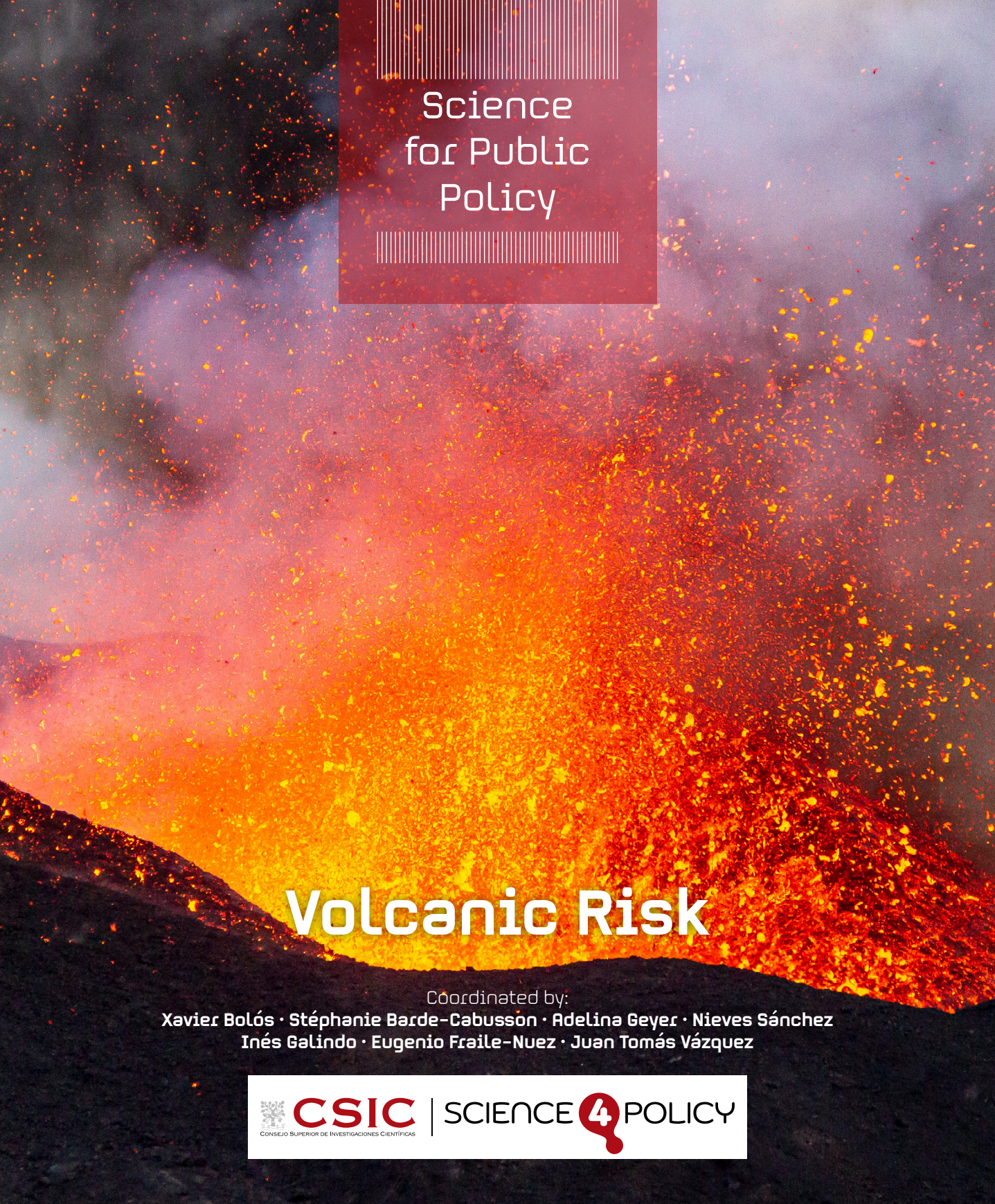




Science
for Public
Policy

Volcanic Risk

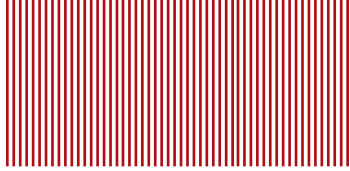
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CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

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Science for Public Policy



Knowledge Transfer
Report



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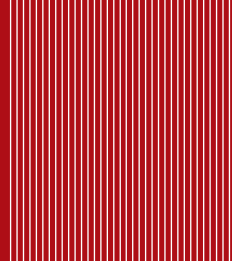
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ONE of the CSIC's functions is to inform, assist and advise public and private entities on science and technology, as stated in article 5 of its Articles of Association. As part of this function, the CSIC presents the report *Volcanic Risk* in the Science for Public Policy collection. This report is aimed at public and private entities, as well as society as a whole. It explores key concepts of volcanic risk, analyses its impacts and provides a comprehensive framework for the study and effective management of volcanic risk under CSIC research lines, enabling early preparedness, coordinated response and sustainable recovery from volcanic eruptions. This report aims to provide essential knowledge for informed decision making and to support scientific development along relevant lines by policy makers, and for the benefit of society at large.

INDEX

one

|||||

What is Volcanic Risk?

- 1.1. Volcanic eruptions, why do they occur and where do they happen?
- 1.2. Volcanic Hazards: A Natural Phenomenon
- 1.3. Living among volcanoes: the human factor in risk

two

|||||

Reducing the Risk of Living with Volcanoes

- 2.1. Anticipating the next eruption: research as a key to reducing volcanic risk
- 2.2. Precursor signals as a prelude to a volcanic crisis: investigation, forecasting, preparedness and action
- 2.3. Actions during an eruption: scientific advice for public decision-makers and communication to the public
- 2.4. Post-eruption research and management

three

|||||

Conclusions and Recommendations

four

|||||

List of Centres

five

|||||

Further Information



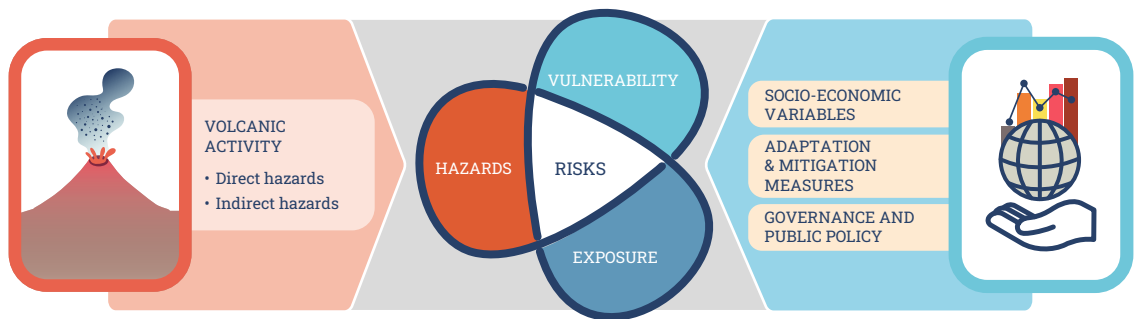
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What is Volcanic Risk?

VOLCANIC risk is defined as the possibility of adverse consequences for life, property, infrastructure and the environment due to volcanic activity. Thus, when referring to volcanic risk, one must consider both the hazard of the natural phenomenon, i.e., the probability of occurrence of a given volcanic event, and the vulnerability and exposure of society and the ecosystem to this volcanic hazard, including the susceptibility to damage, its economic value, and the capacity to cope and adapt.

Figure 1 Venn diagram of volcanic risk



(*) Diagram modified from the 5th Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the UN body for assessing the science related to climate change.

Currently, more than 800 million people around the world live in the vicinity of active volcanoes and may be directly affected by volcanic eruptions. Mitigating the impact of future volcanic hazards requires an adequate forecast and early warning system for an impending eruption, which in turn requires a detailed understanding of the geological processes that control volcanic activity. In this report, we review and analyse such volcanic hazards, their assessment and the associated risk management in the long and short term, as well as during a volcanic crisis.

11.

Volcanic eruptions, why do they occur and where do they happen?

A volcano is a geological structure formed by the eruption of magma to the Earth's surface. Magma, composed of molten rock, solid rock fragments, minerals and dissolved gases, escapes through the Earth's crust in a volcanic conduit, usually creating a crater. This process, known as volcanic eruption, can give rise to a variety of geological morphologies, such as cinder cones, tephra (volcanic rock) rings, stratovolcanoes, collapse calderas, lava domes or fields.



Fissure eruption at Piton de la Fournaise (France). / STÉPHANIE BARDE-CABUSSON

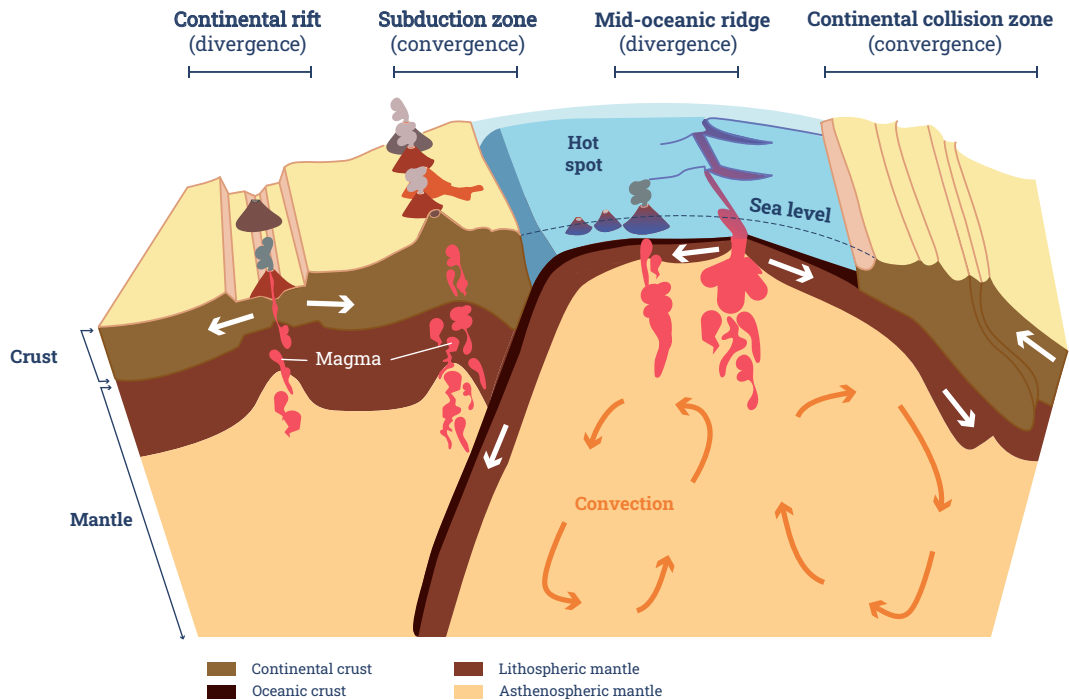
Volcanic eruptions are the result of a series of geological processes involving the generation, ascent and emission of magma to the surface. Thus, magma forms in the Earth's interior, where pressure and temperature conditions are suitable for melting the rocks of the mantle and, in some cases, the Earth's crust. Being less dense than the surrounding solid rock, magma manages to rise to the surface through fractures and faults (fractures accompanied by displacement) in the Earth's crust. Thus, although on



Example of an eruption at Mount Bromo volcano (Indonesia). / XAVIER BOLÓS

the geological time scale and even on the human scale, volcanic eruptions may appear to be relatively brief events, ranging from a few days to years, in reality, they are the result of geological processes that extend over hundreds of thousands or even millions of years. Volcanoes are an integral part of the Earth's evolution and have had, have and will have significant impacts on landscapes, ecosystems and human societies.

Figure 2 Volcanoes and plate tectonics



The global distribution of volcanism on the planet is not random, but is directly related to global dynamics. Active volcanoes are found where pressure and temperature conditions, or changes in the chemistry of the Earth's mantle favour the melting of the mantle and the formation of magma. This occurs mainly in two tectonic settings, convergent or divergent plate boundaries. That is, where the movement of tectonic plates causes them to collide and one sinks under the other (subduction zones) or move apart (in ridges and rift zones). Volcanic activity is mostly concentrated at the margins of ocean basins, particularly in the belt around

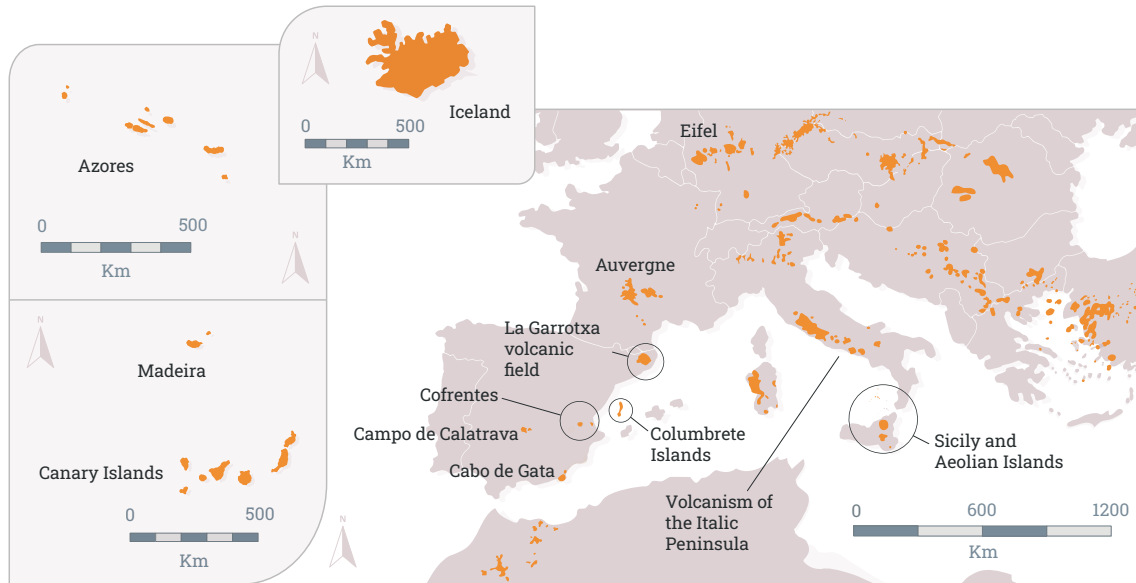


the Pacific, the Atlantic ridge and the African rift. Finally, a modest percentage of the planet's volcanism is located within tectonic plates (intra-plate zones), such as in the Hawaiian Islands or Yellowstone in the United States, where intense volcanic activity occurs. Although the processes that give rise to this type of volcanism are still under scientific debate, one of the most widely accepted is the hotspot hypothesis.

Among the various active volcanic areas in Europe, Iceland is particularly noteworthy, with intense volcanic activity due to its location on the Mid-Atlantic ridge and a hotspot. In Italy and Greece, volcanism occurs mainly along subduction zones, where some of Europe's most famous (and destructive) volcanoes are found, with Etna in Sicily being one of the most active in the world. In the Azores Islands (Portugal), located at a triple point where the Terceira rift connects with the Mid-Atlantic Ridge, there have also been numerous signs of volcanic activity over the last centuries. Finally, the volcanic areas of Auvergne (France) and Eifel (Germany), considered active, are associated with the European Cenozoic rift system, which extends for more than a thousand kilometres from the North Sea coast to the Mediterranean, also generating volcanism in the Iberian Peninsula.

In Spain, the Canary Islands, specifically Tenerife, Lanzarote, El Hierro and La Palma, have been affected by volcanic activity since the beginning of the historical period (end of the 16th century), that is, since there are written chronicles after the conquest of the islands. Many of the eruptions that have occurred in the archipelago, such as Timanfaya (Lanzarote, 1730), the underwater volcano Tagoro (El Hierro, 2011-2012) or Tajogaite (La Palma, 2021) have caused significant economic losses and a great social impact. As far as peninsular Spain is concerned, the most recent volcanism (less than 15,000 years ago) is located in the Garrotxa Volcanic Field (Catalonia) and in the Calatrava Field (Castilla la Mancha), both also associated with the European Cenozoic rift.

Figure 3 Map of the distribution of geologically recent (Neogene-Quaternary) volcanism in Europe and the Mediterranean area (MODIFIED BY BERGER AND BODEN, 1994)



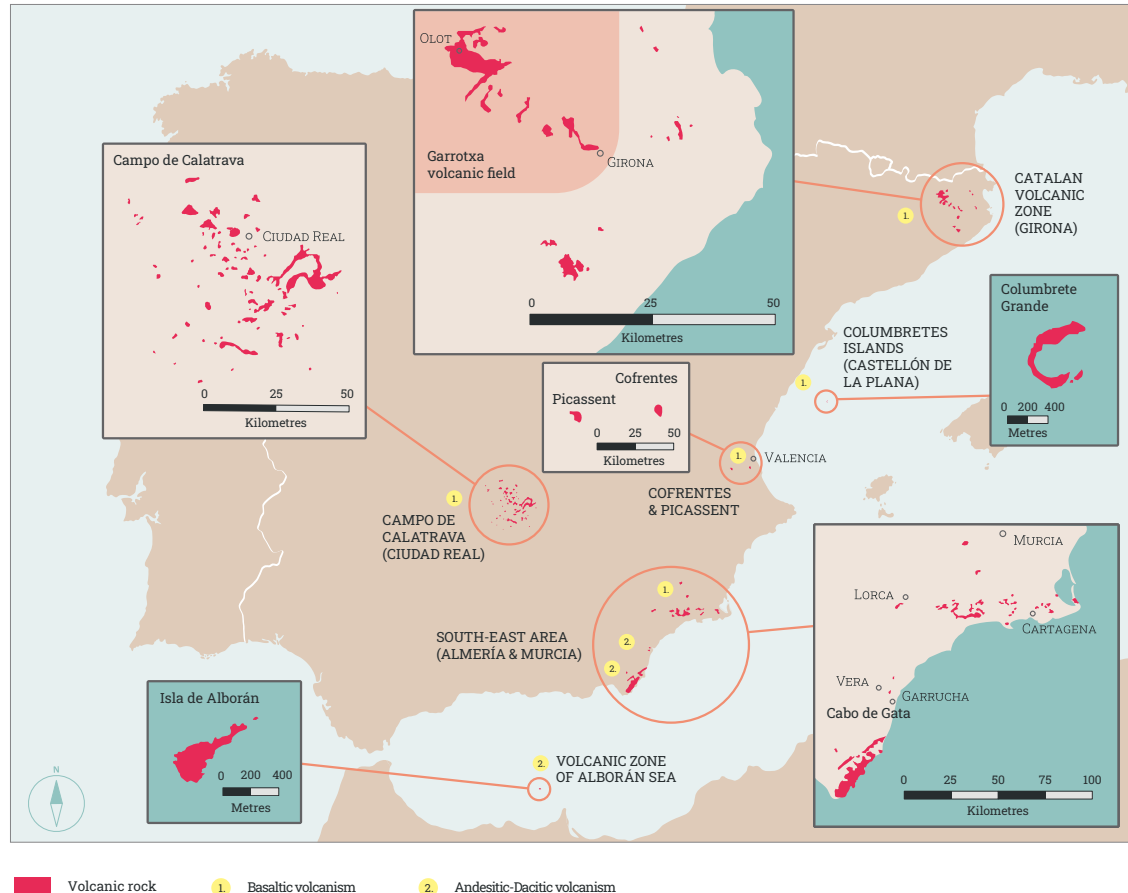
Even though the volcanism is older, although geologically recent, it is interesting to note the Columbretes Islands (Castellón), the Cofrentes volcano (Valencia) and the strip of southeast peninsular Spain, between Cabo de Gata (Almería) and the Mar Menor, as well as Alboran Island. It is also worth noting that Spain has the Gabriel de Castilla and Juan Carlos I Antarctic bases, located respectively within 35 kilometres of the active volcano on Deception Island (South Shetland Islands, Antarctica). During the austral summer, both bases host numerous research projects and scientific, technical and logistical personnel from institutions from Spain and other countries.

The contrast between the scale of geological time and human perception of time highlights the enormous temporal difference between long geological processes, and the brevity of human life and the advance of civilisation. This contrast underlines the

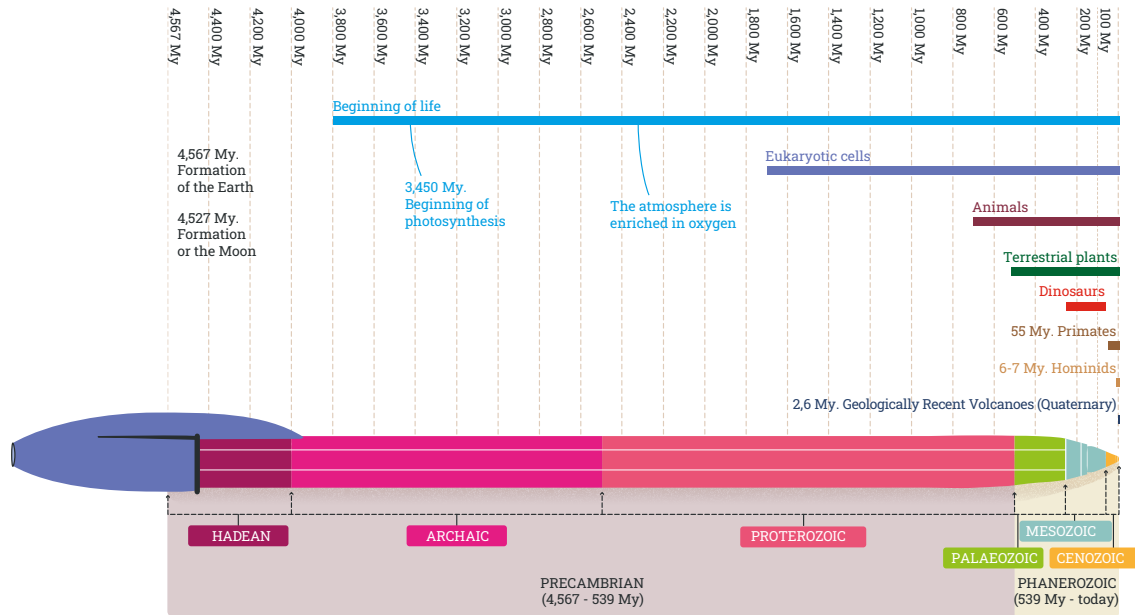
Figure 4 Historical volcanic eruptions in the Canary Islands

challenge of understanding, addressing and managing geological phenomena, such as volcanic processes. This is evidenced by the concept of active volcanism, which considers a volcano, or volcanic zone, to be active when its last eruption occurred in the Holocene (within the last 11,000 years or so) or when geological conditions since the last eruption have not changed. In other words, even if the last eruption occurred more than 11,000 years ago, if the conditions for magma to be generated and reach the surface remain the same, a new eruption cannot be completely ruled out. While those 11,000 years represent a brief instant in the evolution of the planet, they are perceived as an eternity on the human time scale, which often results in a low perception of risk, or false sense of security, in those populations close to a volcanically active area but who have not experienced an eruption in the last centuries or millennia.

Figure 5 Geologically recent volcanic areas (Neogene-Quaternary) in the Iberian Peninsula



In volcanology, the most crucial and, in turn, the most challenging questions to answer revolve around determining when, where and how a new eruption will occur, as they will condition the associated risks and the strategies for their study and management. In this context, it is essential to differentiate between two main types of volcanism: polygenetic and monogenetic. Polygenetic volcanoes can experience multiple eruptions over

Figure 6 Simplified geological time scale on a biro

thousands or even millions of years (e.g., Teide in Tenerife, Vesuvius and Etna in Italy, and Mount St. Helens in the USA), concentrating their activity around a single large (kilometres high) main volcanic edifice. This type of volcanism is usually associated with large volumes of magma stored a few kilometres below the surface, so the magnitude of eruptions can be colossal. In contrast, in monogenetic volcanism, each eruption produces a new volcanic edifice. Unlike polygenetic volcanoes, once the eruption is over, monogenetic volcanoes do not reactivate again, which means that they are much smaller structures, reaching only a few hundred metres in height (for example, the volcanoes Croscat in Catalonia, Chinyero in Tenerife and Parícutin in Mexico). A characteristic of monogenetic volcanism is that it results in a clustering of numerous volcanoes, forming volcanic fields with tens or hundreds of volcanic edifices that can cover large



Teide, a polygenetic volcano. / NIEVES SÁNCHEZ

geographical areas of 100 to 50,000 square kilometres. Examples are the volcanic fields of Garrotxa, with 600 km²; Calatrava, with 5000 km²; or Michoacán-Guanajuato in Mexico, with more than 40,000 km². This means that, despite the smaller size and potential impact of monogenetic eruptions, the uncertainty surrounding the location of future eruptions represents a challenge for volcanic hazard assessment.

During an eruption, either of a polygenetic or monogenetic volcano, there may be more explosive phases of activity, dispersing volcanic material and injecting gases into the atmosphere or ocean, or effusive phases, emitting lava flows. The occurrence of each of these phases is mainly conditioned by the chemical composition of the magma, its gas content and its emission rate. When the volcanic conduit opens, the magma decompresses, causing the volcanic gases, hitherto dissolved in the liquid due to the pressure, to expand and form bubbles. The explosion of these gas bubbles fragments the magma to a greater or lesser extent, generating droplets of various sizes that are propelled outwards



The Garrotxa Volcanic Field, with dozens of monogenetic volcanoes. / XAVIER BOLÓS

(pyroclasts). A similar phenomenon occurs when we open a bottle of champagne or beer and the gas dissolved in the liquid expands and generates foam. In some eruptions, this degassing can be gentle, with little fragmentation of the magma, leading to an effusive phase characterised by lava fountains and lava flows. When degassing is violent, the magma breaks up into particles of various sizes which, once cooled in the atmosphere, solidify into volcanic ash, lapilli, blocks or bombs. During these more energetic, so-called explosive eruptive phases, eruptive columns and ash clouds are formed. Although, as a first approximation, eruptions can be categorised as either effusive or explosive, there is an almost continuous spectrum of mixed eruptions, manifesting both types of activity.

The explosiveness of an eruption can also increase when magma encounters groundwater or surface water (e.g., lakes, groundwater, seawater or ice) during its ascent. Such eruptions are called hydromagmatic or hydrovolcanic eruptions and occur when very hot magma (commonly between 700 and 1300 degrees)



Fragmentation and pyroclast formation during the 2021 eruption of the Tajogaite volcano in La Palma. / ORIOL OMS Y XAVIER BOLÓS

comes into contact with low-temperature water. This produces a violent reaction capable of generating extremely energetic explosions. This process is similar to that which occurs when, during cooking, water droplets accidentally fall into a pan of hot oil. The latter, comparable to magma in an eruption, transfers its heat to the water, which instantly vaporises. This steam expands and fragments the oil, which sprays out of the frying pan at high speed. In the case of volcanic phenomena, the oil droplets expelled would be magma. This type of eruption generates significant clouds of steam, with large quantities of volcanic ash, among many of the other volcanic hazards detailed below.



Effusive activity of the
Tajogaite volcano of 2021 in
La Palma. / XAVIER BOLÓS

The most explosive hydromagmatic activity is typically seen when eruptions occur in lakes, in glacial areas due to the interaction of magma with meltwater, in shallow coastal waters (less than 50 metres deep) and in groundwater (aquifer) sites, in which case it is known as phreatomagmatic activity.

Conversely, when volcanic activity occurs in intermediate or deep marine waters (deeper than 200 metres), eruptions are mostly effusive or low explosive. Following the above analogy, a higher percentage of water rapidly cools the hot oil, reducing the explosiveness of the interaction, which may be zero. This fact, together with the pressure exerted by the water column, explains the low explosiveness of submarine eruptive activity at great depth, which will be given solely by the characteristics of the magma itself. These types of eruptions are difficult to observe, although sometimes floating lava globes or pumice emissions can be seen, as well as yellow or green spots on the surface of the sea.



Phreatomagmatic eruption at Poás volcano
in Costa Rica. / GEOFFROY AVARD - OVISCORI



Submarine eruption in El Hierro with the town of La Restinga in the background. / XAVIER BOLÓS

12.

Volcanic hazards: a natural phenomenon

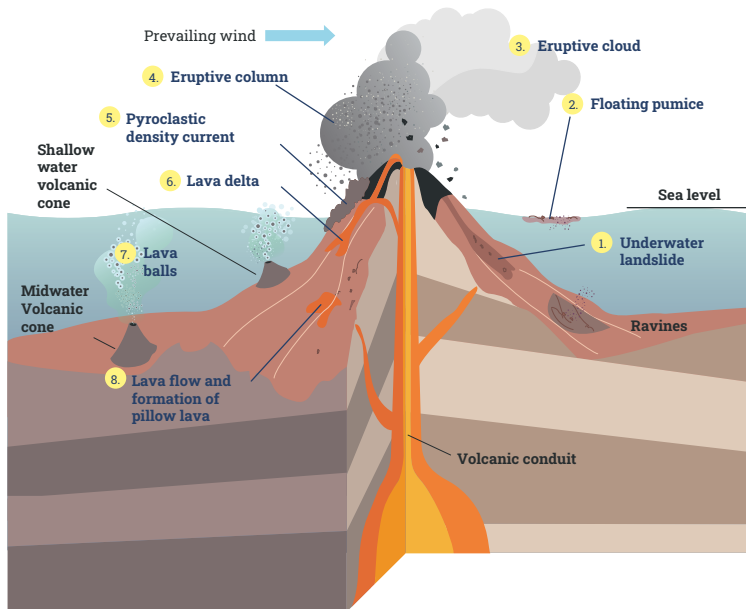
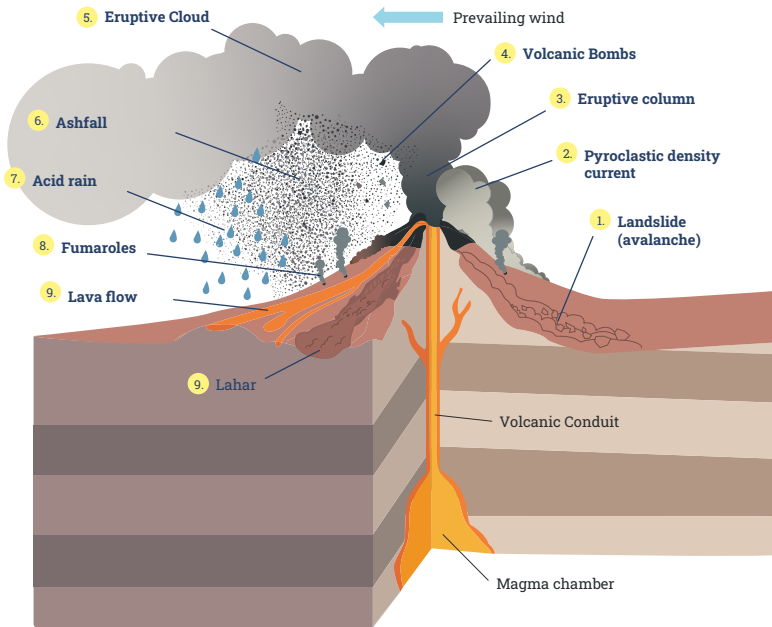
VOLCANIC hazards result from activity occurring at the volcano, or in the volcanic zone, before, during or after an eruption. They can be classified as direct and indirect, and can often occur simultaneously or cascade, reflecting the complexity and interconnectedness of the different hazards associated with volcanic activity.

Direct volcanic hazards are those that derive directly from volcanic activity and primarily occur during an eruption, although many can manifest themselves even before and after the release of magma to the surface. Indirect volcanic hazards, on the other hand, are secondary consequences of volcanic activity.

Direct hazards

- **Lava flows** in subaerial environments can generally be of two types:
 - **Aa:** They have a rough texture, move slowly and form thick lava flows. Their temperature usually ranges from 700°C at the surface to 1000°C in the interior.
 - **Pahoehoe:** They reach 1200°C throughout their thickness, are smooth and flow rapidly, creating characteristic rope-like shapes (cordate lava) as they cool. In underwater environments (e.g., the ocean floor, a deep lake or a water-filled cavity within a glacier), lava cools rapidly into lobes, giving rise to pillow lava.

Figure 7 Volcanic hazards on land and at sea





Pahoehoe lava at Piton-de-la-Fournaise (France). / STÉPHANIE BARDE-CABUSSON

- **Eruptive column**, or ash plumes, can rise several kilometres into the stratosphere.



Photo of an eruptive column of the Tajogaite volcano in 2021 in La Palma. / NIEVES SÁNCHEZ

- The **ash cloud and ash fall** disperse and accumulate fine material around the volcano, in the atmosphere and in the sea.



Photo of ash fall from the Tajogaite volcano in 2021 on La Palma. / ORIOL OMS Y XAVIER BOLÓS

- **Pyroclastic density currents** (or pyroclastic flows and surges) result from a lateral explosion, the collapse of part of the volcano or the partial collapse of the eruptive column. They consist of flows composed of a variable amount of gases, blocks and ash, which descend the slopes of the volcano at speeds of up to 700 kilometres per hour and temperatures of up to 1000°C.



Pyroclastic density currents at Fuego volcano in Guatemala, (1 July 2015)
(Image Conred Guatemala). / LICENSE: CC BY-NC-ND 2.0 DEED - ATTRIBUTION-NONCOMMERCIAL-NODERIVS 2.0 GENERIC

- **Gases**, widely present before, during and after eruptions, can be released throughout the area of volcanic activity, either by diffusion throughout the terrain, in the eruptive cloud and plume, or by forming point source vents, which can reach 400°C. Volcanic gases consist mainly of water vapour, carbon dioxide (CO_2), and sulphur dioxide (SO_2), with hydrogen sulphide (H_2S), hydrogen fluoride (HF) and carbon monoxide (CO) in smaller quantities.



Fumaroles in Vulcano, Aeolian Islands, Italy. / STÉPHANIE BARDE-CABUSSON

Indirect hazards

- **Lahars**, mudflows, which are created when water from heavy rainfall or melting ice or snow washes away volcanic deposits in its path.



Lahar produced by the Fuego volcano of Guatemala (2018). / EDGAR ANTONIO BARRIOS, OBSERVADOR DE INSIVUMEH

- **Seismicity** generated mainly during the ascent of magma, which breaks up rock as it passes through the earth's crust. Occasionally, the most intense earthquakes can be felt by the population near the volcano.
- **Rockfalls** and **landslides** as a consequence of volcanic seismicity or other processes favouring terrain instability.



Rockfall on La Palma, 2021. / INÉS GALINDO Y MIGUEL LLORENTE

- **Tsunamis** of volcanic origin are triggered when a volcanic slope collapses into a body of water or due to the entry of pyroclastic density currents into the water.

- **Fires** caused, for example, by the high temperatures of lava flows or pyroclastic density currents.
- **Acid rain** and **pollution** due to the presence of volcanic gases in the atmosphere and the leaching of chemical compounds of volcanic origin into the soil and water bodies or water column (e.g., aquifers, lakes, marine environment, etc.).

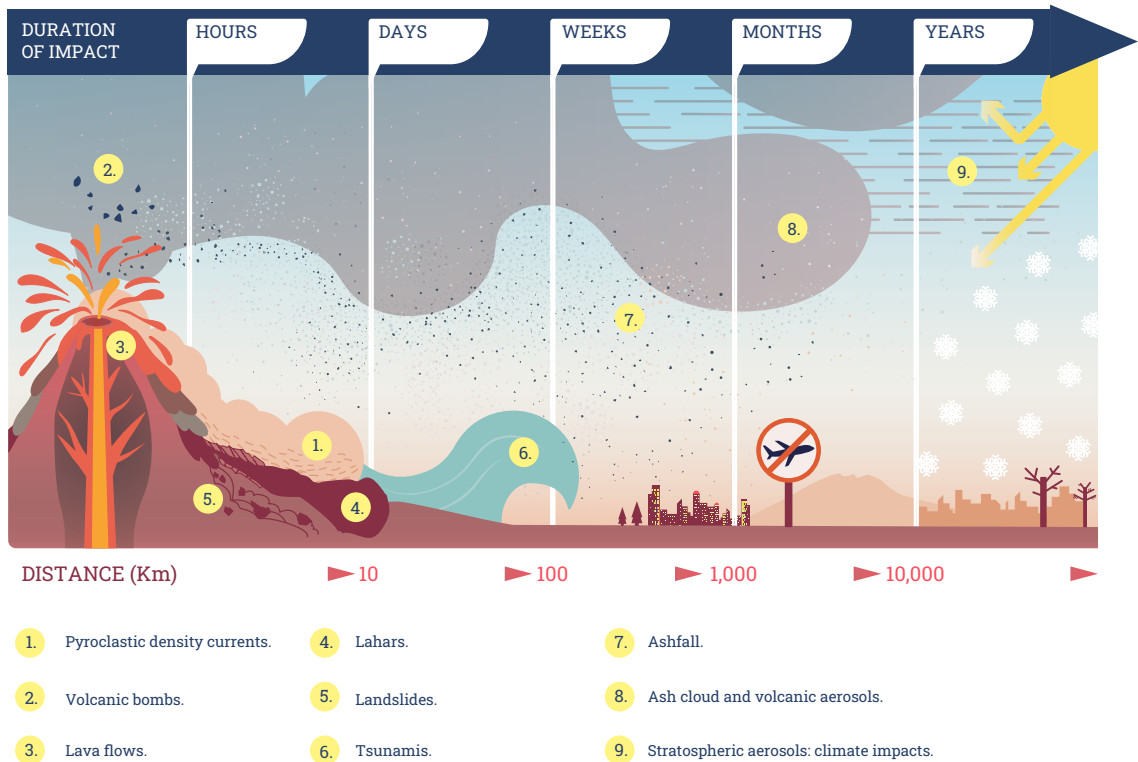


Effects of acid rains on the vegetation on the flanks of the Turrialba volcano in Costa Rica, 2018. / XAVIER BOLÓS

It is important to note that both direct and indirect volcanic hazards can occur as a consequence of each other and can interact with each other, increasing the magnitude, severity and spatial extent of their impact. For example, in 2003 the volcanic dome (protrusion due to the accumulation of viscous lava) of the Soufrière Hills volcano (Montserrat Island, Lesser Antilles) collapsed as a result of heavy rainfall and seismic activity of the volcano, generating pyroclastic density currents, phreatomagmatic explosions and tsunamis.

The relationship and interaction between different hazards are defined under the concept of **multi-hazard management of disaster risk**, a notion adopted by new international initiatives to achieve the goals of the Sendai Framework for Disaster Risk Re-

Figure 8 Duration and extent of volcanic hazard impact



**Image adaptation from The Economist*

duction 2015-2030. Multi-hazard management requires a specific, transdisciplinary approach to assessing the risks that separate analysis of each individual hazard does not allow.

Volcanic hazards have a variable impact in terms of severity, duration and spatial extent. For example, a lava flow can have severe consequences at the local level, such as the destruction of infrastructure or houses (e.g., in the case of the Tajogaite volcano on La Palma), but little or no impact at the global level. On the other hand, when volcanic aerosols (gases and tiny solid

particles) reach the upper layers of the atmosphere during an explosive eruption, they can modify the global climate. The 1991 eruption of Pinatubo (Philippines), the second largest eruption of the 20th century, triggered, on average, a decrease in global temperature of about 0.5°C between 1991 and 1993. This, along with many other examples of eruptions over the past centuries, or even millennia, illustrate how the impact of a volcanic eruption transcends borders and continents, underlining the importance of international coordination of early warning systems and volcanic risk management plans at the global level.

In the case of submarine eruptions, which account for the majority of volcanic activity on Earth, they do not usually pose a great risk because they generally occur in deep areas (deeper than 600 metres). However, it should be noted that these eruptions, and dyke intrusions, can destabilise undersea slopes or cause collapses that can trigger the formation of tsunamis.

As will be discussed in detail in the second part of the report, one of the fundamental pillars of volcanic risk management is to assess the potential environmental and socio-economic impact of future eruptions in order to implement the necessary mitigation measures. In terms of the environmental impact of volcanic eruptions, burning of vegetation, change of soil acidity, contamination of water sources, among many other processes, cause major disturbances in the ecosystems near the volcano. For example, during submarine eruptions, the injection of volcanic materials and heat generate important physical-chemical and biological anomalies in the marine environment, leading to massive mortality of organisms. However, once the eruptive phase is over and the degassing phase begins, the same volcano will release large concentrations of inorganic nutrients, heat and gases into the marine environment, producing the physical and chemical conditions necessary for the process of ecosystem recolonisation to occur at a much faster rate than under normal conditions.



Impact of the ash fall in the 2021 eruption of the Tajogaite volcano in La Palma / XAVIER BOLÓS

From a socio-economic point of view, the effects of a volcanic eruption can last for years or decades and, in some more extreme cases, the affected areas never recover their previous socio-economic situation. In the short term, before and during the eruption, volcanic activity impacts on the economy and crucial infrastructure during a crisis. Lava flows block communication and evacuation routes, while ash accumulation can collapse roofs, underground buildings and other structures, disrupt telecommunications and disrupt power supplies.

With more than 70 active volcanoes or volcanic areas in France, Greece, Italy, Portugal and Spain alone, the question is not whether there will be new eruptions in Europe, but where, how and when they will occur. It is important to consider that the risk associated with volcanic activity in Europe is not only limited to areas close to volcanoes. Historically, some eruptions have

Impact of the lava flows
in the 2021 eruption of
the Tajogaite volcano in
La Palma. / INÉS GALINDO





triggered socio-economic and political conflicts in neighbouring countries, such as the eruption of Laki (Iceland, 1783), which is believed to have contributed to triggering the French Revolution due to global cooling and the food shortages it caused. More recently, the hydromagmatic eruption of the Eyjafjallajökull volcano (Iceland, 2010) produced large ash clouds which, pushed by the wind towards central and southern Europe, posed a threat to air travel, triggering one of the biggest recent aviation crises with the cancellation of more than 100,000 flights and economic losses valued at more than 4 billion euros.

During the 20th and 21st centuries, Spain has been affected by the dispersion of ash and aerosols from international eruptions, as well as by volcanic eruptions in the Canary archipelago. During the eruption of the Tajogaite volcano (La Palma, 2021), lava flows covered more than 1200 hectares, destroying 1676 buildings, large areas of crops (more than 370 hectares), more than 70 kilometres of roads and numerous livestock farms, and also affected the marine ecosystem where they reached the coast. The emission of volcanic gases and ash caused air quality problems, and gas emissions are still a problem in some areas, even years after the eruption. In addition, during the eruption, the abundant presence of ash in the atmosphere intermittently caused the temporary closure of airspace for several days, affecting hundreds of local, national and international flights, with consequent economic and personal damage. The damage assessment transmitted from the national authorities to the European Parliament has been estimated at more than 1 billion euros. There is no doubt that this eruption has had serious consequences for the local economy, but also social and cultural consequences, and has caused, for example, the loss of roots and cultural identity in the population of the most affected areas.

The eruption of the Tagoro volcano (El Hierro, 2011-2012) had a much smaller economic impact as it occurred at sea, relatively far from the coast, and at sufficient depth not to generate hydromagmatic explosive events that could have affected nearby coastal areas. On the other hand, the marine impact was considerably much greater than during the Tajogaite eruption in La Palma, since, in this case, the volcano was completely submerged and all the lava and gases were emitted directly into the sea. Marine fauna and



flora were significantly affected, as well as the usual economic activities of the area (fishing, diving and tourism). However, one of the main dangers included the landslides caused by earthquakes in El Hierro before, during and even several years after the end of the eruption, forcing the evacuation of several areas of the island and the cutting off roads.

The two examples cited are the most recent, but the eruptions that have occurred in recent centuries in the Canary Islands, such as Timanfaya (Lanzarote, 1730-1736) or Garachico (Tenerife, 1706), caused the death of more than 20 people and great material damage. In some cases, these had a great socio-economic impact and involved the relocation of major ports, giving rise to new towns, or forcing emigration, among other things.

All these eruptions have been characterised by low explosivity. However, it cannot be ruled out that hydromagmatic or much more explosive eruptions may occur in the Canary Islands in the future, for example, in relation to the Teide volcano (Tenerife). An eruption of Teide, which is considered to be active, could be devastating on a local scale and even have global effects.

Moreover, taking into account current scientific information, the occurrence of future activity in some volcanic areas of the national territory such as the Garrotxa Volcanic Field (Catalonia), the Calatrava Volcanic Field (Castilla-La Mancha) or the Columbretes Islands (Valencia) cannot be ruled out. Although the only recorded past impact of this volcanism is through the geological record, an eruption today in any of these areas could have terrible effects in the region and nationally. In Spain, in addition to the risks from volcanoes within its territory, the volcanic threat also comes from explosive eruptions of European and other volcanoes.

13.

Living among volcanoes: the human factor in risk

DESPITE their potentially devastating power, the force of nature unleashed during an eruption has never left humans indifferent. Since ancient times, volcanoes have been considered places of worship, the home of gods and demons, or areas where mystical energy is concentrated, attracting and inspiring artists and writers. However, it has mainly been the properties of volcanic soils for cultivation, the resources associated with geothermal energy and the concentration of raw materials (minerals and rocks) useful for the construction of infrastructures (blocks, aggregates, cements), the manufacture of ornamental elements, jewellery, or the construction of tools and utensils, among other applications, that have brought many civilisations closer to volcanoes. Moreover, nowadays, geotourism is a fundamental economic value in volcanic areas, since an important part of the local population is dedicated, directly or indirectly, to this economic activity. The medicinal benefits of the thermal waters or volcanic muds and the great beauty of the volcanic landscapes attract millions of visitors who enjoy the local products and their culture, intimately linked to their geology. This is why many of the world's active volcanoes have some kind of measure to protect their natural environment and, in some cases, are recognised by UNESCO as World Heritage Sites or Global Geoparks for their natural, scientific, educational and tourist value.

Today, under the umbrella of the Sustainable Development Goals defined by the United Nations, technological development and energy needs have focused on volcanic territories. On the one hand, because hydrothermal volcanic activity can generate mineral deposits with high concentrations of strategic metals essential for the production of technological devices and, on the other hand, because the heat provided by magmatic chambers constitutes an unlimited source of energy (on a human scale) that can be exploited to obtain geothermal energy (heat and electricity).



Human occupation of active volcanic territories due to demographic expansion, geotourism activities and the exploitation of material and energy resources poses significant challenges in terms of volcanic risk management, development and land-use planning, as well as preparedness for future emergencies.

Sightseeing at Stromboli
volcano, Aeolian Islands, Italy.
/ STÉPHANIE BARDE-CABUSSON

According to definitions established by the United Nations Office for Disaster Reduction (UNDRR), **volcanic risk** is defined as the potential loss, including both damage and total destruction, of life and assets that a society or community could suffer in a specific period of time. Risk is determined probabilistically as a function of hazard, exposure, vulnerability and capacity.

In one aspect, **exposure** relates to the physical proximity of communities and infrastructure to active volcanoes, as well as their degree of interaction with volcanic areas, including human activities such as agriculture, urbanisation and tourism. In another aspect, **vulnerability** is understood as those conditions, determined by physical, social, economic or environmental factors or processes, that increase the susceptibility of an individual, community or assets to the impacts of volcanic hazards. Finally, the concept of **capacity** includes all the strengths, attributes and resources available in an organisation, community or society that allow for managing and reducing risk and increasing resilience.

Thus, volcanic risk assessment integrates the identification and characterisation of potential hazards (including information on their location, intensity, frequency and probability), the analysis of exposure and vulnerability (considering physical, social, health, environmental and economic dimensions) and the evaluation of the effectiveness of current capacities to cope with likely risk situations and the search for possible alternatives to cope with them. All these aspects, as well as the actions to be taken for risk reduction, are detailed in the next part of the report.



Hellisheiði Geothermal Power Plant in Iceland, 2023. / XAVIER BOLÓS

two



Reducing the Risk of Living with Volcanoes

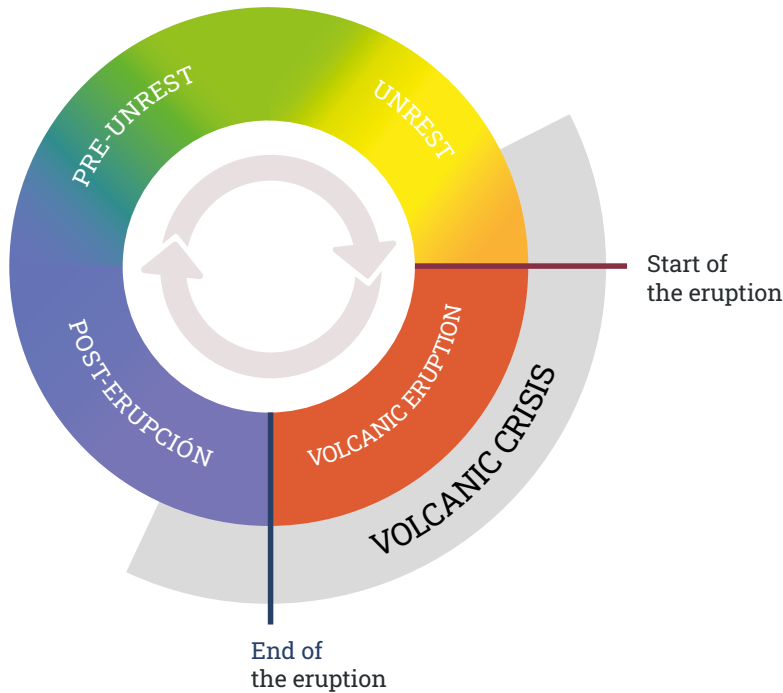


IN dealing with volcanic crises, it is essential to recognise a fundamental fact: volcanic activity is an inevitable geological process and therefore disasters are not natural, but are largely the result of human decisions. The challenge in volcanic risk management lies in learning to coexist with volcanoes, which requires continuous vigilance and constant adaptation. In this sense, each volcanically active region needs a strategy for coexistence, which takes into account both the natural characteristics (geological, environmental, climatic, etc.) and the socio-economic context of the territory. This implies the need for in-depth scientific research on volcanoes in order to gain a deeper understanding of the associated geological, physical and chemical processes. This scientific knowledge makes it possible to be better prepared for a future eruption since, among other aspects, a better interpretation of the signals recorded by volcanic monitoring systems can be carried out, more effective early warning systems can be designed and forecasts can be improved.

Over the last few decades, numerous scientific projects related to volcanism and its associated risk have been developed within the CSIC that have marked significant advances in the multi- and interdisciplinary knowledge of this phenomenon. This research has paved the way towards a comprehensive understanding of volcanic hazards and risks, and the results obtained have enabled the adoption of crucial measures to mitigate their impacts and adapt to their nature, highlighting the importance of science in facing the challenges posed by coexistence with volcanic activity.

This Part 2 of the report provides a comprehensive framework for the study and effective management of volcanic hazards, enabling early preparedness, coordinated response and sustainable recovery from these natural events. To this end, the UN Disaster Management Cycle has been adapted to specifically address volcanic disasters by dividing it into the following interconnected stages:

- Long-term preparedness, when the volcanic system is stable and there are no signs of abnormal activity, or change, from its typical historical behaviour considered as a baseline level.
- Actions and preparations during the stage of volcanic *unrest*, (period of time when a volcano is showing unusual activity or is erupting). This is a period of potentially visible and/or measurable physical and chemical changes indicating variations in the state of the volcano, resulting from a range of phenomena that can occur both at great depth (several kilometres), such as magma ascent and accumulation, and also near the surface (a few hundred or tens of metres), such as activity in the hydrothermal system.
- Measures and actions during the volcanic crisis that are implemented when the situation of volcanic unrest intensifies, increasing the chances of an imminent eruption and generating greater concern among the population. Forecasts are continuously updated and, if necessary, emergency and mitigation plans are put in place, the alert level is updated, etc.
- Volcanic crisis and eruption response. At this stage, emergency plans are activated and measures are implemented to protect lives and property. Evacuation of areas at risk is carried out, humanitarian assistance is provided to affected communities, the response is coordinated between different agencies and organisations, and scientific data is reported to the authorities and the population.
- Recovery after the end of the eruption and preparation for the next event. Once the eruption has ceased, the recovery phase begins, which includes damage and needs assessment, reconstruction of damaged infrastructure, rehabilitation of affected communities and implementation of mitigation measures to reduce vulnerability to future eruptions.

Figure 9 Volcanic risk management cycle

**Adaptation of the United Nations Office for Disaster Risk Reduction (UNDRR) Risk Management Cycle*

This cycle involves coordination between governments, public and private institutions, scientific and technical staff, humanitarian organisations, local communities, the media and other actors to ensure effective volcanic risk management and to promote and strengthen resilience to these natural events. At each stage of this cycle, the CSIC plays a fundamental role in the development and leadership of those lines of research that include, among many others, understanding and elucidating the phenomena that trigger the onset of an unrest phase, assessing short and long-term volcanic hazard, analysing the products emitted during the eruption and their impact on the environment, etc.

21.

Anticipating the next eruption: research as a key to reducing volcanic risk

EFFECTIVE preparation for future volcanic crises, whether to address direct or indirect hazards, requires a thorough analysis of past volcanic activity and its impact, as well as an assessment, in terms of typology, location and size, of potential future eruptions. Understanding the processes that have previously occurred in a volcanic area is crucial to understand how the volcanic system evolves and what triggered past eruptive activity, and serves as a guide to address and manage future events. The CSIC, with staff having expertise in a wide range of applied specialities in terrestrial, marine and atmospheric environments, contributes to advancing this knowledge on a daily basis.

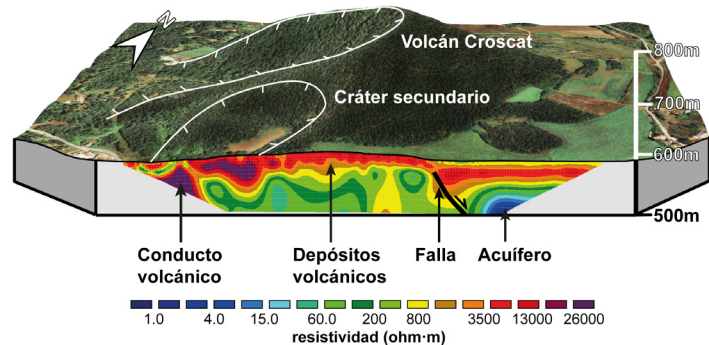
These research activities should preferably take place during quiet periods, when there is sufficient time for data collection and interpretation by all relevant disciplines in the field of volcanology. Much of this research starts with geological fieldwork, with *in situ* observations of volcanic deposits, the collection of rock, water and gas samples or the measurement of physical and chemical parameters. The study of volcanic deposits provides access to hundreds, thousands or even millions of years of eruptive history, and complements information from historical documents collected during more modern eruptions (where such documentation exists). This provides information on the volcanic phenomena involved during the whole eruptive process and allows reconstructing the different phases of the eruption. Furthermore, by identifying and characterising the deposits of an eruption, it is possible to produce isopach and isopleth maps, which describe the thickness of the deposits and the size of their products at different distances from the volcano, as well as their spatial distribution. In this way, the magnitude and extent of eruptions can be determined, allowing, for example, the total volume of material emitted and the height of the eruptive column to be calculated.



Fieldwork on
volcanic deposits.
/ JOSÉ LUIS MACÍAS

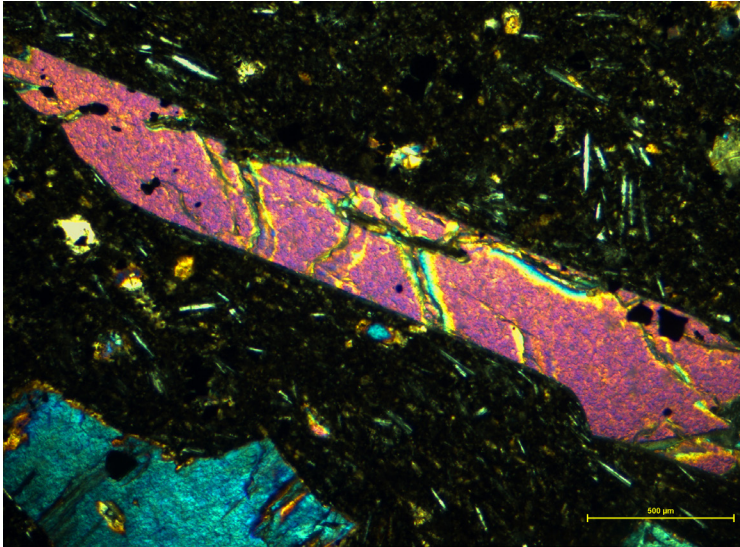
In addition, if they are still preserved, geomorphological aspects, such as the shape of the volcanic edifices, their dimensions, the slope of their flanks, the depth and size of the crater, should be described in detail. These data are of relevance to determine key aspects of the eruption that originated them. Thanks to these studies as a whole, it is possible to explain whether the magma interacted with bodies of water (hydromagmatism), the volume of magma available, the level of explosiveness of the eruption, etc. In addition, it is necessary to make a detailed analysis of the presence of fractures, faults and previous magmatic intrusions (already solidified, such as dykes) and to determine their relationship with the volcanic activity. Any information related to their orientation, length or dimensions, among many other parameters, is of interest to understand the paths that magma could (or may) follow in its ascent to the surface, identify areas more likely to host an eruption in the future, etc.

CSIC research staff have extensive experience in the development of field work, including the application of remote sensing techniques installed on land, at sea (such as buoys or instruments anchored to the seabed), airborne (drones) or satellites. In addition, it has a vast knowledge of different geophysical techniques, which allow, among many other applications, the detection of seismic activity, ground deformations or variations in physical parameters (for example, density and electrical conductivity). All this in order to obtain a picture, or reconstruction, of the internal structure of the volcanic system, or to detect the migration of magma or other fluids in the subsurface. Knowledge of the magmatic feeding system, volcanic structures and fluid circulation in volcanic edifices is essential to study their evolution and also the hazards associated with active zones.



Geophysics model at the monogenetic volcano of Croscat, Garrotxa Volcanic Field.
(MODIFIED FROM BOLÓS ET AL., 2014)

The research work continues in the laboratory, attempting to unveil one of the best kept secrets of volcanoes: the origin of the magma and its residence time, i.e., the years that the magma remains inside the Earth until it erupts on the surface. Both study topics require specialised laboratories in petrology, geochemistry and geochronology, where CSIC staff analyse the rock samples collected and determine the age of the volcano, the original composition of the magma, how and at what depth it formed, how long it remained in the magma chamber and, in some cases, the process that triggered the eruption (e.g., mixing of magmas).

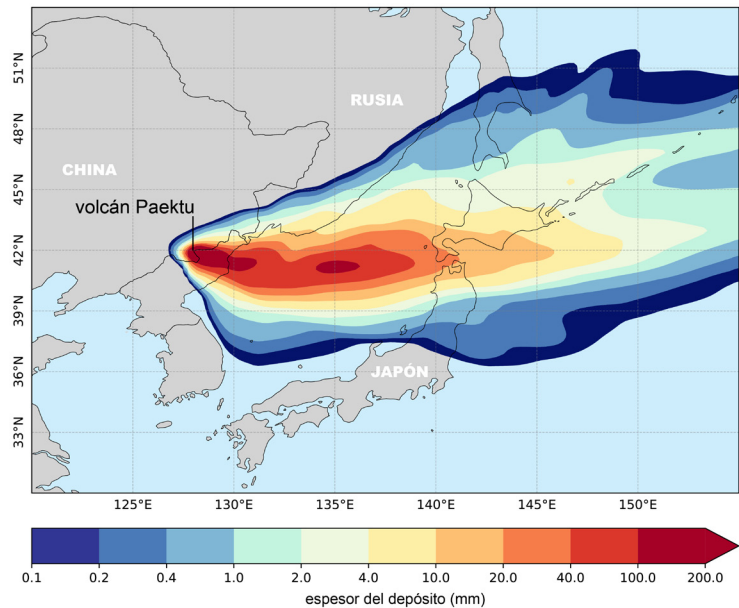


Optical microscope image of volcanic rocks emitted during the 2021 eruption in La Palma.
/ JOSÉ LOZANO (IEO-CSIC-VULCANA)

These, along with many other questions, can also be answered from an experimental point of view. At the CSIC, several research groups have been carrying out pioneering work for years in the design and development of analogue models and experimental petrology applied to the study of volcanic processes. Analogue models make it possible to reproduce natural processes in the laboratory with a time scale factor (speeding up or slowing down the process) and/or spatial scale factor (increasing or decreasing its size). In volcanology, such models are useful, for example, to understand the mechanisms of magma ascent and accumulation. On the other hand, experimental petrology, by subjecting rock samples to controlled pressure and temperature conditions, similar to those existing in the deep Earth, contributes to improve, among other things, the understanding of the evolution of the composition and physical properties (density, viscosity, etc.) of magma, which will control, to a large extent, the volcanic hazard of the eruption.

Finally, the information collected in the field and in the laboratory is used to make analogue models or as input data in mathematical models, which seek to reproduce by means of equations and algorithms the processes occurring both outside and inside a volcanic system. In some cases, this requires sophisticated nu-

merical methods and computational techniques, as well as the use of supercomputers such as those available in the Spanish Supercomputing Network (ICTS-RES). Of particular interest to CSIC scientists is the ability to identify and quantify the key parameters that control the phenomena that occur before an eruption and that may even trigger it, such as the magma ascent rate. The CSIC also has extensive experience in simulating processes that occur after the eruption has started, such as the dispersion of volcanic ash particles and the expansion of the eruptive cloud, the results of which are used both to reconstruct the extent of past eruptions and to predict the impact of future events.

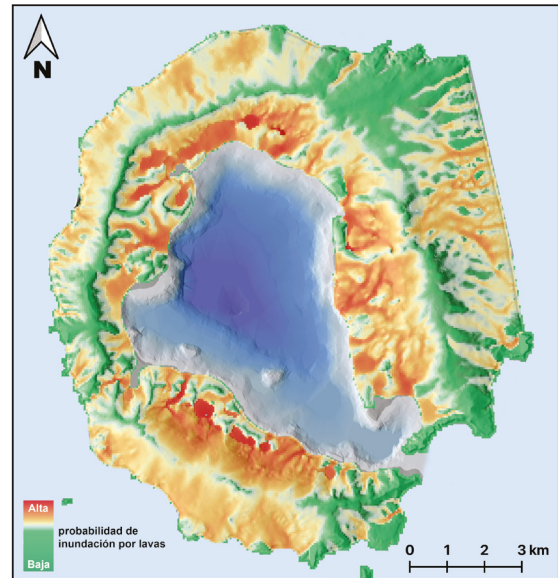
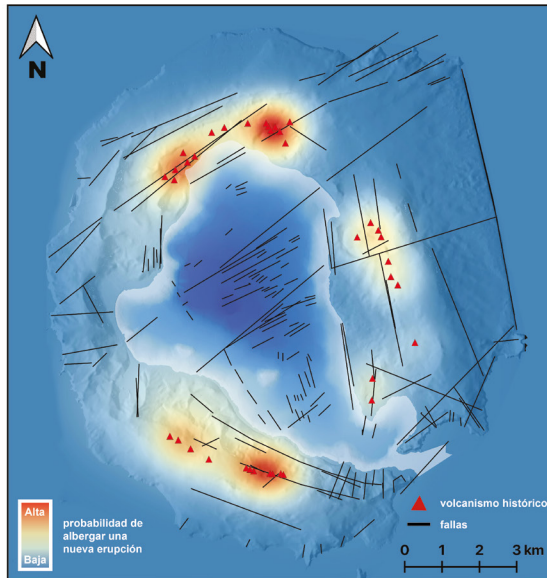


Reconstruction by numerical modelling of ash dispersion during the millennium eruption (AD 946) of Paektu volcano (China). (MODIFIED FROM MINGARI *ET AL.*, 2014)



Having a solid scientific understanding of past volcanic activity and its impacts is a fundamental step towards volcanic risk reduction. To this end, all the information collected is processed in order to make a correct assessment of volcanic hazards. The CSIC has long experience in assessing volcanic hazard in active areas, as in the case of El Hierro, in the Canary Islands. For this purpose, it carries out detailed studies of volcanic deposits to reconstruct the typology of past volcanic activity and its evolution over time. On the one hand, the recording of how, where, when and with what impact eruptions have occurred in a volcanically active area, combined with theoretical models, allows, for example, a temporal analysis to be carried out, estimating the probability of a volcanic eruption occurring in the coming years. The geological information collected is also used to construct so-called event trees. These analytical diagrams are the result of a logical evaluation process that works along a timeline or through a causal chain. Event trees start with a specific event or initiator, e.g., the beginning of an unrest period, and from there, the possible consequences are analysed chronologically.

Simultaneously, a spatial analysis is carried out with the aim of identifying areas with higher volcanic susceptibility or probability of hosting new eruptive centres. This is based on the study of previous eruptive centres, volcanic alignments, fissures, dykes, fractures and faults. Finally, the most likely eruptive scenarios in the study area are defined, establishing what a future eruption will be like (typology and size) according to what has happened in the past in that volcanic area. Simulations are carried out to define the area of impact of the different associated hazards, as well as their evolution over time. The results of these simulations allow the creation of volcanic hazard maps, which are cartographies that identify those areas likely to be affected by the different volcanic hazards, such as ash fall or lava flows.



Example of volcanic susceptibility (left) and lava flow (right) hazard maps for Deception Island (Antarctica).
(MODIFIED FROM BARTOLINI *ET AL.*, 2014)

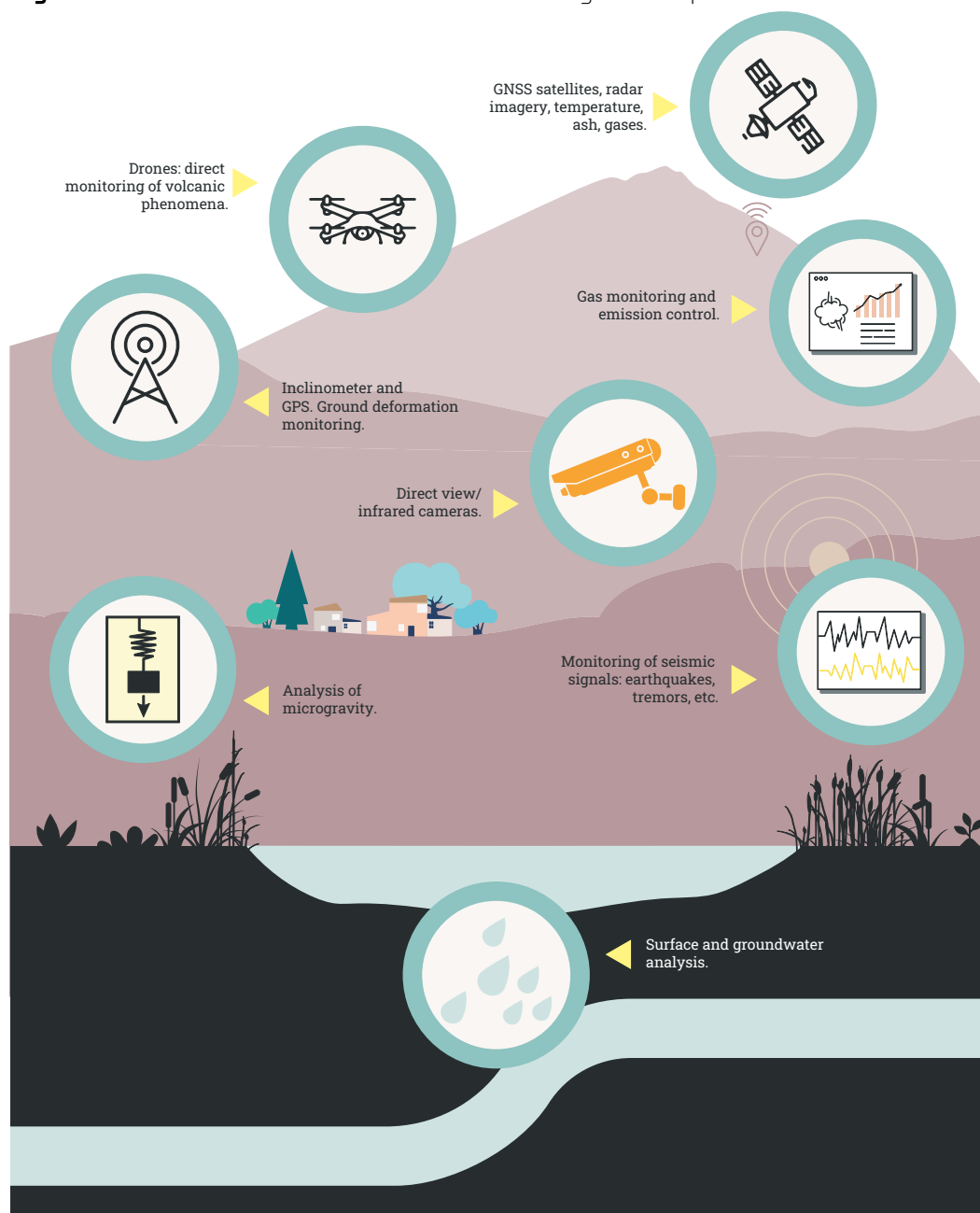
Volcanic hazard assessed according to the information extracted from the geological record is called a long-term assessment and its output, delivered in the form of hazard maps, event trees and scientific-technical reports, is made available to governing bodies and decision-makers. Ideally, the conclusions drawn from a long-term hazard assessment should serve as a fundamental pillar for the next steps in the process of volcanic risk reduction, such as establishing territorial planning according to the level of hazard, defining emergency plans and routes, etc. It is crucial that long-term hazard assessments are reviewed regularly, especially after an eruption, to ensure that all available and most up-to-date information on the study area has been considered.



The time of rest between eruptions is the ideal time to install, check and improve the surveillance or monitoring network. In general terms, it should consist of all the instrumentation that can pick up any signals generated by the volcanic system that can help elucidate whether any sub-surface processes are occurring that could produce changes in the system and potentially trigger an eruption. Each monitoring network will have a specific type of instrumentation, density (number of instruments per square kilometre) and distribution (location of instruments) for the study area. In order to decide on each of these aspects, the type of volcanic system to be monitored and the number of critical infrastructures exposed to potential volcanic hazards are taken into account. Within the framework of European projects, this exercise has been carried out, from an academic point of view, by CSIC research staff in areas such as the Canary Islands, the Garrotxa Volcanic Field or on Deception Island, in order to highlight the need to establish dense and complete monitoring networks in these volcanic areas (especially in the Canary Islands).

The record, or signals, that the monitoring network collects during the time leading up to volcanic unrest is used to establish what is called the **baseline** or base level of activity, specific to each volcanic system. This point is critical to be able to identify when the recorded signals start to deviate from this level, either increasing or decreasing (e.g., increased seismic activity), or changing characteristics (such as variations in the composition of fumaroles), which could indicate the onset of system instability and unrest. In Spain, the National Geographic Institute (IGN) is responsible for planning and managing the systems for monitoring and communicating volcanic activity in the national territory and determining the associated hazards (Royal Decree 953/2018 of 27 July), which has different instrumentation networks deployed on each of the islands of the Canary archipelago and on the Iberian Peninsula.

Figure 10 Volcanic surveillance and monitoring techniques

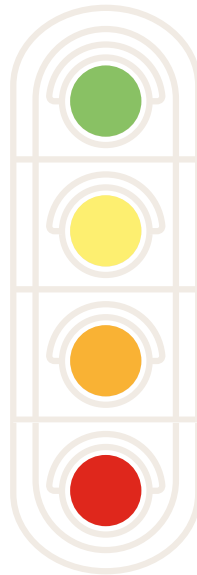




During this period prior to a volcanic crisis, it is also important to have an effective early warning system in place and connected to surveillance networks, in order to be able to communicate a dangerous situation to the authorities as quickly as possible. If signals suggesting an eruption are detected, the system activates the corresponding alerts, allowing preventive measures to be taken and activating the corresponding civil protection plans. These systems require the definition of efficient communication protocols for a rapid and coordinated response to an emergency.

In emergency plans, different levels of volcanic alert are established according to the level of activity of the volcanic system. In volcanology, it is common to use a colour scheme similar to that of a traffic light, where the lowest alert level is usually represented in green and the highest in red, with intermediate levels associated with yellow and amber. Each of these levels implies the activation of a series of means and measures for the affected population and serves to inform all the actors involved (population, media, other authorities, etc.). The definition of the levels of the warning system, as well as the criteria for switching from one level to another, is complex and depends on the country or volcanic area. For example, in the United States the focus is on the hazard, while in Indonesia and Japan it is elaborated on the basis of risk and the required response. In the case of the Canary Islands, the Special Plan for Civil Protection and Emergency Care due to Volcanic Risk in the Autonomous Community of the Canary Islands (PEVOLCA) follows the same four-colour system, referred to as the volcanic traffic light, with indications on the levels of activity and the actions to be taken by the different bodies involved in the management of the emergency.

Figure 11 PEVOLCA volcanic traffic light for communicating the alert level



VOLCANIC TRAFFIC LIGHT:

- **PRE-ALERT: CONTINUE YOUR ACTIVITIES AS NORMAL.**
Green represents such a low-risk condition for the population that no protective measures are required.
- **ALERT: PAY ATTENTION TO OFFICIAL COMMUNICATIONS FROM AUTHORITIES AND THE MEDIA.**
In yellow, the Civil Protection Plan is activated because there are increases in anomalies and/or indicators that predict a pre-eruptive period in the medium term. Make provision for a possible personal evacuation plan.
- **HIGH ALERT: THE EMERGENCY PHASE IS TRIGGERED.**
In orange the records of volcanic activity behaviour indicate that there are pre-eruptive phenomena that show that a pre-eruptive phase is developing. High alert situation and start of preventive evacuation when indicated.
- **EMERGENCY: MANDATORY AND IMMEDIATE EVACUATION.**
Red is activated when the volcanic eruption is confirmed and poses a risk to the population and critical infrastructure. An urgent and compulsory evacuation of the population is mandatory. All persons must cooperate with the authorities in the evacuation.

Estimating the potential location and extent of the impact of future eruptions is crucial to assess the degree of exposure of infrastructure and communities. On the other hand, knowing what hazards to expect allows studies of physical vulnerability (such as, for example, the resistance of roofs to ash accumulation), socio-economic and environmental vulnerability, which should subsequently be translated into specific mitigation actions, such as structural improvements to buildings, proper territorial planning, etc. In this sense, the CSIC contributes by conducting studies on volcanic risk perception, the results of which make it possible to develop training strategies and teaching materials to improve early education and preparedness of exposed communities, thus reducing their vulnerability and improving their capacity to react.

2.2.

Precursor signals as a prelude to a volcanic crisis: investigation, forecasting, preparedness and action

WHEN the volcanic system undergoes a marked change in its baseline activity, a period of unrest is considered to have begun. During unrest, a number of phenomena occur that may be precursors to a volcanic eruption in the short, medium or long term. These include increased seismicity, ground deformations, variations in volcanic gas emission and fumarolic or hydrothermal activity, and alterations in the temperature of water bodies, among others. Ideally, all these phenomena should be recorded by the existing monitoring network. Only in some particular cases can these changes go unnoticed, either because of their low intensity, because they are below the detection limit of the instruments, because they present few and widely spaced signals, or because of the speed of the magmatic process itself. Commonly, eruptions that occur without warning, or with precursor signals that go unnoticed, are those due to phreatomagmatic or phreatic processes (as was the case in 2014 at Mount Ontake, Japan, or on Whakaari Island, New Zealand, in 2019), or open conduit eruptions, that is, with a permanent opening in its crater through which magma is ejected continuously or intermittently (as in the paroxysmal eruption of Stromboli, Italy, in 2019).

At the start of volcanic unrest, the knowledge gained and methodologies previously developed are put into practice and adjusted. Theoretical and general parameters in eruptive scenarios, models and simulations are replaced by precise and specific data corresponding to the current situation. In this context, simulations and susceptibility maps become operational tools to establish revised and concrete eruptive scenarios that are updated on a daily basis. Since a volcanic crisis is constantly evolving, the flow of new information is continuous as the data are dynamic and changing on a minute-by-minute basis. The correct interpretation of the data collected is crucial to understand and evaluate the evolution of the unrest period in time and space, as well as indicators for the correct forecast of possible eruptions in the short term. In this context, the CSIC contributes with scientific knowledge and short-term hazard assessment, updating the hazard and susceptibility maps based on the data collected by the monitoring network during the unrest period.



Depending on the processes that trigger them, unrest periods can have different characteristics, lasting a few hours, days or years, and do not always escalate in intensity towards a volcanic crisis or culminate in an eruption. In fact, statistically, a significant percentage of unrest events end without magma coming to the surface. In most cases, this is because the rising magma is trapped in the subsurface and begins to decrease in temperature, and may cool completely at depth, without ever erupting.

In extreme cases, periods of unrest can last for years with no clear indication of a future eruption. In such circumstances, it is very difficult, and even unfeasible, to anticipate when and how it will end. Therefore, one of the main challenges in volcanology is to address the lack of scientific knowledge about those volcanic systems that experience long periods of stability or quiescence with eruption frequencies that are considerably more spaced out in time compared to the observation period available to determine the baseline activity level of the volcano under study.

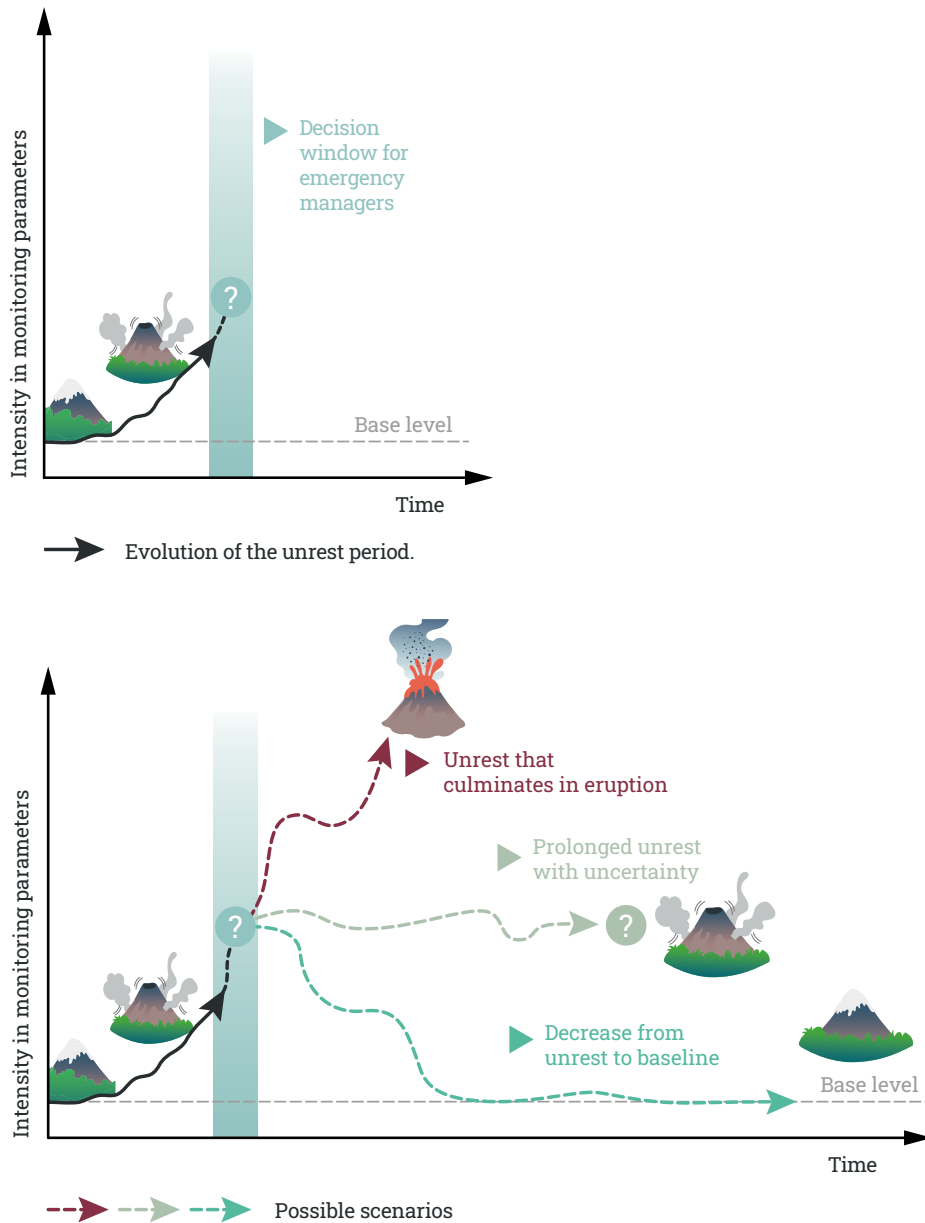
The complexity and diversity of signals collected by the monitoring network, as well as the ambiguities in defining the processes that give rise to them, complicate the task of establishing whether an unrest phase will decrease or intensify. In any case, the phenomena occurring during the unrest period may be a relevant hazard in themselves (such as the release of gases hazardous to health) or trigger other dangerous processes (landslides or rock falls caused by seismic activity). Therefore, even in the certainty that it will not culminate in an eruption, periods of volcanic unrest can also pose a risk to the population.

When the volcanic unrest intensifies, concern increases among scientific staff, emergency managers, political-administrative decision-makers and the community itself in the expectation of a possible imminent eruption. In these situations of accelerating signals, a decision window opens and the authorities, under great political and social pressure, must make a decision regarding the activation of mitigation measures, including, in some cases, the evacuation of the population at risk. At this point, it

is imperative that scientific staff communicate, in the most effective way, all available information, including the forecast of the evolution of the situation. Unfortunately, despite scientific progress in volcanology and volcanic monitoring techniques, it is not always possible to provide an accurate forecast in terms of whether or not an eruption will occur. It should be borne in mind that even with a strong monitoring network, extensive knowledge of the volcanic system and real-time information, the complex nature of eruptive processes can lead to incorrect or uncertain conclusions.

As the volcanic crisis progresses, the increased data collected by the monitoring network reduces the uncertainty associated with forecasting the evolution of eruptive activity, i.e., in establishing whether an eruption will eventually occur, the time frame and where it will take place. The relevant authorities can then have a more solid basis for making decisions, such as increasing the alert level. However, in parallel, the time remaining until the onset of the eruption is decreasing, thus reducing the time available to put in place appropriate mitigation measures. It is therefore necessary to strike the right balance between declaring a warning early enough to avoid human and material losses, but with as little uncertainty as possible, and avoiding generating a false alarm (if the eruption does not occur). This could lead to unnecessary evacuations and disruption of economic and social activities. In addition, activating warnings without adequate justification may lead to a loss of credibility, which will hinder effective response in future volcanic emergencies. The most uncertain scenario occurs when the unrest stage is prolonged, fluctuating in intensity, over years or decades. Scientific staff and public officials are faced with continuous and numerous peaks of activity, during which they must decide whether to modify the alert level or take some kind of complementary mitigation measure. False eruption alarms are common in these circumstances.

Figure 12 Evolution of an unrest period, decision window and possible scenarios





In the context of an unrest period and during a declared volcanic crisis, the role of the CSIC is to advise the authorities, Civil Protection and other volcanic surveillance authorities and emergency managers on the interpretation of the data recorded by the monitoring systems and their possible evolution, as well as on the improvement and design of the various volcanic surveillance networks, if necessary. In addition, where required, the CSIC contributes with its research infrastructures (laboratories, instrumentation, equipment, digital services, etc.) to improve the structural surveillance networks, in an exercise of institutional responsibility and collaboration at the service of society.

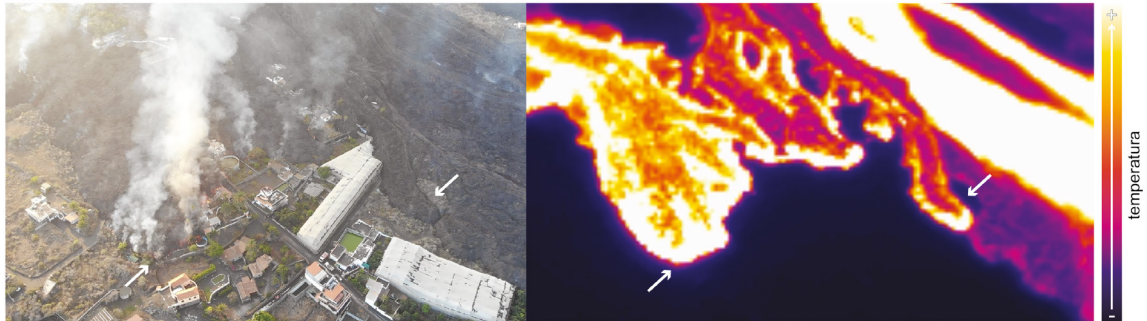
The National Plan for the Surveillance of Seismic, Volcanic and Other Geophysical Phenomena, currently being drafted, aims to optimise resources and improve systems for early warning, monitoring, surveillance, detection and technical regulation of volcanic hazards. In this way, it regulates the strengthening of the national surveillance system through the integration of all available means in the national territory, distributed among various institutions (such as universities and research centres). The aim is to improve the understanding and strengthening of disaster risk governance and to increase disaster preparedness in order to be able to offer an effective response to these phenomena. The participation of CSIC research staff in the development of this plan is evidence of the institution's commitment to joint and coordinated action to mitigate geological hazards, including volcanic hazards.

2.3.

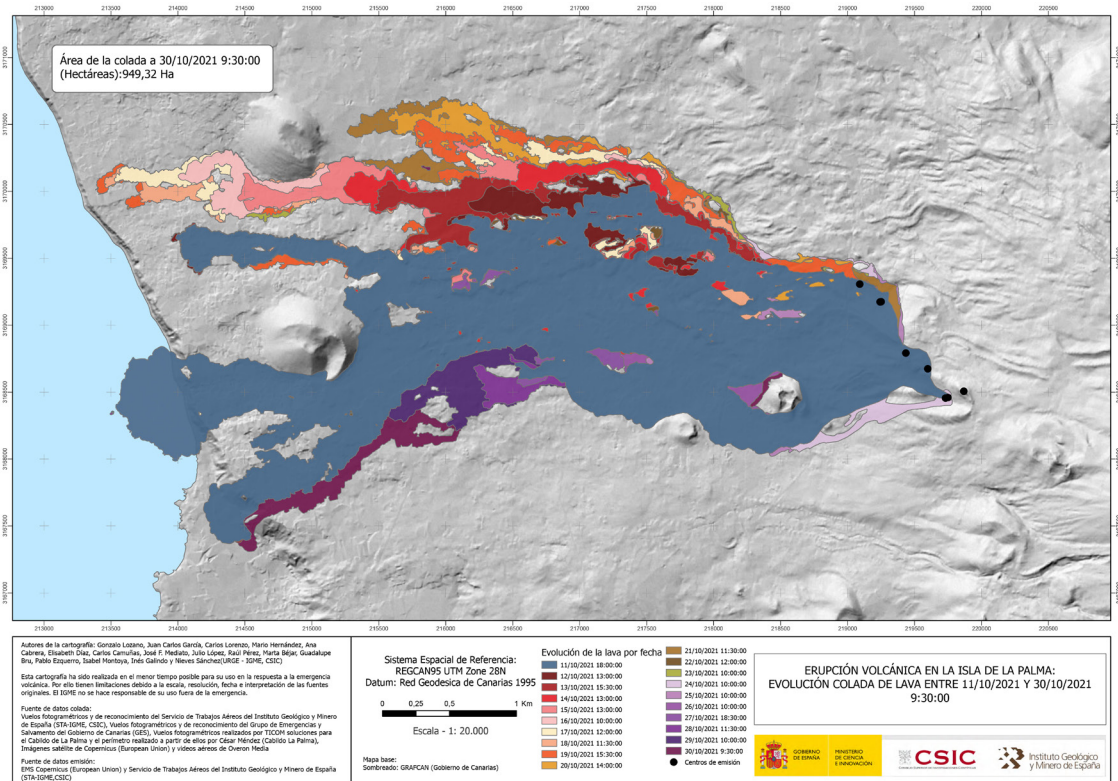
Actions during an eruption: scientific advice for public decision- makers and communication to the public

FROM the onset of a volcanic eruption, monitoring and tracking of the activity is essential to advise the authorities responsible for its management on its evolution and expected dangers. During the course of an eruptive event, institutional collaboration becomes more necessary than ever, both for the reinforcement of the surveillance network and for the interpretation of the huge amount of data collected and their joint evaluation by the scientific committees. In the specific case of the Canary Islands, the latter is called the Scientific Committee for the Evaluation and Monitoring of Volcanic Phenomena (CCES) and is constituted in application of the PEVOLCA. This Committee is made up of representatives from different ICUs and National Centres of the CSIC, each specialising in an area of knowledge within volcanology. The fundamental mission of the CSIC as a member of this Committee is to provide scientific advice to the governing bodies of PEVOLCA, with responsibilities that include establishing the surveillance and monitoring methodology to be applied in the event of a volcanic eruption, assessing the data and information obtained and formulating forecasts about its evolution. Under this scenario, the contribution of the CSIC is key, providing support for the strengthening of the surveillance system, installing complementary networks, and contributing the scientific knowledge of its research staff through its scientific advisory work. For example, during the Tajogaite volcano eruption, the contributions of ground deformation data, seismic activity records, mapping of subaerial and submarine lava flows, and pyroclast dispersion models were fundamental. The CSIC also carried out conventional and thermal imaging using drones, in collaboration with the Canary Islands Government's Emergency and Rescue Group (GES).

14-Oct-2021



Conventional (left) and thermal (right) image taken with a drone during the eruption of the Tajogaite volcano (La Palma, 2021). / STA-IGME-CSIC

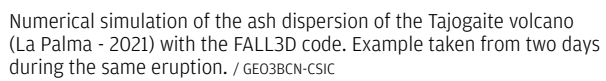


Map of the advance of the lava flows during the Tajogaite eruption (La Palma, 2021). / GONZALO LOZANO *ET AL.* (IGME-CSIC)



The scientific and technical staff also took samples of rock, water and gases which were analysed for their composition and physical properties, providing valuable information on various aspects such as possible contamination by ash leachate, the weight of ash on the roofs, the characteristics and origin of the magma and its evolution before and during the eruption. Equally essential were the volcano-tectonic studies in order to analyse the opening of new eruptive points, the volcanic conduits and their relationship with the system of faults and fractures, the monitoring of air and groundwater quality, the analysis of susceptibility to ground movements or the impact of the eruption on terrestrial and marine ecosystems, as well as other secondary hazards that may pose a risk to the population. The continuous observation of the process, the interpretation of the acquired information and its constant updating, helped to establish the eruptive scenarios likely to occur, with forecasts of the possible affected areas and their impact, supporting the decision making of the authorities. Given the explosive nature of the eruption and the corresponding concern about the release of particles into the atmosphere, the CSIC carried out real-time simulations of ash dispersion, which became an operational forecasting service with a 48h forecast, which was of great importance for the PE-VOLCA scientific committee. This has proved to be an essential tool to inform decision-makers about scenarios of impacts on civil aviation and the likelihood of impact on air quality to determine the confinement of the population.

In the event of a large explosive eruption occurring outside Spanish territory, especially in Europe or in Mediterranean areas, risk management in Spain would focus mainly on mitigating the impact of the massive injection of particles and gases into the atmosphere. Through the numerical simulation of the advance of these hazards and the analysis of vulnerability and exposure, it is necessary to assess and forecast the impact on airspace, air quality, the environment, agriculture, critical infrastructures, transport networks and telecommunications throughout the territory, or in much of it. These large eruptions can have global repercussions, and thus a high economic and social cost, even higher than in the case of smaller eruptions within Spain.



Finally, during a volcanic eruption, whether underwater or on land, but having an impact on the sea, oceanographic observation, including underwater monitoring, is essential and must be reinforced from the outset. This applies especially to volcanic events on islands, coasts and the seabed, and aims to analyse the impact on marine ecosystems, as well as possible secondary risks, among others. To this end, the CSIC deploys specialised oceanographic vessels belonging to the Singular Scientific and Technical Infrastructure FLOTA (ICTS-FLOTA) with multidisciplinary equipment that includes, for example, oceanographic instrumentation or the use of remotely operated robots, which make it possible to study, sample and observe underwater volcanic processes and their consequences on the marine environment. Mobile laboratories for the *in-situ* evaluation of physical-chemical and biological parameters, research and technical staff, as well as specific scientific instruments are also deployed to be anchored in the vicinity of the study area. Sampling the area before the eruptive process takes place or the impact has been generated is vital, as it allows the physical-chemical, biological and geological anomalies caused by the volcanic activity in the marine ecosystem to be determined *a posteriori*.

In parallel to the research and data collection tasks, extensive communication work must be carried out to explain the volcanic process to society. Thus, before, during and after the eruption, CSIC staff have a fundamental duty to share the experience and knowledge acquired over many years of research, putting them at the service of society through dissemination and communication. During the eruption, the proper communication of the emergency situation and the explanation to the population of the volcanic processes taking place is of vital importance for the correct management of the crisis. Beyond official communications by the authorities or the spokesperson of the Scientific Committee, concrete explanations on all aspects related to the geological process itself must be made by scientific personnel with expertise in volcanology who are able to convey the information clearly and based on scientific evidence.



IEO oceanographic vessel Ramón Margalef in front of the lava delta during the eruption of the Tajogaite volcano on the island of La Palma, 2021. / ICMAN-CSIC-VULCANA

2.4.

Post-eruption research and management

At the end of the eruption, the post-disaster reconstruction and recovery phase begins. During this period, a detailed damage estimate is made, damaged infrastructure is repaired, affected communities are rehabilitated and mitigation and preparedness measures for future eruptions are implemented. In many cases, these actions are managed even in the presence of certain dangers derived from the volcanic eruption and its products, such as the high temperatures of the lava flows, the remobilisation of ash deposits during heavy rains, the instability of the volcanic edifice itself, or the emanation of gases that are harmful to health. Some of these hazards can last for years or even decades.

The CSIC, during this stage, contributes by providing continuous scientific advice to the authorities, conducting research that can support recovery efforts by providing information on the characteristics, distribution and volume of volcanic products, as well as their temperature and cooling rate, the concentration and composition of gases in emission, groundwater, terrain stability or impacts on the marine ecosystem, among other aspects. The collection and analysis of these data allow a better understanding of the volcanic process, to assess the extent of its hazards and improve mitigation, preparedness and recovery strategies.

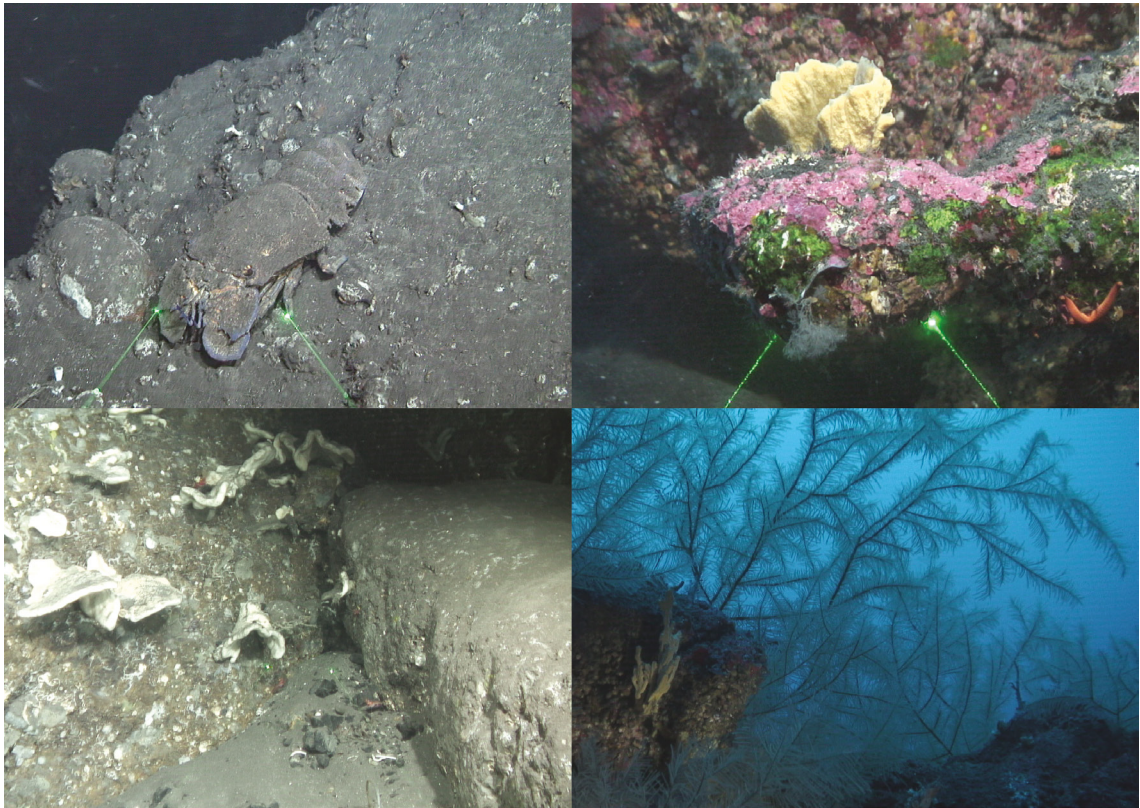
In the case of the Tajogaite eruption, a lava cooling model and a temperature monitoring system were developed, which has been of great interest to the public administrations in charge of the reconstruction and recovery work, and of great use in the construction of new roads and territorial planning in general. In addition, the CSIC has spent more than a decade studying the evolution of the degassing process of the Tagoro submarine volcano (El Hierro). Over the years, the CSIC has been committed to technological innovation for the specific monitoring of these environments, developing and designing new scientific instruments used with underwater robots.

Territorial planning studies are crucial before the reconstruction of the affected areas, and they allow the identification of areas that, due to their unique nature, should be preserved for



Photograph of a caution sign for post-eruptive processes in the evacuated exclusion zone. / RUBÉN LÓPEZ, IGN

scientific, educational and touristic use, thus becoming part of the geological heritage. The geological landscape created during the eruption is an essential part of geodiversity, as well as being a major tourist attraction, so it is essential to consider in advance which areas deserve protection. The design of new tourist products (georoutes, museums, interpretation centres, etc.) must be accompanied by the generation of informative material and the training of guides and tourist companies, always trying to favour local businesses. After the end of the Ta-jogaite volcanic activity (La Palma, 2021), the CSIC has carried out an inventory of Places of Volcanological Interest created during the eruption, assessing them and the danger of their disappearance, proposing new areas of protection for some of them, in order to avoid their destruction.



Example of underwater images of the impact of the 2021 La Palma Tajogaite volcano on the marine ecosystem (left), compared to images of the lava delta formed by the 1949 eruption (right) (Eugenio Fraile). A complete ecosystem recovery can be seen in the area.

For the volcanic disaster management cycle, it is necessary to review whether the procedures used have been adequate in order to improve them for the future. Based on previous experience in volcanic emergencies in various research groups, as well as in other types of emergencies (health, marine, etc.), the CSIC has created an Emergency Advisory Committee as an advisory body to its Presidency. It has also developed a Disaster and Emergency Advisory Protocol (PADE) in order to structure scientific interventions in an organised way, to provide scientific and technical advice in disasters and emergencies through the preparation, activation and coordination of scientific and technical teams, as well as administrative and management staff. In this way, the CSIC places its science at the disposal of the organisations in need in order to contribute to reducing volcanic risk.



In short, CSIC scientists travel to the eruption area both to provide scientific advice and monitoring, and to continue learning about volcanic processes, their impacts and hazards, observing, documenting and analysing them in real time. The data obtained allow, among other things, to investigate the characteristics of the eruption and its products and to make forecasts of possible affected areas and their impact. All this is critical to provide scientific information that allows managers to take preventive measures, such as limiting access to land and marine areas at greatest risk, ordering evacuations or closing airspace, or defining self-protection measures in the face of certain risks. The CSIC has played a crucial role in the last two volcanic eruptions in the Canary Islands: the underwater eruption of the Tagoro volcano on the island of El Hierro in 2011-2012, and the eruption of the Tajogaite volcano on the island of La Palma in 2021. On both occasions, the CSIC has provided scientific advice from the first signs of instability reported by the IGN, to the management during and after the eruption, including the post-disaster recovery period. This scientific advisory work is continuous, as the PEVOLCA Scientific Committee meets periodically to assess the situation of volcanic activity in the Canary Islands, and thus be prepared to react to a possible reactivation that could affect the exposed population and the territory as a whole. In addition, the CSIC has played a key role in the Information and Analysis of Risks and Threats Cell (CIARA) of the Spanish Government's National Maritime Safety Council (CNSM) since 2014. It acts as spokesperson for the Ministry of Science, Innovation and Universities and provides scientific advice in a wide range of areas ranging from underwater volcanic hazards to the protection of biodiversity and marine resources.

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Conclusions and Recommendations

Conclusions

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Volcanic activity is a natural and unavoidable geological phenomenon. Misinformation, lack of preparation and mismanagement are, in most cases, responsible for its catastrophic consequences.

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Volcanic hazards know no borders, their impact can be local to global and can last from a few hours to several years. In Spain, the greatest threat comes both from **active volcanic areas within the territory**, and from the dangers derived **from explosive eruptions of European volcanoes or from other nearby countries**.

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A volcanic system can be active even when there are no obvious signs of volcanic activity, even when its last eruptions occurred a few thousand years ago. **CSIC research is essential to know the current state of activity of a volcanic area and to assess the possibility of future eruptions.** This knowledge is transmitted both to public decision-makers and risk managers and to society, especially in those communities that, although residing in volcanically active territories, have not recently experienced an eruption and have a low awareness of the danger and the volcanic environment in which they live.

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In a volcanically active area, **volcanic risk management requires a thorough understanding of volcanic hazards** which may occur simultaneously, or cascade before, during or after an eruption. This requires a **multi-hazard analysis**, a thorough analysis of past volcanic activity and its impact, and an **assessment of the potential for future eruptions**.

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The CSIC's scientific knowledge has helped in making informed decisions during the management of the latest volcanic crises in Spain. During volcanic unrest and eruption, **CSIC provides scientific support and surveillance support**, while at the same time **investigating volcanic processes and hazards**, making **forecasts of possible affected areas** and **estimates of the expected impact**. The CSIC, working together with other organisations with responsibilities and competences in volcanology, contributes with its research and infrastructures to a more effective management of volcanic risk.

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Living safely with volcanoes requires **proper risk management**. While the natural and inherent **hazard cannot be acted upon, it is crucial to reduce vulnerability and exposure while strengthening the capacity of affected communities**. This is achieved, among other actions, through the implementation of adaptation and mitigation measures, such as land-use planning, building standards, economic and social development, ensuring economic diversity and resilient livelihoods, effective legislation, and education and awareness-raising plans.

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The main challenges in volcanic risk management are to determine whether a period of unrest will escalate into a volcanic crisis and whether or not it will eventually culminate in an eruption and to forecast, with an acceptable degree of uncertainty, **when, where and how it will happen**. The only way to get there is through a comprehensive scientific understanding of volcanic processes and the installation of an appropriate and complete monitoring network.

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The volcanic disaster management cycle includes the **investigation of volcanic products and deposits emitted by the eruption**, which provide valuable information on the effects and magnitude of the volcanic activity. Furthermore, the procedures applied during the volcanic crisis are reviewed for their adequacy in order to improve them for the future, and the damage caused is assessed in order to initiate recovery actions, including, among others, social assistance and psychosocial support, restoration of telecommunications and transport infrastructures, rehabilitation and restoration of cultural assets.

Recommendations

For policy-makers:

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Risk management and mitigation require **short-, medium- and long-term** actions at **social, economic, structural and environmental levels**.

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The nature of eruptive phenomena is highly complex and, even with a strong real-time monitoring and information network, **understanding and interpreting the recorded signals and making accurate forecasts requires extending existing scientific knowledge**. The institutions in charge of providing this scientific advice, such as the CSIC, **need to have the financial, material and human resources** to carry out research before, during and after the eruption.

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It is recommended that **current legislation be re-evaluated so that geologically active volcanic areas in Spain have a Civil Protection Plan** for volcanic risk in the respective Autonomous Community. Ensure that all **territories with scientific evidence of** very recent geologically **active volcanic activity**, or with no changes in geological conditions since the last eruption, **are included, thus avoiding leaving these areas in a legal void** in the event of a possible volcanic crisis.

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The study and continuous monitoring of volcanic areas considered active is necessary in order to **define their respective baseline level and to enable early detection of any signs of unrest**. This requires a clear commitment to research in volcanology, as well as advanced monitoring systems, which allow an **accurate assessment of the state of volcanic activity and its evolution**.

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Improving the understanding of volcanic risk requires a multi-, inter- and trans-disciplinary approach, and it is recommended that institutions adopt a **collaborative approach** at both national and international levels, and **encourage the exchange of data, scientific knowledge and volcanic risk management strategies**.

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Volcanic hazards can go beyond borders and continents. It is imperative that institutions advocate for **international coordination of early warning systems and volcanic risk management plans at the global level**. This ensures an effective and coordinated response to volcanic hazards that may affect multiple countries and regions, and contributes to the **prevention and mitigation of the impacts of volcanic eruptions on a global scale**.

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The volcanic crisis may continue beyond the end of the eruption, so the post-disaster reconstruction and recovery phase must begin even in the presence of some dangers, which may last for years or even decades. This should be taken into account in the preparation of emergency and recovery plans, as well as in the **planning of long-term assistance to the population**.

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Developing efficient strategies to coexist with the duality of volcanic benefits and hazards is an urgent and necessary task, which aims to improve the resilience and capacity of the local population. It is important to ensure a sustainable exploitation of the **resources** offered by volcanic territories, guaranteeing the **preservation of geodiversity**, promoting initiatives for the **valorisation and conservation of geological heritage**, and ensuring the **involvement of affected communities**.

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It is imperative to **invest heavily in training**, in **preparing communication protocols** and **emergency plans**, and in conducting **drills** to improve the speed and coordination of emergency and civil protection response during a volcanic crisis.

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There is a need for extensive **communication and the development of training, education and scientific dissemination strategies**. A better-informed population, with a greater perception and more aware is better prepared to face both the volcanic crisis and the recovery phase, and demonstrates a greater capacity to react, adapt and seek new resources.

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To **enable the recovery of affected people, prevent loss of attachment to their territory and minimise damage to personal property and identity**, institutions need to take actions such as ensuring the digitisation and preservation in public databases of personal documents, such as administrative, banking and identification files, as well as personal photographs and family documents with sentimental value.

For the media:

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Cooperation between the media, volcano scientists and authorities is essential. **The media play a crucial role in effective communication during a volcanic crisis**, so it is necessary that they refer to established **official sources** and consult the **spokesperson of the scientific committee** to ensure that the **information conveyed is accurate, reliable and truthful**. This helps to keep the audience informed and safe, combating fake news and rumours that may generate panic or, conversely, a perception of false security.

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For interviews during **crisis management**, it is **advisable to contact the spokesperson of the scientific advisory committee or the scientific staff authorised** by the emergency committee. **Interviews concerning the volcanic phenomenon**, i.e., the geological process itself, should only be conducted by **scientific personnel with expertise in volcanology**, able to convey the information clearly and based on scientific evidence.

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During the **quiet period** prior to the volcanic crisis, it is advisable for the media to develop an **editorial coverage plan**, determining what type of information their audience needs and how it will be communicated effectively.

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Training of journalists and editors is crucial **to ensure that they understand the processes that occur during a volcanic eruption** and the scientific terms used to describe them, so as to ensure that they can report responsibly on the potential hazards and expected impact.

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It is recommended to always show **sympathy and respect towards the population affected by the volcanic crisis**.

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Even if the eruption has ended, the volcanic crisis may continue for a long period of time, so it is very important to **continue to provide up-to-date information on hazard zones** (e.g., outgassing areas), recovery efforts and cooperative efforts.

For society:

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It is essential to always refer to **official sources of information prior to a volcanic crisis, during an emergency situation and in the recovery phase.**

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During the quiet pre-volcanic crisis period, it is essential to **know the territory, preserve biodiversity and inform oneself about the** direct and indirect **volcanic hazards** to which one may be exposed and what protective measures should be taken.

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Prior to a volcanic crisis, it is essential to **familiarise yourself with the emergency plan** established by the authorities, **evacuation routes** and **meeting points**, as well as to **be aware of the** declared **volcanic activity alert level**. It is also important to follow the instructions in the **Civil Protection guide to prepare the necessary items** for a possible emergency. In addition, plan how to protect and evacuate pets and livestock.

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Once the eruption has started, stay calm, do not approach the volcano, respect the exclusion zone imposed and pay attention to the instructions of the authorities. In case of ash emission, protect the respiratory tract with a mask, even in remote areas, if particles are observed in the air. This, along with other health recommendations, can be found in the Citizen's information guide on volcanic risk of the Directorate General for Civil Protection and Emergencies.

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Citizen input is of great importance to enable scientific staff to consider the questions and concerns of those living in volcanic areas and to improve communication about volcanic risk. In this respect, the **creation of citizen committees** to address these concerns is very useful.

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List of Centres

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CENTRE	WEB PAGE	E-MAIL
Geociencias Barcelona (GEO3BCN, CSIC)	www.geo3bcn.csic.es/	direccion.geo3bcn@csic.es
Instituto Geológico y Minero de España (IGME, CSIC)	www.igme.es	sec.dg@igme.es
Instituto Español de Oceanografía (IEO, CSIC)	www.ieo.es	webmaster@ieo.csic.es
Instituto Andaluz de Ciencias de la Tierra (IACT, CSIC-UGR)	www.iact.csic.es/	direccion.iact@csic.es
Instituto de Geociencias (IGEO, CSIC-UCM)	www.igeo.ucm-csic.es/	direccion.igeo@csic.es
Instituto de Diagnóstico Ambiental y Estudios del Agua (IDAEA, CSIC)	www.idaea.csic.es/	direccion.idaea@csic.es
Instituto de Productos Naturales y Agrobiología (IPNA, CSIC)	www.ipna.csic.es/	direccion.ipna@csic.es
Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS, CSIC)	www.irnas.csic.es/	direccion.irnas@csic.es
Instituto Mediterráneo de Estudios Avanzados (IMEDEA, CSIC-UIB)	www.imedeaiuib-csic.es/	direccion.imedeaiuib@csic.es
Instituto de Ciencias Marinas de Andalucía (ICMAN, CSIC)	www.icman.csic.es/	direccion.icman@csic.es

five



Further Information



United Nations Office for Disaster Risk Reduction (UNODRR)



International Association of Volcanology and Chemistry of the Earth's Interior



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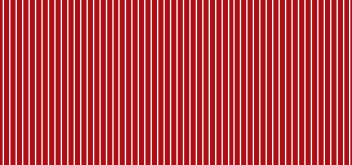
Volcanoes and the Environment. Online ISBN: 9780511614767



Civil Protection Code of 21 July 2023, § 11 and § 12, Official State Gazette.



National Geographic Institute (IGN)



Science for Public Policy



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