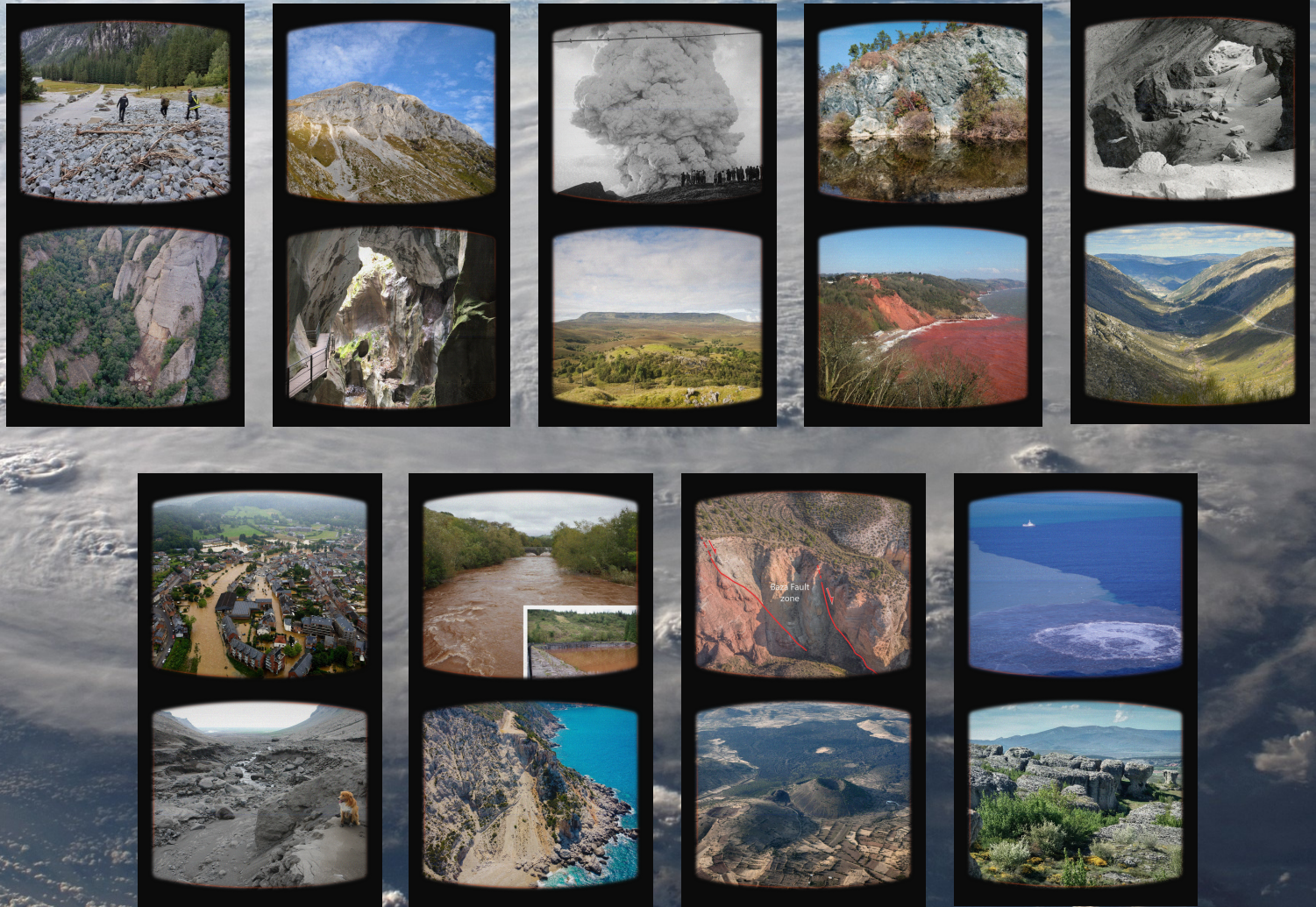


Geohazards in European Geoparks



GEOHAZARDS IN EUROPEAN GEOPARKS

Editors

Xavier MIR PELLICER
Ahmet Serdar AYTAÇ
Alessia AMORFINI
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Prefaces

Foreword by Kula-Salihli Geopark president

Dear Readers,

It is with great pleasure that we introduce to you the book "Geohazards in European Geoparks." This comprehensive work aims to shed light on the geohazard landscape of Europe, focusing on the geohazards in geoparks, as well as educational and dissemination initiatives and activities related to geohazards.

Geohazards pose significant challenges to society worldwide, and Europe is no exception. From seismic events and volcanic eruptions to landslides and coastal erosion, the continent has witnessed the destructive power of nature's forces. Understanding these geohazards, their causes, and their potential impact is crucial for effective preparedness, mitigation, and response.

This book delves into the geohazard situation in geoparks across Europe, where the unique geological features meet efforts to raise awareness, educate, and disseminate knowledge about these. Geoparks serve as living laboratories, providing a platform for scientific research, conservation, and sustainable development. By exploring the experiences and practices within geoparks, this book showcases the valuable work carried out in addressing geohazards and fostering public understanding.

Furthermore, the book emphasizes the importance of education and dissemination activities in geohazard management. It presents case studies, best practices, and innovative approaches to education and outreach, highlighting the efforts to engage various stakeholders, including local communities, schools, tourists, and policymakers. By empowering individuals with knowledge and promoting a culture of resilience, these initiatives contribute to building more prepared and informed communities.

The contributors to this book are experts in their respective fields, including Earth scientists, educators, and practitioners. Their diverse perspectives and experiences enrich the content, providing a multidimensional view of geohazards and the strategies to address them. The book encompasses a wide range of topics, from geological and geotechnical aspects to risk assessment, communication strategies, and the integration of geohazard education into formal and informal learning environments.

I would like to express my gratitude to all the authors and contributors who have dedicated their time and expertise to this book. Their collective efforts have resulted in a comprehensive resource that will serve as a reference for researchers, educators, policymakers, and anyone interested in geohazard management and geoparks.

Finally, we extend our sincere appreciation to the readers who embark on this journey through the pages of "Geohazards in European Geoparks". May this book inspire further collaborations, spark new ideas, and contribute to the advancement of geohazard awareness, education, and preparedness in Europe and beyond.

Yours sincerely,

Cengiz Ergün
Mayor of Geopark Municipalities Union (Mayor of Manisa Metropolitan Municipality)

Foreword by the European Geoparks Network

Humanity is an integral part of nature. Our way of living, our daily choices and our future plans are influenced by the world around us. Immersed in our immediate human timescale, we often underestimate of the power of the Earth. We easily forg

et that our landscapes were forged over millions of years, and yet that they can change dramatically in just minutes.

The European Network of UNESCO Global Geoparks (UGGps) brings together exceptional territories that are skilled in conserving, sharing and educating inhabitants and visitors about Earth heritage. Spanning from the Arctic Circle to the shores of Africa, from the heart of the Atlantic Ocean and deep into the Eurasian continent, these regions present incredible climatic and geographic diversity. Each area has its own character and its own relationship with nature. This includes the natural hazards that cannot be prevented, such as earthquakes, floods and mass movements.

European UGGps' work in partnership with geological surveys and universities, government agencies, education authorities and other partners to understand, inform and anticipate geohazards. They play a crucial role in helping the public and decision makers prepare and plan for these events, and thus reduce the risk.

This book brings together for the first time an important collection of articles about geohazards from the four corners of Europe. The European Geoparks Network draws its strength from our ability to cooperate, share and learn from each other, of which this collective work is a perfect example. The incredible territorial diversity is reflected through the different approaches used in each UNESCO Global Geoparks to proactively manage emerging and existing risks and communicate about geohazards.

At the heart of sustainable development is the need to better understand and manage natural hazards. The many examples presented in this book confirm yet another way in which UNESCO Global Geoparks actively contribute Sustainable Development Goals (SDGs) of the 2030 Agenda. Some are direct examples related to risk informed climate action (SDG 13) or conservation to tackle land degradation, erosion, and flooding (SDG 15). Others provide inclusive educational opportunities to learn about reducing risks from all hazards (SDG 4).

We live in an uncertain world. Here, European UNESCO Global Geoparks share their knowledge and expertise of geohazards to contribute to a stronger management, adaptation, and resilience around the risks we collectively face.

Sophie Justice and Charalampos Fassoulas
EGN Coordinators
19th December 2023

Foreword by the Global Geoparks Network

The Global Geoparks Network (GGN), established in 2004, represents today a dynamic growing network of excellence. The GGN includes 195 UNESCO Global Geoparks in 48 countries. It is a not-for-profit organization where members are committed to working together, exchange ideas of best practice, and promote conservation, management, and communication of the Earth heritage.

Since 2015 the GGN has worked closely with UNESCO for the development and operation of the UNESCO Global Geoparks Programme. The GGN is supporting UNESCO Global Geopark activities, collaboration, and networking to protect geological heritage and promote local sustainable development.

The GGN includes 5 continental Geopark networks, among them the European Geoparks Network (EGN) with 98 UNESCO Global Geoparks.

UNESCO Global Geoparks promote awareness on geological hazards, including earthquakes, volcanic eruptions, tsunamis, landslides, floods, and other natural disasters. All of them have a direct impact on human communities, as well as on natural and cultural heritage. Geo-hazards can seriously damage or even completely destroy communities, natural monuments, historical and archaeological sites or cultural landscapes. In addition to the endangerment of people who live in or visit Geoparks, the degradation of natural and cultural heritage has a negative socioeconomic impact on local communities and involves a loss of identity-generating values and of cultural diversity.

Climate change, which lies behind the rising frequency and intensity of some natural disasters, is exposing Geoparks to new threats where few used to exist and increasing the vulnerability of areas already at risk.

Many UNESCO Global Geoparks provide information on the sources of geological hazards through educational activities for the local people and visitors, as well as, ways to reduce their impact such as disaster response strategies. These efforts build important capacity and contribute to building more resilient communities that have the knowledge and skills to effectively respond to potential geological hazards.

GGN and EGN working groups on geo-hazards coordinate common activities and help prepare disaster mitigation strategies among Geoparks.

This publication of the Working Group of Geohazards of the European Geoparks Network is an excellent tool to communicate geoscientific knowledge, to interpret geo-hazard related geological features and landscapes for the general public and to raise awareness against geo-disasters by promoting geo-hazard risk and disaster resilience based on the experience of the UNESCO Global Geoparks in Europe.

It is also a significant contribution to the exchange of know-how and experiences on geo-hazards risk reduction among UNESCO Global Geoparks at the global level.

Prof. NICKOLAS ZOUROS
Department of Geography, University of the Aegean
Lesvos Island UNESCO Global Geopark
President of the Global Geoparks Network

Foreword by the UNESCO Earth Sciences and Geoparks section

Geohazards, including earthquakes, landslides, volcanic eruptions, tsunamis, and floods, are inherent features of the Earth's dynamic systems. Their impact is wide, impacting human lives, infrastructure, and the environment, and yet their potential devastating impacts can be mitigated through a combination of scientific research, technological innovation, community engagement, and international cooperation. UNESCO has been at the forefront of global initiatives, recognising the imperative need to comprehend these hazards and pool our expertise on the global level.

One of UNESCO's primary mandates is to foster the advancement of knowledge and science for the benefit of humanity. In the realm of geohazards, this commitment translates into supporting cutting-edge research initiatives that deepen our understanding of the underlying processes and mechanisms triggering such events. UNESCO's International Geoscience Programme (IGCP) has been instrumental in uniting Earth scientists worldwide for crucial research initiatives since its creation in 1972, in partnership with the International Union of Geological Sciences (IUGS). This programme aims to equip communities with resilience, preparedness, and adaptive capacity in confronting challenges including geohazards, such as through establishing early-warning systems and monitoring mechanisms for volcanic eruptions and tsunamis.

With the addition of the UNESCO Global Geoparks, UNESCO now has the privilege of connecting with an ever-expanding network of breathtaking 'living laboratories', committed to safeguarding the geological, natural and cultural heritage of our home planet. These geoparks, characterised by their captivating topographies, cultural richness, and varied climates, tell the story of Planet Earth's 4,600 million-year history. Embracing a forward-thinking approach, they work to sustain these invaluable sites for future generations. With the Global Geoparks Network (GGN), and its regional bodies like the European Geoparks Network (EGN), UNESCO continues to promote the concept and train experts worldwide to expand and reinforce the network.

In the face of the paramount modern challenge – climate change – geoparks emerge as pivotal players in steering societies towards sustainability. Embedded within natural landscapes and human cultures, they are crucial entities in a collective effort towards a sustainable future. Many UNESCO Global Geoparks promote awareness of geological hazards and their sources, and educate on disaster-mitigation strategies among local communities and for visitors.

UNESCO commends the authors of this book for bringing together different initiatives and good practices that can inspire others to further cooperation, in the true spirit of UNESCO and the Global Geoparks.

Kristof Vandenberghe
Chief Earth Sciences and Geoparks
UNESCO

Foreword by the book editors

The intent of sharing experiences and promoting best practices on educational activities regarding dangerous natural phenomena is why the working group of the European Geoparks Network on Geohazards decided to publish the volume you are currently holding. This work represents years and years of research, study, and other educational activities that its members have perfected while working in their respective Geoparks.

Most UNESCO Global Geoparks are located in vastly diverse geographical settings and are often subject to natural hazards and weather events which have become more extreme by the years.

In addition, the past decade climate change has affected both geological and hydro-meteorological hazards in terms of intensity and occurrence.

For all these reasons, collecting and promoting best practices for the communication of and education on disaster risk reduction is a decisive factor for the territories embraced by UNESCO Global Geoparks. Moreover, as the intensity of climate change heightens, these territories are already becoming beacons of innovation and best practices on these topics for the whole planet Earth.

The body of this book provides comprehensive and concise information about the geohazards in European Geoparks, reinforcing the image of these territories as natural laboratories showcasing a wide representation of geohazards.

The main effort has been to disseminate concepts that are not simple for a non-expert audience, using understandable language without ever neglecting the scientific correctness of the contents conveyed.

Educational activities and projects serve to raise awareness on the potential impact of climate change and geohazards. They also provide local communities with the knowledge needed to effectively mitigate and adapt to the potential effects of climate change.

Considering that it is a pre-requisite that the UNESCO Global Geoparks develop and operate educational activities for all ages to spread awareness of our geological heritage, it becomes of paramount importance to reinforce the image of European Geoparks as an essential intermediary to better understand geohazards and to contribute to educating and preparing people when these events occur.

Therefore, we hope this volume will become an educational tool not only for the students, but also facilitate all the Geopark actors in the pursuit of building more and more disaster-resilient communities through activities and programmes that engage locals and tourists alike by raising their awareness about natural hazards, the associated risks, and the possible ways to reduce their impact.

The editors

Geohazards in Europe, a brief introduction

Ahmet Serdar Aytaç, Kula Salihli UNESCO Global Geopark

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Geohazards and their impact

In the early twenty-first century, the Earth supports an increasing human population – generally – healthier and wealthier than ever before and there is a very big awareness of risks faced by people and nature (Smith and Petley, 2008). Despite this increasing awareness and the developing technologies, people are more exposed to hazards than ever before. This is because of various conditioning factors, these are: population growth, land use pressure, urbanisation, social inequality, climate change, political change, economic growth, technical innovation, social expectations, and global interdependence (Smith and Petley, 2008). However, fighting disasters and reducing the risks associated with those is undoubtedly possible by increasing knowledge and awareness about potential hazards. In this context, a brief introduction to the different forms of geohazards and their main characteristics is given below.

A hazard is a potentially damaging event, phenomenon, situation, or human activity that may have a negative impact on cultural, economic, environmental, institutional, physical, or social assets (Nadim, 2013). These events are referred to as disasters when they cause loss of life and major damage to property and infrastructure. Geohazard is a term related to natural hazards. Geohazard are potentially dangerous geological, geomorphological, or environmental processes, phenomena or settings that threaten human life, health, property, or the environment (Komac and Zorn, 2013). Although there is an open discussion on the definition and classification of geohazards by academics, this definition is reasonably inclusive.

There are different types of geohazards associated with natural and artificial processes triggering them that have the potential to challenge the normal development of human communities and threaten the safety and well-being of society (Culshaw 2018). These may affect most parts of the world, from coastal areas to glacial landscapes, and from mountain ranges to fertile plains and cities.

Geohazards can occur suddenly or take long periods of time to develop (hundreds or thousands of years) to reach the point when they pose a danger. From this perspective, geohazards can be categorised into two groups. Sudden phenomena comprehend earthquakes, volcanic eruptions, landslides, rockfalls, mudflows, tsunamis, collapses associated with sinkhole formation, avalanches, or forest fires. Slow phenomena include gradual or gentle movements, such as, ground subsidence, erosion, geochemical contamination, soil salinization or groundwater pollution.

Geohazards can also be categorised by the processes that trigger them or the properties of potentially hazardous materials. Broadly, geoscientists have grouped them as geological, geomorphological, geotechnical, hydrological or hydrogeological, climatic, marine and artificial geohazards (Culshaw, 2018).

Geological hazards are directly or indirectly associated with earthquakes and volcanism. These include earthquakes, earthquake storms, surface rupture, subsidence, collapses, liquefaction, tsunamis, volcanic eruptions, lava flows, lahars, debris flows, tephra falls, jökulhlaups and avalanches.

Geomorphological hazards occur at or near the surface, are conditioned by high slope gradients, weathering processes (physical, chemical) or freezing and thawing processes among others, and can be triggered by extreme rainfall events or other geological-climatic factors. The most common are mass movements including landslides, rock falls or avalanches; collapses associated to sinkhole formation in karstic landscapes; bedrock and soil erosion; or drifting dunes associated to aeolian processes.

Hydrological or hydrogeological hazard are linked with surface water dynamics, especially with fluvial systems, as well as to groundwater response to changing geomorphological and climatological conditions. These include floods, flash floods, sheet floods or mudflows triggered by extreme rainfall episodes or sudden groundwater piezometric level changes.

Geotechnical hazards are generally associated with chemical or mineralogical properties of the soil. The most common ones are soil acidification, alkalization, and salinization.

Marine hazards are related to seafloor and coastal dynamics and encompass the generation of submarine turbidity currents; coastal erosion processes strongly related to storm surges; or tsunamis involving massive waves that may be triggered by earthquakes, volcanic activity or massive coastal or underwater mass movement events.

Anthropogenic geohazards generally relate to poorly managed mining or landfill activities that may give way to ground subsidence and collapse and soil, groundwater and surface water acidification and contamination.

Climatic hazards are strongly related to global warming and involve drought episodes triggering wetlands desiccation, large scale wildfires or extreme rainfall episodes prompting flooding events. Long term drought periods or extreme rainfall events may give way to changes in the geomorphological setting and wildfires may provide the context for increasing erosion rates. Furthermore, some areas of the Earth are highly exposed to highly hazardous events such as hurricanes, tornados, or typhoons.

However, geological processes are only considered as geohazards when these have the potential to damage infrastructure or cause loss of property or life. Among the most common and destructive geohazards at a global level we find earthquakes, volcanic eruptions, mass movements and flooding events. See a brief description below:

Earthquakes

Earthquakes consist of the shaking of the Earth's surface caused by seismic waves from sudden energy release in the inner Earth's crust (Qi, 2018). Earthquake magnitude is measured using the Richter or the moment magnitude scale, the latter abbreviated as Mw. The moment magnitude scale uses a logarithmic scale from 1 to 10. This means that for each whole number going up in the scale, amplitude of the wave recorded by the seismograph goes up ten times. It is measure from slightly felt (0 – 2.5), to great earthquakes (> 8) that can completely destroy areas near its epicenter.

Most earthquakes are of tectonic origin and are located at the borders between tectonic plates where strong seismic processes operate. However, these hazards may also be caused by man-made explosions, volcanic events, karstic subsidence, landslides or mining activities. Furthermore, many natural hazards, such as landslides or tsunamis and their subsequent devastating consequences are often related to earthquake activity (Guthrie, 2013).

Earthquakes are the natural disasters that cause the greatest loss of life and property worldwide. The utmost losses of life and infrastructure are found

whenever there is a combination of intense energy release along the epicentre of the earthquake with high levels of human activity (Smith and Petley, 2008). This combination exists where high magnitude earthquakes occur in densely populated areas in combination with poorly constructed infrastructure and buildings (Smith and Petley, 2008).

When earthquakes coincide with densely populated productive agricultural areas they often cause serious loss of life and property. In the last 20 years, major earthquakes around the planet have led to both human and material losses. The recent most devastating earthquake events with the highest casualty rates are presented below:

The 2003 Iran earthquake (Magnitude 6.6) resulted in 30,000 casualties.

The 2004 Indonesia earthquake (Magnitude 9.2) resulted 228,000 casualties.

The 2005 Pakistan earthquake (Magnitude 7.6) resulted in 87,000 casualties.

The 2008 China earthquake (Magnitude 7.9) resulted 87,500 casualties.

The 2010 Haiti earthquake (Magnitude 7.0) resulted in 160,000 casualties.

The 2023 Morocco earthquake (Magnitude 6.8) resulted in 2,960 casualties.

In February 2023, an earthquake in Türkiye and Syria (Magnitude 7.6 and 7.7) resulted in the loss of 55,000 lives. The picture below illustrates the intensity and magnitude of the earthquake in Türkiye.

Earthquake magnitude and intensity are distinct measures that illustrate different aspects of seismic events. Magnitude aims to quantify the energy released at the earthquake's source, gauging its size on the Richter or moment magnitude



Fig. 1: Hatay city centre (Türkiye) following the February 6th 2023 earthquake in Türkiye and Syria (Photo by evrensel.net)

scale. It provides a numerical value reflecting the seismic waves' amplitude and duration. In contrast, intensity, measured by the Modified Mercalli Intensity (MMI) scale, characterizes the earthquake's effects at specific locations and assesses the damage faced by human structures and the Earth's surface. While magnitude offers a standardized measure of the earthquake energy release, intensity focuses on the evaluation of its impact on the environment and human structures.

Volcanism

Volcanism is the phenomenon of the extrusion of molten rock (magma), gas, and ash from within the Earth's crust to the land surface. Volcanoes may erupt explosively, effusively, as flows, or as clouds of superheated or poisonous gases; all the eruption styles can pose a threat to humans (Guthrie, 2013).

Volcanic eruptions can present a wide range of hazards to human life and property and the wider environment. Volcanic hazards comprehend lava flows, pyroclastic falls, release of ash to the atmosphere, pyroclastic density currents, lahars, volcanic gases, and Jökulhlaups (subglacial flood). Some effects are direct, such as the destruction of property by lava flows or death caused by being overrun by a pyroclastic density current. Other are indirect consequences, such as food shortage due to the destruction of agricultural areas or changes in the climatic conditions caused by volcanic activity (Partfit and Wilson, 2008).



Fig.2. Volcanic activity of Capelinhos volcano, close to Faial island. Starting in september 1957, lasted for 13 months (Photo by Fundo Tenente Coronel José Agostinho)

Volcanic regions are often productive farming areas and therefore these are densely populated. For this reason, although rare, volcanic disasters have caused serious loss of life and property. Some examples are the 1985 Nevado del Ruiz eruption in Colombia with 21800 casualties, the 1986 limnic eruption at Lake Nyos in Cameroon with 1746 people death or the 1982 Santa Maria eruption in Guatemala with 6000 people that lost their lives (Guthrie, 2013).

Mass movements

Mass movements are a major cause of movement of rock and soil downslope and are often described as mass wasting events. They are one of the most obvious geological hazards in all parts of the world. They attract public

attention as they cause significant infrastructure damage and many fatalities each year, especially in developing countries and, can also be a major agent of change in the landscape. In coastal areas, landslides are the major control of the landscape and the processes of coastal erosion.

Climate change and especially the impact of increased water vapour content in a warmer atmosphere, and the resulting heavier rainfall events, is having a major impact on landslide stability. In mountainous areas, where permafrost is present, the current rise in global temperature is creating further instability as the ice melts, freeing up more material to move downslope.

There have been numerous attempts at the classification of landslides. Most engineering geologists use the terminology of Cruden and Varnes (1996) and the more recent summary by Hungr et al. (2014). Likewise, the classification system produced by United States Geological Survey (USGS) is commonly used. The most common landslide types described in these classification systems are presented below.

Rotational landslides present a curved slip surface or spoon-shaped. The location of such landslides is often in heterolithic successions where there is a mixture of porous/permeable and non-porous/impermeable sediments. Some very good examples are recorded along cliff dominated coastal areas, such as the one in South England, west Greece or on the main mountainous regions of Continental Europe, such as the Pyrenees, the Alps or the Dolomites.

Flows are the downward movement of material that is behaving as a fluid. They are most often described as mud or debris flows and are occasionally superficial features associated with larger mass movement structures. There is a clear relationship between large rotational landslides, increasing groundwater levels and mudflows.

Long run-out landslides involve a mass of material that travels an extended distance from source; a much greater distance than would be expected from the vertical height involved. One of the best examples is the West Salt Creek landslide (Colorado, USA) which occurred in 2014. It is estimated that 30 million m³ of rock was involved and the runout extended 4.5 km from the point of failure. Some suggested mechanisms involve the displaced material sliding (or flowing) over a layer of water or air which acts as a lubricant.



Fig.3. Landslide in the Dorset and East Devon UNESCO World Heritage Site to the east of Seatown. This occurred in February 2023 and is part of the instability recorded in the wet winter of 2022/2023 (Source Jurassic Coast Trust).

Rock falls are the sudden movement of geological materials, such as rocks and boulders, that become detached from steep slopes or, particularly, cliffs. Separation normally occurs along fractures, joints and bedding surfaces, and the

movement occurs by free-fall, as well as bouncing and rolling of the debris. Falls are controlled by gravity, mechanical weathering, and the presence of increased ground water pressure. In mountainous areas, loss of permafrost, due to climate change, can be a contributing factor.

Topples are a forward rotational movement away from a cliff caused by gravity when the forces holding the cliff in place are broken. Failure is often caused by increased groundwater pressure causing part of the succession to lose strength.

Some landslides are well preserved and have historical significance to local communities, and they can become a tourist destination. A nice example of this is the case of the Visitor Centre adjacent to the Frank Slide in Canada, which in 1903 buried the town of Frank as well as roads and the railway. Also, in South Devon the 1759 Hooken Landslide provides a wonderful view for tourists visiting the area.

Flooding

A flood is defined as a water overflow that submerges lands outside its regular space, which can be a riverbed, a lake or the sea. These are classified according to the style of the flood and the area where they occur as areal (sheetflood), river flooding, coastal floods, and urban floods.

Floods can be prompted by extreme rainfall events, snowmelt, tidal and storm surges, natural and man-made dam and dike creation and or breaching, and subglacial (jökulhlaups) and glacial lake outbursts (Guthrie, 2013).

Floods are one of the most widespread hazards and, at some stage, have affected nearly every country. The flood plains around riverbeds generally are highly populated fertile agricultural areas. This context has conditioned loss of life and property during flooding events since the earliest periods of history. Damage by flooding events in rural areas generally affects agricultural land and infrastructure. On the other hand, floods in cities can result in serious damage to households, workplaces, urban infrastructures and human casualties.



Fig.4: Flooding on 15 July 2021 showing the town of Rochefort and the meander of the Lomme largely invaded by water as the river covers the entire floodplain (Photo by Ben Art shortly after the maximum flood level)

European Geoparks Network



Digital elevation model of <https://data.noaa.gov/onestop/> - WGS84



0 500 1 000 km

- Geoparks in this book
- Other EGN members

Map of the European Geoparks Network

- | | | |
|---------------------------|---------------------------|----------------------------------|
| 1 Adamello Brenta UGGp | 14 Fforest Fawr UGGp | 27 Saimaa UGGp |
| 2 Apuan Alps UGGp | 15 Granada UGGp | 28 Sierras Subbéticas UGGp |
| 3 Azores UGGp | 16 Katla UGGp | 29 Sitia UGGp |
| 4 Beigua UGGp | 17 Kefalonia-Ithaca UGGp | 30a Karawanken-Karavanke UGGp |
| 5 Black Country UGGp | 18 Kula-Salihli UGGp | 30b Ore of the Alps UGGp |
| 6 Catalunya Central UGGp | 19 Las Loras UGGp | 30c Steirische Eisenwurzten UGGp |
| 7 Chablais UGGp | 20 Lesvos Island UGGp | 31 Swabian Alb UGGp |
| 8 Courel Mountains UGGp | 21 Maestrazgo UGGp | 32 TERRA.vita UGGp |
| 9 Cuilcagh Lakelands UGGp | 22 Massif des Bauges UGGp | 33 Tuscan Mining UGGp |
| 10 El Hierro UGGp | 23 Orígens UGGp | 34 Vikos-Aoos UGGp |
| 11 English Riviera UGGp | 24 Pollino UGGp | 35 Villuercas-Ibores-Jara UGGp |
| 12 Estrela UGGp | 25 Psiloritis UGGp | 36 Vulkaneifel UGGp |
| 13 Famenne-Ardenne UGGp | 26 Rocca di Cerere UGGp | |

Geohazards: raising awareness in the Adamello Brenta UNESCO Global Geopark

William Bombarda, Vajolet Masè

Parco Naturale Adamello Brenta Geopark, Trentino, Italy

Geohazards description

The Adamello-Brenta Geopark is located in the Rhaetian Alps, the Italian sector of the central-southern Alps, in western Trentino, and represents a strategic area for understanding the geological history of this mountain range. The area is characterized by remarkable geodiversity thanks to the presence of two massifs, the Adamello and the Brenta, very different both from a geological and morphological point of view. The main geohazards of the Adamello-Brenta Geopark include mass movement events (mainly debris-flows and rockfalls) and snow avalanches.

Debris flow phenomena

Located in the Adamello mountain group, “Val di Genova” is one of the Glacial valleys which head area, in particular, better preserves some of the clearest morphological evidence related to the evolution of the Lobbia and Mandrone glaciers, the two main glacial masses of the Geopark (Carton et al., 1996).

Another peculiar feature of the “Val di Genova” is the presence of numerous lateral hanging valleys. From these, given the presence of large amounts of debris, during summer storms, heavy rainfall peaks trigger mass movements, such as debris flows. These phenomena affect the valley floor, causing repeated damage to the main road system, to trails and trails' bridges and disrupting the entire transit inside the valley for days. The consequences of this geohazard are therefore multiple: starting from hikers' and visitors' safety to the economic damages resulting from the closure of the valley during the tourism peak season.

The side-valleys responsible for most events are those of Gabbioolo, Cercen and Dosson. They are located on the orographic left side of the upper Val Genova. These run from about 1.500 m of the valley floor to peaks approaching 3.500 m.

Due to the presence of countless waterfalls and water features, “Val di Genova” is one of the main attractions of the Geopark, welcoming up to more than 70.000 visitors and more than 20.000 vehicles during summertime.

However, the frequency with which debris flow phenomena affect the valley floor in recent years has increased, making it one of the main sources of danger for people visiting the valley. During the summer of 2023 two important debris flow events were recorded causing interruption of access to the upper valley for several days. It is therefore very important to create awareness about the phenomena, making visitors cautious while traveling through the area on days with highly variable weather. (Figure 1).

Fig.1: Deposition zone on the Val di Genova road – July 2023 (Photo PNAB Archive)



Rockfalls

Another major problem in the Geopark area is associated to rockfalls. The weathering of rock outcrops, linked to frost (freeze and thaw cycles), conditioned by the high temperature range during seasons, is thought to be one of the most common causes of the rock's detachments. The last decade of recorded data by the Capanna Presena weather station located at 2.715 m altitude, near the northwestern border of the Geopark, recorded values ranging from -25,4°C to +20,5°C (Data MeteoTrentino).

Rockfalls are more common in areas dominated by bedrock of the Brenta Dolomites Group, due to the more fragile nature. In fact, there are many historic rockfall events, such as the crash of the Jandl tower in 1957, which missed by a few meters the Agostini refuge hut, and now stands partly as a giant rock right next to the very refuge (Figure 2). Rockfalls are less common in the Adamello-Presanella Mountain Group, mostly because of a bedrock characterized by the presence of tonalite giving a very different geological setting.



Fig.2: The Agostini Refuge in the Brenta Dolomites with the block of rock collapsed from the Jandl Tower in 1957 (photo Rifugio Agostini)

Snow avalanches

Another phenomenon that widely affects the Adamello Brenta Geopark area are snow avalanches. Thousands of ski mountaineers and hikers frequent the slopes and mountains of the Geopark in winter. The ski mountaineering season, especially in the Adamello Mountain Group, is particularly long, from October/November to June. In addition to representing a source of danger for ski mountaineers, avalanches can also affect roads. Therefore, the roads in the Geopark valleys affected by these events are closed to traffic in winter. Their reopening depends on the amount of snow accumulated on the sides of the valleys, which can delay the beginning of the tourist season. In exceptional cases, avalanches can also affect the main road system and impact homes and shelters (Figure 3).

Snow avalanches, also from a historical point of view, have played an important role on the territories of the current Geopark. During the "White War 1914-18", in fact, there were hundreds of victims, soldiers, overwhelmed by avalanches in particularly harsh and snowy winters (Cozzini R., 2018)



Fig.3: Powder avalanche from Cima Brenta (Brenta Dolomites - photo PNAB Archive)

Geohazards education and dissemination

The main activity that the Adamello Brenta Geopark carries out in the educational field about geohazards is linked to the geomorphology project for first-order secondary schools. One of the objectives of the geomorphology project is to recognize the landforms and the processes that generate them. This, in fact, allows to increase awareness of the dynamism of the mountain environment and its intrinsic danger. Recognizing in advance and avoiding being in a potentially dangerous situation can make a difference.

As an example, during an excursion in one of the valleys of the Geopark, students cross avalanche channels, landslides and debris flows. Process observation, analysis and interpretation are carried out. Good habits to be applied in dangerous situations such as strong summer storms in the mountains are also illustrated and discussed to reduce the risk. Among these, for example, some can be remarked, as the preparation of the excursion with a careful reading of the weather forecasts and the use of nowcasting tools (such as the weather radar and its interpretation) and as well as the practicability of the paths according to seasonality and snow conditions.

The hydraulic risk is also discussed, through a role-playing game. Students will have to manage flood risk through three scenarios: protect themselves with structural works, restore space to nature, respond to emergencies. In each of these activities, the goal is to make students aware that natural hazards have always been present.

Nowadays, due to climate change, massive urbanization and overbuilding, together with the increased mountains frequentation, the number of people exposed to these risks have grown exponentially. Therefore, knowledge, information and preventive actions need also to grow.

Floods and earthquakes in the Apuan Alps UNESCO Global Geopark (Italy): from the scientific knowledge to the awareness for local communities

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Introduction

The geological and geomorphological features of the Apuan Alps UNESCO Global Geopark subject the territory to natural hazards, its primary threats consisting of seismic and hydrogeological hazards. In particular, the northern and eastern areas of the Geopark, namely Lunigiana and Garfagnana respectively, correspond to active seismic zones. Since the fifteenth century, the seismicity has been recorded by historical sources with several main earthquakes of estimated magnitude (M_w) equal to or greater than 5.0. With regards to the hydrological hazard in the Geopark, flooding occurs sporadically and with great violence. The chronicles of the past almost always follow the same trend: a few hours of very intense rain results in surface water carrying debris flow and uprooted trees as the rivers swell beyond measure and destroy any obstacle in their race to the sea.

The flood on 19th June 1996

On the day of 19th June 1996, a self-healing storm (also called V-shaped storm) occurred in the Geopark area, probably representing the first severe meteorological event connected with the ongoing global warming in Italy (Rapetti & Rapetti, 1996). It lasted only a few hours, but the rainfall was extremely heavy with more than 450 mm of rain in about six hours over a small area of 60 km².

Destructive flood waves descended from the central-southern Apuan Alps, along the valleys of Versilia and the Turrone di Galliciano respectively, to the west and east of the mountain range. These flood waves were the downstream effect of the landslides that had occurred upstream during the heavy storm: a fluid saturated with rock and plant debris torn away from the mountain slopes and channelled into the waterways by the landslides. More than 640 debris-flows occurred, resulting in an impressive solid transport of the rivers that determined the main devastating consequences.

The outcome of the flood was mostly debris flow and secondarily debris avalanches, talus sliding and rockfall in addition to linear erosion processes activated along the streams. Overall, the landslides and the rains mobilised more than 4,300,000 m³ of debris. The complex geological structure, characterized by the contact between a sedimentary rock succession superimposed on a metamorphic rock succession, has strongly influenced the gravitational processes. It should be noted that most of the landslides activated during the 1996 flood affected the outcropping areas of the metasandstones, dating back to the Paleogene and Neogene periods. The flood led to 14 fatalities, damaged about 600 houses, public infrastructure and private properties, and generated economic damage.

Fig.1: Mt Pania – debris flows mobilised by the 1996 flood (photo by Giuseppe Ottria)



The 1996 flood offered the opportunity to measure and evaluate several geological, geomorphological and land use factors, which played a considerable role in landslide triggering during exceptional rainstorms. In particular, we identified eight different hazard factors (bedrock permeability and layering, slope inclination and shape, drainage density, soil thickness, vegetation type and wood management), which allowed us to define effective rules on soil conservation and water and agro-forestry management in our Geopark planning tools (Ente Parco regionale delle Alpi Apuane-Apuan Alps UNESCO Global Geopark, 2016).

The earthquake on 7th September 1920

Garfagnana and Lunigiana are two large morphological depressions stretched in a NW-SE direction for about 70 km, delimited by a complex system of faults which has controlled - and still controls - their evolution. These faults cross and cut through the entire stacking of tectonic units, from the surface to the deepest levels. It is the activity of these faults that has produced the strong earthquakes still affecting these seismically active territories.

On 7th September 1920, a strong earthquake struck an area of over 1,000 square kilometres; it is considered the strongest seismic event in the entire Northern Apennine and so powerful as to be recorded worldwide. Based on the instrumental recordings of the time and the distribution of macroseismic effects, it is estimated that the earthquake reached a magnitude $M_w=6.5$, similar to that of the earthquake of 30th October 2016 in central Italy (Norcia). The distribution of intensities has been well reconstructed on a large number of sources of different types (press reports, photographs, technical reports, etc.).

The region with the most destruction extended from the Fivizzano area in Lunigiana, to the area of Villa Collemandina in Upper Garfagnana, where the effects reached or exceeded the IX-X degree on the Mercalli scale in more than 70 villages.

Overall, the earthquake caused the death of more than 200 people and injured another 650, as well as the displacement of several thousand people. The number of victims was relatively low when compared to the violence of the earthquake and the size of the area in which there were destructive effects and serious damage. This was primarily due to the fact that the main shock had been preceded the day before by the strong shock of 4:05 p.m.; it had been felt by everyone with fear and prompted many people to spend the night outdoors. Furthermore, when the main shock occurred on September 7th, 1920 at 7:55 a.m., many people were already working in the fields, since the economy of the area was mainly based on agriculture and livestock. In contrast, mainly the elderly, women and children remained in their houses.



Fig.2: Collapse of buildings in the area affected by the 1920 earthquake (photo by L'illustrazione italiana, 1920)

“Rains & Ruins” and “Rumble & Tremble” projects

The Geopark has been pursuing a holistic approach of conservation and protection against natural hazards to build more resilient communities and reinforce cooperation inside the Geoparks Network sharing good practices. In this framework, two main projects were promoted to educate the local communities about natural hazards, using the memory of past disasters.

The “Rains & Ruins” project, concerning the 1996 flood, includes an educational exhibition and its related catalogue (Bartelletti et al., 2017). The exhibition is composed of different sections focused on the event that occurred in 1996, with images and pictures highlighting the complex history of floods since the eighteenth century, in addition to contributions from other European Geoparks who faced similar events and promoted dedicated educational programmes (Bohemian Paradis, Chelmos-Vouraikos and Idrija UGGps). Thanks to this project, several lessons at primary and secondary schools have been developed, using a practical and interactive approach on ad-hoc analogue models to let the children simulate the multiple stages of a debris flow.

The “Rumble & Tremble” project commemorated the centenary of the 1920 earthquake with different educational activities and an exhibition detailing the destruction caused by the earthquake, where the visitor is taken on a journey through the events leading up to the disaster and its aftermath (Amorfini et al., 2020). The exhibition is enriched by educational panels allowing visitors to understand what an earthquake is, how and where it originates, how it propagates and how it is recorded and measured.

A special focus is dedicated to the geological structures producing the historical seismicity in Garfagnana and Lunigiana regions. Furthermore, the project encouraged strong involvement of partners from other Geoparks (Azores, Itoigawa, Mt. Apo and Muroto UGGps) with panels illustrating their educational tools and activities in the framework of disaster seismic risk reduction.

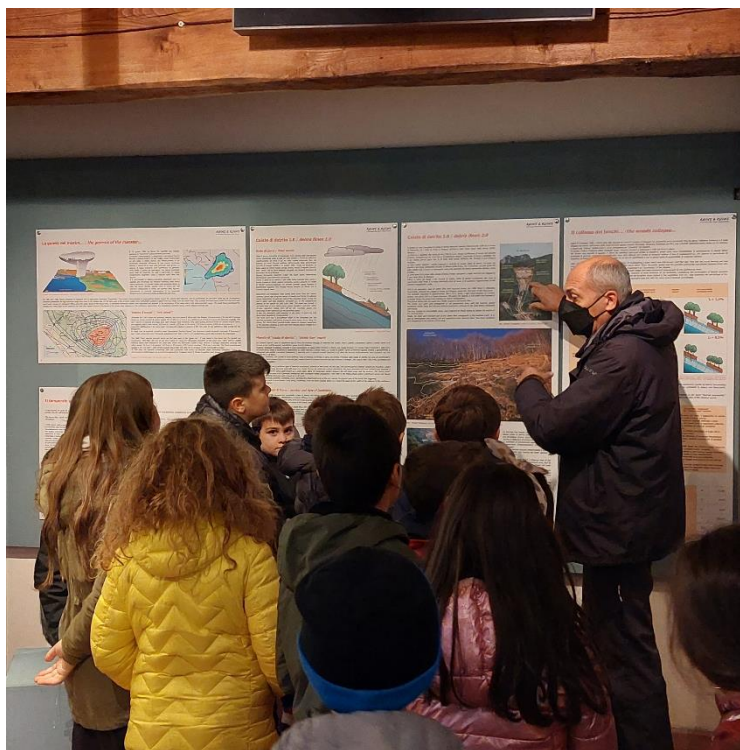


Fig.3: Guided tour at the “Rains & Ruins” exhibition (photo by Ilaria Rosani)

Geohazards in the Azores UNESCO Global Geopark

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Geohazards as expressions of geodiversity

Created in 2013, the Azores UNESCO Global Geopark comprises an area of about 12 884 Km², having as a limit the bathymetric line of 2000 m and includes nine inhabited islands, several islets and the surrounding marine area. Located in the North Atlantic Ocean, the azorean archipelago is of volcanic origin, associated with the complex geodynamic context of this area of the globe – the triple junction of Eurasia, Africa and North America's lithospheric plates (Laughton & Whitmarsh, 1974) and, according to some authors, with the presence of a hotspot. The oldest rocks dated in the archipelago were formed 6 million years ago and are in Sta. Maria Island (Ramalho et al., 2017). The youngest island is Pico, formed around 270 Ka ago (Chovelon, 1982).

The geographic location of the Azores islands, in the context of global atmospheric and oceanic circulation, conditions the archipelago's climate. Atmospheric circulation is controlled by the Azores Anticyclone, and its position, intensity, development, and orientation, influences the meteorological conditions experienced in the archipelago, and around the globe.

In the Azores islands there are currently identified 27 volcanic systems, 16 of them are polygenetic central volcanoes (most with subsidence calderas) and 11 basaltic volcanic ridges. Among these, nine polygenetic volcanoes and seven areas of fissural volcanism are considered active, although dormant. Manifestations of secondary volcanism are identified at Banco D. João de Castro (a submarine polygenetic volcano that erupted in 1720 and is located between the islands of São Miguel and Terceira), and in the islands of São Miguel, Terceira, Graciosa, São Jorge, Pico and Faial. There are about 1750 monogenetic volcanoes in the archipelago (including domes and *coulées*, tuff rings, tuff cones, maars, scoria, and spatter cones), dispersed along the flanks and inside the calderas of central volcanoes or belonging to the 11 basaltic volcanic ridges (Nunes & Lima, 2008).

Due to its volcanic nature, tectonic setting and geographical location, the Azores archipelago is affected by several natural hazards, namely earthquakes, volcanic eruptions, landslides, floods, and tropical storms among others. Since the settlement in the 15th century, that the Azores have been the stage for 26 historical eruptions (Figure 1), the last one in 1998/2001 – Submarine Ridge of Serreta – Northwest of Terceira Island, around 30 destructive earthquakes (Gaspar et al, 2011) and countless seismic swarms. The high seismicity is associated with volcanic activity and with the complex tectonic/geodynamic framework. The concentration of epicentres is considerably higher on plate borders and transform faults of the Mid Atlantic Ridge.

Fig. 1 : Volcanic activity of Capelinhos volcano close to Faial island. Starting in September 1957, lasted for thirteen months. (Photograph by Fundo Tenente Coronel José Agostinho)



The most destructive earthquake experienced by the azoreans, occurred in 1522 in São Miguel Island and reached maximum intensity X (EME 98 – European Macroseismic Scale 1998). The earthquake triggered numerous landslides across a large sector of the island. The largest and most catastrophic of these landslides originated above Vila Franca do Campo, sweeping down into the town and leaving a track of death and destruction. Causing the death of 3000 to 5000 people, this was the second largest natural disaster in Portugal (the first being the 1755 earthquake that destroyed Lisbon).

The seismic activity of tectonic nature, that is associated with the main active faults existing in the Azores region, usually manifests itself in the form of a high number of microseisms (e.g., earthquakes of magnitude less than 3) registered annually in the archipelago's seismic network (Figure 2), occasionally in the form of seismic swarms. Periodically, however, the Azores islands are shaken by moderate to strong, more energetic earthquakes, which affect one or more islands in the archipelago and cause destruction and significant economic impacts.

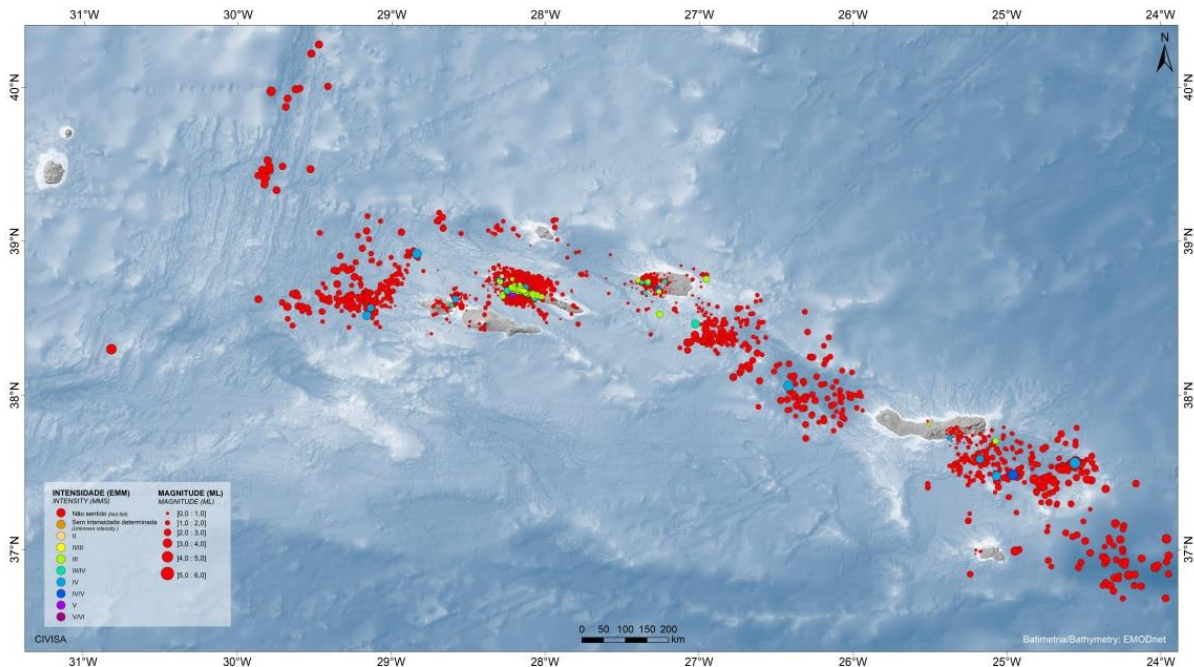


Fig.2: Azores seismicity chart for year 2022 (CIVISA – available at www.ivar.azores.gov.pt)

Since March 19, 2022, there has been a seismovolcanic crisis in the island of São Jorge. After more than a year, it is still ongoing. About 57,000 low magnitude events have been recorded and around 350 earthquakes were felt by the population. The epicentres extend in the western half of the island, formed by an extensive volcanic ridge of about 53 km, with an orientation of WNW-ESE. An intrusion of deep magma has probably reactivated the Fissural Volcanic System of Manadas where several historical eruptions have occurred.

The Institute of Investigation in Volcanology and Risk Assessment (IVAR) permanently monitors and assesses geohazards in the Azores and uses the multihazards assessment methodology, due to the frequent occurrence of coupled geohazards (e.g., in Vila Franca, 1522). It is a fact that the territory of the Azores UNESCO Global Geopark is highly exposed to different geological hazards, causing significant impact, so in order to detect signals and develop early warning systems, the University of the Azores is responsible for a multi-parametric monitoring network, providing data used in a continuous hazard and risk assessment programme to support civil protection, regional and local authorities.

Geohazards - education and dissemination

The Azores UNESCO Global Geopark assumes an important role in the development and implementation of educational activities focused on the community (Figure 3). Directed at schools, the Azores Geopark has created several educational resources, some of them highlighting the importance of disaster risk reduction and focusing on volcanic activity and earthquakes ("Volcanoes of the Azores" and "Why does the Earth Shakes?"). More recently, in the scope of the Portuguese Network of UNESCO Global Geoparks (Naturtejo UGGp, Arouca UGGp, Azores UGGp, Terras de Cavaleiros UGGp and Estrela UGGp), a common activity was created under the theme "Natural Hazards in Portuguese UNESCO Global Geoparks", presented for the first time on the International Day for Disaster Risk Reduction (an important day in all geoparks). Moreover, geohazards and education for risk reduction, is fundamental to the action and communication of the Geopark and is present in interpretive centers (visited by local community and tourists), educational activities and dissemination materials such as the weekly radio program "Azores Geopark in 5 minutes" or the bi-weekly newspaper page "(Geo)diversidades." Education and dissemination play an import role in disaster risk reduction, empowering the community to take actions to reduce their vulnerability to disasters.



Fig.3: Awareness activity at Casa dos Vulcões (Volcanoes House, in Pico Island), using the earthquake simulator.

Geochemical hazard in Geoparks: the assessment of geological compatibility of potentially ecotoxic elements (PTEs) in metaophiolitic soils of the Beigua UNESCO Global Geopark (Italy)

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Introduction

Geochemical hazards associated with natural and agricultural soils are mostly dependent on the presence of high concentrations of trace elements resulting from either geogenic or anthropogenic sources and activities. Geogenic sources are related to the natural weathering of parent rocks and the redistribution of trace elements during pedogenetic processes. Anthropogenic contamination can be diffuse or localized and results from human activities such as industrial emissions, agricultural practices, and mining activities.

Trace elements are defined as chemical elements occurring in mean concentration ranging from 1 to 1000 mg/kg in the Earth's crust. Some of these elements are also defined as potentially ecotoxic elements (PTEs) because they can be either essential or toxic for organisms depending on their concentration in the environment (Kabata-Pendias & Mukherjee, 2007). Among these elements, the content of several metals (cadmium, cobalt, chromium, mercury, nickel, lead, copper, tin, thallium, vanadium, and zinc) and semimetals (antimony and arsenic) in soils is regulated by national and international laws, and threshold values are reported as indicators of potential contamination. However, for the proper management of an area, and particularly of a geopark, it is important to demonstrate whether the presence of high PTEs content in natural and agricultural soils can be attributed to a geogenic origin (whether their presence is geologically compatible), thus ruling out possible human interference.

The metaophiolitic rocks and soils of Beigua UGGp

The Beigua UGGp is characterized by outstanding outcrops of metamorphosed ophiolites representing one of the best-preserved remnants of the Tethyan ophiolites in the Mediterranean area. This peculiar geology resulted from a complex geological history, which comprises i) the opening of the Jurassic Ocean basin (ca. 200-145 Ma) and ii) the Cretaceous–Eocene Alpine Orogenic events (spanning ca. 145–33 Ma). During these events the oceanic lithosphere underwent polyphasic metamorphism from the ocean-floor metamorphic conditions (amphibolite to greenschists facies) to the High Pressure – Low Temperature subduction–exhumation Alpine events (blueschist to eclogite facies peak conditions).

Fig.1: The serpentinite outcrop at Lago dei Gulli (Beigua UGp) capped by poorly developed AC soil (photograph by Gandolfi A.)



The metaophiolitic soils of the Voltri Massif are mostly poorly developed (10-50 cm) and characterized by limited profile differentiation (Figure 1). The Organic horizon (O) is on average less than 5 cm thick, and Topsoil (A horizon) is in direct contact with the Subsoil (C horizon). The A horizon consists of a decomposed organic fraction (humus) and an inorganic fraction comprising parent rock minerals at various degrees of alteration as well as newly formed minerals such as Fe-oxides and clay minerals. The C horizon is mostly composed of weathered and unweathered rock fragments consequently displaying mineralogical and chemical characteristics very similar to the parent rock (bedrock). Based on their geochemical hazard, the soils developing on the ophiolitic bedrocks of the Beigua UGGp can be grouped into two main types: i) ultramafic soils developing on peridotites (Iherzolites with minor harzburgites) serpentinites, serpentineschists and serpentinite-bearing conglomerates and breccias, ii) mafic soils developed on eclogitic metagabbros, eclogites, metarodrigues, and metabasites.

Geochemical hazards in metaophiolitic soils of Beigua UGGp

To assess the geological compatibility of PTEs enrichment in natural and agricultural soils and to exclude anthropogenic contamination, it is necessary to compare not only the chemistry but also the petrography and mineralogy of parent rocks and derived soils. The bedrock type is one of the most important factors influencing the geochemical and pedological properties of soils, particularly in slope soils of hill and mountain environments (Marescotti et al., 2019 and references therein).

This pilot study has been developed by selecting five geosites within the Beigua UGGp territory with extensive outcrops of mafic and ultramafic lithotypes. Rock and soil samples have been analyzed by Polarized Light Optical Microscopy (PLOM), Scanning Electron Microscopy and microanalysis (SEM-EDS), X-Ray Powder Diffraction (XRPD), X-RAY Fluorescence Spectroscopy (XRF) and Inductively Coupled Plasma Spectroscopy (ICP-OES and -AAS).

The resulting data were useful to: 1) determine the PTEs contents in soils and bedrocks of the selected lithotypes; 2) identify the mineralogical species containing specific PTEs; 3) evaluate the stability of PTEs-bearing minerals to assess the possible release of PTEs into circulating waters during their weathering and; 4) demonstrate that the PTEs content in soils can be attributed to a geogenic source.

The chemical results highlighted that the content of Cr, Ni, and Co significantly exceeds the residential threshold values according to Italian law for all the investigated soils; in addition, soils developed on eclogites also exceed the thresholds value for V (Figure 2).

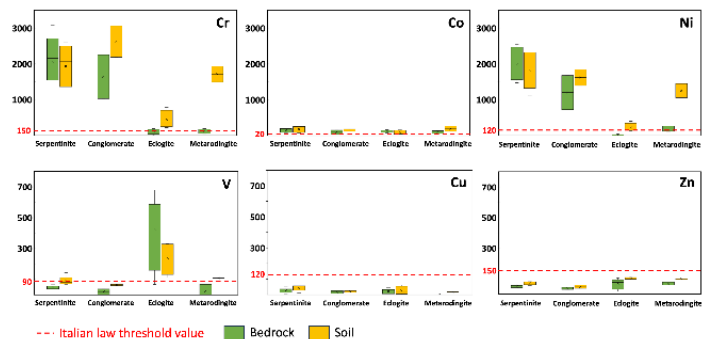


Fig.2: Box plots showing statistical parameters for contents (in ppm) of Cr, Co, Ni, V, Cu, and Zn in bedrock and soils of the studied sites. The red dashed lines indicate the threshold values according to Italian law (D.Lgs 152/2006)

The mineralogy and mineral chemistry of the investigated soils showed that the exceeding PTEs are mostly contained in primary minerals occurring within fragments of unweathered or partially weathered parent rocks. For example, in all ultramafic rocks and soils, chromium mostly occurs within chromite and Cr-rich magnetite whereas nickel is present within Fe-Ni alloy, Ni-sulphide, olivine and serpentine (Figure 3). To a lesser extent these elements were also found in

newly formed minerals such as clay minerals and Fe-oxides that precipitate from circulating solution or directly replace primary minerals. No extraneous phases that can be traced back to possible allochthonous and anthropogenic inputs were identified. Therefore, the extent of these data confirms the geological compatibility of the ophiolitic soils of the studied geosites and excludes any form of contamination.

Geochemical hazard education and dissemination

The natural presence of potentially toxic elements and minerals in an area is closely related to its geodiversity being linked to the geological cycle of chemical elements, which includes all the processes and interactions that develop during the evolution of the Earth's surface (e.g., tectonic, hydrological, atmospheric, pedological and biological processes). For proper land management of a geopark, it is important to have an overview of the presence and natural distribution of harmful metals (e.g., PTEs) and minerals (e.g., asbestiform minerals). This information can not only be useful in ruling out any form of anthropogenic contamination but can also be an indispensable resource in intervention programming and land-use planning. Moreover, without such a basic cognitive tool, any intervention involving the excavation and movement of soils and rocks would dictate management of the materials as waste, with unjustifiably high costs that are difficult to sustain.

For these reasons, a research project is being developed in the Beigua UGGp with the goal of creating a georeferenced public database containing all the geochemical, mineralogical, and petrographic data needed to frame the geochemical characteristics of soils and outcropping rocks with respect to the geologic context (i.e., geological compatibility).

Digital fact sheets containing site-specific information are also being created. These will be made for each geosite in the park and will contain, in a simplified form, all the information needed to understand the characteristics of the outcropping rocks and soils in the area, from mesoscale to microscale. They can also be used as part of educational projects for school or university students and to provide the community with the basic knowledge needed to understand potential geochemical hazards in the geopark.

This type of study and methodological approach can be of great interest in all geoparks and particularly in those with extensive outcrops of ophiolites or rocks with anomalous natural enrichments of PTEs, such as Gravena-Kozani UGGp (Greece), Shetland UGGp (Scotland, UK), and Tuscan Mining UGGp (Italy).

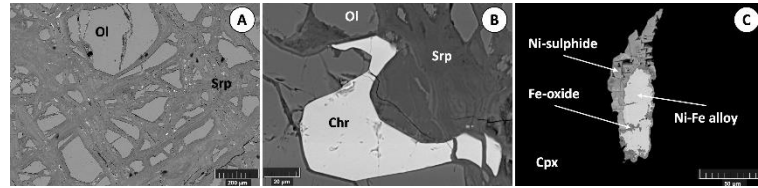


Fig.3: SEM microphotographs showing PTEs-bearing minerals within clasts of ultramafic soils: A) mesh texture in pseudomorphic serpentine composed by Ni-bearing olivine relics surrounded by Ni-bearing serpentine; B) partially serpentinized peridotite with scattered micrometric crystals of chromite; C) partially serpentinized peridotite with Ni-Fe alloy and Ni-sulphide included in clinopyroxene crystal. Abbreviation: Ol: olivine; Srp: serpentine; Chr: chromite; Cpx: clinopyroxene.

Anthropogenic geohazards and their opportunities in the Black Country UNESCO Global Geopark

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Geohazards in Black Country UGGp result from human interactions with the geosphere. The abandonment of large mining areas created unstable land, minerals used in large-scale manufacturing and waste disposal created localised areas of chemically contaminated land. These activities however also created and preserved geological exposures that have become geosites for example Wrens Nest geosite (Figure 1). Ongoing site investigations and land reclamation activity also results in new geological discoveries and temporary excavations that allow new insights to emerge (Worton, 1994, 1996). Abandoned industrial sites also often contain historic structures. Disused mining sites and industrial sites are present in many other European geoparks including Tuscan Mining UGGp, Trodos Mountains UGGp, Bergstraße-Odenwald UGGp or Copper Coast UGGp.

Heavy industry here was resourced by centuries of mining rich seams of coal, limestone ironstone and fireclay. Underground coal mining in the Black Country dates back to at least 1273 (Rowlands, 1987). Rapid expansion of mining and manufacture during the 17th century is particularly related to the 'South Staffordshire Thick Coal'. At 12m in thickness, and being very widespread, it was a huge, easily accessible energy resource and industry flourished because of it. Technological innovation was also stimulated and a number of globally important advances in science and technology resulted. The development of steam pumping engines, the invention of the world's first recording seismograph and palaeontological studies contributing to the definition of the Silurian Period happened here.

During the UK's Industrial Revolution (1750 - 1850), the Black Country was a concentrated urban industrial conurbation with more than 1500 underground mines and thousands of factories. After 1900 minerals resources were declining and the last deep mine closed in 1968. Much of the heavy industry slowly closed after this time leaving significant areas of the Black Country derelict, unstable or contaminated.

The settlement or collapse of untreated mine workings creates areas of surface. Such areas sometimes interact with shallow water table and this may result in a geohazard where contaminated industrial wastes come into contact with groundwater have the potential to mobilise contaminants and create a pollution plume. Where this happens, immediate remediation is enforced. Where the subsidence does not interact with deleterious materials, then it can create safe new wetland habitats, such as Moorcroft Wood geosite (Figure 2). Here an old ironworks deposited boulders of glassy furnace waste in the adjacent subsidence hollow. Essentially man-made volcanic glass, they pose no threat to the waters in the pools and create an intriguing geosite where these remain as monuments to the former ironworks.

Fig. 1: Wrens Nest National Nature reserve geosite, Seven Sisters Mine daylight gallery as it was in the early 1960s



Complex manufacturing sometimes yielded chemically contaminated wastes. Poorly regulated waste disposal (up until the 20th century) allowed their deposition onto the local landscape-resulting in areas of contaminated land. Contaminants are solids, liquids or gases, each phase and chemical type has different conditions under which it may be harmful. The level of contamination geohazard experienced therefore relates to the type and concentration of substances present. Areas containing chemically contaminated wastes still exist in the UGGp and are actively being investigated and remediated, with some sites being used to research and study remediation methods.



Fig.2: Moxley Pools area of the Moorcroft Wood geosite - a flooded mineral extraction site and subsidence hollow with large boulders of metalliferous slag strewn across the landscape, remaining in hydraulic connection with the broken ground associated with flooded mine workings below

The process of land reclamation has also become a complex professional industry. Such work is currently regulated under the

UK's Environmental Protection Act 1990 and its regulations and statutory instruments (Defra, 2012) Old industrial sites are called 'brownfield sites' in the UK, and much of the Black Country is composed of brownfield sites by this definition. The area has become a centre of expertise for investigating and treating contaminated land and hosts the National Brownfield Land Institute (NBI). The NBI aims to develop techniques in this field of work and train young geo/environmental scientists in investigation and remediation of contaminated land.

Dudley's abandoned limestone mines case study

There are a number of anticlines of Silurian strata in the Black Country UGGp. These are highly fossiliferous, layered carbonate-rich sequences surrounded by younger Upper Carboniferous layered carbonaceous siliciclastic sedimentary sequences. They formed during the Caledonian Orogeny and were modified by later Variscan orogenic movements.

Two particularly pure and thick limestone layers (Upper Quarried Limestone and the Lower Quarried Limestone) are present. They were extensively mined below ground using a partial-extraction mining system known as pillar-and-room mining. This created large mine galleries at depths between 10m to 70m. Limestone mining ceased operating in 1924 and mines were abandoned. This left large areas of potentially unstable ground. Over time, mine collapses posed increasing threats to life and property. The UK government recognised this as a significant problem, requiring significant public finances to resolve, and in 1981 established the Derelict Land Grant scheme to help to finance investigation and treatment of many Black Country abandoned limestone mines. Engineering options were fully explored, but the cheapest effective solution (that was used in most circumstances) was total infill of the mining voids with sand and cementitious materials.

A different treatment option was demanded by local people who campaigned to keep open mines and underground canals beneath the Castle Hill Geosite. They argued that this was priceless heritage, important both for education and as a monument to mining communities of the past. Their arguments were accepted, and areas of the mines were re-engineered to create safe public access.

A highlight of that work is the 'Singing Cavern', a limestone gallery with underground canal tunnels (Figure 3). In 1984 a new canal tunnel was driven to facilitate their conservation and access. Old canals were dredged and original brickwork repaired. Rock mass stability was assessed, loose material shotcreted, rock bolted and netted, retaining walls, drainage measures, electric cabling and other engineering works were put in place to ensure the long-term stability of the mine complex. Tunnelling in 1989 created a new underground canal arm providing a circulatory route for canal narrowboats. The system was then re-flooded and the Dudley Canal and Tunnel Trust charity now operates this Geosite from its Portal building visitor centre. They welcome 70,000-80,000 visitors annually introducing them to the incredible geology and industrial heritage of the area.

Inspiration, education and research

The geosites are highly valued inspirational and educational assets. They engage local people, thousands of tourists, and educational groups from infant school to post graduate level. In the field of geohazards, in 2023 a new advanced early-career short course on environmental contamination and remediation was provided by the geopark in partnership with the University of Wolverhampton and the NBI to ensure practical skills transfer to post-doctorate scientists leaving academia.

To many people, geosites present surprising, immersive, emotive and memorable experiences that establish more personal connections to the landscape and its history. These encounters also introduce the geohazards created by past activities, their solutions and opportunities that these can become with imaginative reclamation (Figure 3). Since formally becoming a UGGP in 2020, there is an increasing higher level of educational engagement, universities use specific geosites for applied earth science study/research and also training early career engineering geologists and environmental scientists in support of their professional career development.

The current active research focus is around landscape recovery, climate resilience and biodiversity recovery. Research is investigating the complex interplay between biosphere, geosphere and people, ecosystems and their dependence on the varied disturbed ground conditions in this urban area.



Fig.3: ProGeo conference geoconservation specialists on board the canal narrow-boat visit to the Dudley Canal and Tunnel Trusts 'Singing Cavern' geosite in October 2023

Rock instabilities and subsidence as active examples of societal impact geohazards

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The main identified geohazards in the Catalunya Central UNESCO Global Geopark are primarily related to rock mass instabilities -mainly rockfalls- and terrain subsidence in areas with intense subsurface evaporite karstification and mining. Many of the geohazards in the Geopark are related to erosion, subsidence and mass movements, and such geomorphological processes are controlled by the geomorphic features of the relief (structural, erosive and depositional), lithology and climate (Oms et al., 2016). Erosion has highlighted tabular reliefs, slope reliefs, monoliths (or needles), and massifs. Karstification processes also plays an important role in the Geopark due to evaporitic rocks, limestones and carbonatic conglomerates, intensely affected by faults and diachases.

It's important to emphasize the importance of anthropogenic activity in altering natural landscapes and geomorphic processes regarding geological hazards. Monitoring forms the basis for a prediction and alert system. This work is essentially carried out by the Catalan Geological Survey (Institut Cartogràfic i Geològic de Catalunya, ICGC) (Buxó et al., 2017).

The Geopark is located in the eastern sector of the so-called Ebre Basin. The main rocks are sedimentary, Eocene and Lower Oligocene in age. The oldest rocks were formed in marine environments (sandstones, limestone reef and marlstones), and then, as the sea dried up, there was the formation of evaporative deposits of sulphates (gypsum) and salts (halite, sylvite, carnalite). Finally, about 36 million years ago, alluvial, fluvial and lacustrine processes buried the evaporites beneath a thick sequence of sandstones, lutites and limestones. The geological context exposed here for this evaporite basin could be somehow compared to that of Zagros Mountain Range, either for the tectonics (foreland basins) or the presence of salt and diapirism. Qeshm Island UGGp (Republic of Iran) is a part of this mountain range (Pérez-Villar et al., 2024).

Mountain of Montserrat, rockfall kingdom

Montserrat Mountain range is located south of the Geopark, near Barcelona. It represents a rare geological and geomorphological landscape. Its distinct and spectacular geomorphologic features make it a globally distinctive massif, just comparable to Meteora Region in Greece.

Thick conglomerate layers interbedded with siltstone and sandstone from a Late-Eocene fan-delta (41-36 million years ago) form this isolated massif. It rises over the Llobregat River, exhibiting a local relief of 1000 meters, from 200 to 1200 m.a.s.l. This configuration leads to a stacked shape where vertical layers of calcareous and well-cemented conglomerates alternate with steep slopes of softer ground, covered by densely vegetated colluvial deposits. The relatively low tectonic activity just gently tilted stratigraphic layers, while forming a few dominant joint sets, which are pretty planar, vertical, orthogonal, and persistently spaced, usually ranging from 1 to 10 m.

Fig. 1: Low magnitude rockfall at Canal Plana occurred in 2022 (Credit: ICGC)



This geological structure renders the massif very prone to rockfalls, including large single rock blocks from 1000 m³ up to 10000 m³. Large rockfalls occur due to the weakening of the resistant properties of the rock massif and the triggering actions from climate. On the one hand, it can be distinguished the fall of blocks delimited by the structure of discontinuities in the rock mass (joints or mechanical fractures of tectonic origin enlarged by karstification) and the weaknesses due to the intercalation of layers of less competent materials (siltstones and sandstones) with regards to carbonatic conglomerates. On the other hand, both exfoliation on slabs and disaggregation on conglomerate pebbles also cause rockfalls of lower magnitude and higher frequency (Figure 1.).

In this massif, rock mass instabilities range over 9 orders of magnitude in volume, progressively shaping the landscape. The estimated rockfall frequency is approximately every 10 years with a volume of more than 5 m³, equivalent to 12.5 tons of rock.

Over time, several active and passive protection measures have been implemented along the railway, road accesses, and buildings areas. However, stabilization measures for large rockfalls are only feasible in specific cases. Given the large number of visitors (3 million people in 2019), detecting, assessing, and mapping these geohazards is crucial for devising effective mitigation strategies (Janeras et al., 2017).

Sallent, the silent subsidence

The Geopark also covers the Catalan Potash Basin, where important and historical mining activity have been carried out in Cardona, Súria, Balsareny and Sallent municipalities. This basin contains a significant saline unit from the Eocene period, ranging from 140 to 300 meters thick. It is covered by a sequence of marls and sandstones from the Upper Eocene, except in Cardona, where it emerges as a diapir. The salt extraction from these saline units dates to the Neolithic period and is Catalonia's most relevant underground mining activity.

The mining work has caused some environmental problems, such as subsidence, and surface collapses have occurred due to the combination of water flowing and mining activities. One of the most relevant was the river Cardener collapse at Cardona town at the end of the 90s that in the end, forced to shift the course of the river to avoid a serious environmental impact. Apart from that, another case occurred in the Estació neighbourhood in Sallent town. This was a district developed during the demographic peak of the 1960s and 1970s and occupied part of the land above the Enrique mine. This mining operation started in 1932 and was closed in 1977. In the 1990s, structural damages began to appear in the buildings of this neighbourhood.



Fig.2: Estació neighbourhood before the beginning of the firsts demolitions in 2005, that lasted until 2022. (Credit: ICGC)

Structural pathologies of the buildings were caused by differential settlements, meaning different descents between the foundations of the same building (angular terrain distortion). Complete monitoring and characterization studies determined that the contours of the affected area corresponded to the former mining operations. The area with the most significant subsidence overlies a large natural cavity (120 m high and 40 m wide) that was discovered in the mine in 1954, with its upper arch located at a depth of about 170 meters.

Technicians measured a terrain deformation at about 2 cm/year through topographic leveling in the initial monitoring years. In 2008, an acceleration trend appeared. Cumulative subsidence data suggested potential collapse between 2013-2016. Yet, the acceleration trend ceased by late 2009 and early 2010 after reaching 20 cm/year on the surface. Since 2010, the rate has stabilized with slightly higher and variable speeds (2 to 8 cm/year), causing significant angular terrain distortion (a parameter that directly controls building damage). The projections of these data to estimate potential damages allowed technicians to determine that, in 20-50 years, the subsidence would reach the critical thresholds for the stability of the buildings. The land would then be unsuitable for urban use. Hence, the solution was the closure of the neighbourhood and relocation, and 405 properties were demolished at a cost of over 60 million euros (Marturia et al., 2008). See figures 2 and 3.



Fig.3: Estació neighbourhood nowadays, after the final fases of relocation of the inhabitants and building demolition (2023). (Credit: ICGC)

Despite the closure, permanent operational instruments implemented by the ICGC for more than 20 years turned this geosite into an exceptional experimental subsidence study area, validating techniques like radar interferometry and implementing new measurement technologies as satellite and terrestrial DInSAR and Wi-GIM (Rodríguez-Lloveras et al., 2017).

Use of geohazards as educational tools

Geohazards are inherent within the Geopark, shaped by its geological history, past and present geological processes. However, society often does not identify or perceive these hazards as such. In collaboration with local universities and the ICGC, Geopark uses key geosites as educational and dissemination tools aimed at the general public. Hence, these sites play an important role in various Geopark initiatives: conferences, school activities, field trips, and actions during EGN Week, such as at the Geology Olympiad events and as learning and discussion topics for students (Geopark suitcase, educational activities, etc.). These were also contributed as topics for an academic Geopark 2016 publication, as it was the guidebook for the Teaching of Geology Symposium.

The many Geohazards faced by the Chablais UNESCO Global Geopark

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Incredible geodiversity, many geohazards

The stunning Chablais region conceals multiple geohazards. Since its recognition as a UNESCO Global Geopark in 2015, these dangers have been shared via different studies, publications, and events. Local residents remain generally unconcerned by the events that could impact this densely populated and economically vibrant area at any time.

Extending across 870 km², the Chablais UNESCO Global Geopark has varied terrain ranging from the Lake Geneva in the north and the Alps in the south. Its rich geological history combined with a climate of four clearly defined seasons expose the area to a longer list of geohazards than one might expect: mass movements including rockfalls and landslides (Figure 1), avalanches, earthquakes, flooding, subsidence and tsunamis. Although these geohazards are not equally distributed throughout the region, all areas are prone to earthquakes and flooding (Figure 2).

The Alps have been subject to more than 20 glaciations over the last 2.6 million years. The Chablais has been constantly remodelled during this time, however it is the last glacial episode that has left the strongest impression on the region (Perret, 2014). This glacial legacy is the driving force behind several of the most significant regional geohazards.

60 000 years ago, sub glacial rivers eroded the thick limestone beds through dissolution and mechanical weathering to form gorges. With the melting of the glaciers 12 000 years ago, these have been further incised by the rivers. Since then, the landscape has found a new balance. Regular large rockfalls occur. This type of hazard is typical of our region with its over-steepened, unstable valley sides. Also, a result of this glaciation, thick clay deposits have been deposited in extensive glacial lakes. These fine sediments are many tens of metres thick and cover the valley bottom. Since the glacial retreat and the development of a regime of fluvial erosion, these fine sediments have been deeply incised forming steep valley sides. This has destabilized these fine sediments which have become prone to significant landslides. The biggest, in the municipality of Vailly, covers 422 Ha and ingenious engineering solutions have been employed since 1930's to reduce the landslide potential (Messines du Sourbier et Widmann, 1943).

Looking at deeper Earth processes, the Chablais is exposed to regular earthquakes. In living memory these are relatively weak (magnitude 1 – 3), the largest 20th century earthquake is estimated as magnitude 5.8 and caused 3 deaths and extensive damage (Fritsche & Fäh, 2009). Neighbouring Switzerland predicts a magnitude 6 earthquake during the 21st century. The densely populated areas of the Chablais Geopark coincide with thick glacial deposits where strong site effects are forecast. In the event of a magnitude 4 earthquake the BRGM (the French Geological Survey) expect more than 1100 damaged buildings in the principal town of Thonon, home to 36 000 people.

Fig. 1: The Devils Gorges Bridge, a geosite and major visitor attraction © S. Justice



The Chablais Geopark, an inland territory, is also surprisingly exposed to regular tsunami risk. Two medieval bishops, Marius of Avenches and Grégoire of Tours, documented a tsunami on the shores of Lake Geneva in 563 AD. The written accounts tell of massive destruction and the huge loss of human life all around Lake Geneva. The town of Evian was estimated to have been hit by a wave 8m high, 10 minutes after a large rockfall caused massive slumping of the Rhone delta (Kremer et al., 2012). The origin of the rockfall is linked to the heavily fractured, folded limestone beds of the Chablais Massif and the glacial over steepening of the valley sides. These two factors created a fragile rocky outcrop that was susceptible to gravitational failure. The water saturated delta sediments collapsed under the weight of the rocky debris into the lake forming an extensive, massive, chaotic deposit identified through seismic studies. Seismic imaging of the lake floor shows eight sets of sediments that can be linked to tsunami events. Thought to be triggered by delta slope failure, earthquakes or rockfalls, tsunamis generally take place every 300 to 500 years. The largest event however remains that of 563 AD.

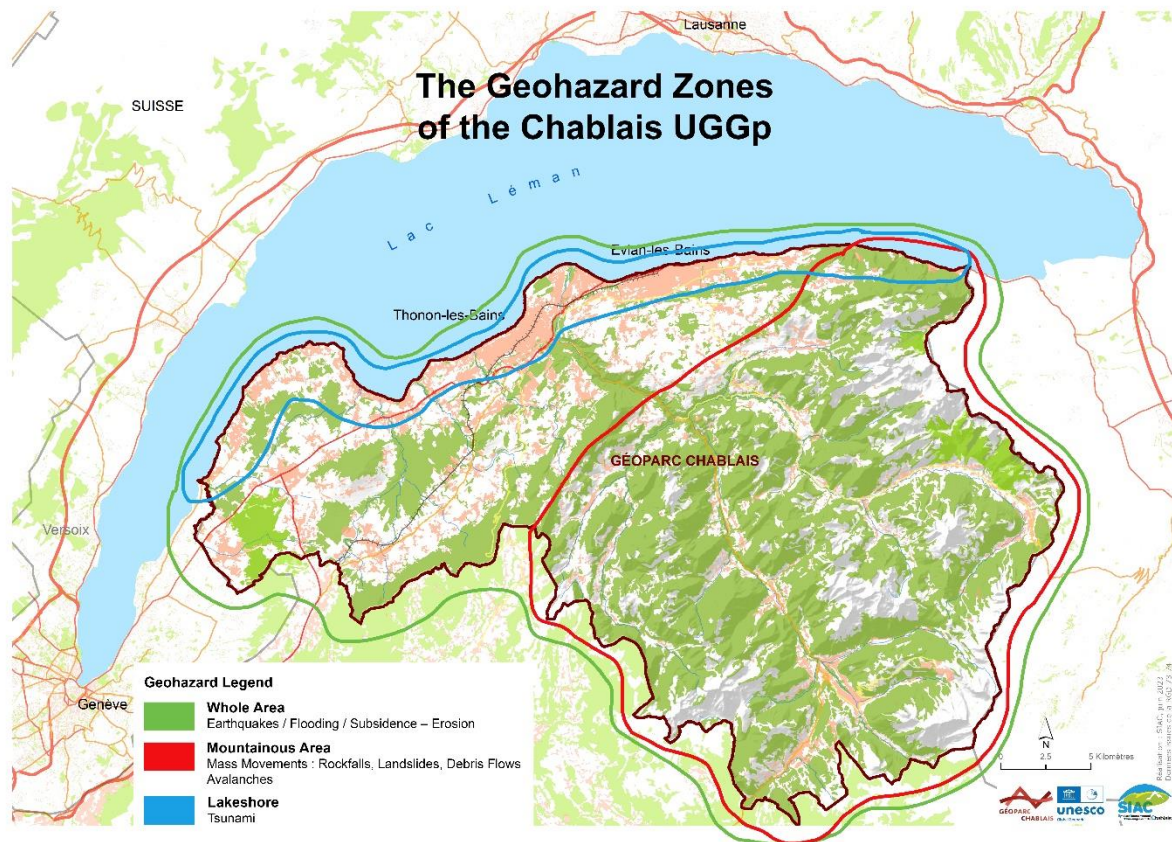


Fig.2: Map of the geohazard zones within the Chablais UGGp region © SIAC

Geohazards education and dissemination for the public and decision makers

The UGGp works to responsibly inform the local population, decision makers and visitors about geohazards. Information about the rockfalls for example is presented at the Devils Bridge Gorges, a Chablais UGGp geosite and an important visitor attraction. Equipped with information panels, the site receives more than 50 000 tourists per year and can be visited with trained Geopark guides.

Elsewhere the Geopark works to help decision makers understand hazards and their implications. For example, in 2017 a large landslide took place in the village of Reyvroz due to the presence of thick glacial clay (Figure 3). In collaboration with the University of Turin, the deformation and potential economic risks to local inhabitants were investigated. Regular meetings with the mayor explained the scientific study and possible consequences. The results were shared with regional authorities.

Earthquake risk in the region is poorly recognised and so the Geopark is developing training to heighten awareness amongst decision makers. In 2022 all Geopark mayors were invited to a general presentation of regional hazards. A special session on earthquakes is planned for 2024.

Another approach of the Geopark has been to develop workshops tailored for adults, or school children. One of these is a very hands-on discovery of the tsunami risk on Lake Geneva which continues to inform and astound the Chablais Geopark population.

The Chablais UGGp works closely with the Sesia Val Grande UGGp that shares a number of these geohazards. This has for example been done during a three-year ERASMUS exchange program for 16 to 18 year-olds.



Fig.3: The head scarp of the Reyvroz landslide one year after the event © S. Justice

Landslides in Cuilcagh Lakelands UNESCO Global Geopark – understanding climate change through geohazards

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Cuilcagh Lakelands UNESCO Global Geopark

Cuilcagh Lakelands UNESCO Global Geopark (CLUGGp) is located in the north-west of the island of Ireland and takes in parts of County Fermanagh (Northern Ireland, UK) and County Cavan (Ireland).

The geology of CLUGGp is dominated by sedimentary sequences from the Carboniferous period (Viséan and Namurian) forming the bedrock of most of the area. Formed in a wide range of sedimentary environments; marine, supratidal and deltaic with shallow marine limestone dominating at lower levels, and fluvio-deltaic sandstones dominating the uplands.

The bedrock of CLUGGp has been shaped by repeated glaciations during the Quaternary period with deep u-shaped valleys, replacing those occupied by rivers, now separating the plateau-shaped uplands. Superficial deposits of glacial till cover much of the area, often sculpted into drumlins or ribbed moraines, with more localised deposits of ice-marginal morainic accumulations also found.

The topographic variations that exist between the uplands and the deep u-shaped valleys, and the steep slopes dominated by upland blanket bog provide ideal conditions for landslides of various types. Several examples have been provided below.

Cuilcagh Mountain

Cuilcagh Mountain (Figure 1) is an iconic landmark at the centre of CLUGGp. The middle slopes of are occupied by one of the most extensive areas of blanket bog in Ireland. This semi-natural habitat forms from plant remains in areas where there is a cool climate and low levels of evapotranspiration, underlain by a poorly drained substrate. These conditions allow for the development of large expanses of peat with typical depths of between 50cm and 3m, although up to 8m is not uncommon.

The northern and eastern sides are covered with over 50km² of blanket bog. According to the Geological Survey Ireland National Landslide Database, there have been approximately 40 landslide events in and around Cuilcagh Mountain, approximately 90% of which have been within the peat. Research by Dykes & Warburton (2007) identified that the blanket bog is particularly susceptible to failure. The two main reasons for this are the attainment of threshold maximum peat depths and, the unconformable deposition of thin layers of glacial till and blanket bog on top of Carboniferous shale formations on the northern slopes of the mountain. This research concluded that there had been

Fig. 1: The internationally important blanket bog on Cuilcagh Mountain has formed in places on top of layers of glacial till and Carboniferous shale, contributing to its instability



a high frequency of heavy rainfall events that had not triggered landslide events so climate change is unlikely to increase the frequency of landslide events, and that their main causal factors were slowly changing internal thresholds. However, in the 20 years since, it is worth noting that this may no longer be the case with climate change, particularly more intense and frequent periods of rainfall, now posing additional threats to stability in addition to a significant increase in visitor footfall.

Magho Cliffs

The Magho Cliffs (Figure 2), located on the southern side of Lower Lough Erne, lead up to the Magho Plateau at an elevation of 300m. The cliffs are formed as an escarpment of Carboniferous limestone that is underlain by Carboniferous shales, the latter of which are only seen in a narrow stretch of ground between the foot of the cliffs and the edge of the lake.

There are three distinct types of landslides that occur along the edge of the Magho Cliffs; rotational slumps, shallow debris slides and active shallow rotational slides (Prior & Graham, 1974). The causal factors for each of these have been considered below.

The rotational slumps involve downslope movement of large blocks of Carboniferous limestone. They are inclined steeply southwards showing that they involved rotation and are seen to be stable at present. These probably date from glacial times when erosion associated with the creation of the deep u-shaped valleys led to the formation of over-steepened slopes, seen as the Magho Cliffs. When slopes become over-steepened and/or undercut, the surface will naturally attain equilibrium leading to instability manifesting as rotational landslides.

Shallow debris slides are seen as vegetated talus slopes below the Magho Cliffs. They are made up of angular fragments of Carboniferous limestone within a clay-rich matrix. There are over 300 of these small slides, each one with a clear source area, some of which are fresh whilst others are vegetated indicating different ages. The occurrence of well-jointed permeable limestone directly on top of impermeable shale promotes high water content in and on top of the shales. This leads to high pore-water pressures that exerts stresses on particles resulting in a reduction of shear



Fig.2: The over-steepened slopes of the Magho Cliffs probably date from glacial times. The resulting landforms lead to rotational landslides as the surface naturally tried to attain equilibrium

strength along a potential failure plane leading to the formation of shallow debris slides upon the slope. It is thought that each of these events is associated with periods of heavy rainfall.

Shallow rotational slides occur at the base of the cliff in the narrow stretch of ground underlain by Carboniferous shale, at an elevation of between 150m and 45m. These events have caused significant damage on the main Enniskillen to Belleek Road over a stretch of approximately 3km. This may be either as a result of subsidence and downslope movement producing linear cracks that damage the road, or as a direct result of being partially buried by slide debris. The mechanism of movement is thought to be instability of the shale as it weathers to produce a clay-rich regolith with high plasticity producing acute shear surfaces. It is thought that this process increases with the absorption of water which further reduces the stability of the overlying slopes although further research is needed.

Geohazards, Education and Engagement

Approximately 850,000 people visit and use CLUGGp sites each year for a range of outdoor recreational and sustainable geotourism purposes. A further 3,000 partake in CLUGGp events and educational programs with a further 4,000 people taking part in large scale sustainable outdoor recreation events and activities.

A range of educational and interpretative tools are used to help local landowners, communities, businesses and visitors understand and work collaboratively to encourage the delivery of successful climate change adaptation and mitigation measures.

Firstly, relevant geohazards are included in interpretation panels around Cuilcagh Mountain and Magho Cliffs. Secondly, outdoor learning and education opportunities with a specific climate change and geohazard focus are being developed for a range of educational sectors from secondary to lifelong learning. Thirdly, CLUGGp is establishing a multi-agency Scientific Advisory Committee with relevant partners from the education, research and statutory sectors that will co-ordinate and encourage further research and dissemination of matters relating to geohazards and climate change within CLUGGp.

Geohazards research and climate change

Geohazards in the UK and Ireland are often considered 'low-risk', primarily because fatalities are rare and financial losses are poorly understood (Gibson *et al.* 2013). This presents a problem for developing risk management plans as they are considered to be low priority and in times of financial austerity there is no desire to provide resources.

Other UNESCO Global Geoparks (UGGps) across the UK and Ireland face similar problems to CLUGGp. For example, the North Pennines in England and the NW Highlands in Scotland are at risk from peat slides and to a greater or lesser degree, all of the UGGps in the UK and Ireland are at risk from rock fall. However, research in this area is increasing, and with greater awareness and understanding of climate change and the impacts it will have, the UGGps have a role to play in developing our understanding and in managing risk.

The Oddicombe landslide: English Riviera UNESCO Global Geopark

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Introduction

Landslides are one of the most obvious geological hazards – often shortened to geohazards – in all parts of the world. They attract public attention as many items of infrastructure can be disrupted by these mass-wasting movements and, in some cases, can cause loss of life. The International Decade for Natural Disaster Reduction (1990–2000) also focussed on the impact and understanding of landslides and represented a major milestone in their understanding.

English Riviera UNESCO Global Geopark

The English Riviera UNESCO Geopark (ERUGGp) in South-West England is well-known as the area in which the Devonian Period was first defined (Sedgwick and Murchison, 1839, 1840) and Devonian rocks (419.2–358.9 Ma) form a substantial part of the of the Geopark territory, particularly the fossil-rich limestones that characterise the area. The Devonian rocks were folded and faulted during the Variscan Orogeny (ca. 290 Ma) before being overlain by Permian (298.9–251.9 Ma) ‘red beds’ that formed in the continental area of eastern Pangaea. These sediments, collectively known as the Torbay Breccia Formation, comprise breccias, conglomerates and sandstones. Aside from a few burrows and other trace fossils (Hart and Smart, 2021), these ‘red beds’ are assumed to be Permian in age, although there is no biostratigraphical information to support this view aside from the general geological setting of these strata.

Major geohazards, aside from a few cliff falls and topples, are rare in the ERUGGp, with one notable exception: the Oddicombe landslide (Figure 1). On the east-facing coastline the Babbacombe and Oddicombe area is characterised by the presence of Lower Devonian sandstones and shales, mid-Devonian limestones and the red sandstones and breccias of the Torbay Breccia Formation (Figure 2). The underlying geology (see Leveridge, 2011, pp. 689–691, figure 48) is complex with a number of major thrust faults and overturned folds. Oddicombe Beach, which lies between the funicular railway and Petitor Point, is backed by the Torbay Breccia Formation and is the location for the landslide which is a rock or debris fall according to the most recent classifications.

The landslide is still active and remains fenced off for public safety. Large boulders of the red sandstone and breccia are present, extending down to sea level and, occasionally, making the sea a bright red colour with entrained sediment. The landslide has a known history of instability, the precise onset of which is uncertain. Despite this knowledge, some of the properties involved in the landslide are clearly of modern construction (Figure 3). The Local Authority records the fact that there was a collapse of the cliff top in January 2001, although there must have been instability before that date as images from the late 19th century show the presence of fallen blocks and damage to infrastructure.

Fig. 1: Oddicombe Landslide with Petitor Head to the immediate north of the red-stained waters of Lyme Bay. Image courtesy of the English Riviera UNESCO Global Geopark (Archive Image)



Chronology of the Landslide

In summer 2023 there is no visible dislocation surface on which movement is taking place. There is also no confirmed record of instability. There is a small landslide visible in images from the late 19th Century and an early, colour postcard records the presence of a small landslide in 1918. After the landslide in January 2001, the beach below the instability was closed to the general public in May 2001. In February 2004 another ~5000 tonnes of rock collapsed. In 2010, Oddicombe Beach was closed for several days after an estimated 5000 tonnes of sandstone collapsed. On the 24th October 2012, most of the garden of a large property collapsed and this was followed by the partial collapse of the house around Christmas 2012. There were further collapses in February 2013 and on 4th April 2013 there was a major landslide that affected Ridgemont House, its gardens and an adjacent property. This collapse 'turned the sea red' in the Oddicome and Babbacombe area. In November 2013, Ridgemont House was finally demolished following further instability.

Following the wettest February on record in 2020, when 202.1 mm of rainfall fell during named storms Ciara, Dennis and Jorge, there were landslides at many locations in the area, including Shaldon, Watcombe, Anstey's Cove, Livermead and Oddicombe. This seems to indicate a clear linkage between landslides and groundwater in areas that contain highly porous sandstone bedrock. Such relationships with heavy rainfall were first described from the Lyme Regis and Stonebarrow area of the Dorset coast, and is now accepted as increasing instability, especially following dry periods.

Features Specific to Coastal Landslides

There are a great many causes of landslide activity including saturation following desiccation. There is quite substantial evidence to indicate that water pressure within a soft sediment can cause instability and the opening of fissures and joints. In many cases, along the Jurassic Coast UNESCO World Heritage Site (located on the Devon/Dorset coast to the east of the ERUGGp), instability can be linked to prevailing weather conditions, and it is probable that climate change – with increased heavy rainfall – is creating more instability: see Denness et al. (1975 and references therein).



Fig.2: Simplified geological map of the English Riviera UNESCO Global Geopark. Oddicombe Beach and Petitor Head are indicated near the northern edge of the map. Image kindly provided by James Quinn, University of Plymouth

Coastal landslides, especially in more northerly areas have other issues to consider:

- In coastal settings the toe of a landslide that is exposed to marine (especially wave) erosion is made more unstable by the removal of the transported material and this is particularly the case at Oddicombe;
- In areas that have been subjected to periglacial activity during the Pleistocene strata will have been made more unstable by the opening of fissures and joints during freeze/thaw conditions, especially as these may have occurred over long periods and of varying intensity. Though rarely described as periglacial features, they must always be considered in the history of a landslide; and
- During glaciations, sea levels will have been much lower; probably 100+ m lower than present day levels. It is well known that the English Channel would have been 'dry' during glacial intervals (Clarke et al., 2022) and that the configuration of the area would have been very different. Offshore Devon and Dorset, adjacent to the Axmouth to Lyme Regis Undercliffs Natural Nature Reserve (Edmonds, 2022) on the Jurassic Coast, there is strong evidence to suggest the presence of Pleistocene landslide 'toes' that now form reefs offshore; forming a wonderful biodiversity than can be directly linked to the geodiversity of the area.

Educational Value and Communication

Supported by an on site interpretation panel the ERUGGp has created an online educational scheme of work for teachers related to the Oddicombe landslide in which it is compared to other geohazards in other UNESCO Global Geoparks, with a suite of resources for students to use. The presence of this prominent landslide in the ERUGGp is a discussion point for all those that visit the location or even just view it from the adjacent cliffs. The educational value is, however, diminished as we cannot see the plane of instability at the base of the landslide or know the geological history of what initiated the Oddicombe Landslide originally. Photographic evidence suggests that, from the late 19th Century the area has become increasingly unstable. Heavy rainfall has clearly had an impact in recent years and, with this being a feature of modern climate change, the instability may become more significant in the future.



Fig.3: Upper part of the Oddicombe Landslide showing debris of collapsed house and the two other properties that are in immediate risk of collapse. Image courtesy of the English Riviera UNESCO Global Geopark (Archive Image)

Post-fire debris flow hazard in the Zêzere glacial valley and Manteigas village (Estrela UNESCO Global Geopark, Portugal)

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Introduction

A debris flow is a mixture of water and sediments that flows down channelized steep slopes, posing a potential hazard in mountainous regions due to high velocities (from very rapid to extremely rapid), high impact forces and extended run-out distances. The initiation of debris flows is generally attributed to the critical combination of three factors: steep slopes, unconsolidated sediments and water. Heavy rainfall, which can mobilize sediments ranging from millimetres to several meters in size, is the most common triggering factor.

In areas recently affected by wildfires, debris flows are frequently initiated by surface erosion along with the entrainment of loose material. The consequences of fires include vegetation consumption, ash deposition, modifications in soil and rock properties and the emergence of water-repellent soils. Therefore, the lack of vegetation, as well as the reduction in infiltration rates on a burned watershed, can increase susceptibility to debris flows, as the amount of rainfall required for their triggering may be lower compared to areas unaffected by recent wildfires. For this same reason, debris flows can occur in areas lacking historical precedent activity.

A global survey conducted across UNESCO Global Geoparks (UGGp) has revealed that slope instabilities, where debris flows are included, stand as the predominant geophysical hazard, impacting 70 % of the analysed UGGp (Fassoulas et al., 2018). On the other hand, wildfires emerged as the second most prevalent hazard after floods, affecting 46 % of these UGGp.

Debris flows and post-fire debris flows in the Zêzere glacial valley and Manteigas village: historical and present-day records

The Zêzere glacial valley (Figure 1) and Manteigas village (Figure 2) are located in the highest Portuguese mainland mountain massif (Serra da Estrela). The valley is a geosite of international relevance and one of the most iconic sites within the Estrela UNESCO Global Geopark (Vieira et al. 2020, Figure 3). The elevation between the village and the upper section of the Zêzere glacial valley varies from 668 to 1990 m a.s.l. The slope angles range between 25 to 35° on 25 % of the surface, while in 14 % it exceeds 35°.

The first reports of debris flow occurrences affecting Manteigas and along the glacial valley date back to the 19th century, at a time when the slopes surrounding the village were devoid of vegetation. In August 1804, a short-intense rainfall event triggered a debris flow in Manteigas along a pre-existing channel ("Vila" stream, Figure 2). The large volume of uprooted trees and transported soil, sand and pebbles destroyed twenty houses, leading to the loss of an

Fig. 1: View over the Zêzere glacial valley (exhibiting its characteristic U-shaped form) with the village of Manteigas in the background



equal number of human lives. This event, the only one to date with reported fatalities, may have been the most significant due to the tragic outcome. However, the records indicate the recurrence of debris flows in that area.

Years later, during a similar rainfall event, a debris flow occurred in another stream near Manteigas ("Lapa" stream, Figure 2). It devastated properties along its banks and surprised residents due to the number and size of boulders that the flow carried onto the bank of the Zêzere river. Some of these large boulders are still visible today. Subsequently, on May 13, 1893, the debris flows triggered in "Sra. dos Verdes" (Figure 2) resulted in damage to private properties.

On August 24, 1899, a two-hour heavy rainfall triggered debris flows in two streams (Figure 2): "Vila" and "Forneas". The sudden appearance of a massive dark flow terrified villagers as it quickly washed away walls and trees, flowing through streets after breaking the channels. Consequently, numerous bridges suffered damage and substantial property losses were documented along both streams. Notably, the areas previously forested experienced minimal damages. A similar event affecting the aforementioned streams occurred again on May 22, 1927, destroying dams and properties in "Vila" stream and surroundings, and resulting in the deposition of large granite blocks. The vegetated slopes were not affected, suggesting that forested catchments in both streams would have mitigated the damages.

During the night of October 15 to 16, 1993, a hotel in the Zêzere glacial valley suffered the impact of a debris flow triggered in "Albagueira" stream (Figure 2), resulting in substantial economic losses. This area was affected by a wildfire in 1991. Additionally, Vieira (2004) highlighted two debris flows occurred near two geosites in the Zêzere glacial valley: in the valley slope close to Lagoa Seca (1996) and in Espinhaço de Cão (2002). The latter was triggered by short-intense rainfall and preceded by a wildfire a few years before the event.

During the summer of 2005, an extensive wildfire affected the Zêzere glacial valley. Afterwards, on October 30, 2005, a debris flow event, triggered by rainfall, impacted the unprotected slopes. A total of 34 debris flows were observed, with the majority occurring along the eastern slope of the valley. While there were no reported casualties, the debris flows led to the closure of the national road connecting the Manteigas village to major tourist destinations in the higher mountain. The identification and mapping of these debris flows were accomplished through aerial photo interpretation, morphological analysis based on post-event topography (at a scale of 1:10,000) and comprehensive field surveying using Differential Global Positioning System, conducted throughout 2011.

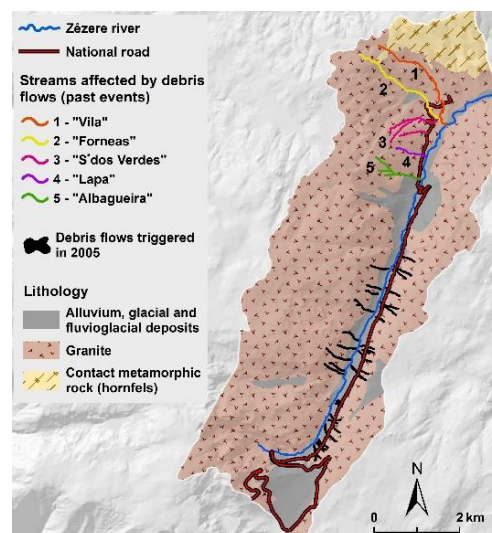


Fig.2: Streams affected by debris flows in historical events and debris flows triggered in 2005

The most recent debris flow event occurred during an intense rainfall episode on September 13, 2022, in a parish named Sameiro, located a few kilometres to the east of Manteigas. This event resulted in damage to vehicles parked along the Sameiro valley streambank, which were swept away, as well as to the sports facility and residences in the

vicinity. Sameiro, like the Zêzere glacial valley, had been affected by wildfires in August of the same year. Furthermore, it is noteworthy to mention that due to the same wildfire and as a risk prevention measure, the national road was closed from December 2022 to at least September 2023.

Following the event of 2005, Melo et al. (2020) designed a methodology aiming to identify structures and infrastructures exposed to debris flows, as well as to estimate the pedestrian travel times to safe zones during an extreme debris flow scenario in Manteigas and in the glacial valley. The basis of this approach relied on a debris flow dynamic run-out model, which was employed to predict potential debris flow intensity, encompassing factors such as the volume of sediments, the depth, the velocity and the travelled distance. In order to develop the pedestrian evacuation model, the structures and infrastructures located in the potential path of debris flows were identified, as well as those where evacuation could extend beyond the anticipated arrival time of the debris flows. Additionally, an estimation of the potentially exposed population for each residential building was derived. This demographic distribution considered different age groups, since the elderly and the young residents are acknowledged as the most vulnerable to debris flows.

Geohazards education and dissemination

The application of the methodology developed by Melo et al. (2020) stands as a significant advancement towards establishing a trustworthy early warning system for debris flows. Conducting evacuation drills, spanning various scenarios including both daytime and nighttime conditions, will be essential for training individuals to react promptly to evacuation notifications, thereby minimizing the risk of unanticipated actions that might compromise a safe evacuation. The verification of these drills, especially concerning evacuation durations, must be supervised out by emergency planners and civil protection authorities.

In parallel, the Estrela UGGp contributes to geohazard education and sensibilization in its activities, in order to raise awareness and prepare local populations for these risks, promoting a more resilient society. Within the educational programmes (for all levels of education) and touristic outdoor activities, geoscientists present and discuss observable geohazard examples,

reinforcing especially the increased risks due to climate changes and associated extreme meteorological events. In addition, Estrela UGGp has also developed, in association with the other four UGGp in Portugal, and the National Committee, a specific educational program on Geohazards, directed to children and teenagers in the school years 7–12. This resource was offered and put into practice starting in October 2023.

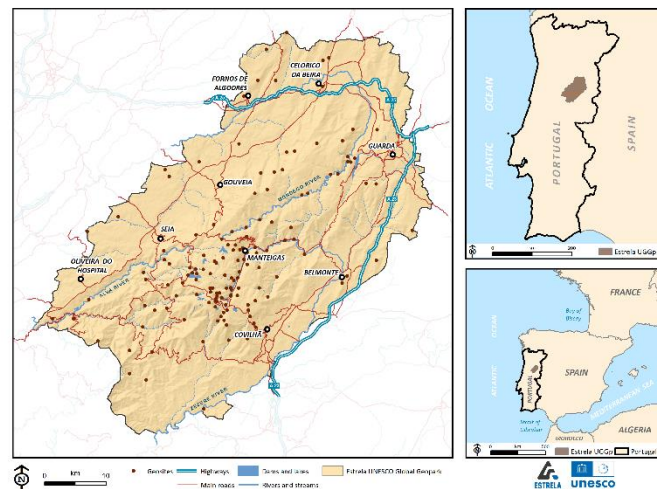


Fig.3: Geosites of Estrela UNESCO Global Geopark



Geohazards in Famenne Ardenne UNESCO Global Geopark

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The Famenne Ardenne UNESCO Global Geopark in Belgium encompasses an area of 915 km² characterized by sedimentary rocks, predominantly composed of Devonian deposits. These deposits underwent folding and faulting processes during the Variscan Orogeny. Over time, the mountain range experienced erosion, transforming into a peneplain that still defines the visible skyline of Wallonia today. During the Meso-Cenozoic period, a hot and humid climate significantly weathered the limestone deposits, giving rise to alterite (Dubois et al, 2014) which served as precursors for the development of caves. In the latter part of the Cenozoic Era, the Ardennes bedrock underwent uplift, accompanied by deepening river systems, erosion of weathered material, and the formation of caves.

The diverse composition of rocks in the area, including sandstone, shale, and limestone, creates a varied relief with altitudes ranging from 540 to 120 meters. This results in a hilly landscape highly appreciated by visitors, where numerous geological formations intersected by various epigenetic rivers can be observed. Running through the centre of the region there is a kilometre-thick band of limestone known as the Calestienne. This area is particularly noteworthy for significant karstification, where processes related to the dissolution of soluble rocks have led to the formation of features such as swallow holes, resurgences, and underground meander cutoffs. Notably, this karst landscape is intricately connected to the river network within the Geopark.

Geohazards description

This geological history combined with a humid temperate climate exposes the region to a list of moderate geohazards such as earthquakes, draughts, floods (Figure 1) and karst subsidence. Global warming, population density and high levels of human activity accentuate these last three hazards. Territories with high vulnerability due to population density and high levels of human activity induce appreciable natural risks.

The Geopark area (Figure 2), like the rest of the Walloon Region, is frequently affected by flooding. This natural phenomenon is not a problem in itself: it is normal for certain rivers to sporadically occupy their flood plain and regularly deposit sediments. But flooding becomes a problem when it leads to soil erosion and, above all, when it affects human infrastructures, residential areas or heritage sites. Global warming, the anthropisation and the sealing of soils increase the severity of the consequences of flooding.

The floods in July 2021 (see Figure 1) are considered the country's most serious natural disaster. Heavy rainfall from July 12 to 15 caused severe flooding in North Rhine-Westphalia, Rhineland-Palatinate, Wallonia, Luxembourg, and the Netherlands.



Fig 1 : Overflow of the Lomme river in the town of Rochefort shortly after the peak flood of 15 July 2021 (photo www.benheine.com/fr)

Saturated soils, drainage issues, and infiltration capacities being exceeded led to water flowing into dry valleys, forming temporary torrents and mudflows. This inundation caused floods, resulting in at least 184 deaths in Germany and 38 in Belgium, along with significant infrastructure damage.

The study of this event indicates that global warming is increasing both the likelihood and intensity of such extreme precipitation events (Tradowsky et al., 2022).

The Karstic hazard (Ek et al., 1999) involve subsidence (slow movement of the ground) or collapse (movement of the ground). It results, typically, from the evacuation of weathered limestone within the massif, rather than from the collapse of a gallery roof because of excessive load for example.

This hazard mainly affects limestone under detrital cover, which is more favourable to the formation of karstic collapses. The main concern in the Geopark is the stability of the base of a pillar supporting a motorway viaduct 30 metres high, built on a karstic area. Such area is characterised by high settlement dynamics and was studied for decades.

Seismic hazard rate in Belgium has been calculated probabilistically, resulting in a map of the maximum ground acceleration over 475 years. The maximum seismic hazard is 0.16g in Hainaut and eastern Belgium, and less than 0.06g in the eastern Geopark. Seismic risks must be considered for surface structures and caves (Camelbeeck et al., 2020) because even though earthquakes may have little impact on structures, they can be of a significant impact on caves, including rockslides, modification of underground streams, and speleothem rupture.

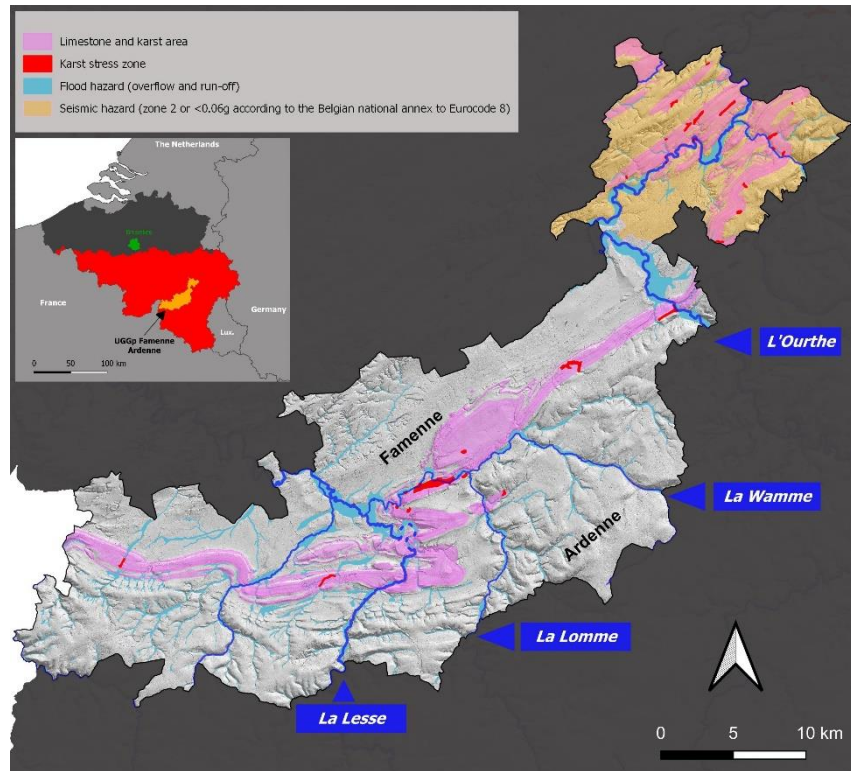


Fig.2: Schematic map of geohazards in the Famenne-Ardenne UGGp.

Geohazards research, education, and dissemination

The sediments found in caves, referred to as endokarstic sediments, serve as valuable environmental archives. A notable correlation exists between detrital sediments and cold periods, as well as between speleothems and warm periods. Speleothem archives possess the advantage of being relatively easy to date using the uranium/thorium method and are widely distributed geographically.

During the torrential rains of July 21, the river system in the Geopark surpassed its known maximum levels, causing chaos on the alluvial plains. Underground conditions mirrored this upheaval: unprecedented water levels flooded galleries that had remained dry since at least the time they were last used or known by humans. Some cavities displayed no traces of water after a few days, while others retained the smell of fuel oil for several months, with omnipresent silt deposits. In extreme cases, the development of black bacterial films occurred in areas that were previously only mineral. Speleothems appear to record such events, offering new avenues for scientific research, especially in studying the return periods of floods. However, research on speleothems extends beyond floods, as the Geopark team, in collaboration with universities and scientific institutions, engages in various research projects in hydrogeology, paleoclimatology (Allan et al., 2018), and paleoseismology (Martin et al., 2020).

The Famenne Ardenne UNESCO Global Geopark team responsibly informs the local population, decision-makers, and visitors about geohazards and aims to mitigate the effect of geohazards through education.

Studies on geohazards are promoted through different tools. Speleothems are powerful tool to show previous geohazard events in the geological record. A nice example is the interpretation panel describing speleothem research results in a very popular and highly visited tourist cave (figure 3). Also, a short movie has been produced in the Geopark area to illustrate recent geohazard issues. The movie, financed by the Wallonia-Brussels Community, is shown in the Geopark House and, under request, at the Geopark partners' locations.



Fig.3: In-situ scientific outreach panel for a research project on speleothems in a popular tourist cave

The Relationship between Landslides and Water Quality in Fforest Fawr UNESCO Global Geopark and the wider Brecon Beacons National Park

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Introduction

Fforest Fawr UNESCO Global Geopark constitutes the western half of the Brecon Beacons (Bannau Brycheiniog) National Park in Wales, UK.

Water is recognised as a significant resource in UNESCO Global Geoparks, which needs to be protected and used sustainably (Zierler et al., 2023). In the Fforest Fawr Geopark and wider Brecon Beacons National Park, reservoirs supply potable water to 1.5 million homes and businesses across south and mid Wales. In recent years Dwr Cymru/Welsh Water has attributed the increase in suspended sediment within the reservoirs, that adversely impact the quality of water, to the effects of an increase in the number of landslides and debris and earth flows in response to intense rainfall events.

In the Geopark, two forms of landslide predominate. On the sparsely vegetated, steep-sided slopes underlain by Devonian sandstones and mudrocks ranging in age between 319.3 – 419.2 million years (Barclay et al., 2015), long, narrow debris and earth flows are typical. Instability on gentler slopes, often with a mantle of weathered bedrock or Late Quaternary-age superficial deposits, tends to result in relatively shallow planar or non-circular rotational landslides (slumps).

Landslide-derived sediment transported by streams and rivers proximal to the flows and slumps then pollutes and contributes to turbid water in the public water supply reservoirs with fine particles of suspended sediment (clay) (Figure 1). The resulting, pink-tinged water typically requires additional filtration and treatment. These “red events” as they have been labelled locally, have been highlighted in national news reporting (BBC Website, June 2021).

Understanding landslides

Landslides are the product of the sudden or slow mass movement of material down valley-side slopes or cliffs and in association with intense rainfall events and flooding, can have a significant geomorphological impact on the landscape. The British Geological Survey (BGS) classify their style of movement into four principal types (BGS Website, 2023a), based on descriptions by Varnes (1978):

- *Falls* – collapses of material from a near-vertical cliff or steep slope.
- *Topples* – rock masses or debris which rotate about a pivot point and move downslope.
- *Slides* – rotational slides that occur on curved slip surfaces and translational slides that occur along distinctive planar surfaces of weakness in the underlying substrate of the slope.
- *Flows* – slope failures in which the downslope movement of mud or debris occurs as a viscous fluid.

Fig. 1: A) The River Usk, which flows for 39.5km through Fforest Fawr Geopark, with a high suspended sediment load after an intense rainfall event. B) Clay fraction suspended sediment in Cantref Reservoir, Fforest Fawr Geopark during a "red event". (photographs by Alan Bowring)



Varnes (1978), further recognised complex failure types incorporating more than a single failure type and assessed their typical forms across three main substrate types of rock, debris, and soil.

Landslides in Fforest Fawr

Landslides in the Geopark and wider National Park are primarily single, non-circular, rotational slump failures or debris and mud/earth flows, or a combination of these processes (Figure 2), reflecting Varnes (1978) more complex failure types. They can occur on a range of scales varying in length from a few metres to tens or hundreds of metres in length, depending on the steepness of the slope and the nature of the underlying substrate.

Landslides in the Geopark are not a recent phenomenon. Numerous small and large landslides have been identified on geological maps, many of which are now stabilised. Photographic evidence from the late 1960s / early 1970s indicate the presence of a number of debris and earth flow-type slope failures on the steep north faces of Pen y Fan and

Corn Du, the highest peaks in the Brecon Beacons massif near the eastern boundary of the Geopark.

Research by BGS has combined monthly rainfall statistics released by the UK Meteorological Office with the occurrence of recorded landslides in the BGS National Landslide Database. Figure 3 (BGS Website 2023b) shows the relationship between rainfall in Wales and the occurrence of landslides during the single month of July 2022. The graph illustrates the direct relationship and lead-and-lag relationship between some summer rainfall events and landslides.

It is recognised that intense rainfall events may not be the sole factor driving the occurrence of landslides, which can result from a number of conditioning factors such as:

- Loading of the upper part of a slope which adds mass, reduces the strength of the material and friction, and facilitates downslope movement.
- The increase in the angle of the base of a slope due to continuous erosion by a river, the sea or human influence.
- The reduction in the strength of unconsolidated slope material by the removal of particles or through weathering processes such as freeze-thaw which reduces cohesion between fragments in the slope cover.

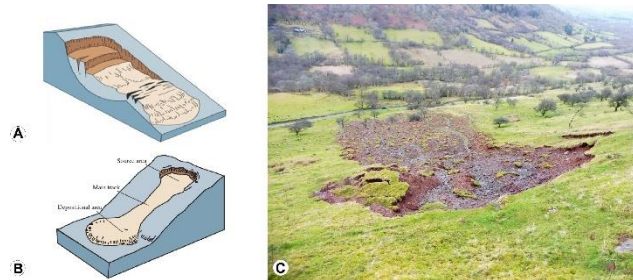


Fig.2: A) Typical appearance of a single rotational failure (slump). B) Typical “hourglass” appearance of an earth flow with a wider source area and depositional areas compared to the width of the main track. (after Varnes, 1978). These diagrams show and name important features seen in the photograph. C) Example of earth/debris flow-type slope failure in periglacial Head deposits derived from Devonian-age weathered Old Red Sandstone at Blaen Senni, Fforest Fawr Geopark after an intense rainfall event. Note the arcuate headwall of the source area in the foreground and the finer-grained depositional area at the foot of the slope in the middle distance. The main track is partially hidden by a break of slope (change of slope angle), which can be initiation points for slope failures. (photograph by Alan Bowring)

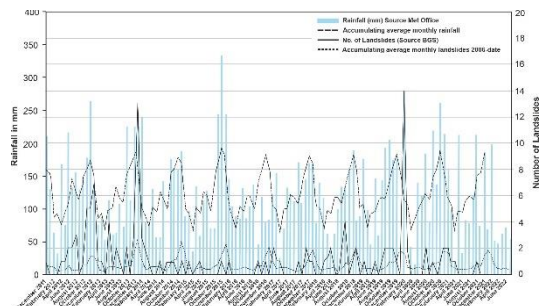


Fig.3: Rainfall (source: UK Meteorological Office) and landslides (source: BGS) in Wales for the month of July 2022. BGS © UKRI

- The absence or removal of vegetation. Plant roots with their interconnecting fibrous nature penetrate fractures and attach the slope material to the bedrock.
- The uptake of water by plants modifies the soil water regime.
- Changes in surface water drainage patterns by human activity through construction or agricultural practices.

However, intense rainfall events, particularly in the summer months, which can be extremely localised, introduce large amounts of water into the sub-surface in a short period of time. This water quickly exceeds local thresholds by reducing the strength of material as it becomes saturated, reducing friction and lowering cohesion of the substrate material, so facilitating downslope mass movement failures.

Landslide frequency and mitigation

Landslides and debris flows in the Geopark were once largely restricted to winter months, following prolonged wet periods or as a consequence of melting snow. They are now an all-year-round phenomenon. The increase in their frequency reflects the increase in intense rainfall events that are attributed to global warming and climate change (BBC Website, June 2021). The pollution and degradation of the water quality in public supply reservoirs due to an increase in severity of “red events” associated with mass movements has resulted in the closure of a water treatment plant and the increased use of chemicals and energy” to clean the water of the red suspended sediment load.

In order to mitigate the effects of landslides on water quality Dwr Cymru/Welsh Water is undertaking a programme of planting thousands of willow whips (*Salix viminalis*) in the catchments of the reservoirs to stabilise land (Dwr Cymru/Welsh Water Website, 2023).

Geohazards education and dissemination

Predicting landslide occurrences such as those associated with intense rainfall is extremely difficult. Through raising awareness of the impacts of climate change, Fforest Fawr Geopark is working with students of all ages to understand the behaviour and occurrence of mass movements, The Geopark is also proactively informing communities and visitors of the risks not only of being directly affected by a landslide event whilst exploring the Geopark, but also raising awareness of the potential adverse impacts on our essential resources.

Conclusion

Intense rainfall events causing an increase in slope failures in the Geopark have been attributed to climate change. These events are resulting in an increase in suspended sediment load in water supplies intended for human consumption. Complex and expensive chemical and filtration treatments are required to maintain water quality, and more nature-based solutions, such as tree planting, are being actively pursued to minimise the impact.

Understanding and mitigating the impacts of mass movements triggered by intense rainfall events associated with climate change will become increasingly important. The results of an international workshop on the role of water resources in UNESCO Global Geoparks (Zierler et al., 2023) highlights their efforts in protecting the sustainable use of their water resources. Assessing slope stability around public water supply reservoirs across UNESCO Global Geoparks in partnership with water service providers and landowners should be actively considered and strategies put in place to reduce the longer-term costs of water treatment to protect this most vital resource.

Seismic hazard in the Granada UNESCO Global Geopark

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Introduction

The geological hazards in the Granada UNESCO Global Geopark are mostly related to the seismic activity, directly tied to the tectonic background of the Guadix-Baza Basin and the central sector of the Betic Cordillera, where the Geopark is located. This tectonic context is characterized by the movement and interaction of several tectonic plates over the course of the last 10 million years: the Nubian (African) plate, the Eurasian plate, and the smaller Alboran plate, situated between these two.

In the territory of the Granada Geopark, plate interaction has produced extension of the Earth's crust. This process is ultimately responsible for the seismic hazard through the formation of several faults (Fig. 1), kilometric fractures that offset and displace large portions of crust in relation to others. The displacement along faults produces friction and locking between these large volumes of rock, leading to the accumulation of significant amounts of energy. When the rupture finally occurs, the fault "unlocks" and all of this energy is released, causing earthquakes.

Most of the faults present in the Geopark (Fig. 2) are normal faults that sink and rise crustal blocks, producing a stepped terrain relief. Some examples are the Graena and Zamborino faults, and most especially the Baza fault. Associated with the activity of the Baza fault, the Galera fault has also developed. This is a strike-slip fault, which produces a main horizontal displacement of the blocks to the north and south of it.

Seismogenic active faults in the Granada Geopark

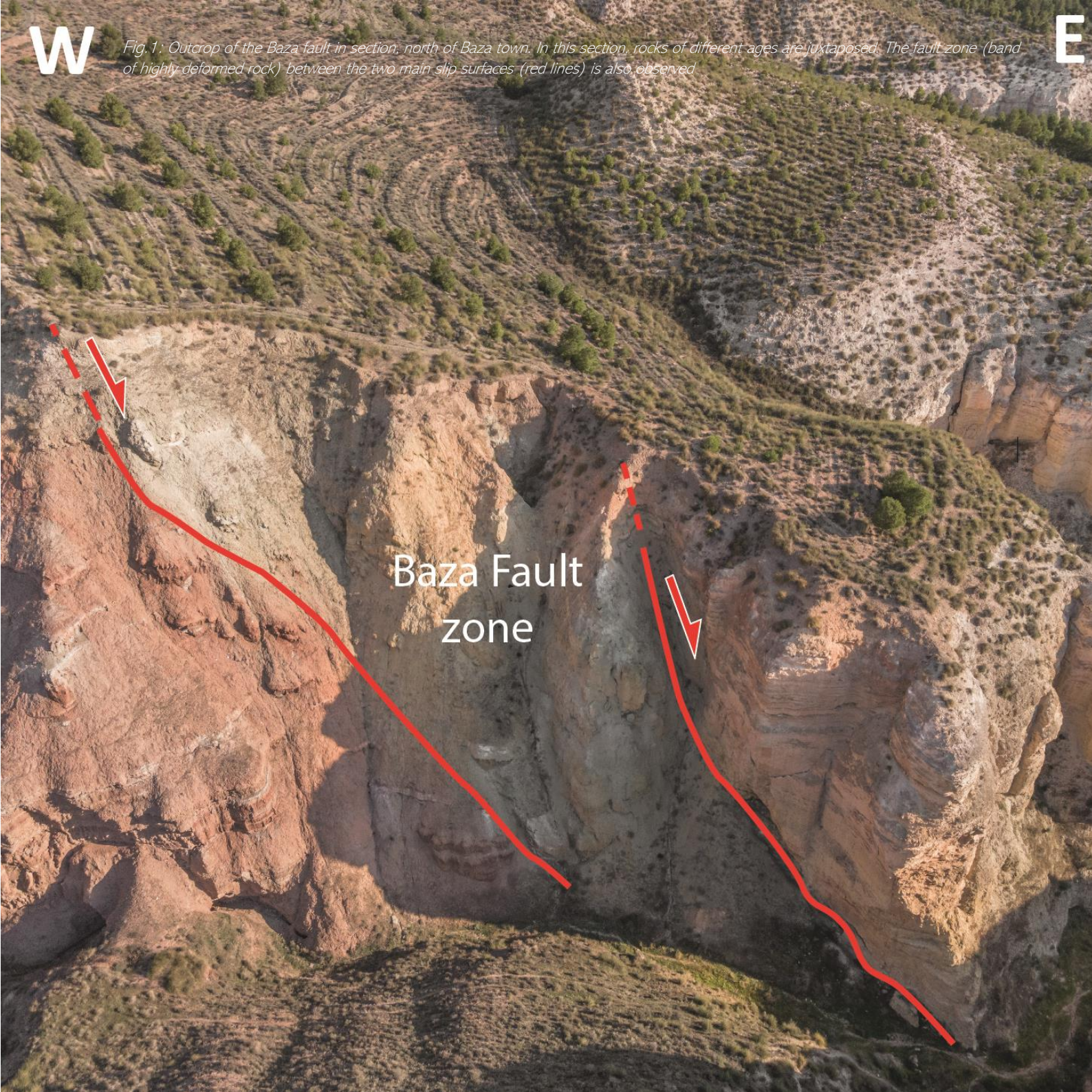
A seismogenic fault is that with the potential of producing earthquakes. The seismogenic potential of a fault and thus its seismic hazard, is defined mainly by two parameters: the maximum earthquake that it can generate, and the time elapsed between earthquakes of this size, referred to as the recurrence time. Moreover, a fault is considered active when it has caused earthquakes during Quaternary times. Within the borders of the Granada Geopark, there are two main active faults: the Baza fault and the Galera fault.

The Baza fault (Fig. 1) is a 40 km long fracture, which crosses the territory of the Granada Geopark from south to north (Fig.2). The Baza fault is a normal fault that raises the western sector and sinks the eastern sector of the Geopark. Since approximately 8 Ma, the fault has produced a vertical displacement of more than 2,000 metres (Alfaro et al., 2008). Geologists have calculated the velocity (slip-rate) of the Baza fault using high precision GPS devices, being estimated in approximately 0.7 mm per year (Alfaro et al., 2021). Despite its low velocity, the Baza fault is one of the most active faults in the central Betic Cordillera and has produced earthquakes during the last centuries. Actually, the most destructive event reported in this region occurred on this fault. This was the 1531 AD Baza earthquake, which shaking, with an intensity of VIII–IX (Martínez-Solares and Mezcua, 2002), was responsible

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Fig. 1: Outcrop of the Baza fault in section, north of Baza town. In this section, rocks of different ages are juxtaposed. The fault zone (band of highly deformed rock) between the two main slip surfaces (red lines) is also observed



for 310 deaths and severe damage in the towns of Baza and Benamaurel. Apart from this big event, the Baza fault has also been responsible for numerous low-magnitude events during the historical (previous to 1900) and instrumental (after 1900) periods (Martínez-Solares and Mezcuá, 2002). Recent studies (Medina Cascales et al., 2020) have estimated the seismogenic potential of the Baza fault, taking into account parameters such as the size of the fault and its velocity. They conclude that the fault can produce earthquakes with a maximum magnitude of 6.7 to 7, with recurrence times ranging between 2000 and 2200 years.

The other large seismogenic structure is the Galera fault, a 30 km long, which runs close to the NE border of the Guadix-Baza Basin (Medina Cascales et al., 2021) (Fig. 2). Although the total displacement of the fault is unknown, it moves laterally about 0.5 mm per year, according to GPS studies. The Galera fault has been responsible for several low-magnitude historical earthquakes, including the 1964 Galera earthquake, with a magnitude of 4.8 and an intensity of VIII (Martínez-Solares and Mezcuá, 2002).

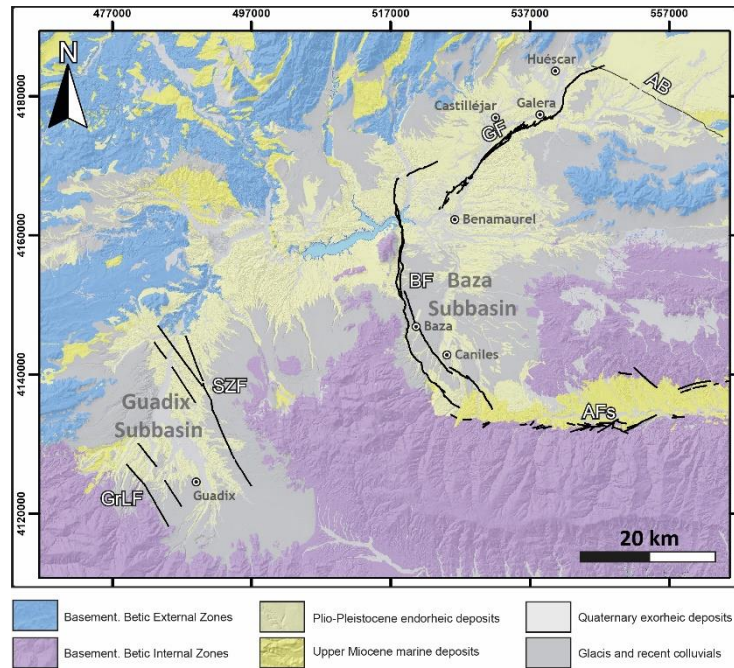


Fig.2: Geological map of the Guadix-Baza Basin and its main active faults: BF: Baza Fault, GF: Galera Fault, AFs: Almanzora Faults, AB: Alfahuara-Botardo structure, SZF: Solana de Zamborino Faults, GrLF: Graena-Lugros Fault

The study of “fossilized” earthquakes to define the seismic hazard

In regions with slow-moving faults like the Guadix-Baza Basin, significant earthquakes occur every few thousand years. The seismic history of the Geopark's faults, such as the Baza and Galera faults, have been recorded for the past 500 years through historical documents, and more detailed study over the last century due to the installation of a seismograph network in Spain. However, our knowledge of large earthquakes remains incomplete and imprecise since they are uncommon. Consequently, to gain a better understanding of active fault behavior and thus improved seismic hazard studies, scientists search for preserved ancient earthquakes in the geological record, known as paleo-earthquakes.

Close to the Baza and Galera faults, there is abundant evidence of paleo-earthquakes in the form of several successive levels of seismic features in rocks dating back 1 to 3 million years (Alfaro et al., 2010). These are sedimentary deformation structures caused by earthquakes. When certain conditions are met, such as loose and water-saturated

sediments with varying density, seismic waves can temporarily transform the sediment into a quasi-fluid state, expelling water and causing rapid deformation. This phenomenon is known as liquefaction. These seismites in the Granada Geopark indicate a moderate to high magnitude, since, to produce liquefaction it is necessary to have enough energy to deform the sediment (earthquakes with magnitudes higher than 4.5).

Apart from these million-year-old-earthquakes, there is also evidence of seismic events in more recent times, recorded within the river terraces of the past thousand years. Geologists have studied these sediments in order to construct a record of recent Quaternary paleo-earthquakes. To achieve this, they search for areas where the fault is covered by relatively recent deposits. Trenches are dug at these locations (Fig. 3), and the scientists analyze whether the fault has deformed the younger sediments. If such evidence is found, it confirms the occurrence of an earthquake. By dating the deformed sediments, using radiometric techniques, the ages of these paleo-earthquakes are calculated.

In the Baza fault, 9 paleo-earthquakes were identified within the past 45,000 years, estimating recurrence times of approximately 5,000 years for these major seismic events (Castro et al., 2018). This number is a minimum frequency, as there could have been additional paleo-earthquakes that are not recorded in the trenches. In the case of the Galera fault, scientists have also found recent evidence of several paleo-earthquakes within the past 20,000 years.



Fig.3: Palaeoseismological site close to the town of Castilléjar. In this site, three trenches were excavated where the Galera fault (red line) offsets recent fluvial terrace deposits

Geohazards education and dissemination

The stunning nature of the outcrops of the Baza fault zone and the Galera seismic rocks has generated great interest, captivating not only international experts in seismology and active tectonics, but also tourists visiting the Granada Geopark. To take advantage of this opportunity and to preserve these structures of geological interest, two geological routes have been designed. These routes feature informative panels that provide insights into faults and earthquakes in order to raise awareness among the general population about the geological hazard occurrences in the region. Moreover, within the educational program of the Granada Geopark, these two routes are a popular destination for primary and secondary school students throughout the province of Granada. They also serve as resources for students from various Spanish universities and abroad, which incorporate visits to the routes into their field studies. In addition, the Granada Geopark itself organizes guided tours to these locations, providing visitors with a comprehensive understanding of the seismic hazard.

The Impact of Submarine Volcanic Activity on the El Hierro UNESCO Global Geopark: A Comprehensive Analysis.

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Introduction

The Canary Islands is a volcanic archipelago located west of the Morocco coast. Geohazards in El Hierro UNESCO global Geopark (and also Lanzarote UNESCO global Geopark) are strongly related with volcanic activity.

The Canary Islands is a volcanic archipelago located west of the Morocco coast. Geohazards in El Hierro UNESCO global Geopark (and also Lanzarote UNESCO global Geopark) are strongly related with volcanic activity. Several historical eruptions and seismic crisis demonstrate that volcanic activity in the archipelago is still significant. Therefore, the methodologies and instrumentation used for seismic, geophysical, geological, geodesic and geochemical monitoring have been developed intensively during the last decades. This is similar to other European Geoparks located in regions of active volcanism such as the Icelandic Katla Geopark (eruption of Eyjafjallajökull) and Reykjanes Geopark (eruption of Fagradalsfjall).

The submarine eruption that occurred in El Hierro between 2011 and 2012 represented a new challenge for the volcanic monitoring centre, the local community, scientific groups, civil protection agency, the administration, and the press. This submarine eruption, off the coast of La Restinga in Hierro, began on October 10th of 2011, and became the second longest and largest historical eruption in the Canary Islands, following the Timanfaya eruption in Lanzarote between 1730 and 1736 (López, 2013).

Alike other historical eruptions in the Canary Islands, El Hierro volcanic process, a fissure type eruption of basaltic/basanite composition, and predominantly characterised by effusive and strombolian activity (Figures 1 and 2), could be considered as a low-risk event (Somoza et al., 2017). However, it had a great impact on society and the local economy. Moreover, considering its submarine nature, it had a significant impact on the underwater ecosystems of the Mar de Las Calmas marine Reserve in Punta La Restinga, one of the best-preserved coastlines in the Canary Islands.

The scientific institutions in the Volcanic Emergency Plan of the Canary Islands (PEVOLCA) Scientific Committee and particularly the Spanish National Geographic Institute (IGN), deployed a multiparameter surveillance system crucial to managing the eruption processes. The experience accumulated in the management of this eruption, and especially in the knowledge of the different eruptive precursors (López, 2012), was key to help on the management of the 2021 La Palma eruption.

Fig. 1: Aerial view of the manifestations of the submarine eruption on the marine surface



A submarine eruption story

The eruptive process began on October 10th (Table 1), 2.5 km from the coast and at a depth of 220 meters, but the first material produced by the eruption was recorded on October 15th, in the form of what came to be called "restingolites". The "restingolites" are rugby ball-shaped objects, up to 30 cm in size, with porous white core (xenopumite), wrapped in a golden-black crust of basanitic composition.

During the first months of activity, both the PEVOLCA working group and the media warned about the possibility of reaching a higher explosive Surtseyan eruptive scenario, and even though the eruptive point reached a depth of 88 meters, the final volcanic scenario produced a less explosive eruption than expected (Pérez-Torrado F.J. et al., 2012).

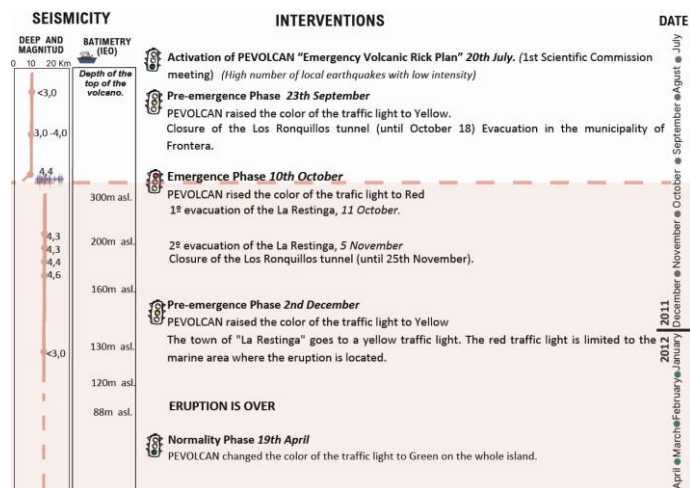


Table 1: Chronicle of the Tagoro volcanic eruption

Impact to the environment and local communities

Before the volcanic eruption there were several seismic movements that were connected to the volcanic event, which generated social uncertainty and fear, especially when the road between the two main municipalities of the island were closed. There were also two evacuations from the municipality and social and economic emergency alarm were declared by the local authorities. On the other hand, the lack of knowledge and information provided to the population about possible scenarios that may accompany the volcanic activity in the following months, added to some media misinformation, made the local community live the eight months-long eruption in an atmosphere of complete uncertainty and restlessness.

When the volcanic alarms began during the pre-eruptive process and the seismic activity began, tourists were scared and left El Hierro, severely disrupting the tourism industry, the island's main source of income. The Restinga area is one of the best destinations in Europe for scuba diving. The eight diving centers had to stop their activity for about eight months. Moreover, fishing was prohibited from October to April. Therefore, the entire economy of La Restinga was strongly affected.

The marine environment was also affected, with some consequences on the "mar de las calmas" sea, considered one of the richest and healthiest ecosystems in the Canary Islands. This area was declared a marine reserve in 1996 and a special conservation since 2011. The volcanic eruption changed the submarine physico-chemical conditions by the increase of temperature, increasing iron concentrations and decreasing Ph and oxygen concentration among others. All these new parameters caused a high concentration of fish mortality, mainly affecting benthic species. During the

volcanic activity no marine life was recorded by the oceanographic boats Ramón Margalef (Spanish Institute of Oceanography) and Atlantic Explorer (Las Palmas de Gran Canaria University) surveying the area (Fraile-Nuez, 2012).

Initiatives emerged after the eruption

Following the submarine eruption a series of actions were carried out to enhance and benefit the local economy and a new type of sustainable and informative tourism, thanks to the impetus and economic commitment of El Hierro local government.

Firstly, the island of El Hierro was declared a Geopark by UNESCO in 2014. The Geopark status was awarded thanks to the application promoted by the Ministry of Industry, Energy and Tourism in collaboration with the El Hierro local government, namely El Cabildo, within a Special Action Plan created to alleviate the effects and impacts from the 2011 volcanic eruption.

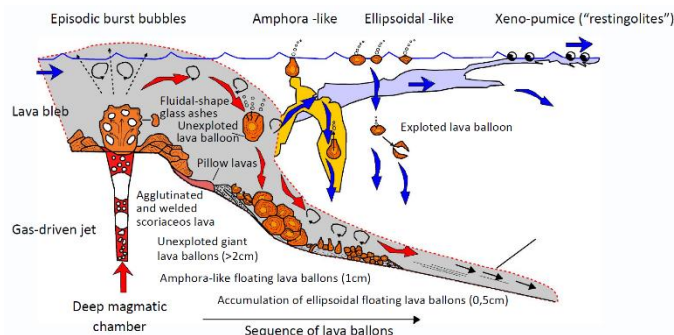


Fig.2: Eruptive model and products of the submarine eruption. Modified from Somoza et al., (2017)

By February 2015, El Hierro Volcanological Interpretation Center was built, thanks to the European Regional Development Funds, promoted by the government to stimulate business and industrial activity and setting up new technologies. The Center, based in the Lajiales de La Restinga and comprising two buildings, motivated the recovery of the space of an old quarry and allows learning about volcanic events, geology, and volcanism in the Canary Islands, focusing particularly on the 2011-2012 eruption that gave way to the Tagoro submarine volcanic structure.

A research project, namely VULCANA, with the objective of producing the first ever multidisciplinary data time series records to quantify the degree of impact on the marine ecosystem of the eruptive processes associated to an underwater volcanic event, showcased that the underwater life recovered faster and stronger than scientists originally predicted. However, this has not only been demonstrated by the videos collected by scientists and their respective published articles, but also by La Restinga fishermen and the diving centers operating in the area, that have noticed how in the years following the underwater eruption, life in the vicinity of the volcano has become much more exuberant than before the volcanic event (Fernández de Puellas, 2021).

On the other hand, following the Tagoro volcanic eruption several educational and dissemination projects related with the different aspects of volcanic risk were implemented throughout Primary and Secondary Education centers of the Island and courses aimed to the local community and tourists.

In summary, the island community managed to find a way to adapt and recover from the Tagoro volcanic crisis and all the issues that came up during this long-term event. Today the crisis is used to show the beauty of nature and the benefits for society.

Geohazards in Katla UNESCO Global Geopark

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Volcanic geohazards and jökulhlaups in Katla Geopark

Geohazards in the Katla UNESCO Global Geopark (UGGp) are closely linked to volcanic activity in several volcanic systems within or partially within the Geopark. These systems include Tindfjallajökull, Eyjafjallajökull, Katla and Grímsvötn (Figure 2). Geohazards resulting from eruptions in these systems encompass landslides, flooding, lahars, lava flows, tephra fall, ash clouds, pyroclastic flows, earthquakes, lightning, and jökulhlaups (glacial outburst floods).

Large jökulhlaups form when subglacial eruptions occur, melting large amounts of glacial ice. This meltwater breaks through the glacier, rapidly spreading over vast lowland areas and carrying volcanic material, icebergs, sediments, and debris (Figure 3). Small jökulhlaups form as result of geothermal activity beneath glaciers, where meltwater accumulates in subglacial lakes that periodically drain, and they can result from ice-dammed lakes. Both types, though smaller than eruption-induced jökulhlaups, are more frequent. For example, Skaftárkatlar subglacial lakes within the Grímsvötn volcanic system drain, on average, every two years.

Due to all volcanic systems in Katla UGGp being at least partially subglacial, eruptions tend to cause jökulhlaups. All systems, except Tindfjallajökull, have caused jökulhlaups in the last 1200 years. While these events have not resulted in high numbers of fatalities in Iceland, they have caused significant property damage, sweeping away roads, bridges, farmland, and other infrastructure.

The most dangerous jökulhlaups stem from eruptions in Katla and Eyjafjallajökull volcanoes. The proximity of agricultural lands around these volcanoes increases the danger, as agricultural areas are often situated on floodplains formed by previous jökulhlaups and sedimentation from glacial rivers since the end of the last glaciation in Iceland. Outwash flood plains still active today include Markarfljótsaurar, Landeyjasandur, Skógasandur, Sólheimasandur, and Mýrdalssandur (see Figure 2).

An important factor to consider is the uncertainty about the direction of the floods. This is determined by the eruption site beneath the glaciers, which is unknown until the eruption begins (Einarsson and Hjartardóttir, 2015; Gylfason et al., 2012; Gudmundsson et al., 2008; Larsen, 2018; Óladóttir et al., 2005).

The 1918 eruption of Katla

The Katla volcanic system (see Figure 2) spans approximately 80 km and comprises an ice-capped central volcano with a 1,450 m elevation. The volcano encompasses a 110 km² and 700 m deep ice-filled caldera and a SW-NE trending fissure swarm. Mýrdalsjökull glacier covers an area of approximately 590 km² and has an average thickness of 230 m, with the thickest part located within the caldera.

Fig.1: Photo taken north of the farm of Þorvaldseyri, showing the pathway and the deposition of the jökulhlaup to the south during the 2010 eruption of Eyjafjallajökull. Subsequently, a small lahar deposited fine ash layer on top of the coarser jökulhlaup deposits. Photograph: Ólafur Eggertsson



The caldera walls are breached at three locations, allowing ice-flow from Mýrdalsjökull glacier to form the three main outlet glaciers: Entujökull in the west, Sólheimajökull in the south, and Kötlujökull in the east. These three outlet glaciers serve as the main pathways for jökulhlaups, with the most common pathway during the last 1,100 years being through Kötlujökull (Larsen, 2018; Óladóttir et al., 2005).

The most recent major eruption in Katla occurred on October 12, 1918, and lasted for 24 days. Earthquakes were felt around 13:00hrs, and an eruption column was observed at around 15:00hrs. Shortly after, the first signs of the jökulhlaup were observed, and the flood followed through the Kötlujökull outlet glacier. The maximum flow rate during this event was estimated to be up to 300,000 m³/s and it carried sediments and icebergs up to 60 m in height. The jökulhlaup affected the area east of Katla, extending the shoreline several kilometers to the south, particularly south of Mt. Hjørleifshöfði (see Figure 2), and raised the height of the flood plain by an average of 2.6 m. The flood damaged agricultural land for 18 farms, resulting in the abandonment of three of them. Roads and bridges over the floodplain and nearby rivers were swept away, and a few hundred sheep perished, along with 37 horses. Fortunately, there was no loss of human life during the jökulhlaup, although several people had close calls as they fled from the flood (Larsen, 2018).

The 2010 eruption of Eyjafjallajökull

Eyjafjallajökull (see Figure 2) is a partially ice-capped central volcano, approximately 30 km long and 15 km wide, with an elevation of 1,650 m. It has a small rift zone east and west of its small

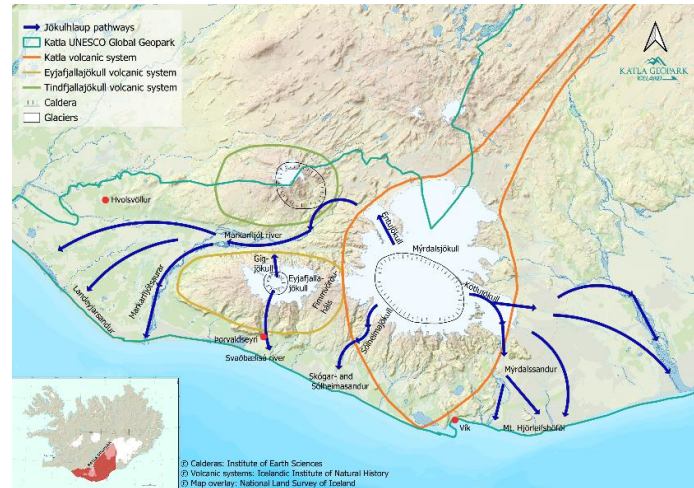


Fig.2: Map of the western part of Katla UGGp, showing the location of the three volcanic systems of Tindfjallajökull, Eyjafjallajökull and Katla, along with the jökulhlaup pathways, their outwash plains and other placenames referred to in the text. Map from Katla Geopark.



Fig.3: Photo showing a part of the Höfðabrekkujökull deposit which was formed by jökulhlaups from Katla in 1721 and 1755. Most of the deposit is volcanic material with a grain size range from silt to boulders, but also has large, brown-coloured pieces of soil that were uprooted in the flood and then imbedded within the matrix of the deposit. Photograph: Katla Geopark.

summit caldera. The Eyjafjallajökull glacier partially covers the volcano, with thicknesses of up to 200 m in the caldera. Ice flowing from the caldera feeds the main outlet glacier of Gígjökull, which flows northward through a breach in the caldera wall. Eyjafjallajökull volcano is at least 780,000 years old and has only experienced four known eruptions in the last 1,100 years, but it is not considered to be very active. The main pathways for jökulhlaups from Eyjafjallajökull are not as well-known as Katla's, but jökulhlaups formed by eruptions within the caldera are most likely to follow the path of Gígjökull outlet glacier down to the lowlands. The 2010 eruption was preceded by four intrusion and seismic events from 1992 to 2010, culminating in the flank eruption of Fimmvörðuháls on the 20th of March, followed by the summit eruption of Eyjafjallajökull (Einarsson and Hjartardóttir, 2015; Gylfason et al., 2012).

The 2010 summit eruption started on the 14th of April from a fissure in the caldera of Eyjafjallajökull and was phreatomagmatic as the eruption melted its way through the ice. The eruption caused several small jökulhlaups in the following weeks, with the first flood being the largest at approximately 2,500-3,000 m³/s. All the jökulhlaups, except one, flowed through Gígjökull outlet glacier and then into the Markarfljót glacial river. Damage caused by the jökulhlaup was minimal, as levees built to control the flow of the Markarfljót river held, preventing damage to agricultural land, and the main road was cut to preserve the bridge over Markarfljót (Einarsson and Hjartardóttir, 2015; Gylfason et al., 2012).

A small jökulhlaup, caused by a short-lived eruption vent south of the caldera, traveled down the southern side of Eyjafjallajökull. The jökulhlaup created a 3 km long trench in the glacier and flowed into the river Svaðbælisá. The flood eroded the riverbed before depositing large amounts of sediments, including large boulders, on the outwash plain (see Figure 1). The flood also caused damage to agricultural land and threatened the farm of Þorvaldseyri, but pre-existing levees managed to divert most of the flood away from the farm (Gylfason et al., 2012).

Geohazard awareness and education

Due to the high risk from jökulhlaups in the Katla Geopark, having knowledge about these events and how to respond to them is essential for both residents and visitors in the area. It is particularly crucial for people living within the Geopark, but it should also be known by those who are visiting the area for a shorter time. School children in the towns of Hvolsvöllur and Vík, the two towns that can be affected by jökulhlaups from Katla and Eyjafjallajökull, are taught about volcanic eruptions and jökulhlaups from an early age, and regular response exercises are held in the communities. Extensive research has been conducted on the nature and size of jökulhlaups, their pathways, and how to minimize the risk and damage they can cause. This research has significantly contributed to mapping out flood pathways and timings, as well as creating evacuation plans for the affected areas (Gudmundsson et al., 2008; Larsen, 2018; Óladóttir et al., 2005).

Given the increased tourism in the region, bringing people into risk areas that would otherwise be empty, educating both residents and visitors about the potential hazards is paramount. Geology students, both from Iceland and elsewhere, often visit the outwash plains to study the deposition during jökulhlaups. These educational visits provide valuable insights into the geological processes involved and the impact of jökulhlaups on the landscape. Additionally, students have the opportunity to explore a paleo-forest that was both destroyed and preserved by a past jökulhlaup, adding a unique dimension to their studies.

Kefalonia-Ithaca UNESCO Global Geopark, an earthquake laboratory

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Introduction

Kefalonia and Ithaca Islands are the westernmost islands of the External Hellenides. They are located very close to the Greek arc, which is the most tectonically active region in Europe (Tsapanos et al., 1990, Mavroulis et al., 2017). Due to their geotectonic position, the islands present rich geology and great seismic activity, on which we find an excellent depiction of the dynamics of related terrestrial processes, through the numerous and wide variety of geological features. Two geotectonic zones (alpine formations) bordered by a major thrust are present. They are mainly represented by carbonates of Jurassic to Miocene age and Triassic evaporates. Plio-Quaternary post-alpine sediments can also be found lying uncomfortably on the alpine formations. Kefalonia-Ithaca UGGp is located on a key location very close to the Greek Arc, where the African plate sinks below the Eurasian plate. This has resulted in, the geopark's presents rich geodiversity and high level of significant seismic activity - the greatest in all of Europe. The geopark's surface geology is dominantly limestone. Tectonic activity, the climatic conditions and the processes of erosion and deposition of this limestone has created the mountainous topography with numerous steep cliffs, rock falls and landslides, as well as underground and surface karstic geomorphological features.

Earthquake a phenomenon directly linked with Kefalonia-Ithaca UGGp

The intense and powerful seismic activity is a major and constant hazard in the geopark. The historical archive has recorded more than 65 devastating earthquakes of more than 5R magnitude on the two islands since 1469. Kefalonia has a remarkable seismic history which can be traced back to antiquity. Significantly, the contemporary history of the Islands changed immediately after the occurrence of the Ms=7.2 earthquake of August 12, 1953 (Stiros et al., 1994). Most buildings in Kefalonia collapsed while 455 people died and 2.412 were injured. This resulted in an intense migration of Kefalonians, particularly many of its most creative and dynamic people, depleting the cultural potential here. Catastrophic earthquakes in 1953 led to the destruction and dereliction of entire villages and the 2014 earthquake also had significant social impacts and caused significant infrastructure damage (Papadopoulos et al., 2014, Mavroulis et al., 2017)

Rock falls in Platia Ammos (Geosite 7)

Platia Ammos is one of the most impressive beaches of the Paliki peninsula, and Kefalonia as a whole. At the westernmost point of the peninsula, it has very difficult access throughout a via with more than 400 steps, much of which was destroyed by the earthquake and subsequent torrential rains in the winter of 2014. The impressive landscape and the wild beauty that we observe in Platia Ammos is a result of its lithology and its geotectonic setting. In the area thick bedded Eocene-Oligocene limestones rest stratigraphically on top of the Cretaceous limestones. Platia Ammos is characterized as a steep, straight, relatively deep beach. Its geomorphology is the result of large faults that testify to the intense tectonic activity of the area. These facilitate earthquake activated t rock falls,

Fig. 1: View of Platia Ammos beach from the West. Scree cones or scree can be seen caused by earthquakes (photograph by Haris Andronos)



sometimes resulting in huge masses of debris, creating scree cones (which are the most common consequences of earthquakes here). Platia Ammos is characterized by intense deformation and very high levels of significant seismicity. This is because it is located at the end of the Greek arc in western Greece. Access to the beach is now dangerous (after the 2014 earthquake) and steps need extensive repair. Protective measures and access prohibitions have been put in place.

Rock falls Kipouria Geosite

The geotectonic position of the Kipouria is very close to the NW end of the Greek arc. Its lithologies and faults along the coastal zone of the area, are responsible for the formation of steep cliffs (about 100m high). There are also rock falls, landslides and slope failures that testify to the intense tectonic activity. Eocene-Oligocene thick bedded limestones, stratigraphically located on top of the Cretaceous limestones (like Platia Ammos) are present. Kipouria is located on the westernmost point of the Paliki peninsula. Here, the Holy Monastery of Kipouria is built on the steepest cliffs of Kefalonia. The geology here has created an astonishing viewpoint which has inspired people and gave a sense of being closer to God. So here they constructed a religious monument. The monastery was founded in 1759 by Archimandrite Chrysanthos Boyko-Petropoulos. It was administratively subordinated directly to the Patriarchate (until 1907) and bears a very rich cultural and religious history. Its name "Kipouria" comes from the Greek word "kipos" (land, vegetable garden) as the monks supported themselves by cultivating all the land around the monastery. The monastery was impacted several times by earthquakes (1767, 1867, 1953, 1972, 2014) and has lost all parts of its original buildings.



Fig.2: View of the geosite where Rockfalls, landslides and slope failures that testify the intense tectonic activity. The Holy Monastery of Kipouria can also be seen (photograph by Haris Andronos)

Rock falls in Myrtos Geosite

Myrtos bay is the most famous beach of Kefalonia and one of the main sightseeing locations. The geological formations of the area, from the earliest to the latest, consist of limestones of the Upper Cretaceous, fine-bedded pelagic limestones of the Paleocene, bedded pelagic limestones of the Eocene and finally Miocene marl (clayey) formations. Apart from its scenic beauty, it has special geological interest represented by its geomorphological features and intense active tectonics. The limestone rocks are highly fragmented with large open cracks. Heavy rainfall events and intense tectonics make these rocks prone to rock falls and landslides, while scree deposits accumulate at

the base of the slopes. The earthquake of 2014 was an important event for the initiating landslides and rocks falls on Myrtos beach and along the road network in Charakas. The failures on the road network occurred in Cretaceous (145.5-66.0Ma) to Miocene (23.03-13.65Ma) limestones of the Pre-Apulian zone. They caused damage at five points on the road network due to intense tectonic activity associated with the fracture zone found in the Harakas area. Although the destruction of the road caused travelling problems, it also allowed the opportunity for different ideas to come together in order to design and build a novel road bridge over an active fault zone that is resilient to earthquake activity. This constitutes a significant achievement of engineering (unique in Europe).

Geohazards education and dissemination in Kefalonia-Ithaca UGGp

The geotectonic position as well as the consequences of seismicity of the geopark is the subject of research in all Greek and many foreign universities. This research could be a key for future education as well as a tool for the improvement in protection measures for earthquakes.

Another significant challenge for the geopark is the potential future damage resulting from climate change. Sudden rainfall events and the accompanying floods pose a threat on several geosites. Recent examples occurred in Kefalonia and Ithaca (September 2020). Intense weather phenomena and resulting floods caused severe damage throughout the whole islands. Geopark staff are constantly observing and



Fig.3: The newly built bridge of Charakas which is built on an active fault zone (photograph by Haris Andronos)

recording the weather conditions in order to warn about extreme events and potentially dangerous situations by announcing them through press releases. The Geopark is also constantly vigilant through daily shifts of the personnel and record possible damage in the geosites and in the geopark's area in general related to natural hazards and inform the competent authorities. Kefalonia-Ithaca UGGp also regularly organizes conferences, workshops and outdoor activities directed towards informing the local community and schools about the importance of geohazards management and adaptation, environmental safety, and the ways of protection against harm from geohazard activity.



An Outdoor Laboratory for Geohazards: Kula Salihli UNESCO Global Geopark

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Introduction

Kula Salihli UNESCO Global Geopark covers the administrative borders of Kula and Salihli districts of Manisa province in Western Anatolia. The geopark is in a tectonically active region and hosts evidence of more than 600 million years of Earth history (Aytaç et al. 2023, Aytaç and Demir 2023). The area reflects the characteristics of the Mediterranean climate and offers a unique opportunity to observe different natural disasters from both the present and the past. In terms of geological hazards, Kula Salihli Geopark can be considered as a field laboratory to study earthquakes, volcanism and a wide range of surface processes including floods, droughts, and mass movements. These will be explained briefly below, along with education and dissemination activities connected to geohazards.

Earthquakes

Kula-Salihli Geopark partially covers the eastern part of the Alasehir Graben and the horst block at its northern boundary. Since the geopark is located in a tectonically very active region, earthquakes represent a constant threat. Many major earthquakes have occurred in the region since ancient times, causing numerous casualties and severe material destruction. The damage caused by these earthquakes during historical times is recorded in the Ancient City of Sardis, the capital of the Lydian Empire. In recent times severe earthquakes hit the region in 1965 and 1969. The 1965 Salihli Earthquake (5.5 MAG) destroyed 150 buildings and killed 12 people in the Salihli District. The 1969 Alasehir earthquake (6.5 MAG) devastated 4370 houses and caused 50 casualties.

Volcanism

The volcanism in Western Anatolia began in the Pliocene and has continued into the Holocene (Richardson-Bunbury 1996). It is related to the Earth's crust rifting processes that resulted in the formation of the Alasehir (Gediz) Graben. The Quaternary volcanism continued in different phases in the Geopark and its surroundings up to 2,600 years BP ago. (Maddy et al. 2020). Therefore, this area is considered one of the youngest volcanic regions in Türkiye with Volcanic activity with over 80 volcanoes has resulted in the formation of basaltic lava plateaus covering extensive areas and including numerous forms of lava flows. In particular, the younger volcanic cones formed during the last volcanic activity and its associated lava flows reached 10-15 kilometres long, evidence of volcanic hazards that threaten people in that period (Fig.1). Kula Salihli Geopark considers tracking and documenting volcanic activity as a geological disaster. The most convincing evidence of this can be seen in the prehistoric human footprints near the



Fig.1: Sandal Volcanic Cone and its lava flow. The lava flowed approximately 15 km to the Gediz Valley (Photo: Kamil Altıparmak)

settlement of Sindel in the western part of the geopark and the rock paintings depicting volcanic activity on a schist block in Kanlikaya (Aytaç et al. 2023, Aytaç and Demir 2023).

Volcanic activity and related eruption materials have substantially changed the landscape of the region and have had a significant impact on the lives of people. Indeed, the volcanic landscapes and features observed in the area are among the geopark's most popular and internationally significant geosites. There are currently no active volcanoes in the geopark area, which used to be the site of intense volcanic activity in the past. However, volcanism is still considered a geohazard since the geopark is in the middle with the eastern parts of the tectonically active Gediz Graben.

Lava-Dammed Lake Formation and Catastrophic Floods

Quaternary Volcanic activities in the Kula volcanic region also affected river systems and led to important geological disasters. During the Quaternary, volcanism and associated lava flows partially or completely blocked the Gediz River and some of its tributaries, creating many lava-blocked lakes upstream in the valleys. Lava-dammed lakes caused flooding of large areas including human settlements and croplands. Furthermore, the eventual collapse of some of these lava dams caused sudden catastrophic floods downstream in the valley. The latest example of this type of



Fig.2: Gigantic conglomerate and travertine rock blocks transported by catastrophic floods in the Gediz Valley (Photo: Ali Karatas)

catastrophic spill event is the formation of a lava dam lake because of volcanism and the subsequent dam burst and associated flood event that occurred approximately 2,600 years ago (Late Holocene). Traces of these catastrophic events, such as gigantic conglomerate and travertine rock block deposits transported by catastrophic floods, rapid river valley incision into the previously existing lake sediments prompted by erosion and related mass movements in the valley are still present and well preserved within the geopark (van Gorp et al., 2013) (Figure 2).

Landslides

There are some landslide prone areas within the geopark. The surrounding of the Burgaz, Sarnıç, and Ibrahimaga plateaus covered with Quaternary basalt lava flows, are the most visible examples of contemporary landslides in the region. Another notable example can also be seen on the poorly cemented strata of the north-facing slopes of Bozdağ Mountains, located west of Kula Salihli Geopark. Damatlı Village is also an excellent site to observe historical landslide events that severely destroyed the village, notably the historical structures, and changed the community's development.

Erosion

The Kula Salihli Geopark lies in the Mediterranean climate zone, which is generally hot and dry in summers and mild and rainy in winters. Due to this circumstance, a vulnerable ecology has developed in the area. Human activity has taken place in this region since the beginning of documented history. Due to overgrazing, anthropogenic deforestation, fires, and other factors, the vegetation in the area has suffered serious damage. Badlands cover a vast majority of the region within the geopark, comprising the most prominent example of runoff erosion.

In terms of erosion the Temple of Artemis is a very important example in the geopark. The Temple of Artemis is recognised as one of the greatest temples built in antiquity, the fourth largest Ionic temple of the ancient world. By the 5th century AD it lost its significance, and from the 9th century onwards it was buried by sediments. When excavations began at the beginning of the 20th century, it was seen that all parts of the temple were covered with soil, except for the heads of its two 18 m-long columns. This situation illustrates the very high rates of erosion and sediment accumulation occurred in the last 1000 years.

Drought

Western Turkey is significantly affected by the general atmospheric pressure zones in the northern hemisphere and their associated general atmospheric circulation. Winter precipitation in the region generally occurs due to cyclones originating from both the Polar Front and the Mediterranean basin. However, because of changes in general atmospheric pressure and circulation, some winters can be quite dry, causing significant agricultural losses and disruptions in the hydrological cycle. Climate change, which is significantly affecting the Mediterranean basin, is very notable in this region. Particularly, records show a substantial decrease in the flow rates of the rivers in the region, which has affected the Gölarmara Lake, which has almost completely dried out (Figure 3). On the other hand, summer droughts and high temperatures in the region have also amplified the forest fires.



Fig.3: Gölarmara Lake has almost completely dried out (Photo Ali Karatas)

Geohazards education and dissemination

The Kula-Salihli Unesco Global Geopark offers an education programme to the local community and visitors from all age groups. The educational tools developed address the geological hazards that may threaten the local population and proposes potential mitigation strategies. On scheduled days and weeks, school visits are carried out in connection with geological disasters, other natural disasters, and natural resources. Additionally, online training sessions and meetings are held, information is shared on social media, and activities like tree-planting and garbage collection take place. Natural and geological disaster storytelling books for elementary school students have also been published with the premise that geohazards education should begin at a young age.

Las Loras UNESCO Global Geopark: a useful scenery to disseminate and communicate natural hazards in the context of a risk society

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Introduction

Las Loras is located in the Cantabrian Mountain Range, in the north area of the Castilla and Leon region (Spain) and within the provinces of Burgos and Palencia. It offers a series of unique landscapes shaped by the action of external agents, such as rain and wind. However, the same external agents that created these spectacular landforms could cause their disappearance. High environmental impact catastrophic events, such as extreme rainfall episodes linked to climatic change, could trigger the obliteration and even disappearance of these unique geological landscapes. For this reason, we propose to use the Geopark as a scenery to communicate geology and the risks that can potentially impact on the geoheritage and the local population activities.

Las Loras Geopark encompasses unique geological features that have been qualified as geological heritage sites by the Spanish Geological Survey (IGME), these sites contribute to the characterization of: (1) the karstic systems in carbonates and evaporites of the Iberian Peninsula and Balearic Islands; (2) the rifting of Pangea and the Mesozoic successions of the Betic and Iberian Mountain ranges and; (3) the fossils and ichnofossils from Mesozoic continental successions of the Iberian Peninsula.

Chemical weathering of Mesozoic limestone, groundwater action and gravity are responsible for the construction of the singular landforms found in the karstic landscape of Las Loras Geopark (Figure 1). Las Loras was declared as Global Geopark by UNESCO in 2017, due to the international importance linked to the geological and cultural heritage. It houses numerous landscapes and natural landmarks, building up its exceptional heritage. The attention of visitors in the Geopark is immediately drawn to the powerful visual impact and natural beauty of its landscapes, consequence of surface processes that have been operating for millions of years.

Geoparks refer to geodiversity, use and exploitation of geological resources (e.g., rocks, minerals, and critical raw materials), but also refer to anthropic and natural hazards that may eventually put the Geopark's heritage at risk and threaten the local community. Anthropic and natural hazards can cause the complete obliteration of a world heritage site, like the Iran's World Heritage Site Qeshm Geopark, endangered due to the negligence of the authorities.

Although Geoparks are not a protection figure, in some cases it may include or intersect protected natural areas. In any case, geoheritage sites should be protected by the implementation of local, regional and/or national laws to preserve them for future generations. Geoparks should lead the protection of geological sites, and communicate potential risks (e.g. landslides, rockfalls) that may affect them to the population living in the surroundings areas. The Horadada canyon, one of the most visited sites of Las Loras UNESCO global Geopark, has a landslide that could be

Fig. 1: The landscape of Las Loras Geopark combines structural reliefs like mesas and singular morphologic features known as "Rock city" and "giant mushrooms". This area of the Geopark is called Las Tuerces and it is a natural protected area



reactivated if extreme rainfall events affect the area in the future (Figure 2). This is also the case of Villaescusa de las Torres, where the threatening aspect of the limestone escarpment profile could evolve into rock falling over the village (Figure 3).

Experts should provide expert advice on the potential risks that affect the area throughout seminars, talks and meetings on the framework of Geopark and UNESCO activities. Furthermore, geoparks should support prevention management plans involving the implementation of structural measures to protect individuals, property and geoheritage and to reduce the impact of potential geohazards. These measures should not be only based on heavily engineered interventions, but natural approaches should also be considered. As an example, the use of wetlands, detention basins or natural channelization networks could help reduce the impact of potential flooding events. The measures taken should be compatible with the landscape and geosites of the geopark and executed following existing good practices in other territories.

As an example, dynamic changes of the hydrogeological system have triggered geohazards such as landslides, rockfalls or debris flows in the Luochuan Loess Geopark (Wang et al. 2019). Field investigations indicate that the Potou section, loess column, loess wall, and loess bridge geosites at the Luochuan Loess Geopark are undergoing threats from geohazards. Researchers are currently working on applying measures to avoid losing such valuable geological heritage.

Potential risks at las Loras Geopark

Understanding the threats faced by society of an area is capital to prepare a risk analysis assessment and implement appropriate prevention measures. The aim of risk analysis is to reduce the potential impact of geohazards even in instances where there is not a historical record of such events. Risk communication is part of the prevention measures. This involves real-time exchange of information, the reception of advice from geohazards experts in the case of a Geopark, and from civil protection bodies dealing with risks to health, economy and wellbeing of the communities living in and visiting the Geopark.

Geoparks are an ideal scenery to communicate science. Las Loras Geopark can be a model example of the significance of communicating risk and prevention measures to preserve the geopark population and geosites. Although structural measures are of great importance when dealing with geohazards prevention, communication and outreach are of

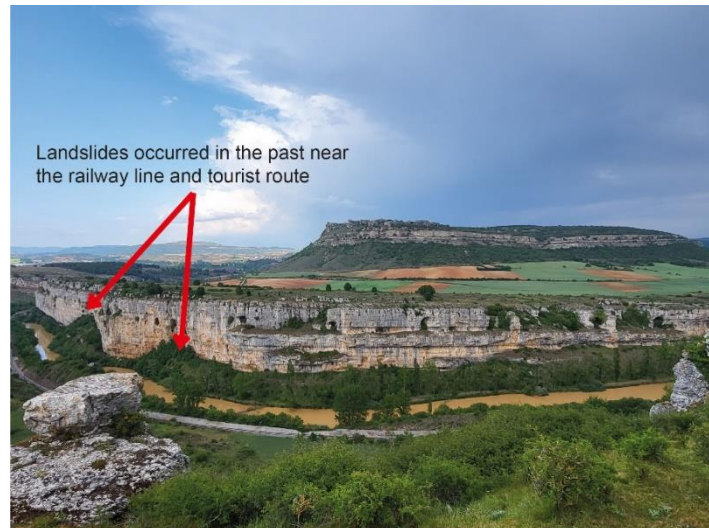


Fig.2: Landslide examples occurred close to a hiking trail in La Horadada Canyon, in Las Loras Geopark. No casualties were reported, but lack of prevention could put hikers at risk.

extreme importance to wake awareness to both the local community and visitors. Otherwise, individuals are unfamiliar with the cultural values that geology has defined and about what can be lost if a natural hazard strikes an area. Science communication, including risks and prevention of risks, both natural and anthropic, is key when dealing with geohazards. Dissemination makes the population more resilient to geohazards impact. Adaption to the new scenario following geohazard events demands the implementation of engineering measures to accompany social measures. These potential new circumstances should be communicated to the Geopark technical staff and the local community throughout educational and outreach activities.

The protocol to follow should avoid unnecessary alarmism, but a comprehensive communication and dissemination procedure, as part of the activities of the Geopark. The aim is to transfer knowledge in a context of societal risks. At present, the scientific committee of the Geopark meets periodically to discuss initiatives involving the scientific community, but also engages citizens, and students that are starting to learn and appreciate about their local geoheritage with the objective to meet the UNESCO sustainable development goals.



Fig.3: Potential risk of rock falls over the village of Villaescusa de las Torres, in Las Loras Geopark

However, an effort should be made to include further prevention measures such as the implementation of infrastructures to channel excess water during flooding events or measuring vertical fissures of Las Loras karstic monuments. The latter can provide a path for surface water penetration and groundwater erosion. Field tests like freeze-thaw testing, can give information on the evolution of these fissures that can provide information about potential collapse of these morphosites and the risk to the population living in the area, as well as to the visiting tourists.

Geohazards education and dissemination

Geoparks have produced enormous amounts of guides to assist tourists through walking paths to admire the natural landscapes and geology. Las Loras Geopark offers online hiking guides that include descriptions of geologic and natural features. Also, a novelized guide of the geopark has been published (Pereda, 2021), where the author mixes the description of landscapes with popular legends about a mythological being, and the hiking trails that allow exploring the area. However, these guides do not assess potential risks within the geopark or descriptions on previous catastrophic natural events. A more recent publication by Tascón González (2023) describes the fragile landforms and the potential natural hazards that could damage the Geopark geosites. Finally, a presentation of the singular landscape of Las Loras Geopark and how it could disappear under the influence of catastrophic natural events linked to climate change was projected during a session of Education in the GeoMinas meeting in Maputo (Mozambique) in May 2023.

Research and outreach activities on seismic hazard risk reduction in Lesvos Island UNESCO Global Geopark, Greece

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Seismic hazard in Lesvos Island UNESCO Global Geopark

Lesvos Island is located in the Northeastern Aegean Sea, Greece, covering a total surface area of 1.636 km². Lesvos Island UNESCO Global Geopark, founded in 2000, already counts two decades of successful operation (Zouros, 2021). Its most important geological feature is the Lesvos Petrified Forest, a protected natural monument with large accumulations of exposed fossilized tree trunks that has been included in the list of the 100 first IUGS Geological Heritage Sites (IUGS 2022). The Natural History Museum of the Lesvos Petrified Forest, a non-for-profit organization that was founded in 1994 is the management body of Lesvos Island UNESCO Global Geopark which comprises of 150 geosites that reflect the rich geodiversity of the island its geological history and the processes that formed it. Educational activities represent the core of Lesvos Geopark's operation.

Lesvos Island UNESCO Global Geopark identified the seismic hazard as a major geo-hazard threat for Lesvos Island and thus participates in research projects and organizes educational and outreach activities on the seismic hazard in partnership with local authorities and research institutions such as the University of the Aegean, the National Observatory of Athens, the Aristotle University of Thessaloniki, the Natural History Museum of Crete and the Earthquake Planning and Protection Organization (EPPO) of Greece.

Lesvos Island is affected by significant active faults (Zouros et al., 2011; Chatzipetros et al., 2013) located both onshore and offshore (Figure 1) which show high seismic potential. Right opposite the northern shore of Lesvos lies the Edremit fault zone which defines the southern coastline of Biga Peninsula (Turkey). It is one of the most hazardous seismic sources while its synthetic and antithetic faults are possible seismic sources of lower potential.

On Lesvos Island, the most significant faults—potential seismic sources are the following:

- a. The right-lateral Aghia Paraskevi fault (Fytikas et al., 1999) was the one activated when the 1867 earthquake ($M_s=6.8$ R) occurred. It cuts off the central part of the island from N to S, while its visible length onshore has earthquake magnitude potential of 6.7. This means that it continues to the sea, as far as the Kalloni gulf possibly, as it arises from the microseismic epicentre distribution.

LESVOS - 2017 Seismic activity

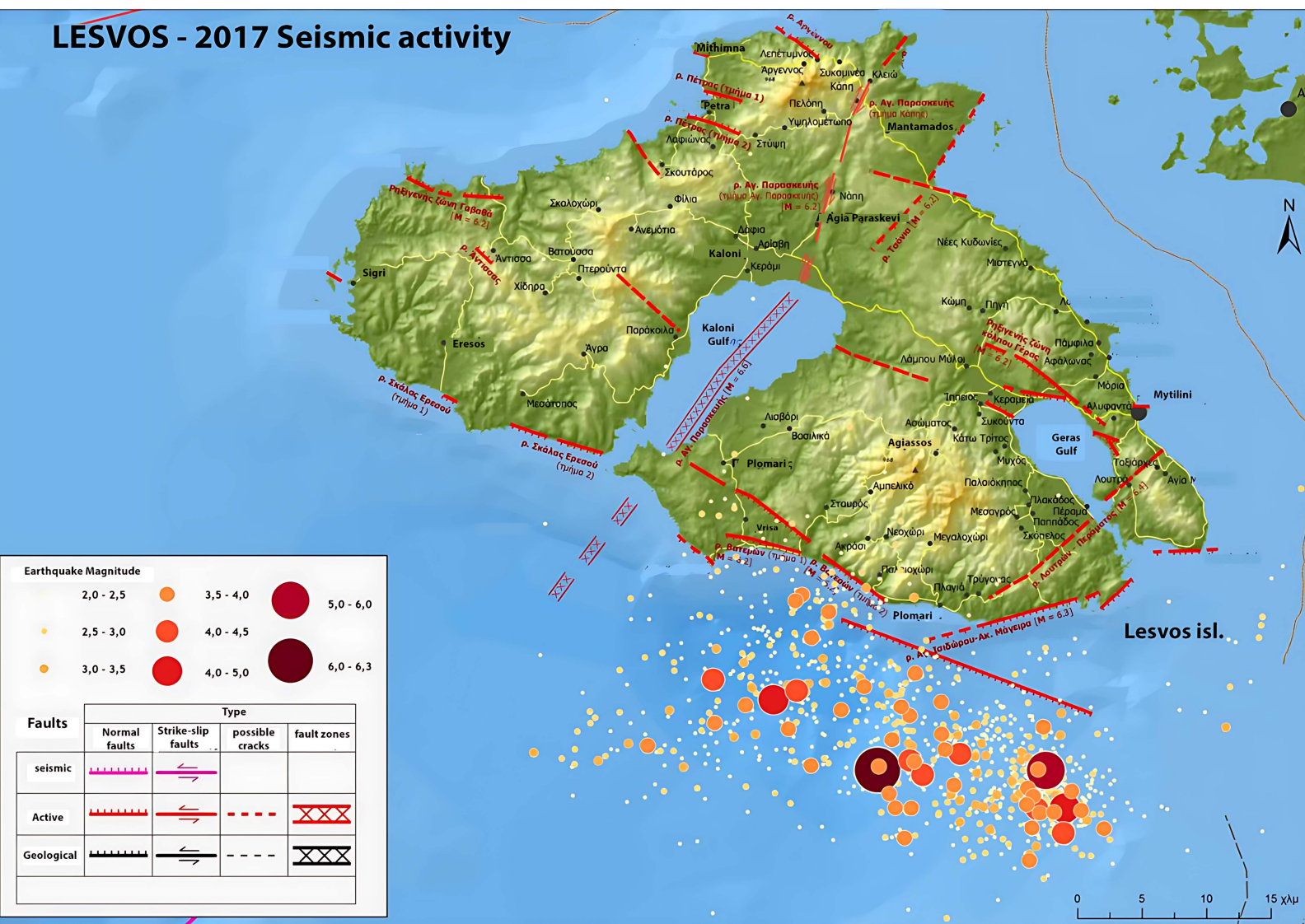


Fig.1: Active fault map of Lesvos Island, showing the main active faults (red lines) and the seismic sequence of the Lesvos 2017

- b. The WNW–ESE trending seismic fault on the southern shore of the island play an important role in shaping the coastal morphology. According to their length, the maximum earthquake magnitude potential is 6.6–6.8. This fault is the seismic source of the 2017 Lesvos earthquake.
- c. The WNW–ESE striking Vrisa fault is active. Microseismicity shows a linear offshore distribution implying the fault's presence and continuation. According to the length, the maximum earthquake magnitude potential is 6.8. Along this fault occurred surface ruptures and landslides during the 2017 Lesvos earthquake.
- d. The NW–SE striking fault at the eastern shore of the Gulf of Gera comprise a zone that has particular importance because of the short distance from the town of Mytilene. The earthquake potential reaches the value of 6.5.
- e. The ESE–WNW striking Larsos – Mytilene Fault zone comprise a zone that has particular importance as it is probably associated with the 1383 Mytilene destructive earthquake.

Several other smaller faults, i.e., Antissa fault, the WNW–ESE Gavathas fault zone, Voulgaris fault, Petra fault, Argenos fault, Stipsi fault, Tsonia fault, Makara Fault, Eressos fault, Nissiope fault and Plaka fault, have been identified on Lesvos Island affecting Miocene volcanic formations and showing characteristics which fit well with the active stress pattern.

The Natural History Museum of the Lesvos Petrified Forest hosts the Seismological Station of Sigri which is connected to the National network of Seismological Stations. It organizes outreach activities including thematic exhibitions and educational programmes aiming to introduce to students and adults the geo-scientific knowledge on earthquake hazard and disaster mitigation.

A major earthquake ($M_w=6.3$) occurred on the 12th of June 2017 (12:28 GMT) offshore, south of the SE coast of Lesvos Island, in an area characterized by normal faulting with an important strike-slip component in certain cases. The hypocentre was located at a depth of 7 km in the upper crust. The mainshock ruptured a WNW–ESE striking, SW dipping, normal fault, projecting offshore and bounding the Lesvos Basin (Kyratzi 2018). Over 900 events of the seismic sequence occurred between 12 and 30 June 2017. The earthquake partially ruined the village of Vrisa causing one fatality and severe structural damage in the villages at the southern part of the island. The event was strongly felt in the north Aegean islands and the neighbouring Turkish coast, while it was also felt in the Greek mainland.



Fig.2: The collapsed school of Vrisa from which students and teacher escape after the main shock. The had experienced before the Earthquake educational program of the Lesvos UNESCO Global Geopark (photograph by N. Zouros)

The school of Vrisa suffered severe damages (Figure 2) during the main shock but the students and the teacher, who have previously participated in the educational activity on earthquake hazards on June 2nd, 2017 at the Natural History Museum of the Lesvos Petrified Forest, managed to exit the building safe and without been injured.

The educational activities on earthquake hazard risk reduction at the Natural History Museum of the Lesvos Petrified Forest offer to students the opportunity to increase their understanding while it motivates them to learn more, and to explore the fascinating world of Earth sciences.

The Natural History Museum of the Lesvos Petrified Forest and the Lesvos Island UNESCO Global Geopark in close collaboration with the UNESCO Chair on Geoparks and the sustainable development of insular and coastal areas at the University of the Aegean organize activities aiming to public awareness on seismic hazard, including thematic exhibitions, seminars for teachers and educational programmes for schools, while information on seismic hazard is communicated to the local authorities and the public. Community lectures and seminars for the local communities are organized in case seismic events occur (i.e. Vrisa 2017, Lepetymnos 2023).

Geohazards education and dissemination

The educational activity “Understanding Earthquakes — Living on a seismic active island” aims to familiarize students and citizens with earthquakes, active faults and the seismic hazard. The educational programme, includes six main stages:

- Multimedia presentation on earthquakes and active faults illustrate seismic damage and community disaster response.
- Plate tectonics understanding using interactive installations to present plate movement, volcanoes and earthquakes.
- Seismic hazard exhibition presents data from the seismic history of Greece and the set of active faults and seismic hazard maps of Lesvos Island. The exhibition provides the links between large faults and the most recent seismic activity and other catastrophic natural phenomena linked to the earthquakes.
- Monitoring seismicity. This part includes activities explaining the recording of the digital seismographs in real time.
- Active fault study. Participants become familiar with active fault morphological characteristics, geometry, appearance, recognize an active fault and understand how the rocks deform, fracture and move along the fault plane.
- Earthquake simulator. The installation simulates the seismic movement of destructive earthquakes in Greece and the world. Participants sit at their desks in a school-classroom shaped platform (Figure 3), experience the tremors, and learn how to react during and immediately after an earthquake.



Fig.3: Students participating in the educational programme on earthquake hazard using the seismic table at the Natural History Museum of the Lesvos Petrified Forest (photograph by D. Mpatsios)

Geohazards in the Maestrazgo UNESCO Global Geopark, Spain

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The main geohazards in the Maestrazgo UGGp include landslides, floods, and potentially subsidence related to sinkhole occurrence. The frequent storm events in this mountain area with strong Mediterranean influence largely govern the spatial and temporal patterns of landslides and floods. Damaging floods are relatively frequent in the Guadalepe and Bergantes rivers, with a flashy regime. A remarkable event among the historical floods of the Guadalepe River corresponds to the 1787 flood in La Ginebrosa, which severely damaged a dam under construction. This structure, which was finally dismissed, was designed by the prestigious Neoclassic architect Juan de Villanueva. Another disastrous flood occurred in 1883 in the Monleón River, causing 26 fatalities in the village of La Estrella (Mosqueruela). Landslides commonly occur in slopes formed by rocks of variable mechanical resistance and erodibility and in dip slopes with favorable bedding attitude. This type of slope movements is particularly frequent in road cuttings (artificially over-steepened slopes), often causing service interruptions despite their relatively small volume. This problem is nicely illustrated by the recurrent cuts in the road that gives access to the Pitarque Natural Monument.

Below we describe some of the most remarkable examples of landslides and collapse sinkholes, which constitute examples of great educational value to illustrate the damage caused by geological processes, and how human activity can contribute to trigger or intensify hazardous processes (human-induced hazard).

Landslides in the reservoir of the Guadalepe River

The Santolea Dam, built in 1932, is located in a narrow water gap carved by the N-flowing Guadalepe River across the northern limb of a WNW-ESE-trending syncline. A project for increasing the height of the dam and the impoundment capacity of the reservoir was dismissed in 2014 because of the discovery of a large landslide on the left abutment. This is an old wedge-shaped translational landslide developed on a S-dipping Late Cretaceous carbonate succession (Figure 1A). The displaced mass, with limited runout and internal deformation, is around 700 m long, 500 m wide, and has a local relief of around 130 m. It shows local evidence of recent activity, including a fissure cave along the NE edge of the landslide (Figure 1B), and deep penetrating unloading cracks on a limestone cliff at the toe of the landslide and just upstream of the dam (Figure 1C). The cave entrance is located along the projection of the dam axis 70 m to the NW, in a limestone quarry excavated during the construction of the dam. The formation of this cave is not related to dissolution, but to gravity-driven displacement across a subvertical failure plane (i.e., landsliding) and associated collapse processes.

After discarding the heightening of the Santolea Dam, two new dams have been constructed: the Cañón de Santolea Dam, and the Puente de Santolea Dam, 1.2 and 3.5 km upstream, respectively. Recently, a landslide located 200 m SW of the Puente de Santolea Dam created some concern (Figure 2). This slope movement, around 400 m wide,

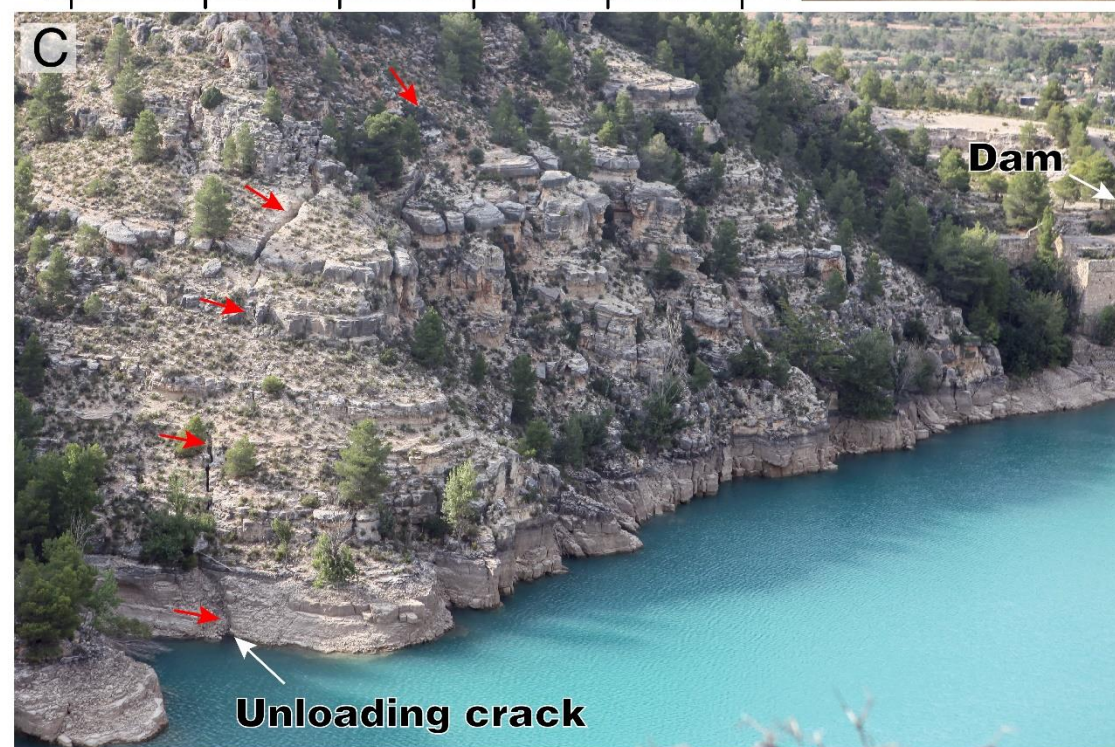
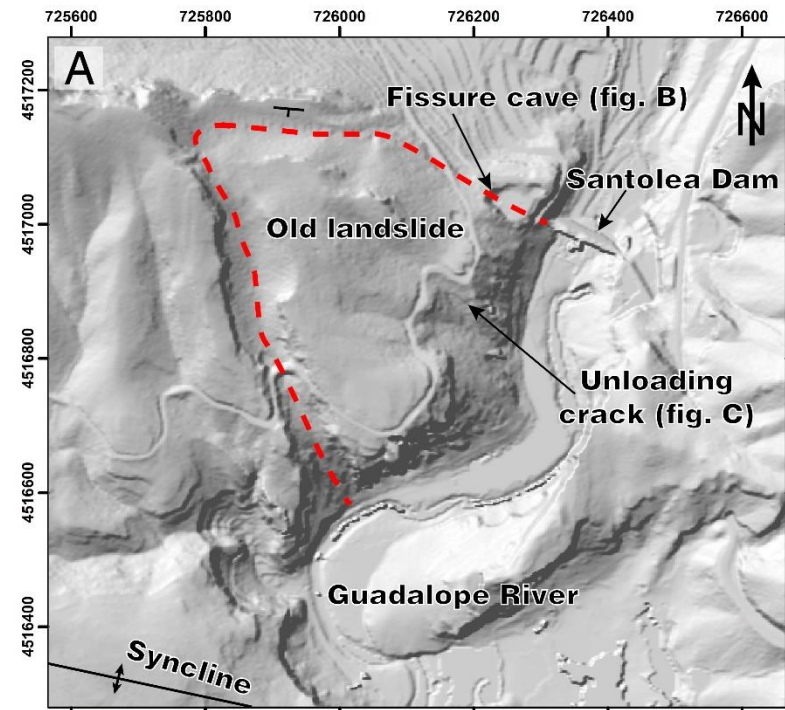


Fig.1: A: Shaded relief model showing the large old landslide located on the left abutment of the Santolea Dam (Castellote), which led to the dismiss of a dam-heightening project

B: Fissure cave associated with the lateral edge of the landslide and located 70 m to the NW of the dam. Inset shows cave entrance situated in an old limestone quarry

C: Deep-penetrating fissure in a limestone cliff at the toe of the largest landslide and just upstream of the dam

occurs in a NE-SW oriented cliff overlooking the reservoir. The escarpment is made up, from base to top, of mechanically weak Cretaceous sands of the Utrillas Formation, Cretaceous limestones, and Oligocene conglomerates lying on an angular unconformity. This mass movement, with strong scarp-parallel elongation, seems to correspond to a rotational landslide with a curved sliding surface rooted in the Utrillas sands. In the upper part it is expressed as scarps and fissures that bound downdropped and laterally displaced panel-shaped blocks of conglomerate and limestone. In 2021, rock falls and topples from the northern sector of the landslide that reached the reservoir water led to the prohibition of recreational activities in this sector of the lake (e.g., swimming, kayaking). Large rapid landslides can create small tsunamis (i.e., impulse water waves) in reservoirs. The hazard has been significantly reduced by excavating the upper part (i.e., beheading) of the more unstable northern portion of the landslide. Nonetheless, the excavation area shows conspicuous active fissures and scarps indicating ongoing activity. Recent or current activity in the southern portion of the landslide is indicated by the presence of cracks and fresh sinkholes generated by ravelling of superficial deposits into subsurface wide-open fissures (inset of Figure 2). Most probably the activity of this landslide will be influenced by water level changes in the reservoir, especially rapid and significant drops that may involve high pore fluid pressure and loss of lateral support.



Fig.2: Active landslide located 200 m to the SW of the left abutment of the Puente de Santolea Dam (Castellote). The northern, more active portion of the landslide has been partially stabilised by removing the upper part of the displaced mass (weight reduction by beheading). The edge of the southern portion of the landslide, with limited displacement, is defined by a subvertical fissure that leads to the formation of sinkholes in the upper part of the scarp (inset, with circle indicating a dog for scale)

Destruction of the Virgen de La Peña Hermitage by a rock fall

The “Virgin of the rock” Hermitage of Berge village is located on a slope with terraced crop fields below a cliff underlain by Late Cretaceous limestones and dolomites (Figure 3). This scarp forms the pointed NE edge of a prominent NE-SW oriented ridge, flanked by outcrops of Paleogene detrital formations. In December 1936 a rock fall from the cliff destroyed most of the old hermitage, which was subsequently rebuilt in 1950. The detachment and collapse of the block was favoured by two parallel nearly vertical joints perpendicular to the scarp face and probably also slope undermining. Interestingly, the block, with a wedge-shaped basal geometry, descended as a “ploughing block” excavating a rectilinear groove 15 m wide flanked by ridges (i.e., levees) related to the lateral accumulation of deposits. This trough clearly crosscuts the artificial terraces situated on the slope underlain by detrital Paleogene sediments. The block situated at the distal end of the trough is 25 m long, 20 m wide, and has experienced a vertical drop of 40 m and a horizontal displacement (i.e., run out) of 100 m. The ratio between the vertical drop and the run out is used to assess the mobility of various types of landslides (0.4 in this case), which has an influence on the damage capability of the landslide. Close examination of the block reveals that it corresponds to a very massive and competent dolomitic breccia, which is strongly karstified, showing decimetre and metre-scale voids lined by large

calcite crystals (i.e., geode). It also shows in the underside a small leaning tree that was partially buried but surveyed to the event. Numerous additional smaller rock falls can be observed in the area.

Sinkhole hazard in La Ginebrosa area

Three main mechanisms may participate in the development of subsidence sinkholes (Gutiérrez, 2016): (1) collapse; (2) sagging, or gradual downward bending of sediments; and (3) suffusion or internal erosion of unconsolidated cover deposits through subsurface voids. Collapse sinkholes in bedrock commonly result from the upward propagation of cavities by the progressive breakdown of the roof, until the void intercepts the ground surface. La Ginebrosa area includes a very interesting cluster of bedrock collapse sinkholes (Barrón et al., 1997). There is an extensive outcrop of Jurassic dolomites with a general SW dip that forms part of the hanging wall of a NE-verging thrust. Here, the topography is dominated by a well-integrated valley network, but there are also a number of bedrock collapse sinkholes (i.e., fluviokarst landscape) at different evolutionary stages. The sinkhole field at La Ginebrosa includes six bedrock collapse sinkholes of different relative ages.

Geohazards education and dissemination

The *Geopark's Day* 2023 was held in La Ginebrosa where multidisciplinary information was given by geologists, speleologists, and naturalists to interpret the landscape, as well as to promote a culture of risk awareness and disaster reduction on a global level. Near the karst area, an information panel was placed to explain the origin of the outcrops of carbonate rocks and the development of sinkholes. During the day, different karstic landforms were presented on the field and complemented with workshops and the presentation of a new paper-covered work of popular science that sets out keys of this fluviokarstic landscape.

Another dissemination activity linked to geohazards are geological fieldtrips in kayak around the Puente de Santolea Dam developed intermittently since 2018 (Mampel et al., 2019). On the other hand, for the celebration of the International Day on Disaster Risk Reduction 2021, new audiovisual material was presented through the Geopark's YouTube channel. This material includes the presentation of the main geohazards linked to the territory to support the local communities of the Maestrazgo Geopark to cope with these circumstances.

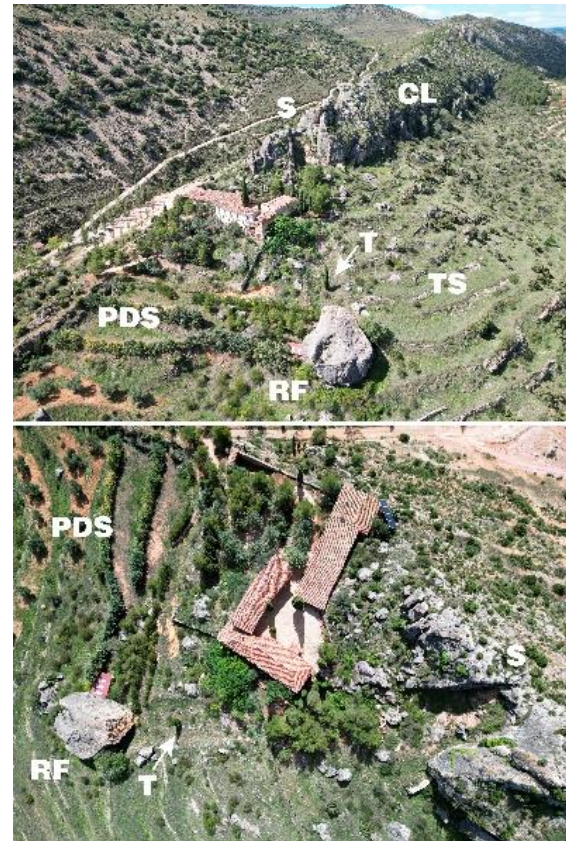


Fig.3: Oblique (up) and vertical (down) views of the rock fall that destroyed the old Virgen de la Peña Hermitage (Berge) in 1936, which was rebuilt in 1950. CL: Ridge of Late Cretaceous limestone and dolomite; S: Source of the rock fall; T: Trough with lateral ridges carved by the "ploughing block"; RF: Rock fall; TS: Terraced slope; PDS: Paleogene detrital sediments

The Nant des Granges active landslide and geotourism in Massif des Bauges UNESCO Global Geopark, french northern Alps

Massif des Bauges regional nature parc / UGGp avenue Denis Therme, 73630 le Châtelard - France

Introduction

The deformed Mesozoic and Cenozoic deposits at the front of the Alpine chain are subject to a variety of gravity phenomena. They bear witness to the erosion of this folded sedimentary cover. Whether landslides, collapses, sliding packages or torrential lava flows, these phenomena bear witness to the alteration of the relief after the Alpine orogenic phase. Some are also evidence of stress relaxation following the deglaciation of the Alpine valleys. The tectonic style (folding, thrusting) and the distribution of lithologies, and therefore rheologies, explain the variety of these phenomena. Several of these are geosites where we are developing a tourist and educational approach to help visitors understand the geological history of the massif and its role in the distribution of natural resources and natural hazards.

The Massif des Bauges UNESCO Geopark, a catalogue of gravity phenomena

The diversity of gravity phenomena can be appreciated in the massif: in the Bange cluse, the Saint Jacques Towers form a "paquet glissé" (slippery pack) that began its course as a result of slope relaxation following the retreat of the glaciers. GPS measurements have shown that this stack of limestone layers is moving by an average of 2.6 cm per year.

The plainpalais collapse is an example of a slope collapse crowned by a limestone cornice. The scars of the landslide and the morphology of the scree cone are perfectly preserved and explain the presence of wetland micro-environments. This scree is also responsible for the presence of an aquifer that gives rise to a spring feeding the Leyse river.

There are various cones of debris on the massif, some of which are still subject to the formation of debris flows. The rapid growth of vegetation on a massif that receives a lot of water tends to quickly erase the traces of these catastrophic events, but an observation of the relief shows their omnipresence and the need to remain alert to these phenomena. The massif is also at risk from avalanches and flooding. The risk of flooding particularly concerns the Isère river, which was dammed up between 1830 and 1860, excluding a large part of its floodplain from its historic expansion zone. The change in rainfall pattern from nival to pluvial poses a risk to these areas reclaimed from the river.

The Nant des Granges, a historic landslide that is still active

The Garins landslide was at its most active in 1931, making national news in France. A particularly wet autumn triggered a vast landslide, which turned into a destructive mudslide at the entrance to the commune of Le Châtelard.

The nature of the rocks, the geological structure and the geomorphology of the catchment area triggered a process that is regularly reactivated during very wet spells or major snow melts. The site is monitored and managed by the mountain land restoration (RTM) department of the forests national office (ONF) and is designed for public use.

Fig. 1: Location of the Nant des granges torrent landslide in the Châtelard syncline with a schematic diagram of the 1931 landslide



The Garins site (Figure 1) is characterised by a syndinal gutter, reinforced by a thick layer of Urgonian limestone. It is one of the most remarkable perched synclines in the massif. One side of this syncline is cut by the Manaux Gorge. This incision affects the heart of the syncline, which is made up of softer rocks including marl, clay and glacial moraine, the stability of which is much more sensitive to water content. These deposits, on a steep slope, were destabilised in 1931 during a particularly wet autumn. At the time, the area was occupied by mountain pastures with inhabited hamlets. The landslide turned into a mudflow as it passed through the Manaux gorge. These mudflows destroyed buildings at the entrance to the village of Le Châtelard. Studies (Gex, 1931) (BRGM, 1971) (ADRGT, 1985) estimated the depth of the landslide at 60m, with a mobilizable volume of 6 million m³. All the geological formations subsequent to the Urgonian limestone have been destabilised in this gorge. The mountain land restoration service has been commissioned to manage the site and prevent further landslides. Upstream, this involved creating a vast network of drains (22km in total) and planting trees to prevent water infiltration and encourage evapotranspiration. Downstream, preventive measures included the creation of vast deposit beaches to contain the solid fraction of potential future run-off (total capacity of around 105,000 m³). Since 1931, the landslide has reactivated on a

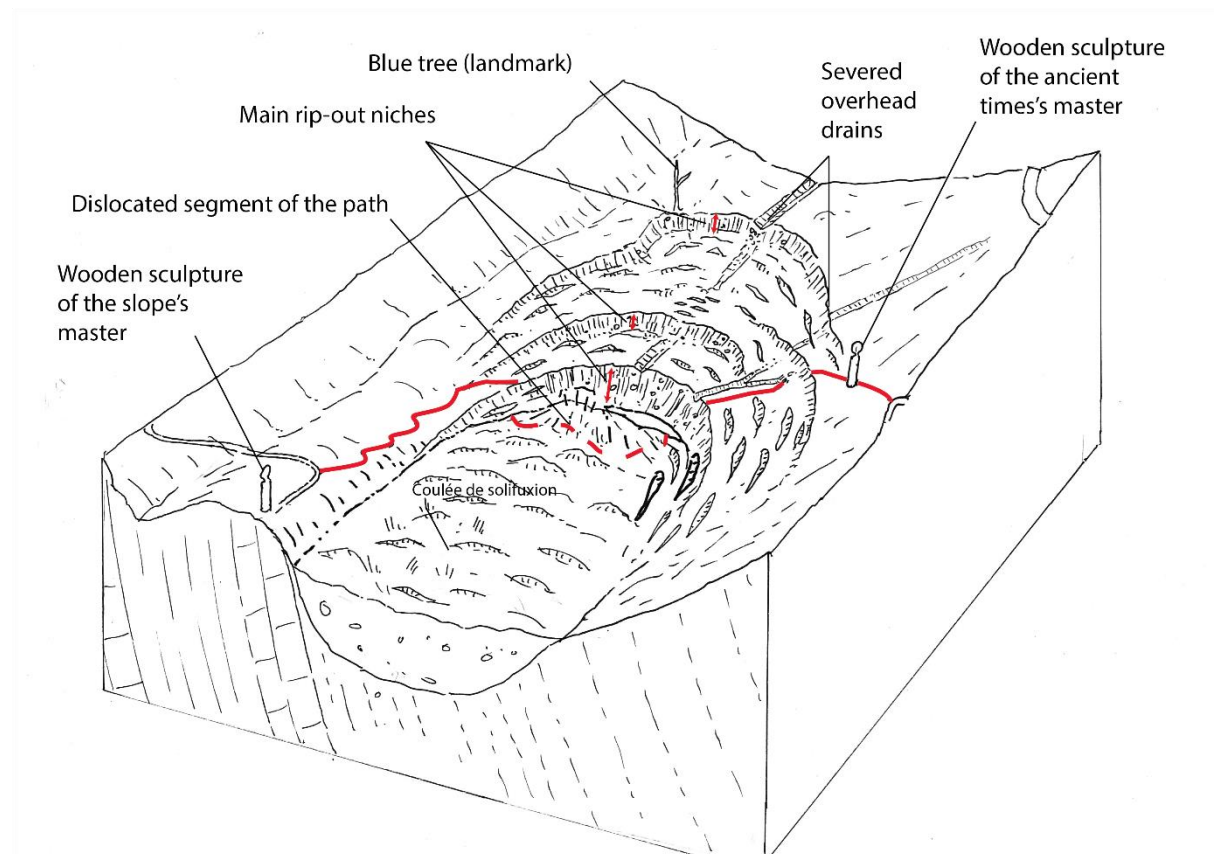


Fig.2: Detail of the landslide reactivation in 2015

number of occasions (Figure 2) but has not produced any significant mudflows that could reach areas at risk (except in 1944). Since then, the site has been regularly maintained, with upkeep of the drainage network (covered and open) and management of the state-owned forest (ONF, 2009). It is also subject to scientific monitoring, with the displacement of numerous landmarks being measured. It has recently been the subject of a geophysical campaign (electrical profile) to characterize the geometry and estimate a volume of 6 million m³ destabilised.

Reception and scientific popularisation

In 2014, an interpretation trail was created on the initiative of the Office National des Forêts, with the help of the Massif des Bauges UNESCO Global Geopark. It consists of 2 loops of walks staged on the themes of the masters of the deserted mountain. The first concerns the upstream part of the system and comprises a series of stops punctuated by the presence of monumental wooden sculptures representing the "masters" (Figure 3). The "masters" correspond to the various elements that contribute to the site's destiny: the slope, the water, the subsoil, the forest, etc. The second, shorter route takes in the features built to limit the impact of potential mudslides, such as deposit beaches and debris flow dams. The 2 routes are supported by a game, explained on a flyer, linking to a dedicated website. The site has also been the subject of a film (*Les maîtres du Mont déserté* / *Masters of the deserted mountain*) produced by IRMA (Major Hazards Institute) (Gominet, 2015). It can be accessed independently by the public and is used by environmental educators and teachers. The site is regularly upgraded to adapt to recurring landslides (new interpretation panels are currently being installed). The route, for example, has been changed twice since it was first created, when certain sections became impassable. The aim is to show visitors around and explain an active site that deals with hazards. Various graphics, drawings, animated films, and drone videos have been updated to reflect the site's evolution and are shown in conferences. It's a site of discovery, with an educational vocation, welcoming summer tourists who enjoy its shady walks as well as students.



Fig.3: Example of a master's wooden sculpture

Addressing wildfire impact on the Courel Mountains UNESCO Global Geopark

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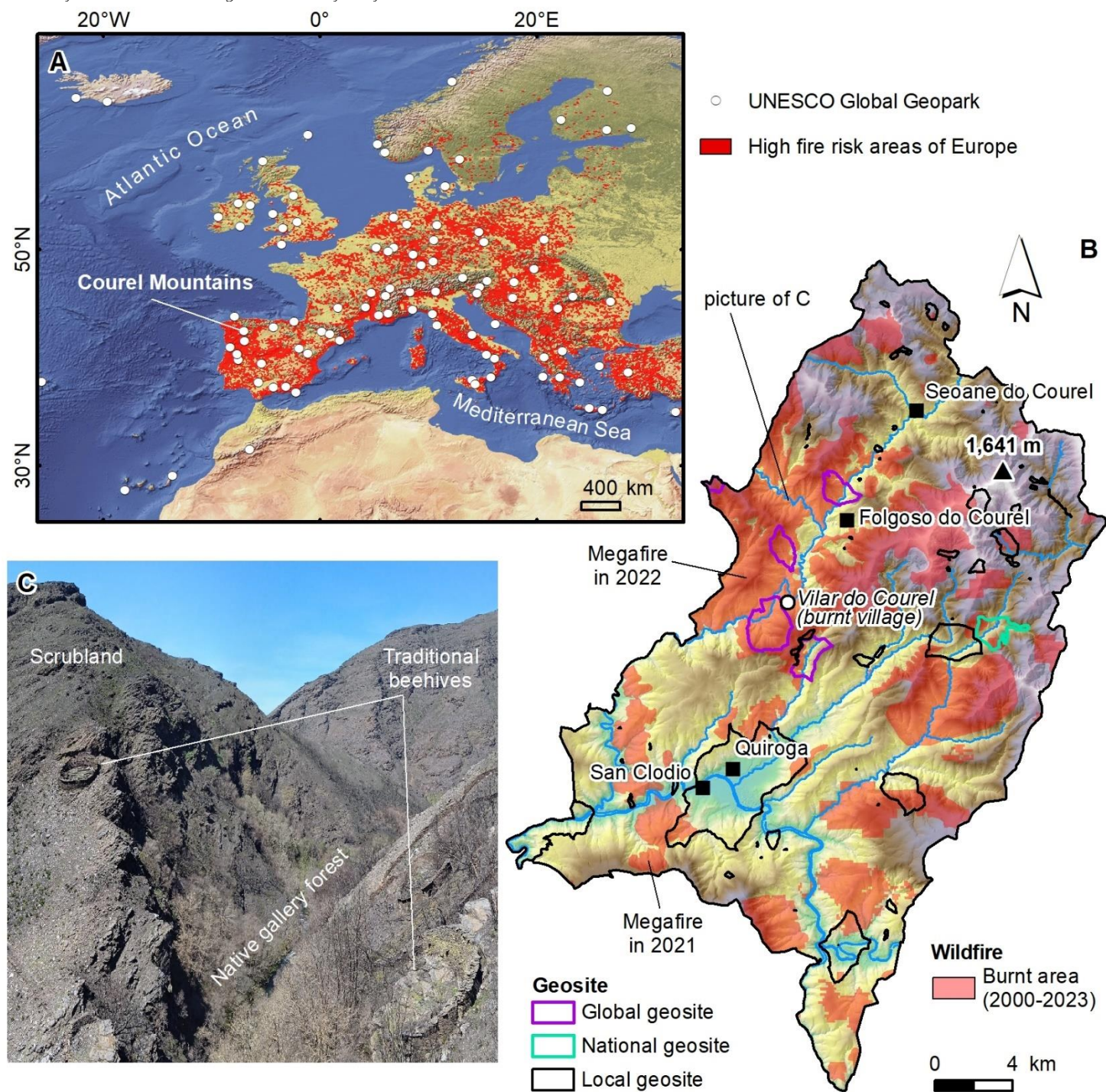
Wildfire impact

The Global Change is increasing wildfire frequency and intensity around the World, especially in depopulated rural areas where the abandonment of traditional agriculture and livestock practices generates vast expanses of highly flammable scrublands. In these rural areas which coincide with UNESCO Global Geoparks (UGGp) declared in Europe (Figure 1A), all the nature, cultural heritage and local industries are valuable features that are significantly impacted by wildfires at the present-day (Gómez-Heras et al., 2009), posing a serious threat to UGGp. Just in the 21st century, the fire has affected 30% of the Courel Mountains (Figure 1B), resulting in the destruction of scrub areas, coniferous woodlots, unique native forests and many local constructions (Figure 1C). In 2021, a catastrophic megafire wreaked havoc on vast coniferous woodlots in southern UGGp, triggering a state of panic and fear as the sky turned dark with smoke and ashes. Numerous villages were threatened and evacuated, and local traffic came to a standstill, disrupting both a railway and a national road. All of this instilled a profound sense of helplessness with the local community. The forest fire revealed alarming signs of erosion in the burnt area, including gullies and grooves developed on the soil before the megafire. These erosion evidence, reaching depths of 5 m, exposed the frequent occurrence of wildfires and their detrimental effects on the soil. The fire exacerbates the existing issues of soil erosion and aridity. Another devastating megafire impacted the northern region the following year, leading to yet another tragedy. In this case, the fire destroyed a traditional village (named Vilar do Courel, Figure 1B) including its dwellings and an ethnographic museum of the UGGp, as well as numerous infrastructures such as viewpoints, information panels, wooden bridges and indicators. The fire completely had a severe impact on local industries including agriculture and farming, tourism, quarrying and wood processing. In response to these challenges, the Courel Mountains UGGp has taken proactive measures to mitigate the impact of wildfires on the local population and the territory. This initiative draws inspiration from previous efforts in other UNESCO designated areas, such as the Sierras Subbéticas UGGp in Spain, the Beigua UGGp in Italy, and the Naturtejo UGGp in Portugal. To address the wildfire risk, the Courel Mountains UGGp is employing a three-pronged approach: scientific research, land management strategies, and outreach efforts.

Research

The UGGp is actively promoting new scientific research as part of an agreement funded by the Government of Lugo Province. This effort includes laboratory testing and Geographic Information System (GIS) analysis. Within the

Fig. 1: A European Geoparks Network projected on areas of high fire risk according to European Forest Fire Information System (EFFIS), Copernicus Programme (European Union). B Burnt areas and geosites of the Courel Mountains UNESCO Global Geoparks (UGGp). C Traditional circular stonewalls used to protect beehives from brown bear attacks. These structures revealed a significant honey production since ancient times, closely linked to the local vegetation destroyed by fires



laboratory, temperature tests have been conducted to assess the impact of fire temperatures on rocks and possible risks associated. This testing aimed to determine changes in density, colour, hardness, and wave velocity propagation. Rock samples collected from unburned areas of the Courel Mountains were introduced in ovens and subjected to controlled temperatures ranging from 50 to 800°C. Under an optical microscope, the observed damages caused by high temperatures in these samples were found to be like those observed in rocks collected from burnt areas within the UGGp (Figure 2).

The results of the laboratory tests revealed significant fire impacts. Generally, rock colour transitioned to reddish tones when exposed to temperatures exceeding 400°C, while density, hardness, and wave velocity propagation decrease beyond 600°C. Among the rocks studied, slate was found to be the most affected local rock, with the potential to disintegrate at 200°C, leading to bedrock erosion and instability processes in the Courel Mountains. Consequently, wildfires not only pose a direct threat but



Fig.2: Laboratory sample of a quartzite collected from a burnt area in the Courel Mountains UGGp after the megafire occurred in 2021. The surface of the rock displays a dark coloration due to the presence of ashes, which have permeated the porous media of the rock, as observed under a microscope. Additionally, the sample exhibits fractures that are likely a result of the intense heat generated by the fire

also exacerbate other geohazards prevalent in the UGGp. The laboratory findings have enabled the creation of a susceptibility map using the Geographic Information System (GIS) of the UGGp. These high-fire-susceptibility areas are associated with approximately 40% of the geosites designated in the Courel Mountains by the UGGp. Notably, the bedrock of 42 local geosites consists of Cambrian to Silurian slate, which encompasses geologically significant features: paleontological and mineral sites, glaciomarine diamictite, sulphate-bicarbonate and ferruginous springs, and glacial, fluvial and slope landforms. Additionally, the white quartzite, which show large to small folds of international interest, one of them declared Natural Monument, will experience notable colour changes due to fire temperatures. Finally, the Geopark designated evidence of soil erosion, such as a prominent gully, as a local geosite, aiming to emphasize its occurrence and recognize its significant value as an outreach resource.

In present times, the realm of scientific research encompasses ongoing efforts to optimize a fire temperature proxy by leveraging mineral magnetism variations. This innovative approach holds the potential to offer valuable insights into the impacts of wildfires, thus representing a significant scientific advancement towards a better understanding of the fire impact on rocks.

Management

The Courel Mountains UGGp forms part of an interdisciplinary commission established by the Regional Government to facilitate the recovery of the Courel Mountains. Working alongside its partners, including municipalities and the Ribeira Sacra-Courel local action group, the UGGp primarily focuses on implementing initiatives to restore the devastated villages and infrastructure. Additionally, they also play a crucial role in managing public aid and compensation for affected property owners and farmers, as well as revitalizing local industries and facilities. One specific endeavour entails the development of a new forest landscape for the severely impacted village of Vilar do Courel (Figure 3A-B), which served as the epicentre of the destructive megafire in 2022. Another significant effort involved the restoration of information panels and indicators destroyed by the fire (Figure 3C).

Geohazards education and dissemination

Educational actions include a BSc Thesis in Environmental Sciences at Universidad Autónoma de Madrid (Spain), focused on fire impact on the Courel Mountains (Estévez, 2023), and ongoing outreach activities. These actions are being developed to raise awareness about the impact of wildfires on the geological features and geoheritage in the framework of the Global Change. In October 2023, we carried out a hiking trail in an area affected by the 2022 megafire, highlighting its geological, ecological and ethnographical values (Figure 3D). Local villagers and honey producers joined us in this activity to tell how they experienced the catastrophic situation first hand. Additionally, efforts will be made to disseminate information about wildfires and associated risks, including its effects on rocks and geoheritage through panels, press, social media and UGGp visitor centres. A noteworthy feature of these outreach efforts is the exhibition of rock samples affected by high temperatures to visually demonstrate the destructive consequences of fires on solid rocks. By engaging the public through educational and outreach activities, the Courel Mountains UGGp aims to foster a greater understanding of the importance of protecting and preserving unique geological heritage against wildfire, as part of their impact on biodiversity, cultural heritage and rural communities.

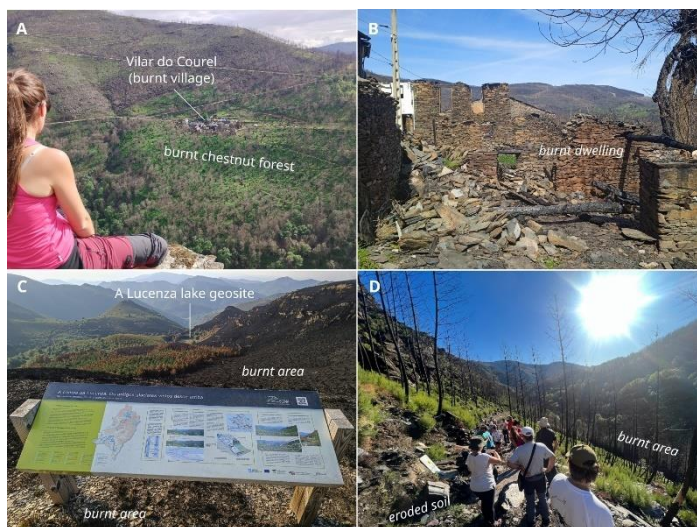


Fig.3: Megafire impacts in 2022 related to the development of the Courel Mountains UGGp: A Traditional village named Vilar do Courel and its singular chestnut forest burned by a megafire in 2022; chestnut has been the cornerstone of local gastronomy for many years, making it a remarkable and celebrated local delicacy to this day. B Dwellings of Vilar do Courel village burned in 2022, including an ethnographic museum belonging to the visitor centres network of the UGGp. C Fire impact on the A Lucenza lake geosite in 2022, showcasing the restored information panel; this area includes the most hiking routes of the UGGp. D Outreach activity by means of a guided tour through the area affected by the megafire between Vilar do Courel and Froxán villages

Mass movements, flooding and education in Orígens UNESCO Global Geopark

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Introduction

Geohazards in Orígens UNESCO global Geopark are strongly linked to its orography and bedrock configuration. Intense fluvial, glacial and aeolian processes during the Neogene and Quaternary periods shaped a landscape with mountains reaching over 2.900 m.a.s.l and deep river valleys cutting across spectacular gorges on the lowland areas down to 400 m.a.s.l. This context is reflected by a dramatic topography prone to the development of phenomena linked to gravitational forces. Therefore, the Geopark area involves a wide range of geohazards, comprising of avalanches in the mountainous areas, recurring flooding events along riverbeds and ravines, and large number of mass movement of very diverse types and magnitude. The latter are particularly active along the valley slopes carved by the Noguera Pallaresa river and its tributaries. Among those, there are two particularly well-expressed examples that illustrate how the study of these landforms can help understanding and preventing risk associated with mass movement, both in our Geopark and in parts of the world. These are the Puigcercós rotational landslide and the Peracalç lateral spread.

Puigcercós, a village obliterated by a landslide

South of Tremp Town, the Noguera Pallaresa river cuts across an area with a geological setting constituted by soft sediments, composed of thick Paleogene clay and marl beds overlain by harder bedrock, represented by strongly fractured limestone and sandstone layers. These setting, paired with intense fluvial erosion, has shaped valleys sides with steep slopes that provide the conditions for the development of different types of mass movements, such as lateral spreads, earth flows, rockfalls or rotational and translational landslides. Due to this great geodiversity, the area has become a natural lab for the study of geomorphology and geohazards by universities and other academic and research organizations, which frequently take fieldtrips to visit the most illustrative sites and landforms. Mass movements in this area have a direct impact to the local community with recurring mass movement events blocking and eventually destroying local roads, and among those a tragic rock fall event in 2018 that took the life of two people.

The Puigcercós landslide is with certainty the most visited landslide in this region. This particularly well-preserved feature consists of a 5.5 Hm³ mass movement with rotational and translational sliding components in the upper part and a fluidal component in the frontal lobe (Figure 1). The slid mass comprise red clays at the base capped by a strongly fractured sequence of calcarenite, limestone and marl. As far as we know, the movement includes three main episodes of displacement. The first event recorded in 1857 opened vertical fractures and increased the infiltration capacity of the terrain, favouring the oversaturation of the red clays during the subsequent episode in 1881. This second event, occurring under strong rainfalls (Vidal, 1881), caused the resettlement of the Puigcercós village to a safer area. The last movement, in 1889, was the largest one and brought the main scar to its current position. Today, the landslide displays from top to bottom a 50 m high semicircular shaped crown scar with colluvium deposits at its

Fig.1: The Puigcercós landslide displays a well-preserved main scarp with still active rock falls leaving colluvium deposits at its foot. (Photo by Jordi Peró)



base, result of continuous and still very active rock falls; a rotational platform presenting irregular and convex topography and; the frontal part expressed as lobated terrain. The reactivation of the movement in 1881 and 1889 caused the damming of a stream flowing along the landslide foot, and the formation of ephemeral lacustrine basins upstream from the landslide barrage. Today, well preserved lacustrine dam-slide deposits remain, which witness the landslide stream damming episodes from the past.

This landslide has been studied and characterized thoroughly. During the last decade, the Barcelona University RISK-NAT research group has been monitoring its main scar using terrestrial laser scanner, photogrammetry, GPS and seismic control to assess new monitoring techniques, aiming towards the development of early warning systems for landslides and rock falls in other parts of the planet (Abellan et al., 2010).

Peracalç, the largest mass movement described in the southern Pyrenees

Downcutting by the Noguera Pallaresa and the Flamisell rivers favoured the development of massive deep-seated landslides in their watershed area between Gerri de la Sal and la Pobleta villages. Here, it outstands the still active lateral spread of the Peracalç Range (Gutierrez et al., 2012). This mass movement affects a 250 m thick Cretaceous limestone and Paleogene conglomerates sequence that slides over Triassic halite-bearing evaporites and clays. The pressure exerted by the cap rock composed by the limestones and conglomerates caused deformation and flowing of the underlying Triassic evaporites. During these movements, the brittle cap rock fractured and accommodated the deformation configuring a system of horsts and grabens expressed as “piano keys” looking topography. This gravitational deformation has left behind impressive landforms such as aborted paleodrainages expressed as wind gaps or defeated streams. The significant vertical displacement component in this rock spread is attributed to subsidence caused by underground evaporite dissolution, as supported by dissolution-induced collapse structures recorded at the foot of the Peracalç mountain range. This colossal feature, covering about 4.5 km² and with an estimated volume of 0.9 km³, is considered the largest mass movement described on the

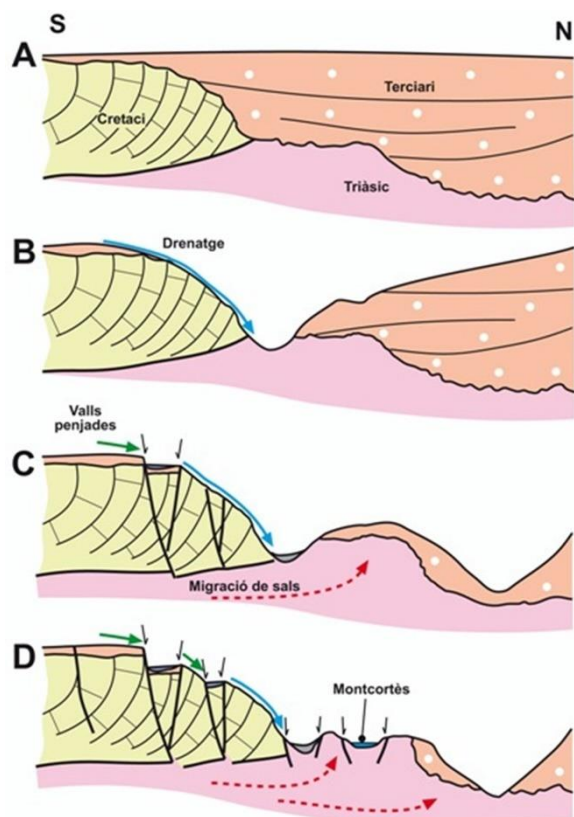


Fig.2: Peracalç landslide evolutionary model. (A) Initial stage. Paleogene conglomerates covered the area. (B) Conglomerates erosion. River courses (C) and (D) develop on the slopes of the Peracalç range. As erosion progresses and creates an empty space, large blocks of limestone break and move along with the flow of evaporites, developing a sequence of horst i grabens in the form of “piano keys”. Ancient river courses are defeated and abandoned. (Modified from Linares and Zarroca 2012)

southern slopes of the Pyrenees (Figure 2). Research work involving trench analysis techniques combined with geophysical surveys allowed estimating the initiation of the movement at about 45,000 years ago and rates of movement from 1 to 3 mm/year (Gutierrez et al., 2012).

The lake of Montcortés, one of the only two lakes in the Pyrenees of non-glacial origin, is also result of a collapse associated with dissolution and the deformation of the terrain. The local population already knew about this geological event and expressed it throughout the following tale. Says the legend that a village was set where the Montcortés lake is today. One day a beggar came asking for alms from the houses to be able to eat, he wandered all over the town without anyone giving him a single crumb of bread. That night a strong storm came upon and rained so hard that the village collapsed under water and the Montcortés lake was formed.

Geohazards education and dissemination

The landslides described here are clear examples of areas prone to mass movements and constitute key educational and dissemination tools. The Puigcercós landslide is a classic site for fieldtrips by secondary school and university students where they are taught about landslide characterization, and the controlling and triggering factors favouring those. The Peracalç area also takes geo-fieldtrips to observe and study the relationship of karst processes and large mass movement events. Furthermore, the Geopark and the Catalan Geological Survey organize field excursions and seminars in areas affected by mass movements to disseminate the research being carried out in the area, such as landslide monitoring techniques or landslide susceptibility maps production and to support the local communities to deal with this type of geohazards.

Another recurring and quite destructive geohazard in the Geopark are flooding events. Salt production was an important source of income for the Gerri de la Sal village from the 8th to the 20th century. A large flooding event in 1982 destroyed most of its salt pans placed along the shores of the Noguera Pallaresa river. The local community had to adapt to the new context by transforming the salt industry infrastructure left into what is today a thrilling interpretation centre describing traditional salt production methods. Also, the geopark has organized outings to recall the largest flooding events from the 20th Century in 1937 and 1982, to describe the monitoring systems put in place to prevent casualties on future events and, to provide basic knowledge to the local community (Figure 3) on how to proceed during intense rainfall events potentially leading to catastrophic flooding.



Fig.3: Dissemination activity carried out during the International Day for Disaster Risk Reduction on flooding events recorded along the Noguera Pallaresa River

Landscapes and Geohazards in the Pollino UNESCO Global Geopark

Luigi Bloise, Egidio Calabrese

Pollino UNESCO Global Geopark, Italy

Introduction

The area of Pollino UNESCO Global Geopark (UGGp) is located in Southern Italy, on the border between Basilicata and Calabria. The Geopark has several massif mountains that rise up to the higher elevations of the Southern Apennines with all summits reaching over 2000 m above sea level (asl).

In the Pollino UNESCO UGGp tectonic movements and morphogenetic processes have combined to generate unique phenomena and environments of rare scenic beauty and of significant scientific interest, but also with great geo-risk problems in numerous inhabited centers (e.g. Civita, Frascineto, San Lorenzo Bellizzi, Terranova del Pollino).

Geomorphological hazards in Pollino UNESCO Global Geopark

One of the most representative areas of the interaction between tectonic phenomena and geomorphological instability in the Pollino UGGp is the area of the Raganello Valley between the municipalities of Civita and San Lorenzo Bellizzi.

The village of Civita is in northern Calabria, on the southern slopes of the Pollino carbonate ridge; to its hydrographic right, it overlooks the deep gorge of the Raganello Stream. The area is in a vast valley open to the SE, partly lying on ancient, sometimes cemented, limestone debris and partly on limestone outcrops (Figure 1) at the foot of a modest relief called "La Sentinella" (601 m asl), located SW of the village. La Sentinella is made up of locally fractured and brecciated gray and light limestones from the Cretaceous period (Pollino Unit). The Calabro-Lucano Flysch Formation outcrops to the north of Civita and it is in tectonic contact over the Pollino Unit.

The most important phenomenon of instability within the area (Figure 1) is a massive landslide (with dimensions of about 3 by 4 km) which includes the entire valley near to which the village stands. The large gravitative depression (found in the Civita basin north-west of the village) is clearly ancient as it indicated by the considerable degree of morphological evolution recorded by the linear and areal erosion processes that tend to mask signs of ancient gravitational events.

The deep gravitational deformation outcropping above the main scarp described above, in Mount Moschereto - Timpa del Castello, has highly prominent morphological aspects. The deformations are attributable to gravitational phenomena in the form of lateral expansion in Jurassic-Cretaceous carbonate rocks.

The gravitative deformations described above (both in the Jurassic-Cretaceous carbonates and in the Cretaceous limestones) originate from the superposition (due to tectonic movement) of a rigid block with mechanical behavior (carbonates) over lithologies characterized by ductile mechanical behavior (Calabro-Lucano Flysch).

Continuing along the road which leads from Civita to La Falconara, a relief is reached (Colle Marcione) from where one can easily appreciate the evidence of Pleistocene tectonics that developed in the area. From the Colle Marcione viewpoint there is a spectacular view towards the high valley of the Raganello stream. The torrent flows between

Fig. 1: Overview from the Belvedere of Civita



rocks of flysch origin, where tectonic movements combined with morphogenetic processes have generate these unique environments of rare scenic and scientific beauty (Figure 2).

Colle Marcione provides a view of the peculiar structures of this area of the Geopark, consisting of faults, thrusts and massive gravitational phenomena that caused several flash flood episodes (Hidrogeological risk) associated with the Raganello stream and affecting the village of Civita. Some of these episodes, as the 2018 one, involved the loss of human lives (Figure 2)



Fig.2: The Raganello stream valley (Photo by Pollino UGGp)

Geohazards education and dissemination

The Geopark set up a geo-route named “On the trail of the Pollino Line”, where the visitors can appreciate throughout information panels installed along the way, the geological, geomorphological, and tectonic processes that have shaped the present-day structure and landscape.

The Georoute itinerary is presented through a rich collection of pictures with descriptions and interpretations, together with a geological/excursion map indicating the location of the observation points. “Points” or “Stops” are indicated on the map and, some of these, include information or interpretation panels. These panels are designed so they have low visual impact and include a digital system that allows visitors to obtain further information through their smartphone.

The guide aims to immediately promote the fruition of the geological aspects of the territory and moves through topics such as geology and geomorphology, the landscape, geohazards and, more generally, those still unresolved issues in the subject of Earth Sciences.

The morpho-tectonic processes of the area encountered along the georoute are described and illustrated in the Pollino guide. Moreover, the Pollino UGGp staff carries annually some dissemination activities on the landscape evolution of the territory and the geological risks connected to it.

From this point of view, the guide represents a tool for the promotion of tourism, at the same time that tries to reconcile visitors with the issues related to the protection and conservation of such important geosites.



Fig.3: Educational activities on geohazard risk in Pollino UGGp

The living memory of the 365 AD earthquake at Psiloritis UNESCO Global Geopark, Crete, Greece

Charalampos Fassoulas

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The devastating 365 AD, 8.2R, earthquake

Crete is one of the most earthquake prone areas of Europe due to its position on top of the active Hellenic Subduction zone. Plate convergence between Eurasia and Africa, as well as additional lateral motion of the Anatolia microplate contribute to a complex tectonic regime that results in surface normal faulting, strike slip and deep thrust, subduction related movements, that create the present seismicity of the island.

The strongest of all historically recorded events happened on 21st July 365 AD with an epicentre offshore of the southwestern edge of the island of Crete (Papadopoulos, 2011). Travellers and monks of that period report that on Crete, all the 100 Roman cities were totally destroyed, similarly cities at the northern coast of Africa (including Alexandria), Sicily, and southern France (including Nice) suffered severe damage. In addition, the earthquake caused the largest ever tsunami in the Mediterranean area that magnified the effects of the earthquake in the coastal zones.

"The terrible disaster took place all of a sudden throughout the world, such as we find neither in legends nor in true historical accounts... The sea was driven back and its waters flowed away to such an extent that the deep-sea bed was laid bare and many kinds of sea creatures could be seen embedded in the mud and great ranges of mountains and valleys could gaze upon the rays of the sun. ..." (Marcellinus, 378AD). This was part of the report of Ammianus Marcellinius a historian of that time who was at the harbour of Alexandria and experienced the tsunami propagation, a description so detailed it is now used for tsunami modelling.

The impact of this earthquake on the island of Crete was very profound and still visible. Half of the island (the western part) was risen up during the earthquake at various levels (Pirazzoli et al. 1982); from 9m at the southwestern edge that was closest to the epicentre, to 6m at the harbour of ancient Falasarna, 5m in the area of Kissamos at the northern coast, and up to 1.2 m in the Agioa Pavlos area in the central part of the island. Sea notches, marine terraces and ancient ruins mark this co-seismic land uplift (Figure 1). All these data, as well as the tsunami, helped to estimate the earthquake magnitude at the level of 8 to 8.3 on the Richter scale, which marks the event as the strongest ever recorded in Europe and Mediterranean.

Both the exact epicentre as well as the seismogenic fault(s) of this earthquake are subject to a long-lasting scientific debate. Most researchers claim that either the subduction interface south of Crete, or parallel to that thrust was activated to produce the earthquake (Shaw et al., 2008). Other researchers, based on the tsunami modelling and the lack of apparent fault evidence, assert that the interaction and activation of two large normal faults located south and west of Crete were the reason for the rock uplift, the devastating tsunami and other effects of this earthquake (Ott et al., 2021). Regardless, the earthquake mechanism and source, this earthquake and its side-effects are of universal reference and value.

Fig. 1: Sea notches at about 1.4 m above present sea-level in the area of Plakias in central, south Crete raised during the 365 AD earthquake (photograph by Charalampos Fassoulas)



Psiloritis UNESCO Global Geopark (UGGp) is located in the central part of the island of Crete, distant enough from the epicentre to exhibit clear evidence of this earthquake along its northern coast. However, inside the UGGp is the town of Eleftherna and at its southern border is Gortis, the capital of the island at that time, both of which were totally destroyed by the earthquake. Archaeological excavations in Gortis have documented the devastating effects of the earthquake in the functioning of the town, which was abandoned after that.

Eleftherna on the other hand was located in the centre of Psiloritis UGGp, north of Psiloritis Mountains, and in the municipality of Mylopotamos. It was a very old establishment that flourished mainly during the Hellenistic and Roman times based on trading. It was located at a strategic location between two big cities, Kydonia to the west and Knossos to the east and incorporated two nearby harbours, Panormos and Stavromenos. Today, the ruins of the cities are spread over the scenic valley of Prine in which more than 16 excavation sites, monuments and other landmarks can be found (Figure 2).



Fig.2: A section at the harbour of Falasarna in Western Crete where remnants of the 365 AD tsunami are evident. The mixture of small boulders with sand and marine and terrestrial shells at the middle of the section (approximately where the pickaxe is located) represents the tsunami deposits. (photograph by Charalampos Fassoulas)

Water collection systems supported by large underground tanks and quarries exist at the sides of the valley. In addition, remnants of the acropolis are still present on a small hill (Figure 3), a Hellenistic bridge is still intact, and ruins of buildings and neighborhoods are widespread. The most profound site is the Necropolis, the ancient cemetery where the most precious discoveries were unearthed. Evidence of the devastating shaking of 365 AD are apparent in many places and monuments, like bent and cracked walls, broken and compressed stairs or collapsed ceilings and roofs. In one of those houses, three skeletons of the members of a family were found trapped under the ruins, which was an important archaeological and geological discovery.

Raising awareness on earthquakes in Psiloritis UGGp

The 365 AD earthquake is a benchmark in the tectonic history of Crete and the eastern Mediterranean. It is not only the strongest earthquake that ever occurred but also the most devastating and disastrous leaving its marks on the

natural environment, the landscape and the human history of the island of Crete. For these reasons, this earthquake is being used by Psiloritis UGGp as a case study and living memory to help sensitise citizens and raise awareness of earthquake and tsunami risk.

The main partner of Psiloritis UGGp, the Natural History Museum of Crete (NHMC) demonstrates the case of 365 AD earthquake at its exhibition halls through posters and other displays. In addition, under an EU Civil Protection Mechanism funded project, titled RACCE, in which the Lesvos and Reserve Geologique Haute Provence UGGps were also partners, the NHMC developed a special training program performed at its earthquake simulator. The program uses images and impacts of this earthquake to highlight the earthquake and tsunami risk in Crete, reproducing simultaneously real earthquakes.

In addition, the Museum of Ancient Eleftherna, another partner of Psiloritis UGGp, is currently managing the exhibition halls at the Eleftherna site. It is a modern site-museum and very popular with tourists, where basic information on the destructive force of the 365 AD earthquake and its impact on the town are displayed. As the town and other constructions are spread over a large area, several walking trails are under development and will soon be opened to the public, offering access to many of the important sites and excavations, as well as to the Necropolis and to the natural heritage of the area. Along these trails, sites and monuments that have captured the impact of the earthquake will be highlighted as a memory of a disaster that will inevitably happen again in future.



Fig.3: Parts of the acropolis and water collection system at Eleftherna (photograph by Charalampos Fassoulas)

The Geopark itself has also developed several initiatives to raise awareness amongst local communities and visitors on the earthquake risk and share good practices. These have taken the form of repeated public talks in schools, activities to celebrate the International Day of Disaster Risk Reduction by the Global and the European Geoparks Networks, and special educational programs in collaboration with the NHMC, like the “When Engelados awakes”. In all these activities the case of the 365 AD earthquake and the impact at Eleftherna are always used as the closest example of an earthquake disaster to the UGGp, a memory that helps us to be alerted and prepared for the next disaster.

Geoparks as Natural Laboratories: digital geological tools to enhance fruition and hazard awareness. The case of Mt. Capodarso and Imera Valley (Sicily, southern Italy)

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Introduction

The R.N.O. Monte Capodarso e Valle dell'Imera meridionale, managed and protected by Italia Nostra Onlus, stands as one of the most significant Natural Reserves in central Sicily, within the Rocca di Cerere UNESCO Global Geopark in southern Italy. The landscape of this reserve has been shaped by the Salso (Imera) river and its tributaries. Two prominent hills dominate the valley: Monte Capodarso, reaching an altitude of almost 798 meters above sea level to the east, and Monte Sabucina, with a height of 710 meters above sea level to the west (Figure 1).

Internationally renowned for its archaeological and geological heritage, the Natural Reserve bears witness to ancient civilizations and historic Sulphur Mines, exploited during Sicily's economic boom in the 19th century. Although these mines are no longer operational, they remain key archaeological and historical attractions within the Natural Reserve, offering various paths for tourists and experts to explore. Moreover, Monte Capodarso is particularly captivating for specialists due to its exceptional Pleistocene carbonate outcrops, providing insights into sea-level and climate change. However, these carbonate cliffs represent the primary hazard in the reserve. Evidence of past rockfalls is visible along the river gorge and slopes, with the most recent landslide event recorded in 2007. This event impacted the main geotrekking path, posing a threat to the stability of surrounding infrastructures.

Rockfalls in Monte Capodarso e Valle dell'Imera meridionale Natural Reserve

The landscape of the Natural Reserve is profoundly shaped by the Salso (or Imera) River, creating dramatic bedrock exposures. The slopes of Monte Capodarso and Monte Sabucina exhibit clay/marl lithologies at the foothills, and clay and marls interbedded with Pleistocene carbonates towards the hilltops. The latter, composed of calcarenites utilized for both ancient and modern artifacts, have given rise to inactive quarries scattered throughout the area. Presently, only one quarry, situated at the foothills of Mt. Sabucina, remains operational due to legal restrictions protecting archaeological sites, resulting in the closure of others.

Guided tours and tourist events, unrestricted by age or trekking abilities, are frequently organized. There are two official trails. The first one is the "Sentiero Natura" (Figure 2), encircling Monte Capodarso and extending for about 2 km along the Imera River, showcasing packstone cliffs and their depositional architecture. The trail passes through

Fig.1: Panoramic view of Monte Capodarso and its trekking path Sentiero Natura from Monte Sabucina, belonging to the R.N.O. Monte Capodarso e Valle dell'Imera meridionale. (Photo by Martina Forzese)



inactive quarries, reaching the old Sulphur Mine of Giumentaro at the foothills.

The second trail ascends from the bottom to the top of the western side of Monte Sabucina, culminating at the prominent Sulphur mine of Trabonella. Atop Monte Sabucina, archaeological remains of an ancient civilization from the Late Bronze to the Hellenistic age are preserved. Both trails are suitable for novice trekkers and mountain bikers.

Fractures and joints in calcarenites, coupled with the differential erosion of carbonates and marls/clays, give rise to rockfalls, particularly after intense rainfall. Groundwater circulation in porous and permeable carbonates contributes significantly to the weathering and instability of the rock mass.

On January 21st, 2007, a rockfall event occurred in the Sentiero Natura of Monte Capodarso, obstructing the ancient bridge and compromising the trekking track. Although no damage occurred to the viaduct pillar due to a retained wall (Figure 3), the surrounding infrastructure, aqueduct, cottages, and the natural route of the R.N.O., had to be temporarily closed. Local authorities conducted a thorough geological and hydrogeological investigation resulting in a detailed report (Lucchesi, 2004), designating the area as highly risky. As a result of frequent rockfalls, the gorge of Monte Capodarso is now full of calcarenites blocks, which at times can roll down in the Imera riverbed.

Following the 2007 rockfall event, a gate and warning signals were installed at the entrance of the trekking path, and access to the natural reserve and Sentiero Natura is now permitted only under the supervision of authorized guides. Trekking is subject to checking meteorological conditions on the Protezione Civile website to ensure slope stability.

A 3D photogrammetric geological model (Bollati et al., 2022; Fazio et al., 2022), has been developed using aerial drone pictures. It was useful for: 1) mapping calcarenite blocks from past rockfalls, and accelerated erosive processes (e.g. badlands) on clay and marls (See Figure 3); 2) identifying

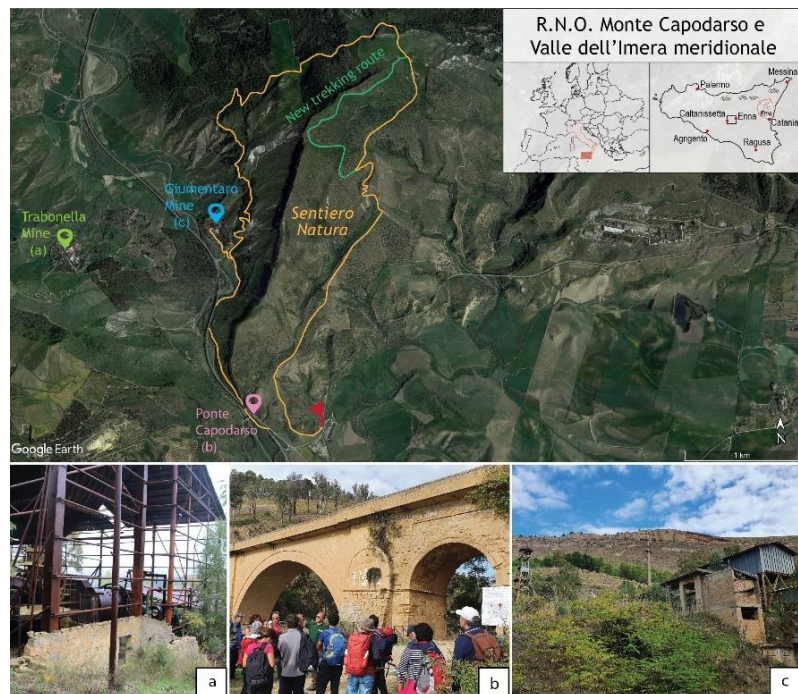


Fig.2: Map view (from Google Earth) and geographical position of the geotrekking path of Monte Capodarso (Sentiero Natura). Pins and pictures are linked and represent the main attractions (photographs on a; b; c). In green, the new geotrekking route to visit the archaeological rests, traced during 3D model development. (Photos by Martina Forzese)

infrastructures threatened by rockfalls. This model facilitated the exploration of new and safer routes, including a trekking path to a little-known archaeological site on top of Monte Capodarso, revealing the remains of an ancient city wall from the Iron Age. Ongoing studies employ digital tools, from 3D models to satellite surveys, to define the archaeological site's specific compounds and features. The newly traced route not only unveils previously unknown archaeological findings but also offers a safer alternative away from rockfall-prone areas, providing panoramic views of the Imera gorge, the calcarenite cliffs of Monte Sabucina, and the Giumentaro Mine to the north.



Fig.3: Rockfall January 2007: several blocks rolled down the gorge, stopping very close to the first viaduct pillar and on top of the main natural path (Sentiero Natura). To the right, the elaborated map of visible rockfalls and accelerated erosion affecting the Sentiero Natura. (Photo by Daniele Maglitta)

Geohazard education and dissemination

Since 2021, the Rocca di Cerere UNESCO Global Geopark, the R.N.O. Monte Capodarso e Valle dell'Imera meridionale, and the University of Catania have collaborated as partners in the UNESCO project IGCP 714 3GEO – Geoclimbing & Geotrekking in Geoparks (<https://en.unesco.org/international-geoscience-programme/projects/714>) (Forzese et al., 2021; Bollati et al., 2022). Esteemed participants in the UNESCO Global Geopark initiative include Estrela in Portugal, Kutrakura in Chile, Psiloritis in Greece, and Sesia-Val Grande in Italy. The reserve annually attracts between 5000 to 6000 visitors, comprising hobbyists, scholars, and university students. The primary objective is the promotion and enhancement of the geological heritage of Geoparks and Geosites through innovative tools. Geoclimbing and geotrekking serve as effective common activities. However, the associated risks are sometimes overlooked. To address this, new straightforward methodologies have been implemented to easily disseminate the geological heritage and raise awareness of related risks (Fazio et al., 2022). Explanatory panels have been strategically placed along the tracks at key points of interest, serving as educational stops for guided tours and geotrekking activities. Additionally, high-resolution aerial photogrammetric models will soon be made available. These models aim to offer pervasive digital access, even during periods of travel restrictions (linked to the pandemic and energy transition). Importantly, they will contribute to enhancing awareness of hazards and risks connected to outdoor activities.

Saimaa UNESCO Global Geopark, Finland – Geohazards

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An Ancient and stable bedrock

The ancient bedrock of Lake Saimaa originated at the bottom of an ancient sea around 1,900 million years ago. The bedrock evolved over time; the ancient sea receded, a high mountain range rose above the present-day Lake Saimaa, the rock masses crystallized into gneisses and granites in its depths, and gradually, over millions of years, the mountain range eroded away, leaving only sand on the shores of Lake Saimaa. The broken base of the mountain range is still visible as a mosaic-like landscape, alternating between water, rocky and terrestrial areas. (Saimaa Geopark, 2023).

Finnish bedrock consists of very old rock types – such as granite and gneisses. The bedrock is stable in Finland because its location is far from the edge of large tectonic plates. Thus, strongly moving and seismically active structures do not occur (Geosto Oy, 2023), nor do geohazards resulting from them, such as strong earthquakes, volcanic or hydrothermal eruptions or tsunamis.

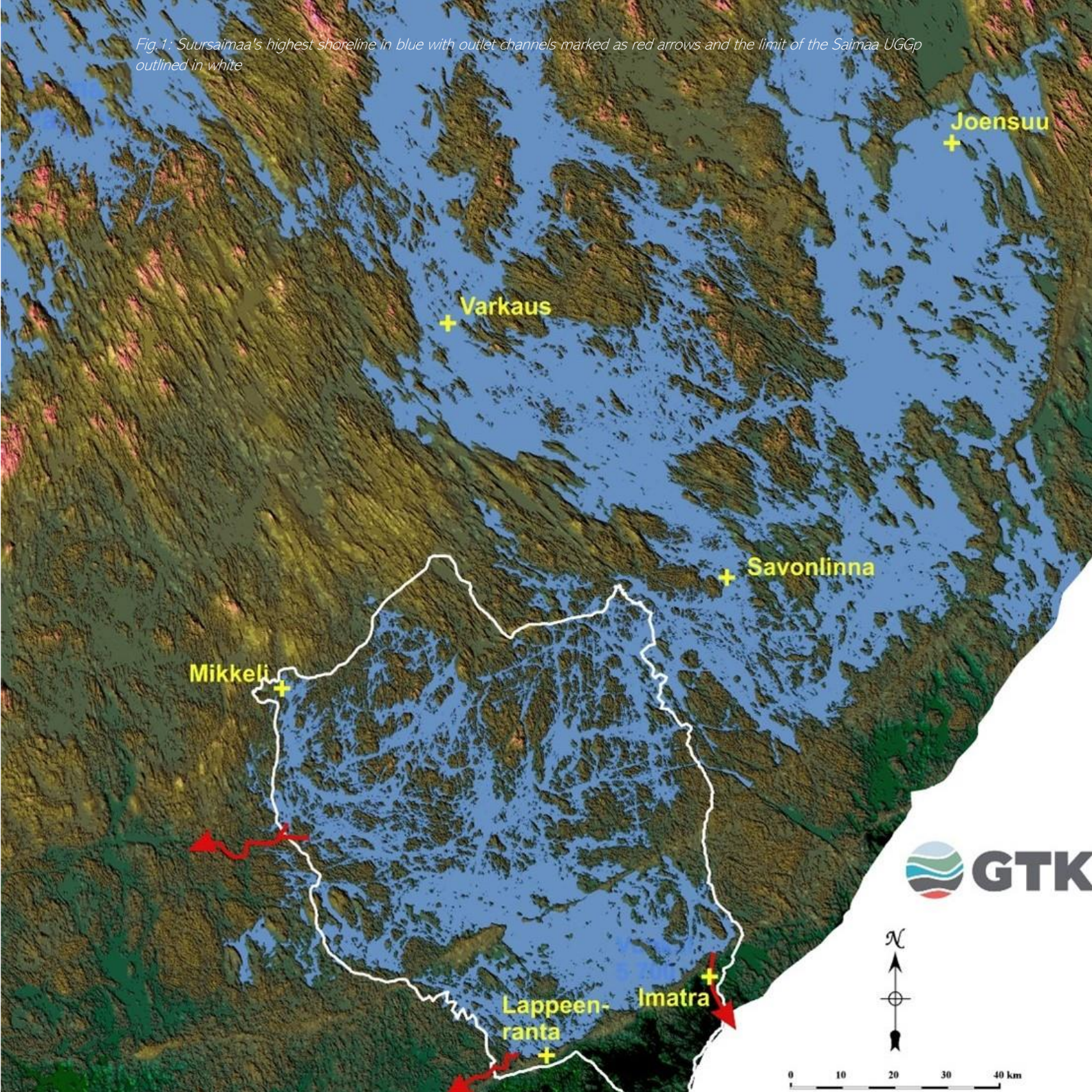
Instead, the observed rock movements and seismic events are related to the uplift of the land after glaciation and the slow recovery of the rock mass after the ice load has disappeared (Geosto Oy, 2023). The biggest single geohazard in the Saimaa Geopark area - the outbreak of the river Vuoksi - occurred 5,700 years ago, and is specifically related to the tilting, and uplifting of the land.

A Flood lasting millennia (11,000 – 5,700 years ago)

The waters of the Saimaa region have their own wonderful adventures. Land uplift, which is greater in the northern parts of the watershed than in the south, tilts the Earth's crust. This caused Saimaa to flood at one time, when the ancient Greater Saimaa Lake Area was formed (Geological Survey of Finland / GTK, 2018). The reason for the millennia-long rise in water levels in the lake areas was not however uplift itself, but rather the tilting of the crust towards the southeast because of uneven uplift.

As the outlet channels of the lakes in the ancient Vuoksi watercourse area were in the north, where the basins were rising most rapidly, water began to rise onto dry land in the southern parts of the basins. This led to inundation that lasted for 5,000 years, during which time the water areas expanded and merged to form Greater Saimaa, which extended from the First Salpausselkä to Iisalmi in Northern Savonia. Greater Saimaa therefore refers to the large, ancient lake which covered the present-day Saimaa watercourse area. The form "Suur-Saimaa," which is now used as a geographical name, encompasses only the southernmost bay of the ancient Greater Saimaa Lake area (Figure 1). Around 7,500 to 7,000 years ago, Greater Saimaa was also connected to Ancient Päijänne. Together, they formed a water area known as the Great Lake of Central Finland. In southern Saimaa, the all-engulfing flood only began to recede once the Greater Saimaa Lake complex's outlet channel moved first from the Selkamyslampi channel in Northern Savonia to Matkuslampi in Ristiina, and then to Kärenlampi in Lappeenranta. Matkuslampi functioned as an outlet channel for Greater Saimaa 6,900 to 5,700 years ago, and Kärenlampi from 6,300 to 5,700 years ago.

Fig. 1: Suursaimaa's highest shoreline in blue with outlet channels marked as red arrows and the limit of the Saimaa UGGp outlined in white



The current flowing river, Vuoksi, broke through the sand-dominated ridges of I Salpausselkä about 5,700 years ago (Geological Survey of Finland / GTK, 2018).

The breakthrough of the river Vuoksi – the latest outlet channel of Lake Saimaa

5,700 ago, tilting of the Greater Saimaa basin towards the south-east, caused by uneven land uplift, had reached a critical stage. At the site of present-day Vuoksenniska, water flooded over sand-filled ridges, and a deep channel was rapidly grooved through the flood point. The Greater Saimaa water masses rushed through, along a passage indicated as Virasoja, draining from Lake Immalanjärvi into any fractures and planes of weakness that could be found in the bedrock, until finally ending up in the ancient bay of Jääski at Lake Ladoga.



Fig.2: Riverbed kettles usually emerged around small knolls in the bedrock. (Geological Survey of Finland / GTK. 2016, p. 10)

The birth of the River Vuoksi reduced the water level in the Greater Saimaa by about three metres in a short period of time, creating a large outwash delta at Jääski. (Geological Survey of Finland / GTK. 2016) In Imatra, the sudden breakthrough of Vuoksi can be seen in Linnansuo, about 5km downstream from Vuoksenniska, where wood and flood sediments (silt and fine sand) have been deposited on top of the peat. In Jääski, the eruption delta was formed into an ancient bay of Ladoga. The delta consists of alluvial material, i.e., silt and fine sand, but there are also remains of plants and even tree stumps (Remes et al., 2013).

The earliest Vuoksi riverbed is most easily visible along the nature trail winding through the current Kruununpuisto park. There are dozens, if not hundreds of river-bed kettles in the area, gouged in the uneven bedrock by strong water currents with the help of transported rock material and cavitation (Figure 2). Cavitation refers to gas bubbles that emerge in water in pressure minimums and then collapse, causing surrounding pressure waves. These slowly crumble the nearby rock surfaces. The same physical phenomenon may cause pockmarks on ship propellers and power plant turbine blades. The walls of the river-bed kettles, as well as those of giant kettles caused by much bigger meltwater streams, display spiral grooves that indicate the direction of water flow.

The vertical flow in the middle of the kettle removed the grinding stones that had been ground to a smaller size in the bottom currents, and any detritus. In other words, the preconditions for kettles arising in rapids include sufficiently large and fast-flowing rapids and variations in the riverbed that cause large pressure changes in water. The river-bed

kettles in Kruununpuisto Park are 0.3 to 1.0 metres in diameter, with a depth varying from 0.5 to 1 metre half to one meter. The kettles were created quite rapidly after the river Vuoksi broke through the Salpausselkä ridge, at a stage when the river was much wider at this point than it is now (Geological Survey of Finland / GTK. 2016).

The consequences of the birth of River Vuoksi

The evolution of River Vuoksi 5,700 years ago (Figure 3) changed the course of Lake Saimaa's development. The water level dropped by a few metres and River Vuoksi began to regulate the development of Lake Saimaa and the lake landscape of Eastern Finland. For today's hikers, the multi-phase history of Lake Saimaa can be seen in the form of raised beaches of different altitudes (Saimaa Geopark, 2023)

When the Vuoksi stream was born, the water level in Saimaa dropped suddenly and revealed thousands of square kilometres of new, vibrant land. New vegetation began to grow in the soil, such as grass, hay, and hardwoods. Fresh vegetation attracted moose and soon after the moose came people, with new ways of life. The culture that used asbestos in its pottery disappeared. A culture using moose, log buildings, flint and amber took its place – the comb ceramic culture. The birth of Vuoksi and the resulting cultural change have been studied in an interdisciplinary project by biologists and natural scientists and archaeologists from the University of Helsinki together with the Swedish Museum Agency, the Institute of Game and Fisheries Research and the University of Bristol.

Geohazards education

Dozens of earthquakes occur in Finland every year. However, these earthquakes are relatively weak, ranging from 0 to 4 in magnitude. Finland has a relatively high number of storm days, floods and avalanches in winter. Finland's weather varies greatly through the seasons. Temperature ranges from +30°C or more on hot summer days to -30°C or less on the coldest winter days. Climate change is also affecting Finnish nature. Habitats are changing and species adapted to northern conditions are finding it more difficult to survive. Saimaa Geopark has prepared guidelines about how to hike and explore the nature in a safe way. Saimaa Geopark organize basic geology courses open to all publics and has also produced many different guides and maps.

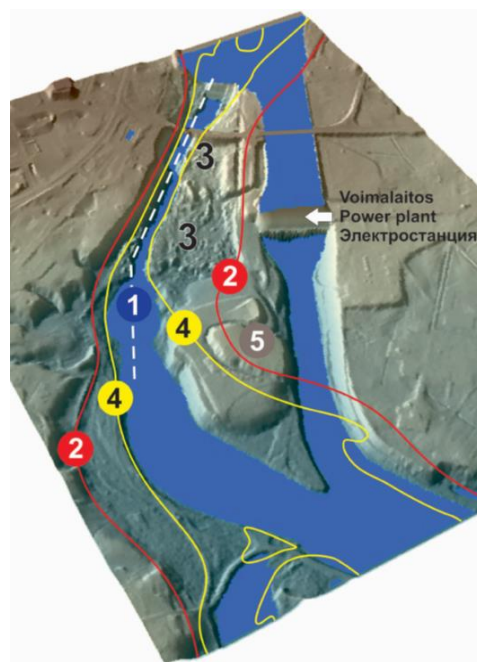


Fig.3: The old River Vuoksi basin came into being when the Greater Saimaa flooded over the First Salpausselkä at Vuoksenniska some 5,700 years ago. Through a rapidly deepening water outlet, masses of water sought their way into an old rock fracture valley (1), where a minor river used to flow from Lake Immalanjärvi. With the enormous initial water masses, and erosion of the riverbed only just beginning, the Imatrakoski rapids were wider than they are today (2). The giant kettles in the Voimalaitosniemi (3) were born at this stage. The riverbed soon scoured its way deeper into the rock fracture and narrowed down to its natural size (4). The dumping sites of the dredging lands from the lower passage (5) make it difficult to decipher where the early rivers used to run. (From Geological Survey of Finland / GTK, 2016)

The need for education and awareness in forest fires – Sierras Subbéticas UNESCO Global Geopark (Spain)

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Introduction

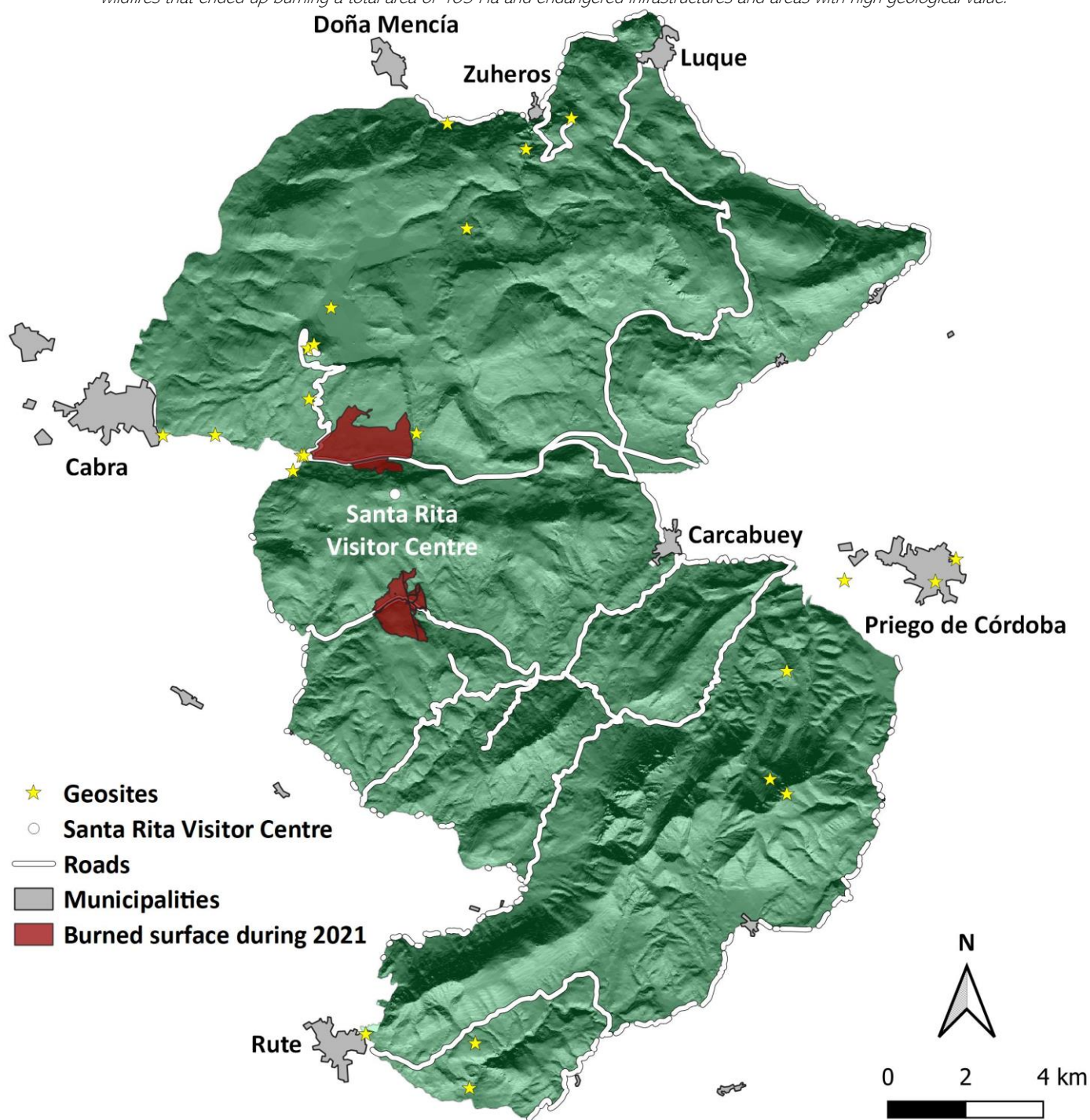
The geographical location of Andalusia in the south of Spain, coupled with the meteorological conditions during spring and summer, creates an environment where forest fires can have devastating consequences. Strong terrestrial winds, although a significant factor, are not the sole driving force behind wildfires. For many, including large-scale wildfires, topography has been identified as a crucial conditioning factor. When combined with a high fuel load, such conditions can trigger the development of convective fires. The human use of fire, deeply ingrained in rural culture, further exacerbates the wildfire risk. Practices such as burning waste, clearing agricultural remnants, eliminating weeds, and regenerating pastures, while culturally rooted, become particularly concerning in a region as vulnerable to wildfires as Andalusia. Recognizing the potential impact of wildfires on Geological Heritage and Biodiversity, the Geoparks in Andalusia—specifically Sierra Morena of Seville, Cabo de Gata - Níjar in Almería, Granada, and Sierras Subbéticas in Córdoba—are actively aware of these issues. They understand the risks associated with wildfires that impact the region Geological Heritage and Biodiversity.

A lapies marked by a wildfire

The worst wildfires in Sierras Subbéticas Geopark occurred in 2021, involving several incipient fires that collectively burned an extensive area of 405 hectares. Two significant events occurred in the municipality of Cabra. The first fire was declared on the 24th July in Gaena Mountain, affecting 148.9 hectares of holm oak, scrub, and grass. The second fire, declared on the 31st July in the area known as "Los Pelaos," near the Santa Rita Visitor Centre, affected 255.1 hectares of scrub and grass (see Figure 1). Investigations into the causes of the fires concluded that the Gaena mountain fire was accidental, while the "Los Pelaos" fire was intentional.

The second fire, near the Santa Rita Visitor Centre, was particularly concerning as it persisted for over a week, only being extinguished on the 9th August. It impacted a territory of great geological and scenic value, originating on the right bank of the access road to the Hermitage of Virgen de la Sierra. This area is home to seven Geosites, including the lapies, "Picacho de Cabra," the tectonic island, "Los Pelaos" fold, "Los Pelaos" paleokarst, "Los Frailes" fountain, and the Santa Rita viewpoint (Figure 2). Given the proximity to the road, there was also concern that the fire might cross it and cause damage to the Santa Rita Visitor Centre (Figure 2). The fire initially spread in an east-northeast direction, influenced by prevailing winds, partially affecting the lapies geosite. A second spread in an east-southeast direction crossed the road, reaching the entire area around the Visitor Centre and the recreational area. Fortunately, the forest's structural conditions and defense infrastructures, such as firebreaks and clearings around the recreational area, prevented further spread.

Fig. 1. Burned surface during 2021, the worst year in Sierras Subbéticas regarding forest fires with several incipient fires and wildfires that ended up burning a total area of 405 Ha and endangered infrastructures and areas with high geological value.



Causes of the forest fires

The data presented in Figure 3 reveals a cyclical pattern in the virulence of fires recorded in Andalusia in recent years. The graph highlights a robust correlation between the occurrence of fires and meteorological conditions. This relationship has been extensively studied by Martin et al., (1998) and Estirado and Molina (2005), and it has been interpreted as being linked to meteorological severity, primarily caused by low rainfall and high temperatures over extended periods. For instance, the years 2015 and 2017, both witnessing extensive burned areas, experienced the lowest annual precipitation and the highest maximum temperatures in Andalusia.

The fires in Sierras Subbéticas Geopark in 2021, whether accidental or intentional, are not coincidental. Unfortunately, the harsh reality is that negligent and intentional fires together constitute approximately 62% of all fires, with intentional fires accounting for 32% and negligent fires for 30%. The percentage of intentional fires raises serious concerns, especially because, regardless of their frequency, they pose a greater danger for extinguishment and sometimes escalate into large fires, causing significant losses.

It is disconcerting that in a region like Andalusia, with conducive climate and vegetation conditions exacerbated by a substantial accumulation of fuel in the mountains, the population may not be fully aware of the dangers associated with their actions. Moreover, even if they are aware, there seems to be a pernicious culture regarding the use of fire.

Prevention and mitigation of forest fires

The region of Andalusia has implemented an Emergency Plan for Wildfires, known as the INFOCA Plan, to enhance the prevention and extinction of wildfires. Since its professionalization in 1995, the plan has continually improved and established procedures to achieve a high level of efficiency, resulting in a significant reduction in the number of interventions to attempted wildfires (80%). The INFOCA Plan stands out as one of the most ambitious programs of the Ministry of the Environment, featuring a growing budget each year and a dedicated team of approximately 5,000 individuals.



Fig. 2. Above, "Los Pelaos" area, a territory located in the municipality of Cabra, of great geological and scenic value. The figure shows the lapis and Picacho de Cabra tectonic island, two Geosites of Sierras Subbéticas UGGp. Below, the forest fire that took place in 2021 in "Los Pelaos" area (photograph by Felipe Osuna)

Despite the continual enhancements introduced along this path, the fight against wildfires necessitates a social pact. Therefore, the INFOCA Plan, in collaboration with the Sierras Subbéticas Geopark, conducts workshops and programs to raise public awareness about the dangers and consequences of wildfires. The communication campaign of the INFOCA Plan carries the slogan "Against fire, we all act." The plan's staff engages in social education actions against forest fires, particularly with schoolchildren, either through school visits or by hosting them at the Sierras Subbéticas Forestry Defense Centre.

Moreover, the Geopark has a longstanding tradition of conducting informative and educational campaigns. Some are directed at the general public, while others target specific population groups such as farmers and shepherds. The goal is to increase awareness about the dangers of fires and encourage changes in local community habits. As part of the Geopark's Environmental Awareness Programme, specifically aimed at the local population and entities, two specific activities were developed in 2021 and 2022 following episodes of severe wildfires. Additionally, the Geopark organized awareness campaigns during the International Day for Disaster Risk Reduction, including forest restoration works, targeting the general population and school groups (see Figure 3).

Conclusions

Wildfires are intricately linked to annual meteorological conditions, with high temperatures and low rainfall playing significant roles. Unfortunately, in the context of climate change, forecasts do not bode well, especially as predicted scenarios reinforce the trend toward higher temperatures and potentially stagnant annual precipitation levels. As illustrated in Figure 2, the annual average temperature has been steadily increasing. In 2022, the average annual temperature was 3 degrees higher than in 2010, and even in the most favorable scenario, annual precipitations remain stagnant at 500 mm.

This changing climate scenario contributes to a rise in the annual number of wildfires, expanded burned surfaces, and an increase in the severity of fires each year. However, the most concerning data point is the origin of fires, with up to 60% attributed to negligent human behavior. It is crucial to significantly improve these numbers, and the role of the Geopark is instrumental in achieving this by raising awareness among citizens about the potential hazards and losses associated with wildfires. Public education and awareness campaigns conducted by the Geopark can play a vital role in fostering responsible behavior and preventing wildfires.

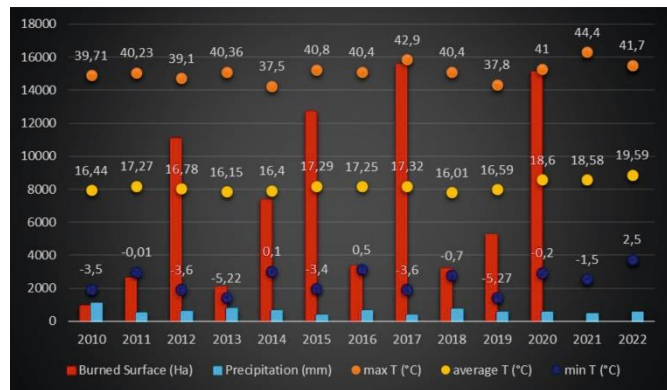


Fig.3: Meteorological conditions between 2010 and 2022 registered in the Weather Station IFAPA Centre of Cabra and the total surface affected by wildfires in Andalusia during the same period (modified from INFOCA Plan)

Floods in Sitia UNESCO Global Geopark in recent years

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Floods in Sitia area

The town of Sitia is located at the mouth of the Panteli river. It got its name from a spring of the same name. The Panteli hydrological basin has an area of 129 Km² and the total length of its watershed is 59 Km (Figure 1). The hydrographic network is dendritic. In the urban fabric of the town of Sitia there is also a minor stream with its own hydrological basin with an area of 5 Km². The Vaga stream, as it is called, has been active for over 60 years. The last 420 m consist of an underground channel along the town of Sitia that drains into the port town.

In the last five years, two floods have occurred. The first was in April 2019 and the second in October 2022 (Figure 2). The first flood episode occurred exclusively in Panteli river basin, while during the 2022 rainfall event both streams were flooded. The consequences, especially in the October 2022 flooding event, were devastating.

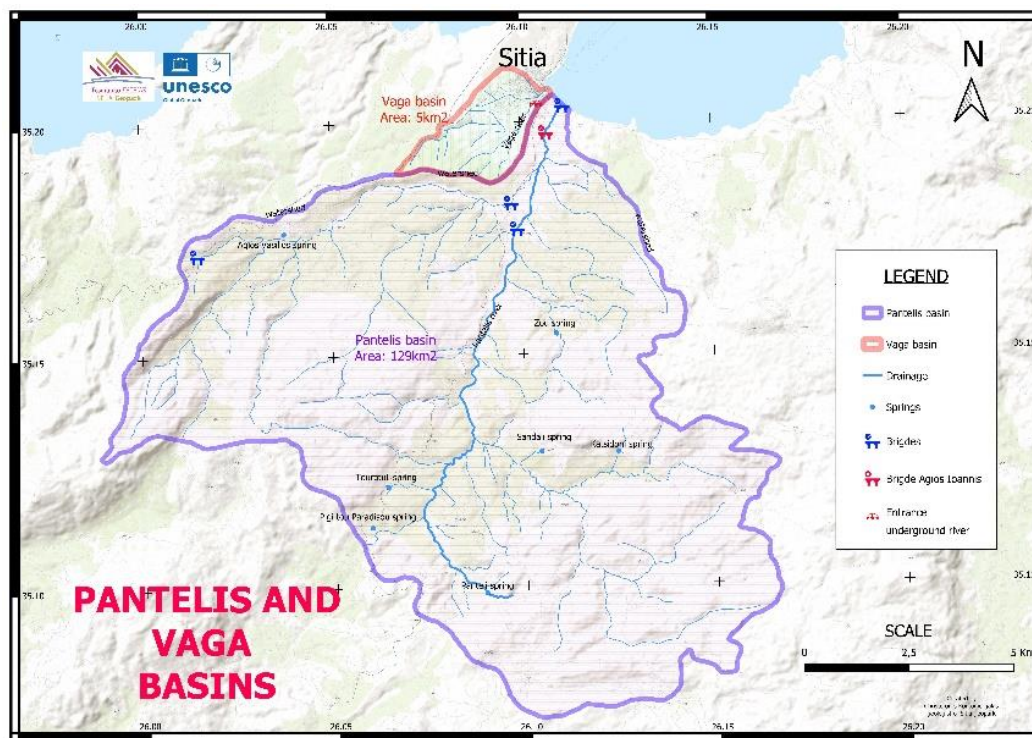


Figure 1. Map of the hydrological basins of the Panteli River and the Vaga Stream in the region of Sitia

Fig.2: Consequences of the flooding at Sitia in October 2022 (photograph by Zoglopitis Giorgos)



Zoglo
Photography

According to the meteorological station installed outside of the General Hospital of Sitia by the National Observatory of Athens, the rainfall recorded on 15/10/2022 was 88 mm, which was the recording capability of the rain gauge. The report of the National Observatory of Athens quantified that the total rainfall on the day in question was between 288 and 388 mm and the average rainfall rate estimate was 96 – 130 mm/h, since the rain fell in a short interval lasting about 3 hours. The volume of water received by the hydrological basin of the Vaga stream in these 3 hours interval was estimated at 1,440,000 – 1,940,000 m³ (Figure 2).

The big problem was presented at the point of undergrounding of the stream, at the entrance of the town. A section of the stream, before its undergrounding, is used as a road. This resulted in a car being swept away by the water and obstructing the mouth of the underground tunnel. Two garbage bins were also involved in this as well as other portable materials that were carried away by the stream. Therefore, the overflowing of the stream was inevitable. The result was the destruction at 120 businesses, 100 houses and 150 cars in the urban fabric of Sitia. Also, the Sitia UNESCO global Geopark information centre was severely affected.

At the same time, extreme rainfall was recorded in the Pantelis drainage basin with an area is 129 Km². Especially the streams located in the lower ground area of the river basin overflowed and caused flooding of agricultural crops, greenhouses collapsed, and agricultural machinery was swept away. Furthermore, The Pantelis River overflowed on the little bridge located at the Agios Ioannis position (middle little bridge), flooding the nearby houses and a large hotel complex located at the estuary. The study for the construction of this bridge was completely wrong, as its small cross-section quickly collapsed and prompted the flood episode in the lower reaches of the river. The same thing happened in 2019. The bridge was subsequently demolished and today is temporarily replaced with a military Bailey bridge, which has almost twice the cross-section.

The quantity of materials that were transported into the sea and into the port of Sitia was enormous. Inside the port, the isobaths changed by at least 2 m. With the help of mainly volunteer groups two-wheelers, agricultural machinery, watering pipes, dead animals were collected from the port and the sea. A year later, the waters of the sea and the port are still cloudy and muddy from the huge number of fine-grained materials carried by the two streams.

It is worth noting that on the same date heavy rainfall events were recorded in other areas of Crete with also disastrous results. Near the UNESCO global geopark of Psiloritis and especially in the area of Agia Pelagia, the rainfall was as much as 130 mm. The intensity of the rain combined with the great slopes of the hydrological basin, resulted in flooding the stream in the area and mourning a dead person, flooded homes, businesses, and hotel units.

The human factor in the two flood phenomena had the large share of responsibility. The misguided studies, on the one hand, for the small bridge in Agios Ioannis and on the other hand, for the undergrounding of the Vaga stream in the urban fabric of the town, contributed to the disastrous results. The proper cleaning of the streams and not using the Vaga stream as a road are key factors to avoid similar phenomena in the future. However, climate change seems to also have a share of responsibility (Proutsos et al., 2019) as in the Sitia region, extreme weather phenomena such as prolonged periods of drought, intense torrential rains, dry stormy southerly winds, etc. have intensified.

Geohazards education and dissemination

Climate change and the effects on the natural and man-made environment is certainly one of the biggest issues which we are called to manage as geoparks in the coming years. One of the main "weapons" that we have is increasing citizens awareness, and especially the new generations, through educational programs (Sitia UGGp educational programs) concerning natural disasters available at Sitia Geopark.

For this reason, a comprehensive educational activity on climate change and Mediterranean geoparks has been designed with the aim of:

1. Informing, training and raising awareness of teachers and students about climate change.
2. Developing knowledge and skills through emotional and experimental activities (Fassoulas et al., 2013).
3. The cultivation of communication through the interaction of teachers and students.
4. The approach and deepening of our understanding about natural phenomena and their effects, of how human activities have contributed to the rise in global temperature and how the rise in temperature affects climate behaviour (Figure 3).



Fig.3: Educational activities with students at the Panteli River ((photograph by Vangelis Perakis)

The program is aimed at primary and secondary school students and to their respective teachers. Through interactive educational practices, in the classroom and in the field, the students and teachers are informed and are taught on how to formulate proposals for dealing with natural disasters and what is the role of citizens in this type of extreme events.

Moving mountains – landslides as geosystem services in Austrian UNESCO Global Geoparks (movemont.at)

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Landslides in the Austrian UNESCO Global Geoparks

Landslides are prevalent phenomena in mountainous regions, constituting a fundamental aspect of their gradual degradation over time. From a societal perspective, these occurrences can pose both risks and disasters, which have spurred extensive research efforts. Nevertheless, landslides also hold the potential to embody valuable natural and cultural heritage while providing various benefits to society. These facets remain relatively unexplored and can be incorporated within the somewhat underutilized concept of geosystem services (e.g. Argentin et al., 2021)

Within this context, landslides offer insights into the functioning of Earth's surface systems. UNESCO Global Geoparks (UGGps) serve as ideal settings for investigating and emphasizing geosystem services related to landslides. This is especially true in Austria, where the three existing UNESCO Global Geoparks (Karawanken/Karavanke, Erz der Alpen and, Styrian Eisenwurzen) are distinguished by the presence of a wide array of landslide types and magnitudes.

Each of the three Austrian UGGps showcases landslide processes and the associated landforms. These landslides span a wide range of occurrence times, from prehistoric to recent events, often occurring in former mining areas. They vary in volume, from small rock fragments to approximately one cubic kilometre in size. Mechanisms and velocities also differ, ranging from slow creeping movements to extremely rapid debris flows and rock avalanches. On one hand, these landslides pose threats to human populations and disrupt critical infrastructure. On the other hand, they offer mineral resources and hold ecological and cultural significance. See also Hejl et al., (2018).

Research on landslides in the Austrian UGGPs is diverse. For instance, Geologist from the Karawanken/Karavanke UGGp developed a map that assesses landslide susceptibility and runout for shallow landslides in the province of Carinthia, which includes the Austrian part of the UGGp. In contrast, Geologist from the University of Graz documented and analysed a remarkable event that significantly impacted the landscape in the eastern part of the Styrian Eisenwurzen UGGp: the Wildalpen rock avalanche (Figures 1 and 2), which occurred between 5900 and 5700 years ago. This landslide event involved a massive volume of around one cubic kilometre, and its deposits stretch over a total length of 12 km in the Salza Valley. The unique landscape created by the rock avalanche serves as a source of drinking water for Vienna. However, its full potential for geological, geomorphological, hydrological, ecological research, and environmental education has not yet been fully explored. See also Mergili et al. (2021).

Fig. 1: Rock avalanche Wildalpen in the Styrian Eisenwurzen UGGp – example 1 (photograph by Heinz Peterherr).



Based on these data, the research project MOVEMONT (www.movemont.at) was devised aiming to better understand these phenomena. The project aims are the following:

- Constructing a comprehensive theoretical framework that encompasses landslide processes and their societal significance across various temporal and spatial scales. This framework will address both the opportunities and risks associated with landslides. In doing so, we will adopt the concept of geosystem services, a term that has appeared sporadically in the literature as a derivative of the more commonly used ecosystem services but has not yet gained widespread recognition.
- Conducting a uniform mapping and characterization of landslides (Figure 3) within each of the participating UNESCO Global Geoparks. This will be achieved by employing a standardized methodology and utilizing existing databases as the foundation for subsequent investigations. Our research will delve into the role of landslides in shaping karst landforms and advancing karst-related studies (Bauer, 2015). Additionally, we will explore how landslides contribute to biodiversity, including their significance in providing habitats for rare or endangered plant and animal species, as well as their influence on microbial diversity in the soil. See also Petermann et al. (2021).
- Creating an integrated set of tools for GIS-based simulations of landslide predisposition and dynamics. This will entail a focus on the large-scale analysis of stress distribution in mountainous regions and its impact on slope stability. We will also investigate the dynamics of slow-moving mass flows, complex deep-seated landslides, and slope deformations. These simulations will serve educational purposes, potentially through immersive virtual reality visualization.

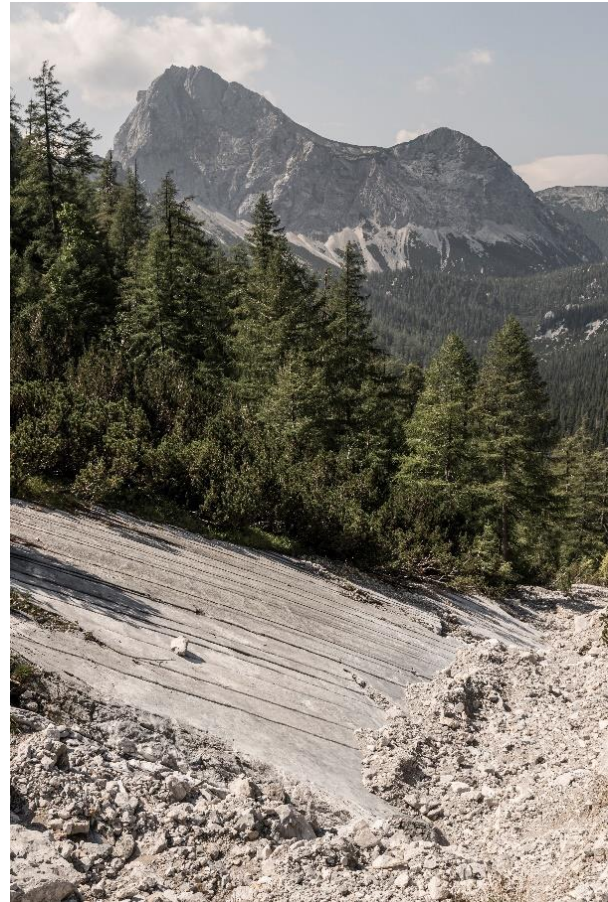


Fig.2: Rock avalanche Wildalpen in the Styrian Eisenwurzen UGGp – example 2 (photograph by Heinz Peterherr)

- Design and implementation of strategies to leverage landslide occurrences for broader environmental education. The participating UNESCO Global Geoparks will serve as pilot areas for these strategies. As landslides often result in spectacular phenomena that shape remarkable landforms, they offer a compelling means to generate enthusiasm for geoscientific topics among the public. Consequently, they are valuable for demonstrating intricate geomorphological processes.

Geohazards education and dissemination

The three UGGps in Austria have a basic knowledge transfer regarding natural hazards in their territories. All Geoparks work closely with their local schools, inhabitants, tourists, or other target groups. Styrian Eisenwurzen and Ore of the Alps UGGp have both climate change adaptation regions in their area. These are funding programs from the national Austrian government to disseminate the challenges of natural hazards. Karawanken/Karavanke and Ore of the Alps UGGp have both well established, state-of-the-art visitor centres which also raise awareness on Geohazards for various target groups. Finally, Styrian Eisenwurzen has project days related to the topic for schools and other organizations. These are some examples regarding dissemination and education activities on mass movements and natural hazards in Austrian Geoparks. The Geoparks management bodies have been working strongly on these topics and hope for further development throughout the project movemont outputs.

The project will be carried out by a team of researchers from the Universities of Graz and Salzburg, alongside environmental education experts from the three collaborating UNESCO Global Geoparks. It will be integrated into the international research and geopark networks through various partnerships.

To illustrate a planned pilot initiative, the Styrian Eisenwurzen UNESCO Global Geopark intends to present the Wildalpen landslide to its visitors at the Spring Water Museum of Wildalpen. This museum presents an excellent opportunity to incorporate this topic into its exhibition since it is situated within the area affected by the rock avalanche, aligning with the exhibition's thematic focus. The museum is also planning to launch a new exhibition within the next two years, providing a seamless opportunity to integrate this pilot initiative into the upcoming exhibition, which will cover subjects related to geology, nature, and local history.

More Information: www.movemont.at

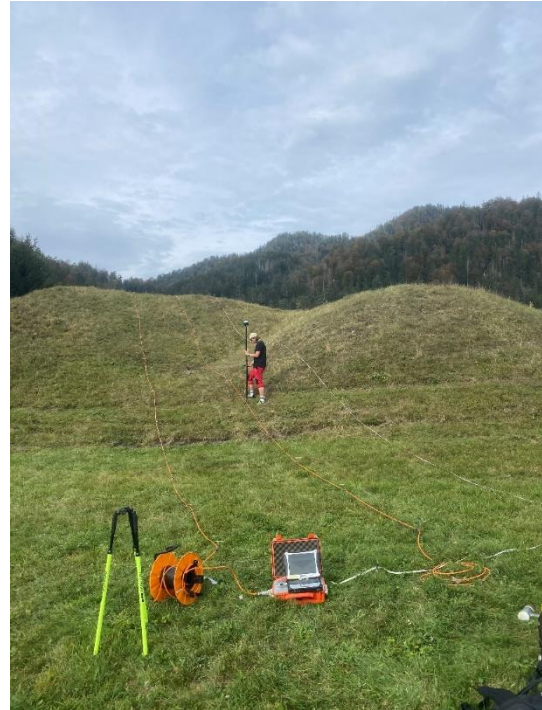


Fig.3: Geophysical surveys carried out to understand mass movements within the Movemont research project (photograph by Ore of the Alps UGGp)

Landslides on the Swabian Alb UNESCO Global Geopark (Germany)

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Introduction

Landslides are among the most hazardous processes on Earth and often occur in alpine and sub-alpine mountain regions. Rockfall or rockslide events destroy and reshape landscapes in only a few minutes, whereas earthflows, for example, may last several weeks or even years. Large areas including infrastructure, agriculture, settlements, and historic and touristic places may be affected and irrevocably ruined. Before collapsing, landslides often develop over long periods of weathering and erosion, regulated by climatic conditions and dependent of the characteristics of the bedrock. Limestones in particular react with a widening of cracks in a densely jointed bedrock and are therefore often prone to fail. Limestones are abundant from Southern Germany to Northern Italy, which were originally deposited millions of years ago in a large primeval ocean called *Tethys*. Well-known landslides occurred in such strata in at least two UNESCO Global Geoparks: Swabian Alb and Carnic Alps.

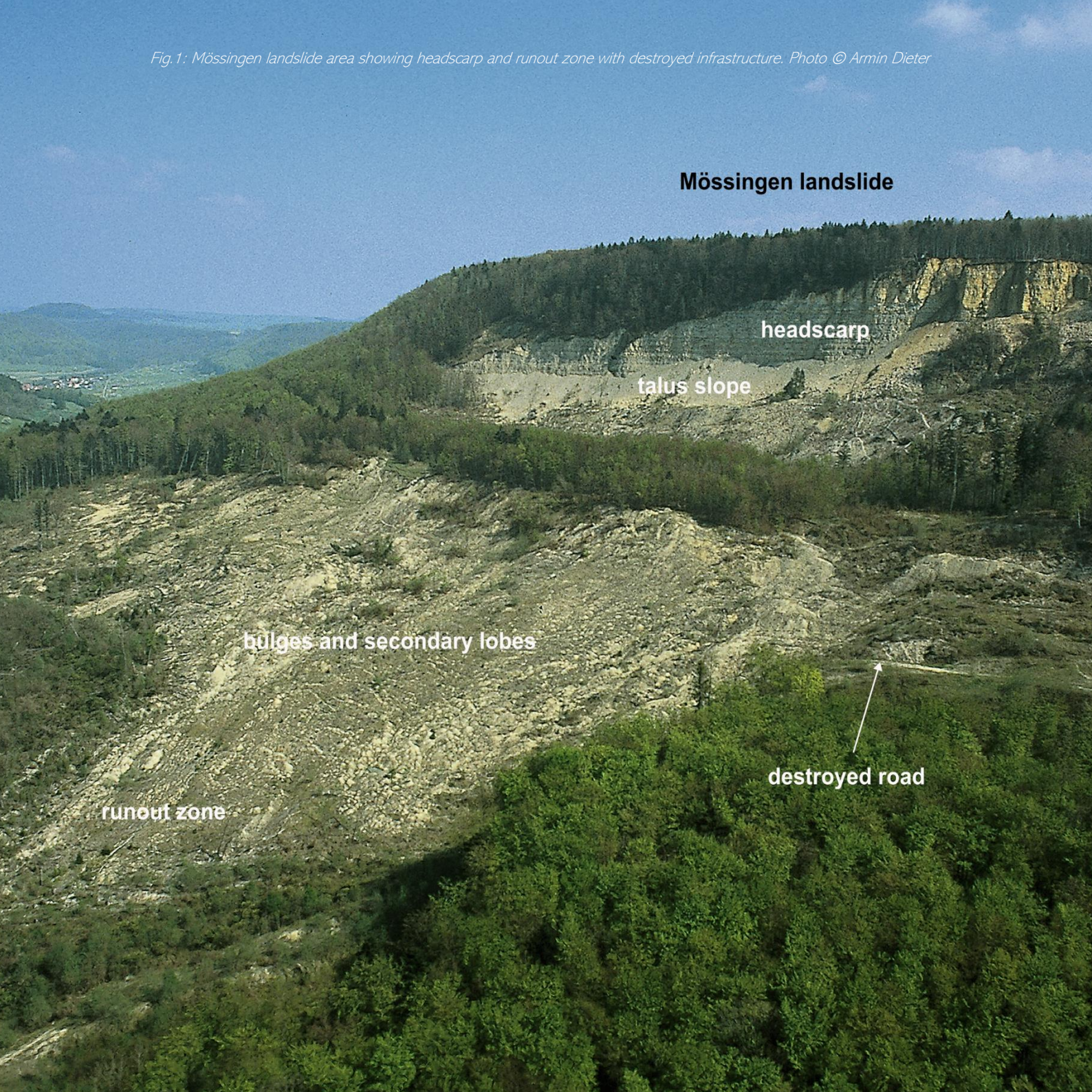
Landslides in the UNESCO Global Geopark Swabian Alb

The Swabian Alb in Southwest Germany is one of the largest karst regions in Europe and part of the Jura Mountains, which is a sub-alpine mountain range stretching from Western Switzerland to Eastern Bavaria in Germany. The sedimentary rocks mainly consist of clay-, sand-, marl- and limestones, and were formed during the middle Triassic up to the late Jurassic. During the Tertiary, the rock units were tilted to the Southeast during the unfolding of the European Alps and the formation of the subsiding *Rheingraben*. The tilted, alternating tough and soft rock units form marked escarpments at the northern ridge of the Swabian Alb, which is called *Albtrauf*. Here, the top layers of Jurassic limestone show steep cliffs and are susceptible for sliding on the clayey sediments below. Along the *Albtrauf*, several rockfalls (e.g. above Honau), rockslides (e.g. Mössingen and Öschingen) and sliding rafts (e.g. Spielberg and Rechberg) are known.

Mössingen landslide on 12th April, 1983

Forty years ago a huge landslide occurred close to the town of Mössingen. At Mount Hirschkopf at an elevation of 820 m a.s.l., the cliff wall collapsed after heavy rainfall (Figure 1). Several rock towers toppled, rotated, and slid downwards. This included up to 20 m thick surges of loose talus material that were entrained in the sliding rock mass (Figure 2). The rockslide had a volume of ~ 4 million m^3 and a runout of ~ 700 m length. Further propagation during reactivated sliding at the front of the slide lasted several days up to three weeks and reached a maximum runout of ~ 1000 m and affected an area of 0.48 km^2 . The rockslide changed the landscape completely. The size of the headscarp enlarged by $\sim 300\%$ and in the runout zone secondary slides and lobes formed bulges across the slope (Schaedel and Stober, 1988). These bulges are typical of rockslides and are well-known from other rockslide areas (e.g. Eibsee rockslide; Knapp et al., 2021). Older bulges and wetland at the foot of the slope hint at an older slide,

Fig. 1: Mössingen landslide area showing headscarp and runout zone with destroyed infrastructure. Photo © Armin Dieter



Mössingen landslide

headscarp

talus slope

bulges and secondary lobes

runout zone

destroyed road

so the 1983 event was partly a reactivation. This former rockslide was dated back to at least 3000 years ago (Bibus, 1986).

In June 2013, another rockslide occurred close to Mössingen in the village of Öschingen. This event was much smaller, but 29 people had to be evacuated and had to leave their houses.

Why do landslides occur?

When talking about the reasons for landslides, it is important to distinguish between preparing and triggering factors. Preparing factors are based on geological characteristics and climatic conditions. The clayey *Omatenton-Formation* on the Swabian Alb is one of the most susceptible layers for sliding, as it shows weak shear strength, especially under wet conditions. This layer often functions as sliding plane for the *Impressamergel-Formation* with marlstones and limestones full of cracks.

Physical, biological and chemical weathering processes dissolve or destroy rock. Also, permafrost degradation weakens the rock, which plays a major role at times of climate change in the European Alps. In general, preparing factors work on a longer timescale and increase the probability of a landslide event in a certain region.

Triggering factors, however, act on a much shorter timescale, depending on the factor, and make it therefore hard to set up an early-warning system. Triggering factors may be, for example, heavy rain fall, and earthquakes.

The number of heavy rainfall events increases with propagating climate change (e.g., Fuhrer et al., 2006). The large amounts of water enter the rock body quickly, especially in karst regions full of cracks, and lead quickly to high water pressures in the rock wall and the talus slope.

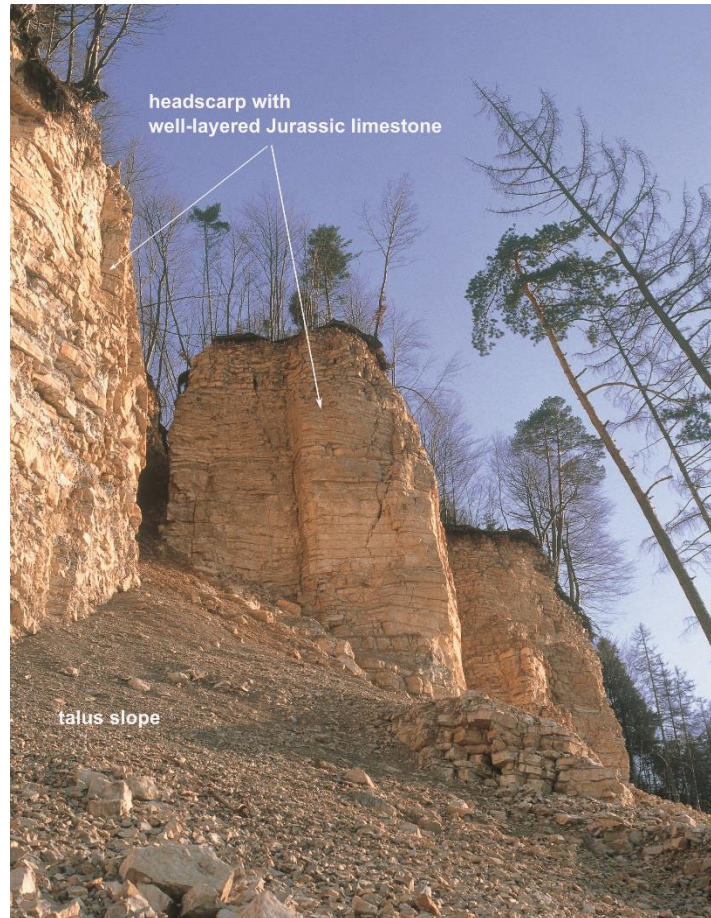


Fig.2: Mössingen landslide, view of the headscarp with layered limestone and talus slope. Photo © Armin Dieter

The Swabian Alb is earthquake-prone so that seismic tremors need to be considered as a possible trigger for landslides. Rockfalls and rockslides are among the most abundant types of earthquake-induced landslides, and especially weakly or moderately indurated sedimentary rocks tend to collapse (Keefer, 1984). Earthquakes, landslides and the link between them in the UNESCO Global Geopark Swabian Alb have not been sufficiently recognized yet. But it is known that the Albstadt earthquake in 1911 was strong enough to trigger a landslide, so these geohazards need more attention in the Swabian Alb area. It is possible that more events have been triggered by other earthquakes but without being witnessed. The seismic activity on the Swabian Alb has increased since the middle of the 20th century (Langer, 1986), and the UNESCO Global Geopark Swabian Alb disseminates knowledge on the involved processes and causes.

Research and education on the Mössingen landslide

After the event in 1983, the government declared the Mössingen landslide as a nature reserve. Since then, researchers work in an interdisciplinary project on the analysis of natural succession and regeneration, and the resettlement of wildlife in the landslide-destroyed area. The landslide is regarded as a one in a hundred years event and is therefore of great interest for geological, biological and cultural studies. Today, the passionate local guide Armin Dieter leads regularly tours through the rockslide area, also with a special focus on senior people, and children from kindergarden and schools. He also wrote the book „Nationaler Geotop Mössinger Berggrutsch“, that is recommended for further reading (<http://www.alberlebnis.de/buecher.html>, in German). Moreover, the teachers of the Geopark School in Dusslingen regularly visit the Mössingen landslide with pupils from their geography classes on excursions. The Mössingen landslide is explained and illustrated with informative signage (Figure 3) for visitors. The UNESCO Global Geopark also set up a Geopoint at the Mössingen landslide in 2016 and stays in strong collaboration with Armin Dieter.



Fig.3: Information board on the Mössingen landslide, showing two geotrails with background information, and cooperation partners like the UNESCO Global Geopark Swabian Alb. Photo © Geopark Swabian Alb

The promotion of the threat of soil erosion and the protection of soil in the UNESCO Global Geopark TERRA.vita, NW Germany

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Introduction

Soil, along with water and air, forms the foundation of our existence. Preserving and sustaining its fertility has always been essential for successful agriculture in the UNESCO Global Geopark TERRA.vita (NW Germany). Nevertheless, the escalating effects of the global climate catastrophe are causing a significant geohazard in the UNESCO Global Geopark TERRA.vita area – soil erosion (Elhaus et al., 2020; Fischer & Semenova, 2023). This issue becomes especially critical when valuable agricultural land's fertile soil is damaged due to large-scale soil removal. However, the severity of soil erosion varies across different cultivated areas. In the TERRA.vita region, locations situated on steep slopes and loess-based regions are particularly vulnerable to increased erosion risks, prompting the implementation of protective measures in these endangered areas. TERRA.vita promotes the value of soil, the threat of soil erosion and the need for the protection of soil in various ways, such as digital and printed information material, educational material, in extracurricular education centers, and on guided tours.

Understanding soil erosion

Soil erosion refers to the removal of surface soil material by water or wind through natural processes. The global climate crisis exacerbates soil erosion, with more frequent droughts and heavy rains causing increased damage worldwide (Elhaus et al., 2020). The extent of soil erosion is influenced by factors such as the presence of vegetation cover and human activities like soil sealing, usage intensity, and care practices. Soil erosion should not be underestimated, as it leads to the loss of soil material from agricultural areas, decreasing their fertility. In addition, the deposition of soil material in bodies of water can cause environmental pollution, and when it reaches human settlements, it can cause severe damage to infrastructure and endanger human lives.

In densely populated Germany, land areas face significant pressures due to intensive usage, with approximately 50% of the country's land allocated to agriculture (aid infodienst, 2015). As a result, agricultural lands are particularly vulnerable to erosion, especially when they lack vegetation cover, such as before or after sowing, leaving the soil exposed to erosion agents like rain and wind (Figure 1). Certain crops, such as grapes, hops, potatoes, corn, or sugar beets, which require wide row spacing, are particularly endangered by soil erosion. In addition, arable land located on steep slopes and specific soil types such as silty and fine sandy soils are particularly at risk. Intensive agricultural cultivation as well as inappropriate farming machinery and techniques further increase soil vulnerability. In the TERRA.vita Geopark, where a significant portion of land is used for agriculture, numerous small and a few large erosion events occur (Fischer & Semenova, 2023).

Figure 1: This area of the UNESCO Global Geopark TERRA.vita is very well protected against soil erosion: The fields are mulched, plowing and planting took place parallel to the slope, and the slopes are divided by lines of trees and bushes to catch run-off soil material and to function as a wind erosion barrier (Photo by TERRA.vita).



The risk of soil erosion in the UNESCO Global Geopark TERRA.vita

The UNESCO Global Geopark TERRA.vita, with its mountainous and hilly structures like the Teutoburg Forest, the Wiehen Hills, and the southern Osnabrücker Land, faces a significant risk of water erosion (Figure 2; Elhaus et al., 2020; Steinhoff-Knopp, 2021). One contributing factor is the prevalence of soils rich in silt-sized grains, known as loess, making these areas highly susceptible. The presence of steep slopes further amplifies the risk of water erosion. Despite their vulnerability, loess sites possess a unique advantage with their high water-storage capacity and rich nutrient content, making them among the most fertile soils.

In contrast, the northern Osnabrücker Land and valleys, such as the areas between Schaferberg and Teutoburg Forest, are at a high risk of wind erosion (Figure 2; Elhaus et al., 2020; Steinhoff-Knopp, 2021). These regions experienced the deposition of shifting sand layers during the Weichselian glaciation (approximately 115,000 to 11,700 years ago) and the current Holocene warm stage (last 11,700 years), which creates conditions favorable for wind erosion, especially during dry periods.

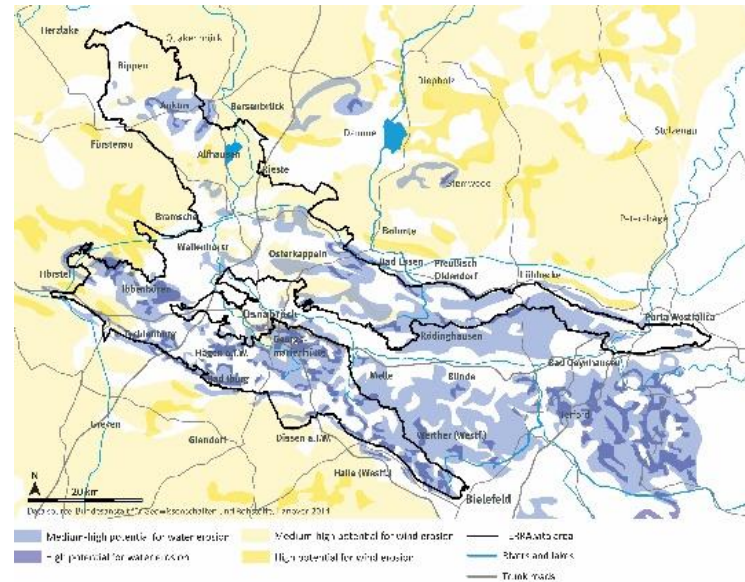


Figure 2: Map of the UNESCO Global Geopark TERRA.vita showing the risk for water and wind erosion (data from Bundesanstalt für Geowissenschaften und Rohstoffe, Hanover, 2014)

Soil protecting measures implemented in the TERRA.vita area

Soil protection holds immense significance for both humanity and nature. In Germany, this commitment is enshrined in law through the Federal Soil Protection Act of 1998 (§BBodSchG). In the TERRA.vita Geopark, landscapes particularly susceptible to water and wind erosion require measures for soil protection without preventing agriculture. The Soil Protection Authorities of the counties and the State Chambers of Agriculture provide individual information for farmers and advice on possible protective measures.

It is essential to recognize that not all fields require the same level of erosion protection. In the UNESCO Global Geopark TERRA.vita, each area must be assessed individually before applying specific protective measures. For instance, arable land used for grain enjoys greater coverage and protection against erosion compared to widely sown corn fields. Therefore, the implementation of protective measures must consider the farm's overall context, business orientation, machinery used, and future developmental perspectives. Often, a combination of protective measures proves most effective (Figure 1).

Here are some examples of measures farmers in the TERRA.vita area apply to combat soil erosion:

- Slope division
- Planting parallel to the slope
- Site-adapted, erosion-reducing crop rotation
- Under sowing a second crop with the main crop
- Humus-increasing management
- Mulch sowing or direct sowing (almost) without using a plough
- Water and field margin strips
- Farm vehicles that protect the soil
- Artificial barriers against water erosion
- Structures that slow down wind erosion

By implementing these measures and promoting soil protection, the continued health and productivity of the precious land can be ensured.



Figure 3: The TERRA.park Fascination of Soil is an example for a measure to promote the value of soil in the UNESCO Global Geopark TERRA.vita. Inside the soil pavilion of the TERRA.park, profiles of different soil types existing in the Geopark and interactive hands-on objects are exposed (Photo by TERRA.vita)

Promoting soil, the threat of soil erosion, and the protection of soil

The UNESCO Global Geopark TERRA.vita promotes high soil diversity in the area and the need for the protection of soil in a variety of ways. Therefore, education for sustainable development is crucial as it fosters self-reflection and motivates action towards sustainability. Regarding soil, it aligns with SDGs 2 (Zero Hunger), 13 (Climate Action), and 15 (Life on Land). You can find more information on the following projects on www.geopark-terravita.de.

- BodenKoffer: The "Suitcase on Soil" is distributed among kindergartens and school classes. The educational tool provides a book on experiments, handcrafting ideas and songs on soil, instruments for the experiments such as a microscope, different types of sediments and soil, a key to identify soil organism species, and a tabletop game on soil.
- TERRA.info Soil, Soil Erosion, and Soil Protection: This TERRA.info brochure provides information on the value of soil, on the threat of soil erosion and on the protection for soil (Fischer & Semenova, 2023).
- Atlas of Soils: This comprehensive atlas, compiled by soil scientists from the Osnabrück University of Applied Sciences, presents the diverse range and distribution of soil types in the Geopark (Dahlhaus et al., 2018).
- TERRA.park Fascination of Soil: The two-hectare (five-acre) large indoor and outdoor education center provides information on soil, land use, and contaminated sites, as well as on TERRA.vita's geological history (Figure 3).
- Plaggen Soil Information Center: Located at the Lechtingen Windmill, this small information center informs on the cultural-historical plaggen agriculture and the anthropogenic caused plaggen soil.
- Logging horses and workhorses: TERRA.vita's logging horse Ella showcases the advantages of a horse for small-area landscape maintenance measures.

Tackling seismic hazard through monitoring and education at the Tuscan Mining UNESCO Global Geopark (Italy)

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Introduction

Located in the western sector of central Tuscany, Italy, the Tuscan Mining UNESCO Global Geopark (TMG hereinafter) extends over a total area of 1183 km². The region is of great geological and geo-mineral interest due to the presence of sulphide ore bodies and extensive geothermal fields. The exploitation of these georesources has strongly characterized the settlement dynamics and the mining landscape from the third millennium BC up to the present day. TMG manages the Mining Museum in Gavorrano, which includes an underground itinerary through a gallery network inside a disused pyrite mine (Figure 1).

The Italian National Institute for Geophysics and Volcanology (INGV) is an Italian Research Body that operates under the control of the Ministry for Research and University. INGV's primary mission is to monitor the dynamics of the Earth in both its fluid and solid components, thus contributing to the mitigation of the related hazards. As a component of the National Civil Protection System, INGV oversees the nation-wide earthquake monitoring, volcano surveillance, and assessment of seismic and volcanic hazards.

In 2023 INGV and TMG established a framework collaboration agreement for carrying out joint activities aimed at: (i) improving the knowledge on the geological setting of the Geopark, also by specific scientific surveys; (ii) increasing the quality and effectiveness of seismic monitoring in the area through the provision of underground, low-noise monitoring sites; and (iii) implementing dissemination and educational programs, with the specific goal of spreading awareness on geohazards. This contribution describes the activities currently ongoing and those planned for the near future, in the framework of this collaboration.

Geological Background

TMG lies in a stretched portion of the inner Northern Apennines, an area which has been affected by extension since the Pliocene. Such extensional dynamics, clearly evidenced by a reduced crustal thickness (20–26 km; Di Stefano et al., 2011), prompted partial melting in the lower crust/upper mantle, which generated crustal and hybrid magmas and significant intrusive processes, giving rise to the so-called Tuscan Magmatic Province. The presence of cooling magmatic bodies at shallow depths controlled the minerogenesis and caused relevant geothermal anomalies. This is the case of the Larderello - Travale geothermal field where the world's first geothermal power plant was constructed in the early twentieth century, and that is now supplying about 2% of Italy's energy needs.

The region covered by TMG includes seismically active areas. Recent seismicity is well documented by INGV's instrumental catalogue (ISIDe, 2007), which reports almost 2000 earthquakes since 1985, all with magnitudes

Fig. 1: Mining Museum in Gavorrano



lower than 4. Most seismicity affects the NE sector of the Geopark, in coincidence of the productive geothermal areas. Hypocentral depths are generally shallower than 5-9 km, because of the high thermal gradient of the area, where temperatures as high as 500 °C are encountered at depths of about 3 km. Such reduced thickness of the seismogenic layer poses a limit to the depth of faulting, and hence to the magnitude of potential large earthquakes. Nonetheless, historical records report the occurrence of damaging earthquakes, such as those that in 1414 and 1724 struck the NE portion of the study area with moment magnitudes M_w of 5.7 and 5.1, respectively (Figure 2; Rovida et al., 2020; 2022).

Instrumental Monitoring of Seismicity

As for the rest of the country, the study area is monitored by the Italian Seismic Network, managed by INGV (INGV, 2005). This infrastructure is made up of hundreds of seismic stations distributed throughout the national territory, whose signals are continuously transmitted to the INGV National Earthquake Observatory (<http://terremoti.ingv.it/>). These data streams are analysed in real time for the timely detection of earthquakes and the subsequent estimate of their location and magnitude. This

procedure requires determining the time and amplitude of the seismic waves observed at the different recording sites. The accuracy of these measurements is hampered by the continuous background vibration of the solid Earth, caused by forces associated with both human activities and natural phenomena. Such vibrations, usually referred to as the ambient noise field, are ubiquitous, although their amplitude depends on location, time, and frequency. The search for low noise sites is therefore among the top priorities in the development strategy of any seismic monitoring programme.

Most noise sources, of either natural or anthropic origin, act on the Earth's surface; underground sites usually have favorable noise conditions and are therefore of great value for seismic monitoring. Following these arguments, TMG provided INGV with the end part of a tunnel belonging to the Mining Museum in Gavorrano. That site now hosts a broadband seismic station (Figure 3), whose noise characteristics are suitable for its integration into the national network. Furthermore, such good conditions make the site ideal for testing the performance of different earthquake measuring instruments.

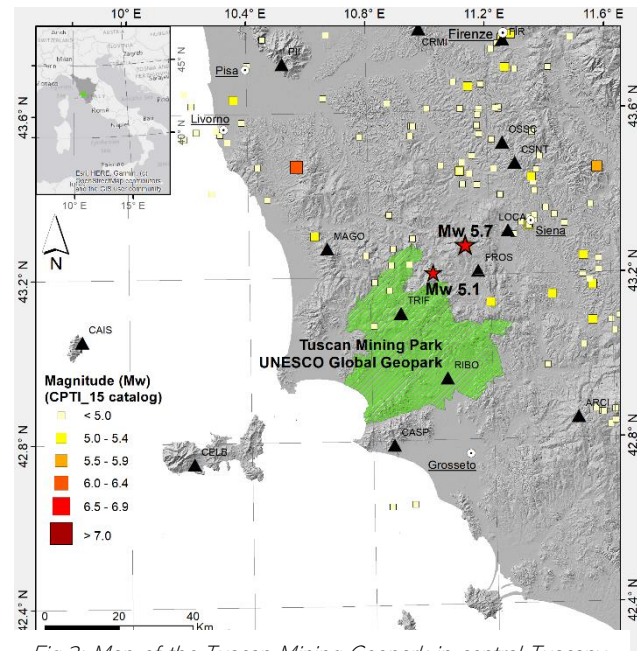


Fig.2: Map of the Tuscan Mining Geopark in central Tuscany. Squares indicate the most significant historical earthquakes; size is proportional to magnitude, red stars indicate the strongest earthquakes occurred in 1414 and 1724 (after Rovida et al., 2021). Triangles mark seismic stations of the earthquake monitoring program managed by INGV. The inset shows the location of the geopark with respect to Italy



Fig.3: Installation of a broadband seismic station within the Mining Museum (photograph by INGV)

Geohazards education and dissemination

Education plays a crucial role in preparing communities to respond effectively to geological hazards. A key element to building prepared and resilient communities is to foster knowledge and awareness through comprehensive dissemination plans focused on the scientific understanding of the hazardous geological processes. TMG and INGV have a project under implementation for equipping the Mining Museum with a section specifically dedicated to seismic hazard. In particular, the project foresees installations dedicated to increase the understanding of the earthquake-related processes by integrating observation, conceptualization and active experimentation. Dedicated dissemination materials (poster, brochure) will provide the scientific background for understanding the physics of earthquake source process and wave propagation. Specific experiences will be dedicated to show in real time how the ground shaking is recorded for scientific purposes. In this experience, ground vibrations are excited by the visitors' jump, sensed by a seismometer, and visualized live on a screen. An additional experience will concern the sonification of seismic data, which provides a fascinating and instructive complement to the "wiggly line" representation of ground motion time series used in the classical seismogram. By converting the seismic recording into an audible signal, visitors will directly experience (hear) the differences between earthquake sources of different size, distance and nature.

Seismic hazard in an actively uplifting area: the case of Vikos-Aoos UNESCO Global Geopark, NW Greece

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Introduction

The Vikos-Aoos UNESCO Global Geopark (UGGp) in the region of Epirus, NW Greece, covers an area of 1,200 km² across the Pindus Mountain Range (Figure 1,2). In the geopark large scale folding and faulting have drastically shaped a mountainous and rugged landscape, interrupted by steep gorges and elongated narrow valleys, while glaciation and karstification have further shaped the regional landforms. Human settlement in this tightly structured environment dates back to the Late Upper Palaeolithic to Mesolithic era (16.5 to 9.5 thousand years before present), when confronted with geohazards stemming from the post-glacial environment, such as flash flooding and downslope movements of scree. Nowadays, the most alarming geohazards in the Vikos-Aoos Geopark are related to seismic activity. The Konitsa fault is a well-studied active seismogenic normal fault, while a recent earthquake (2016, NW Ioannina, M= 5.5) showed that the unexposed thrust faults lying deeper in the crust are also highly significant in seismic risk assessment.

Structural history of the Vikos-Aoos Geopark

The exposed rocks in the geopark illustrate the story of how the Ionian Zone was shaped over time. They document the mountain-building processes that occurred during the Alpine Orogeny. The Mitsikeli anticline, which could be described as a large bedrock fold, was created during the main mountain-building phase. Other folds and kilometer-long structures found near Konitsa were formed when segments of bedrock units originating from the Pindos Zone were thrust over the Ionian Zone between 33 and 20 million years ago. More recently, several normal faults were developed further fracturing the mountainous terrain into smaller blocks (Figure 2).

The mountain of Tymfi rises up to form an elevated surface that gently tilts towards the southwest. On the other side of the mountain steep slopes appear descending sharply towards the northeast. The most recent tectonic structures, identified at the surface, include normal faults trending NE-SW (Galanakis et al., 2007). Across Tymfi Mountain the Kapesovo, Astraka and Konitsa large faults are recorded. Additionally, the Topolitsa and Sarantaporos faults are identified further north (Figure 2).

The Konitsa fault (N55E strike, 45°-75°NW dip, and 15 km of maximum depth) forms a ~1 km high abrupt feature separating the Konitsa plain from Tymfi mountain range, while Quaternary alluvial fans from the erosion of the footwall are well developed (Figure 3a). The Aoos River quickly flows towards the SW side of the Konitsa plain as it escapes the Aoos Gorge by crossing the Konitsa fault. Numerous tectonic features, such as cataclasites with polished and striated limestone surfaces, have been linked to the Konitsa fault activity and are well documented. The vertical offset

*Fig.1: View of the exit of the Vikos Gorge to the Voidomatis river basin. The exit of the gorge is 2,420 m wide and 1,144 m deep
(Photo by Christos L. Stergiou)*



of the fault is estimated to have up to 2.7 km, with a suggested slip rate between 1 and 1.8 mm/year. The Astraka fault is older than the Konitsa fault and is responsible for the near vertical relief noted at the end of the upper Vikos Gorge (Figure 2), where the sub-vertical gorge walls indicate active uplift of the footwall. By taking into consideration active tectonics and the overall incision in the Vikos and Aaos Gorges. It is suggested that the footwall uplift drastically controlled the formation of the Vikos and Aaos Gorges.

Seismogenic faults and recent earthquakes

The Konitsa earthquake sequence of 1996 is the most devastating seismic series documented in the Vikos-Aaos Geopark. On July 26, an earthquake (Magnitude (M)=5.4, 9.3 km deep) affected the geopark area, which was followed by a second (August 5, M=5.7, 8 km deep) and a third earthquake (August 20, M=5.3, 8.7 of deep) (Papanastassiou, 2001). Several minor earthquakes (n=183) occurred between July and September. The defined values after seismology correlated the seismogenic source of these events with the Konitsa fault (Papanastassiou, 2001). Based on its structural and geometric characteristics and using empirical relations such as the ones proposed by Wells and Coppersmith (1994), the estimated maximum earthquake potential of the Konitsa fault is M=6.6 (this study).

The earthquake affected an area of 10 kilometers radius around Konitsa. Coseismic effects included the ground sinking by 5.6 centimeters in the Konitsa plain, with soil fissures running almost parallel to the fault zone and several rock falls. Building inspections in Konitsa found that 208 buildings were uninhabitable and 278 were temporarily unusable (Galanakis et al. 2007 and references therein). Most of these buildings were built at the lower part of Konitsa, on cultural debris and alluvial deposits. Secondary effects were also documented, including changes in water discharge from springs and boreholes, and the release of a strong hydrogen sulfide (H₂S) odour (Galanakis et al. 2007).

Another significant earthquake sequence, which affected areas of the Vikos-Aaos Geopark, occurred on October 15, 2016 (20 km NW of Ioannina city). It had a magnitude of 5.5 and over the next three days after the main event, 156 aftershocks were recorded with magnitudes between 1.4 and 1.9. The fault related to this seismic event refers to a reverse fault, trending NNW-SSE and dipping 27° towards the east, which does not show surface indications (Pavlidis et al., 2016). The earthquake's impact was limited to minor building damage, rock falls, and road cracks, as well as soil deformation and subsidence.

While the Ionian Sea region, where the Kefalonia-Ithaca Geopark is located, is characterized by high seismic activity and has been extensively studied, Epirus experiences moderate levels of seismicity, with strong earthquakes occurring



Fig.2: A map of the Vikos-Aaos Geopark showing the epicentres of the 1996 Konitsa and 2016 Ioannina earthquakes. Major mountains and rivers, as well as the location of the Vikos and Aaos gorges are shown

rarely (Pavlidis et al., 2016). However, intermediate-magnitude earthquakes, such as the 2016 Ioannina earthquake, deserve particular attention as the seismogenic faults are not visible at the surface (i.e. "blind" faults), making their precise study challenging. A review of the regional geology suggests that similar faults may occur deep beneath the surface of the Vikos-Aoos Geopark adding to the potential of the region for regional intermediate-magnitude earthquakes.

An opportunity for advancing seismic science and awareness on seismic hazards

The Vikos-Aoos Geopark area is the only known area in Epirus where typical extensional settings occur, associated with the seismogenic Konitsa fault zone and active uplift. In addition, the geopark is an area with rich cultural and historical elements that receive many visitors yearly. The inhabitants of the Vikos-Aoos Geopark appear to have a deep understanding of seismic phenomena, particularly the low-pitched rumble that often accompanies minor earthquakes. The infrequency of strong earthquakes and the remarkable resilience of the traditional stone buildings regarding the Konitsa (1996) and Ioannina (2016) seismic events seem to have instilled in them a sense of calm amidst the earth's tremors. Thus, the significance of advancing seismic awareness seems to be crucial for individuals and communities in order to prepare for and mitigate the risks associated with earthquakes.

The quantitative study of active tectonics, and its dissemination, advances social awareness on seismic hazards and connects communities to the geopark by understanding local geology. To this effort, the Vikos-Aoos Geopark actively supports the implementation of novel technologies (e.g. aerial morphometric mapping of faults) advancing the interdisciplinary study of seismogenic faults. Furthermore, the geopark administration supports dissemination by holding public lectures on the Konitsa fault activity and seismic vulnerability, and by organizing annually a summer school for students in geosciences (Figure 3b, Chatzipetros et al., 2022). The 2023 summer school, centered on "Geohazards, Natural Disasters, and Climate Change," was organized by the School of Geology, Aristotle University of Thessaloniki and the Development Agency of Epirus (Epirus S.A.) and was supported by the Municipality of Konitsa. Thirty participants attended the summer school and were introduced by twelve expert scientists to topics related to structural geology, engineering geology, engineering seismology, karst vulnerability and climatology through lectures, field trips and teamwork.

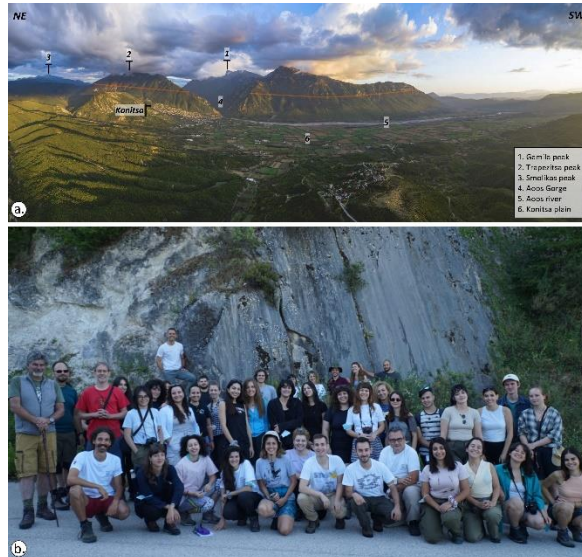


Fig.3: a. Aerial photograph of the Konitsa fault zone taken from northwest. The abrupt relief controlled by the fault activity is shown, as well as the location of Konitsa in respect to the fault zone. Major geomorphological aspects are highlighted (Modified, photo by Epirus S.A. and Antonis Vroikos). b. Commemorative photo of the participants of the 2022 Vikos-Aoos Geopark

Forest fires: from the origin of Villuercas-Ibores-Jara UNESCO Global Geopark (Spain) to the educative project Geocentros

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Introduction

Villuercas-Ibores-Jara UNESCO Global Geopark is located in a quiet place, tectonically speaking, on the Iberian Peninsula, so geohazards such as volcanoes, earthquakes, tsunamis, etc., are not currently a problem in this area, except for small landslides. However, due to the rugged terrain and climate, forest fires are an increasing source of concern every summer. With climate change, the risk season is getting longer. In fact, one of them was the original idea for the project that resulted in the area becoming a UNESCO Global Geopark.

The collaboration with INFOEX (Forest Fire Prevention and Extinction Service of the Autonomous Community of Extremadura) is always present. Training its agents by the Educational and Scientific Committee of the Geopark and talks and workshops for the schoolchildren and teachers of the educational project are some of the activities that are normally carried out to try to mitigate this forest fire problem that endangers the heritage of the geopark and their habitants.

The geopark that was born from a forest fire

The Villuercas-Ibores-Jara UGGp is located in the southeast of the province of Cáceres between the basins of the Tajo and the Guadiana rivers. Morphologically, it is described as a mountain core surrounded by ancient peneplains, with a system of mountain ranges and valleys aligned in a northwest-southeast direction. The whole landscape is the result of millions of years of erosion on a macrofold, which occurred during the Variscan or Hercynian orogeny, during the late Carboniferous (approx. 300 Ma). This fold was levelled by erosion throughout the following periods and rejuvenated by fractures and upward movements of large blocks during the Alpine orogeny (35 Ma). The current modelling of the river network acting on this intensely folded and fractured territory has shaped the present landscape, with its characteristic geomorphology known as “Appalachian relief” analogous to the geomorphology found in the North American Appalachians (Muñoz Barco and Martínez Flores, 2005). This has led it to its inclusion in two of the Spanish geological contexts of international relevance by the IGME (Geological Survey of Spain; García-Cortés et al., 2000).

Due to its geographical location, geological origin and climate, Villuercas-Ibores-Jara UGGp is not unduly influenced by geological catastrophes at present. However, through its geosites and points of interest, it is possible for us to explain major events that occurred in the last 600 Ma of the planet's history: Avalonian-Cadomian orogeny, late Ordovician glaciations, Variscan or Hercynian orogeny and Cenozoic climate changes.

Fig. 1: Materials and activities of the Villuercas-Ibores-Jara educational project in relation to Geohazards and, especially, forest fires. (Photos by Villuercas-Ibores-Jara UGGp)

VILLUERCAS IBORES JARA

GEOPARQUE MUNDIAL DE LA UNESCO

The Geocentros with INFOEX on the
International Day for Disaster Risk Reduction
#IDDR2018 @ResilienceForAll

The INFOEX helicopter taking
care of the Geopark!!!



Activity sheet 1. Tools used by Geopaca

Mark with an X what Geopaca uses in her work.



Broom

☐

Helmet

☐

Hose

☐

Hammer

☐

Picker

☐

Gloves

☐

I am a firefighter



Currently, the greatest natural risk in the geopark is forest fires. Due to the landscape morphology and the climate, this is a high-risk area in the hottest months of the year. These hot weather conditions are increasing due to current climate change.

In fact, the idea of the region becoming a UNESCO Global Geopark arose from the local inhabitants after a devastating fire. On July 21st, 2005, 12,000 hectares out of almost 36,000 burned for 12 hours, until it could be extinguished. That day the humidity was 5.6 percent (a value typical of a hot and dry desert), the maximum temperature reached 39° C and wind gusts of 50 km/h were recorded. It had not rained in the area for 65 days. During the time, there were several outbreaks of fire started intentionally which were tragic and will remain embedded in the memory of the local people for a long time. However, from that disaster arose the seed of what today has become the main driving force of that territory, the Villuercas-Ibores-Jara UGGp.

The Geocentros project: mitigating the effect of geohazards through education

The Geopark educational project, has at its heart raising awareness of the devastating effect of forest fires locally and takes on board the United Nations Sustainable Development Goals. The collaboration between the Geopark and INFOEX is continuous. In fact, INFOEX depends on the Department of Forest Management and Rural World of the Government of Extremadura, which is a member of the Geopark Council (Figure 1).

For this reason, many of the teaching materials and educational activities of the Geocentros project are designed and implemented to address the best-known disaster risk in Extremadura and the Geopark: Forest fires. The objectives are to know the causes, the consequences, and the ways in which the local population can collaborate in general prevention. The Geopark Environmental Knowledge book and other materials, and the talks and workshops originating from the educational working group are directed to specific parts where geohazards are discussed, with special mention of forest fires.



Fig.2: Various INFOEX activities with Geocenters. (Photos by Villuercas-Ibores-Jara UGGp)



Fig.3: Two examples of materials and activities. On the left, Geopaca as a female firefighter in the "Coeducational Notebook. Office of Equality and Gender Violence." On the right, a Geocentro visiting the volcano interpretation room in Lesvos UGGp. (Photos by Villuerca-Ibores-Jara UGGp)

In addition, after or before the high-risk period, Geocentros have the opportunity to meet the people who monitor and extinguish forest fires. This raises awareness and increases the prevention of fires resulting in safeguarding the heritage and people of the Geopark. To achieve this, different types of activities are prepared together with the INFOEX (Figure 2): (1) classroom workshops and firefighting service demonstrations; (2) visits to INFOEX headquarters; and visits to the Guadalupe helicopter base.

This topic is also treated equitably, so that gender equality (cards with Geopaca, our mascot, working as a firefighter; Figure 3), actions for the climate (knowing the consequences of climate change and how to mitigate it), responsible production (local varieties and vegetation mosaics), etc., also reflect different ways of facing this problem. This ensures that students and teachers are made aware of the topic and become involved in its solution from multiple perspectives.

The Geopark also promotes the Spanish, European and Global Geoparks networks. For example, related to geohazards, Geocentros teachers and students have visited other UGGp where they have received training on other types of geological risks, such as large landslides and earthquakes (for example, visiting the museum and earthquake simulator in Lesvos Island UGGp; Figure 3). A must-see event in this regard is to celebrate the International Day for Disaster Risk Reduction on October 13. As well as formal education, the Geopark also works on this geohazard aspect with the rest of the population, undertaking special work prior to the greatest risk.

Soil erosion and mitigation measures in Vulkaneifel UNESCO Global Geopark

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²Climate Protection Manager of the Vulkaneifel District

Description of the geohazard

The severe storms and heavy rainfall events like the ones in Rockeskyll, Germany, in 2016 that caused significant challenges, including floods, flash floods, mudslides, and soil erosion, where the result of atmospheric low pressure around many European countries. The quaint village, located in the Vulkaneifel Nature Park and UNESCO Global Geopark, experienced flooding from the overflowing Kaulbach stream, leading to sediment-laden water inundating roads, residential areas, and the cemetery. During these torrential rainfall events, measuring 54.65 mm/m² in nearby Gerolstein in four hours (Deutscher Wetterdienst DWD, 2017), large parts of Rockeskyll were affected (Figure 2). The intensity and duration of the rainfall, combined with the topography and insufficient ground cover, contributed to soil erosion and the transport of loose soil particles to lower-lying areas. In response, an alternative crop the *Silphium perfoliatum* (see Figure 1) was strategically planted to enhance biodiversity and to reduce soil erosion. Further details on this initiative are provided within the paper.

Torrential rain events pose a significant hazard to soil stability and contribute to erosion, with the intensity and duration of rainfall determining the erosive force. Short, intense downpours result in increased runoff and erosion. Natural conditioning factors include climate (intensity of precipitation and saturation of the soil), soil texture (susceptibility of grain sizes to erosion) and the terrain morphology (slope and shape of the terrain). If sloping areas are intensively farmed, this can have far-reaching consequences for the soil's susceptibility to erosion. In turn, other conditioning factors include the slope length, crop types, cultivation system and direction.

Detached soil particles are transported downslope along the path of least resistance, resulting in sheet erosion, which uniformly removes a thin layer of topsoil over large areas. Additionally, the concentrated runoff may form small channels or rills, deepening and widening them in a process known as rill erosion. In extreme cases, especially on sloping terrain like in Rockeskyll, torrential rainfall causes the formation of larger and deeper channels called gullies, leading to significant soil loss. From an agricultural perspective, the transported sediment often represents valuable topsoil, and its loss can diminish soil productivity, affecting crop yields and necessitating additional soil management measures.

The water's velocity determines the capacity to transport different-sized particles, with larger, heavier particles settling first, and finer particles remaining in suspension for longer distances. As the runoff water loses velocity, such as when it reaches flatter areas or enters bodies of water like streams or rivers, it may deposit sediment. Sediment-laden runoff can impact downstream areas, altering the riverbed morphology.

Flower of the cup plant with a bumblebee © Natur- und Geopark Vulkaneifel



Rockeskyll village, situated in a valley surrounded by sloping terrain particularly vulnerable to soil erosion. This led to the deposition of eroded soil particles within the village (Figure 2) and the loss of vital topsoil from agricultural areas in sloping terrains. Mitigating soil erosion requires understanding and addressing conditioning and triggering factors. Practices such as contour ploughing, cover cropping, and vegetative buffers along water bodies help stabilize the soil, reduce runoff velocity, and trap sediment. Additionally, improved drainage systems, erosion control structures, and sustainable land management practices are essential for effective erosion control.



Fig.2: On May 28, 2016, torrential rain inundated Rockeskyll, flooding the village with sediment-laden water © Ortsgemeinde Rockeskyll, www.rockeskyll.de

Scientists emphasize the connection between extreme rainfall events and climate change, predicting an increase in such events in the future in Europe (European Commission, 2023).

Implementing strategies to adapt to changing climatic conditions is crucial to minimize the impact of severe weather events on soil erosion and its consequences for agricultural and residential areas.

Mitigation and adaptation

The efforts to mitigate soil erosion involved the classification of agricultural areas based on their potential risk to erosion by the State Office for Geology and Mining of Rhineland-Palatinate in 2010 (Landesamt für Geologie und Bergbau Rheinland-Pfalz, 2010-2023). The classification supported agricultural consultations, land consolidation procedures, and flood prevention measures. The identified high-risk areas corresponded to observed fieldwork findings.

The "LIFE-IP ZENAPA - Zero Emission Nature Protection Areas" project, coordinated by the Institute for Applied Material Flow Management (IfaS), was initiated in 2016 as part of the EU funding program for the environment, nature conservation, and climate policy "LIFE." The project, spanning ten years, involved 16 partners from eight German federal states and Luxembourg. ZENAPA aimed to develop a management system for enhanced environmental protection and nature conservation through optimized energy crop cultivation. Three farms, two institutes and a foundation are working on potential measures and solutions to improve environmental protection and nature conservation. One of the participating farmers from the neighboring municipality of Niederbettingen, who originally cultivated maize as an energy crop for a biogas plant, in some fields near Rockeskyll which were severely affected by erosion from the 2016 events, experimented in a trial field with an alternative energy crop—'cup plant' (*Silphium perfoliatum*, Fig.1).

Unlike maize, 'cup plant' is a perennial crop that does not require tilling for at least 10 years (Gansberger, Montgomery, & Liebhard, 2015), reducing the risk of soil erosion. The 'cup plant' demonstrated its effectiveness in

preventing soil erosion during heavy rainfall events such as those in 2018 or 2021. Thanks to its deep rooting system, no ploughing requirement, and counter directive planting (Grunwald et al., 2020), heavy rainfall events no longer had those before mentioned hazardous effect on the trial field (Figure 3). Additionally, *Silphium perfoliatum* is a flowering plant which also increases biodiversity (Figure 1) (Schorpp et al., 2016).

Silphium perfoliatum has economic drawbacks such as lower biogas yield. According to the farmer's records, the "cup plant" only achieves 65% of the yield of maize due to its lower biomass and methane yield. In addition, the digestibility of the "cup plant" is not as good as that of maize, which made a cavitation unit necessary, which improves the biogas production by mixing and breaking down the organic matter.



Fig.3: Experimental field close to Rockeskyll which is prone to soil erosion and surface runoff © Natur- und Geopark Vulkaneifel

As mentioned above, *Silphium perfoliatum* is grown as a perennial crop that does not need to be tilled for years. This reduces the farmer's workload and the risk of soil erosion. Also, cultivation in the Rockeskyll area now follows the natural contour lines of the land, creating rows of crops aligned parallel to the elevation contours. This deliberate arrangement functions as a protective measure, forming effective barriers against water runoff. By adopting this method, the agricultural landscape acts as a series of natural terraces, mitigating the risk of soil erosion (Grunwald et al., 2020). These parallel rows not only enhance quality and preventing the degradation water retention and infiltration but also contribute to sustainable land management practices, safeguarding soil of essential topsoil resources.

In summary, crop replacement for the perennial "cup plant" dramatically reduced soil erosion in the experimental fields. However, this crop also has some drawbacks, such as a reduced biogas output. However, given that maize was no longer a viable option due to its high erosion risk, *Silphium perfoliatum* still generates more revenue than discontinuing the use of the field and it contributes to local biodiversity (Grunwald et al., 2020). The cavitation method proves highly effective, yielding biogas almost as efficiently as traditional maize cultivation, contributing in this way to a more sustainable land management practice.

Educational/Dissemination activities

The Vulkaneifel Geopark's commitment to creating a sustainable community in the rural landscape aligns with its focus on geohazard reduction, with a priority on addressing soil erosion caused by floods. The geopark plays a crucial role in promoting awareness about geohazards and implementing strategies to deal with climate change impacts in the region. This is done through public lectures for residents, media publications in regional newspaper or online and educational work.

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