from the EUROVOLC web page and is expected to become part of the Gateway, which will also take over the EUROVOLC domain to ensure continued access to the main EUROVOLC information.

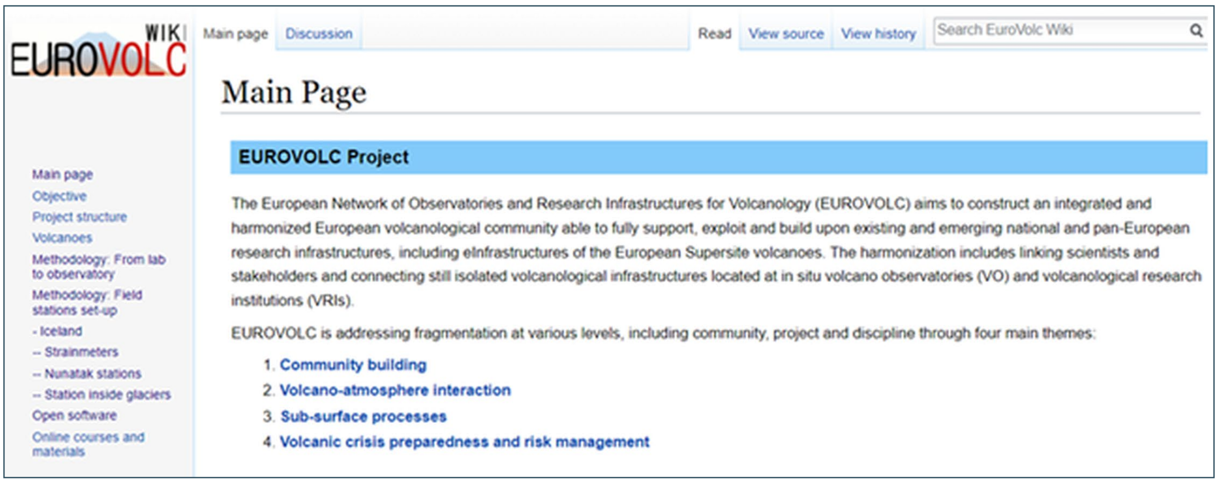

Figure 11. Main page of the EUROVOLC Wiki, holding information on Volcano Observatory infrastructures, software, and on-line courses information.

Two summer schools for young scientists were carried out, the first one which focused on subsurface processes was held at the Etna volcano. The second one, on explosive eruptions was planned in Iceland, but delayed by the pandemic and finally held as a virtual school with recorded videos, which will be made available through the EUROVOLC website.

Under the Volcano-atmosphere interaction theme metadata standards for the various characteristics of volcanic tephra deposits were harmonised, adapted to EPOS standards and a common metadata structure defined. Characteristic information from a list of volcanic eruptions was collected to populate the database. Best practices in data sampling were also defined. The database, which can be used as a testbed for testing atmosphere-plume interaction and models for transport and dispersion of volcanic ash, was shared with the research activity on volcano-atmosphere interaction. Two community meetings were held on strategies for sharing data on volcanic ash in the atmosphere and improved communication between VOs, VRIs, VAACs and the International Civil Aviation Organization (ICAO). The first meeting was in Exeter, the second a virtual meeting held jointly with the EPOS SP project. The meetings provided a unique forum for direct interaction between the institutions, facilitating streamlining of data sharing and harmonisation of the interaction. The main decisions of the meeting and a roadmap for future updates, delivered as separate reports are available on the EUROVOLC web page. Under the same theme a joint field survey for volcanic gas sampling in fumaroles was carried out and analysed at different laboratories, to examine the variation in analysis results between different procedures in preparing the observational equipment. The analysis returned guidelines on best practices, but further data collection is needed for better constraints.

Under the Sub-surface processes theme, data sets not available in the collection of services of the VO-TCS were selected, quality checked, and adapted to EPOS standards. Special emphasis was on opening access to quality checked multidisciplinary data from several recent important volcanic events. Examples of datasets prepared were seismic and GNSS data from the Bárdarbunga 2014 eruption and interferograms from the recent Reykjanes peninsula unrest and eruption. Most of the prepared data fulfil EPOS standards and are shared though existing EPOS VO-TCS services or existing services of the other EPOS TCS communities such as seismology and GNSS.

Under the management of volcanic hazard theme, a list of a scientific advisory group to respond to volcanic emergencies was defined and surveys were carried out to determine the information needs of Civil protection and define standards for communicating hazard to authorities, civil protection, and the public. This networking activity was the one most affected by the pandemic as well as repeated volcanic unrest and eruptions in Iceland and Italy during the project, often making Civil Protection personnel unavailable for the project. However, through on-line interviews it was possible to collect the required information and reach all the main goals in the extension period of the final year. The reports summarising the outcomes are published on the EUROVOLC web site.

5.2.2 6.2.2 Joint research activities

Joint research on volcano-atmospheric interaction was focused on early warning eruption detection schemes and near-real-time detection of eruption source parameters. For the early warning of explosive eruptions, joint application of infrasound array processing and weather radars was used [Ripepe et al., 2018]. Applicability of this approach to real-time operations will be further examined. To improve volcanic plume models, a multisensor approach was applied with different combinations of observation tools, including distrometers, volcanic ash sampler, weather radars, and satellite data to provide improved near-real time estimation of eruption source parameters, like particle sizes, ash accumulation rates, aggregation etc. [Feret-Lorgerill et al., 2021; Feret-Lorgeril et al., 2022; Rossi et al., 2021]. Plume height measurements were also estimated with webcams [Barnie et al. 2022]. The methods were tested in case studies at Etna and in Iceland by comparing ash accumulation rates, and particle sizes [Marzano et al., 2019; Mereu et al., 2022]. The Database on eruptive parameters from the Networking activity was used and geophysical data were integrated in dispersal models to produce source parameter Probability Density Functions for future eruptions [Pardini et al., 2018].

Joint research on sub-surface processes involved developing tools for automatic real-time processing of pre-eruptive seismic signals, RETREAT [Smith and Bean, 2020], correlation of seismo-acoustic signals [Ripepe et al., 2018] and near-real time processing of geodetic signals with the GBIS and LiCSAR software [Lazecký et al., 2020]. RETREAT, which applies array-processing software to track back-azimuth and slowness of tremor signals to track subsurface magma migration was tested on array data from Bárdarbunga [2014] and will be further tested on data from three 8-element arrays operating on Reykjanes peninsula during the unrest and volcanic eruption in 2021. The dyke and associated plate boundary slip has been analysed and mapped through multidisciplinary analysis with high-precision mapping of the seismicity, analysis, and modelling of InSAR and GNSS signals [Sigmundsson et al., 2022]. The seismo-acoustic eruption onset detection software was developed and tested on data from eruptions at Mt Etna and the GBIS software was developed and tested on Sierra Negra volcano. A VOLcano Unrest Detection software (VolUnD) using deep learning models was developed in the project and tested on volcano unrest data from Mt. Etna and Stromboli with promising results [Cannavò et al., 2022]. The tool that performs anomaly detection in volcanic historical data in an unsupervised way, is trained on normal data to identify deviations from normal status as anomalies.

Joint research on risk management was focused on constructing the European Catalogue of Volcanoes and volcanic areas (ECV; https://volcanoes.eurovolc.eu/), a web resource containing descriptions of key European volcanoes, their eruptive history, characteristics, and volcanic hazard (see Figure 12). The Catalogue follows the same format as the Catalogue of Icelandic Volcanoes (CIV https://icelandicvolcanoes.is/), generated under the FUTUREVOLC project and supported by ICAO. The Catalogue currently describes 18 European volcanoes in addition to the 32 Icelandic volcanoes already provided. Such information is provided through a standard format and volcanoes and volcanic eruptions are described by a common metadata structure. Text, images, photos, references, and event trees are the key ingredients of the ECV, which, for the first time, makes the information provided by the Vos accessible directly to the public. Additionally, data on eruption source parameters provided by the activities under the volcano-atmosphere theme are made available in the catalogue through an eruption search function. All participating countries provided information about at least one volcano and for all volcanoes; the information is available in English and in the national language. A table providing an overview of possible eruptive scenarios for different volcanoes is also provided for the aviation sector. The catalogue will be maintained in the long term through the EPOS VO-TCS. The survey gathering information for the definition of the ranking system for Volcano monitoring levels, mentioned in section 5.2.1 was also processed under this theme. A collection of existing volcanic hazard assessment tools in a searchable, on-line catalogue describing their function was carried out under this theme and application by hazard managers of a selection of tools were tested in a table-top exercise for a selected volcano. The catalogue of hazard tools is accessible on the VO-TCS Gateway (see section 4.4.3). A new citizen science tool in the form a web service was also developed enabling people to report information of a witnessed volcanic eruption.

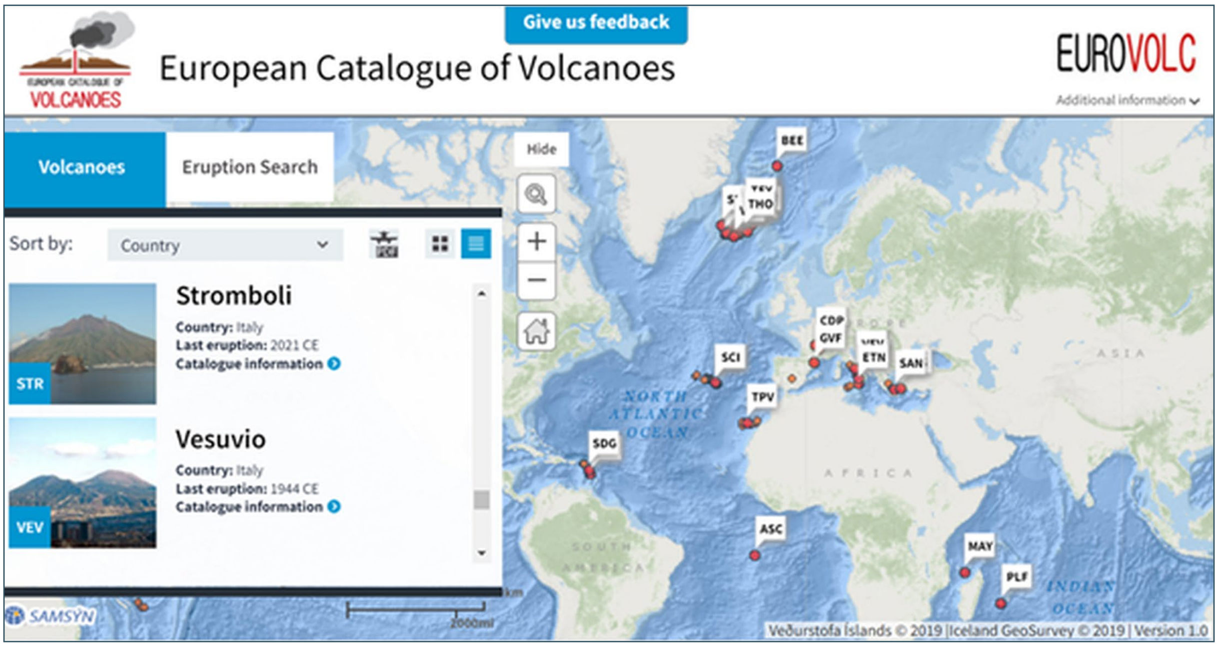

Figure 12. The home page interface of the European Catalogue of Volcanoes, showing the different "European" volcanoes around the world.

5.2.3 Transnational and virtual access activities

Four institutions managing Vos (IMO, INGV Mt. Etna and Vesuvius Observatories, UAC, IPGP observatories at Guadeloupe, Martinique and Piton de la Fournaise – La Reunion Island) and four VRIs (IU, INGV computational facility at Pisa, CNR-IGG, CSIC at Barcelona) opened physical or remote transnational access to their Research Infrastructures, including VO facilities, observational networks and computational and modelling resources. A total of 27 proposals were submitted and 12 projects were funded under the first TA call in 2019 and 39 and 27 respectively under the 2nd Call in 2020. The projects were selected based on their excellence by an external scientific evaluation panel and they covered a wide field within geophysics, geochemistry, and volcanology. The users were required to deliver a report describing the activities and sign an agreement to make the data collected accessible. The TNA projects contributed to all EUROVOLC themes; however, about one half carried out research on the "Sub-surfaces processes" theme. The provenance of the research teams was mainly from Europe, but some American teams were funded. Pandemic emergency postponed most of the projects of the 2nd Call until late summer or fall 2021. To allow enough time in summer and fall 2021 for the TNA projects to be completed before the project ended, a 10-month extension was granted by the European Commission. The projects ran into late fall 2021 and all but one were successfully completed. Considering the very difficult environment during the period of the projects, the fact that such a high number of projects were carried out to completion can be considered great success for EUROVOLC and its TA program.

Seven virtual accesses services were created or improved upon in EUROVOLC. They provide free open access to modelling tools for full seismic wavefield modelling (DIAS), inversion of surface deformation for subsurface sources (UAC), magma ascent, simulation of pyroclastic density currents, and calculation of saturation surface of fluids in silicate melts (VDCC INGV in Pisa). The University of Leeds provides access to a forum on petrological diffusion modelling, the University Manchester provides access to SO_2 time series for volcanic plumes and their heights obtained from satellites and the UAC provide access to satellite products. INGV OE provides access to the EPOS VO-TCS Gateway to data products and software networked in EPOS (see section 4.4).

6. Final Comments and Future perspectives

An effective integrated multidisciplinary volcanological infrastructure is aimed at applying the Open Science paradigm to the volcanology research, thus overcoming the fragmentation of the community resulting from institutions with heterogeneous objectives (e.g., VOs vs. VRIs) or from the lack of common scientific objectives and programmes. As a consequence, the need to share data, products and best practices both in monitoring and research methods, as well as to foster the access to the observatories, laboratories or computational facilities to strengthen the community has become crucial. In recent decades, volcanologists have launched some initiatives aimed at creating a favourable framework for overcoming the fragmentation gaps. At the European level, the last and most effective initiative materialised in the framework of EPOS by means of the implementation of a few strategic projects (FUTUREVOLC, MED-SUV and EUROVOLC) and the design and establishment of the VO-TCS. The overarching objective of the VO-TCS is to implement a sustainable system to access the data, products and services provided by the VOs and VRIs to the volcanology community as a component of the EPOS delivery framework. To achieve this objective, technical, governance, financial and legal aspects have been analysed and managed over time (in the framework of EPOS-PP, EPOS-IP, and EPOS-ERIC). Indeed, the main technical issues concerned the heterogeneities of the data and metadata formats, as well as the different structure and aims of the IT systems managing this information. A deep and detailed harmonisation work was carried out at different levels (from the source of the information from the observation systems in the field to the databases archiving such information) in the framework of the implementation of the EPOS ICS. The key element to manage the technical issues has been the implementation of a customised e-infrastructure, named "Gateway". Benefitting from the experience gained in the framework of the EUROVOLC project, the "Gateway" is now able to interface with EPOS ICS to provide EPOS services and to offer access to DDSSs (e.g., TNA to facilities) useful to carry out advanced research in volcanology provided by EPOS and no-EPOS institutions. To ensure the long-term sustainability of the access to the volcanological information and facilities, it is essential to properly manage the governance, financial and legal aspects. The governance of the VO-TCS is structured in five bodies (Consortium Board, Executive Committee, Technical Committee, Transnational Access Committee and Advisory Board). Overall, the governance aims at defining the strategic actions of the VO-TCS, managing the day-to-day activities and interfaces the VO-TCS with all the components of the EPOS ERIC to contribute to the EPOS delivery framework. Among the strategic actions, the utmost concerns regard the financial and legal aspects and the link with the broader volcanology community. The first two are crucial to guarantee the long-term sustainability of the services and the compliance with the Open Science principles. The link with the volcanology community has the twofold objective of receiving suggestions for the improvement of the services and engaging new participants in the VO-TCS. To date, the efforts of the participants in the VO-TCS have mostly focused on implementing it and launching the activities in synergy with the current activity of the EPOS Pilot Operational Phase. Reasonably, this kind of activity will characterise the next two years, possibly by also expanding the number of the VO-TCS participants. In the medium to long term, it could be envisaged that the VO-TCS will increase the portfolio of the services provided both in the numbers and in the level of the products or services, thanks to the increase in participants and benefitting from the feedback of the access to data and the use of the facilities. Considering the intrinsic multidisciplinary nature of the volcanological infrastructures, the VO-TCS is the ideal candidate for promoting and undertaking cross-disciplinary research in volcanology that involves different domains of the Environmental Sciences and has significant benefits for the society, continuing the trend developed in several current projects and research initiatives.

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