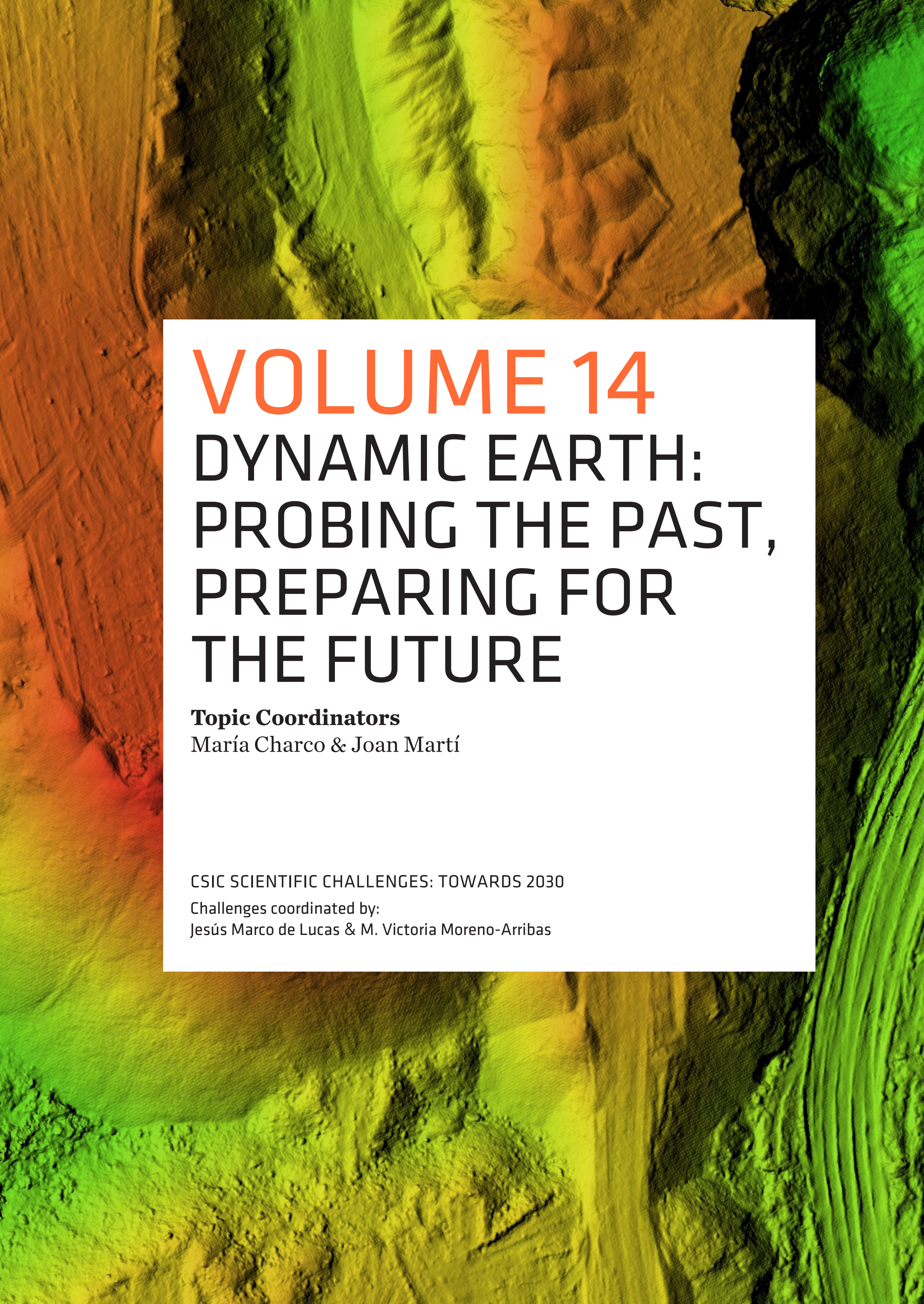

VOLUME 14

DYNAMIC EARTH: PROBING THE PAST, PREPARING FOR THE FUTURE

Topic Coordinators
María Charco & Joan Martí

CSIC SCIENTIFIC CHALLENGES: TOWARDS 2030

Challenges coordinated by:
Jesús Marco de Lucas & M. Victoria Moreno-Arribas

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CSIC SCIENTIFIC CHALLENGES: TOWARDS 2030

What are the major scientific challenges of the first half of the 21st century? Can we establish the priorities for the future? How should the scientific community tackle them?

This book presents the reflections of the Spanish National Research Council (CSIC) on 14 strategic themes established on the basis of their scientific impact and social importance.

Fundamental questions are addressed, including the origin of life, the exploration of the universe, artificial intelligence, the development of clean, safe and efficient energy or the understanding of brain function. The document identifies complex challenges in areas such as health and social sciences and the selected strategic themes cover both basic issues and potential applications of knowledge. Nearly 1,100 researchers from more than 100 CSIC centres and other institutions (public research organisations, universities, etc.) have participated in this analysis. All agree on the need for a multidisciplinary approach and the promotion of collaborative research to enable the implementation of ambitious projects focused on specific topics.

These 14 "White Papers", designed to serve as a frame of reference for the development of the institution's scientific strategy, will provide an insight into the research currently being accomplished at the CSIC, and at the same time, build a global vision of what will be the key scientific challenges over the next decade.

VOLUMES THAT MAKE UP THE WORK

1. *New Foundations for a Sustainable Global Society*
2. *Origins, (Co)Evolution, Diversity and Synthesis of Life*
3. *Genome & Epigenetics*
4. *Challenges in Biomedicine and Health*
5. *Brain, Mind & Behaviour*
6. *Sustainable Primary Production*
7. *Global Change Impacts*
8. *Clean, Safe and Efficient Energy*
9. *Understanding the Basic Components of the Universe, its Structure and Evolution*
10. *Digital and Complex Information*
11. *Artificial Intelligence, Robotics and Data Science*
12. *Our Future? Space, Colonization and Exploration*
13. *Ocean Science Challenges for 2030*
14. *Dynamic Earth: Probing the Past, Preparing for the Future*

CSIC scientific challenges: towards 2030
Challenges coordinated by:
Jesus Marco de Lucas & M. Victoria Moreno-Arribas

Volume 14
Dynamic Earth: Probing the Past, Assessing the Present, Preparing for the Future

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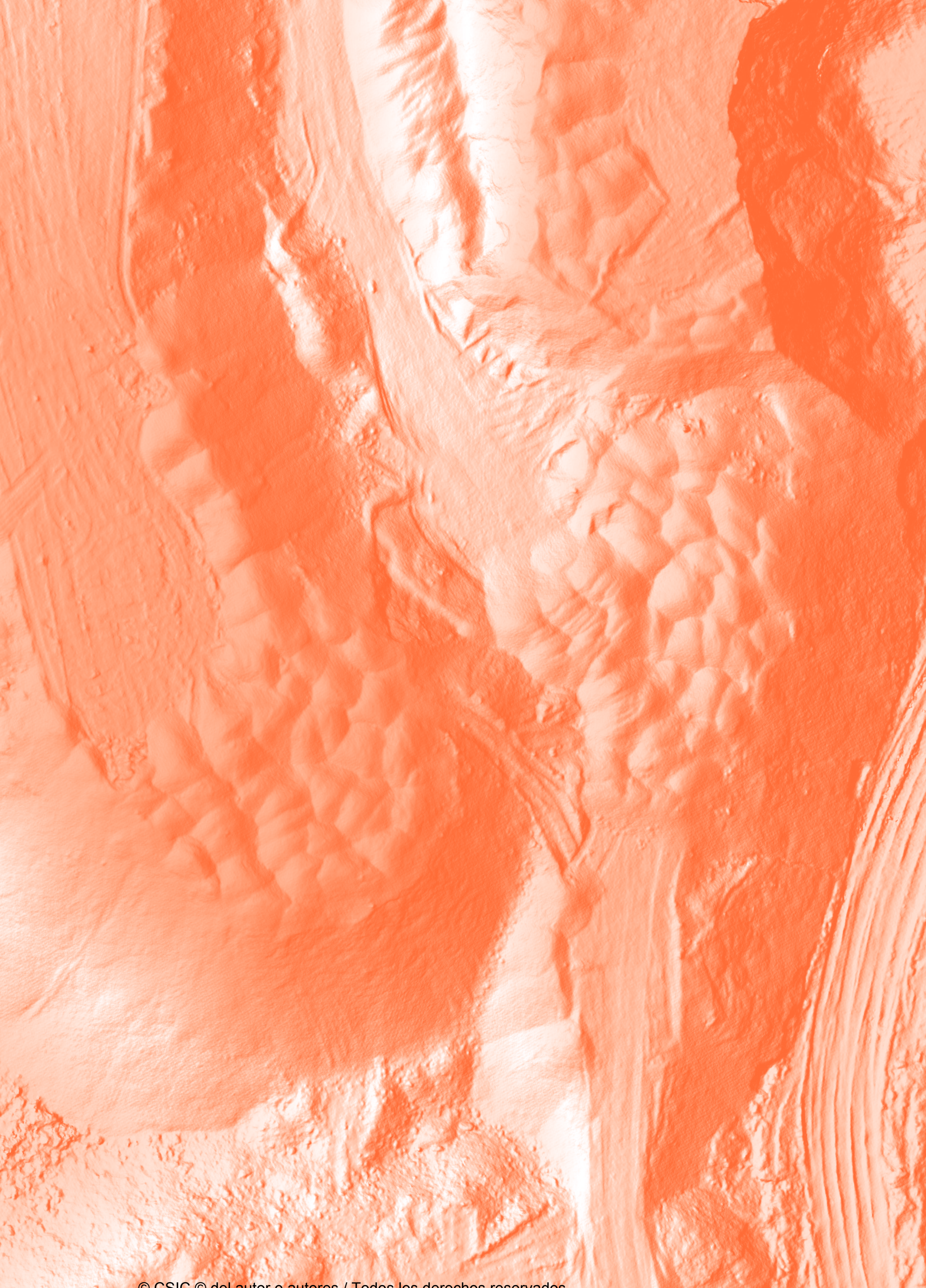


CONTENIDO

ABSTRACT

Critical research challenges within the Earth Sciences include the quantification of Earth's dynamic processes on all scales, as well as geohazards and georisks, the assessment of environmental quality, the development of models for exploration and sustainability of geological and water resources in an advanced economy, the energy transition in times of global change, the development of advanced models for environmental management and the measurement of the impact of global change, among others. Scientific advance in these areas, together with the understanding of their connections, are essential for the sustainability of our society as a whole.

KEYWORDS

Planet Earth · geosciences · geodynamics · georesources · water resources · air quality · geohazard · global change · environment · geoheritage · planetary geology

EXECUTIVE SUMMARY

During the last few decades, Earth sciences have evolved rapidly and are now able to produce scientific models that can help to reconstruct and forecast the past and future processes of the Earth system. This includes forecasting the future behavior of geological systems, and also the prediction of future geological patterns. But these models need high quality observations for their development and validation. Every day human activities involve interaction with our planet Earth. Everything around us is built upon the Earth, grows on Earth, or depends on the environments and internal dynamics of the Earth to some degree, even humans, or specially, humans. Every parcel on land belongs to a hydrological basin. The structure and processes occurring at the interior and on the surface of our planet Earth have strong relevance for humanity's basic needs, such as supply of water and resources, protection against the effects of natural hazards, and control of the environmental degradation on the Earth. Therefore, the knowledge about the Earth is the key to develop an informed citizenry and a global awareness of a common Planet and a common future.

Most important challenges posed by our modern society that wants to be safe and sustainable in its immediate future cannot be addressed without the direct contribution of geosciences, and in this sense, it is essential to create public awareness of geoscience's vital role to society. The increasing pressure that we are placing upon the environment makes us increasingly vulnerable, as evidenced by global assessments (IPCC, 2018; IPBES, 2019; UN Environment, 2019). As it was already stated during the International Year of Planet Earth 2005-2007, we have an urgent need for scientifically advanced "geo-prediction systems" that can accurately locate subsurface resources and forecast the timing and magnitude of earthquakes, volcanic eruptions and land subsidence (some of which is caused by human activity) (www.esfs.org). The design of such systems poses a major multidisciplinary scientific challenge. The complexity in the prediction of Earth processes also imposes important constraints on predictions in oceanographic, hydrologic, and atmospheric sciences, including climate variability (Fig. 1) and its subsequent impacts on anthropogenic environments, population exposure and human health. At the same time, hydrologic and atmospheric processes have direct critical interactions with life and climate. Therefore, it is crucial to recognize the key role of geosciences to ensure the sustainable development and exploitation of our planet resources. A review of the Sustainable Development Goals defined by the United Nations as the blueprint to achieve a better and more sustainable future for all humankind, show that they are intimately related to or depend on our current and future knowledge on the structure, evolution, and dynamics of our planet.

FIGURE 1. Simplified pictogram showing the basic framework for global tectonics and geological environments, cast into the whole Earth system, and extending into the Solar system, and galaxy (Van Wick de Vries *et al.*, 2018)

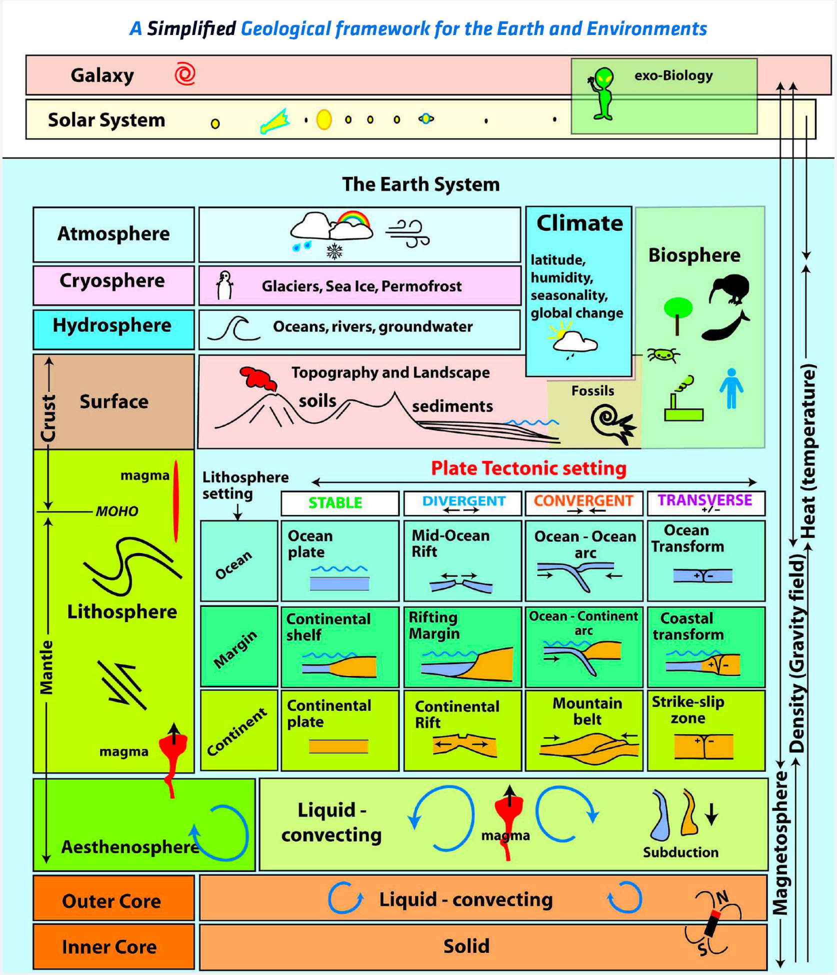
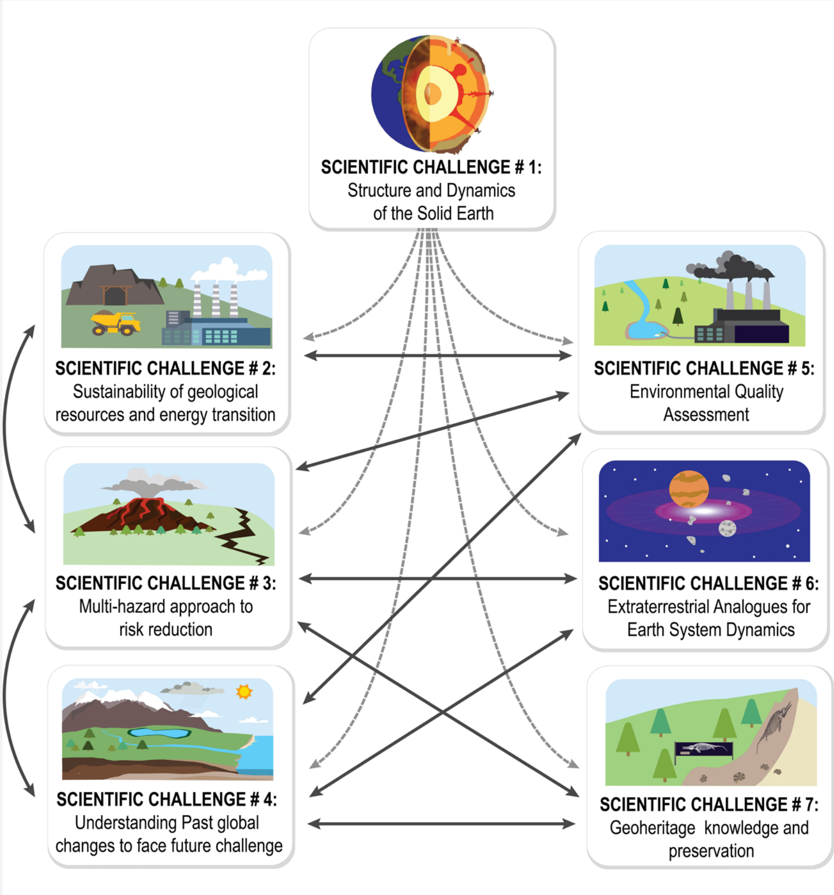
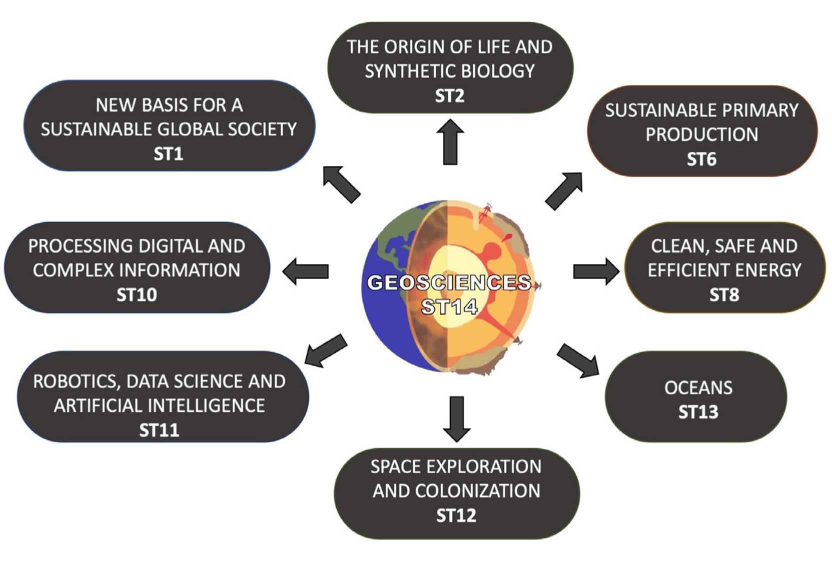


FIGURE 2. Interrelation between challenges included in Strategic Theme #14



Predicting the behavior of geological systems requires observing the present and reconstructing the past. This implies the study of both ancient and currently active processes that have contributed to the present day Earth. To maximize the benefit, CSIC scientists must investigate these processes wherever they are active or preserved in the past, regardless of geographic or political boundaries. In this sense, this Strategic Theme aims, through observation and modeling, to generate fundamentally new conceptual developments addressing the main challenges imposed by our society in relation to the planet Earth. A corollary to this is the continued internationalization of CSIC's geoscience program through leading edge research and the stimulation and support for placing its geoscientists in international leadership roles. While there are many world- class scientists and labs in Spain, and in the CSIC in particular, there are still very few leaders of international organizations, decision-making bodies, journal editors, etc. This is also a clear challenge in the Spanish geosciences that we also plan to face within this Strategic Theme.

FIGURE 3. Cross-links of Geosciences Theme with the other Strategic Themes



In order to make this Strategic Theme successful, seven scientific challenges have been identified (Fig. 2), each of them including several key challenging points that correspond to the most urgent and necessary aspects to be developed from a geoscience perspective in the mid to long term. All scientific challenges share knowledge and methods, so transversality inside this Strategic Theme and among all participating will be maximized (Fig. 2).

In the same way, this Strategic Theme shares interests and objectives with other CSIC Strategic Themes, so full collaboration between them will be also promoted (Fig. 3). This will also contribute to enhance international collaboration and to increase our participation in international research programs and projects.

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CHAPTER 1

ABSTRACT

The structure and dynamics of Planet Earth are unique in our solar system because of Plate Tectonics, a process coupled to deep mantle convection whereby continents drift and collide, and oceanic lithosphere is continuously created at mid-oceanic ridges and consumed at subduction zones since more than three billion years ago. This dynamic process has made Earth habitable thanks to planetary-scale mass transfers that have regulated Earth's atmosphere volatile cycling and temperature. Plate tectonics is the deep engine that wheels most basic humankind needs and threats, such as water and geothermal resources, natural hazards (volcanic eruptions, earthquakes, tsunamis, landslides), environmental degradation, and availability of energy and critical raw material. Observing active processes in different plate tectonic settings at various time and length scales provides vital information on current Earth's dynamics and structure. Earth's dynamic processes exceed historical times, and their study requires a reconstruction of the past through tectonic, sedimentary, petrological, and geochemical studies of the geological record exposed on the Earth's surface or drilled in oceans and continents. Advances in palaeomagnetism, seismology, geodesy, Geodynamics, thermodynamic modeling, experimental petrology, sedimentology, rheology, high-precision geochronology, and stable and radiogenic isotope geochemistry provide essential information and new toolsets for decoding the geological record at unprecedented temporal and spatial resolution. A better understanding of the structure and dynamics of the Solid Earth must advance in multiple fronts in three critical challenges aimed at deciphering the (i) structure and dynamics of the Solid Earth in four dimensions, (ii) the rheology of the lithosphere and fault zone behaviour, and (iii) the complex interactions between Earth-surface processes and topography. Undertaking these three key challenges will allow discoveries on the mechanisms driving Plate Tectonics and the nature and evolution of Planet Earth's lithosphere and mantle since its accretion.

KEYWORDS

Solid Earth | Plate Tectonics | Lithosphere | Earth's mantle | Geodynamics

CHAPTER 1

STRUCTURE AND DYNAMICS OF THE SOLID EARTH

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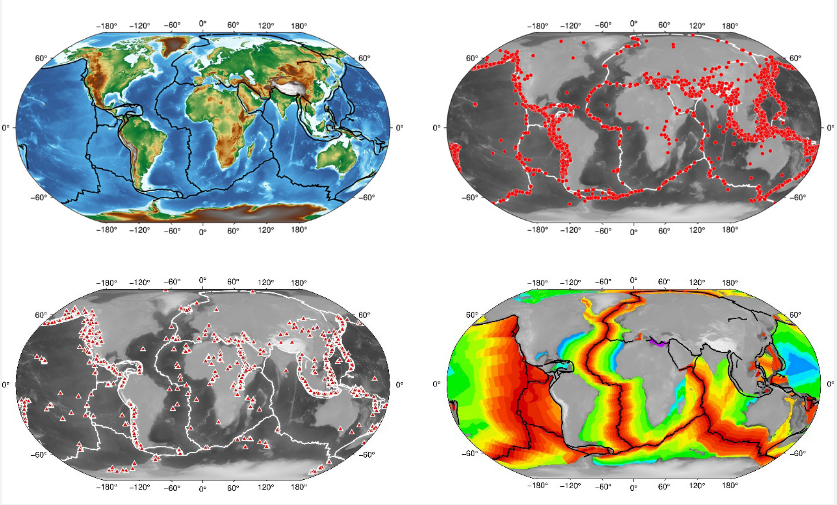
1. INTRODUCTION AND GENERAL DESCRIPTION

The structure and dynamics of Planet Earth are thought to be unique in our solar system because of Plate Tectonics, a process coupled with deep mantle convection whereby continents drift and collide, and oceanic lithosphere is continuously created at mid- oceanic ridges and consumed at subduction zones, since more than three billion years ago. One of the most outstanding consequence of Earth´s internal dynamics is the generation and evolution of the continental and oceanic masses, a feature that remains unique to our planet and that has been the substrate for live evolution. This dynamic process has made Earth habitable thanks to planetary-scale mass transfers that have regulated Earth's atmosphere volatiles cycling and temperature, and the generation of a protective magnetic field. The dynamic processes that drive Plate Tectonics may sound far from Society everyday concerns but is the deep engine that wheels most humankind basic needs and threats, such as water and geothermal resources, natural hazards (volcanic eruptions, earthquakes, tsunamis, landslides), environmental degradation, and the availability of energy and critical raw material, among others (Fig. 4). Volcanic and seismic hazards mostly occur where plates sink into the deep Earth and, to a lesser extent, where continents break apart (Fig. 4). Topography — the landscape shape and essential control on local climate and formation of basins where most population inhabits and freshwater resources are available— is the product of the interaction between deep and surface processes and the atmosphere. Hydrocarbon resources are found in the proximal and distal areas of both continental and marine basins. Critical raw materials necessary for the energy transition are systematically associated with different plate tectonic controlled environments.

Observing current active processes in various plate tectonic settings at variable time and length scales (mountain ranges, sedimentary basins, subduction zones, continental margins) provides vital information on the Earth's dynamic processes in these settings.

Large international multidisciplinary initiatives using state-of-the-art methodologies and technical advances in geophysics and space Earth observation are providing breakthroughs in our understanding of Earth's structure and dynamics. Among key recent achievements are the imaging of the deep structure of volcanoes, subduction and collision zones, mountain ranges, and oceanic basins. They are also unveiling data about dynamic processes such as the world map of stress, and information on how Earth's mantle rocks flow controls the thickness and strength of the lithospheric plates and the extent of coupling between plate motions, and the pattern of convection in the asthenosphere and melt extraction at mid-ocean ridges and continental rifts.

FIGURE 4. Global map delineating the main tectonic plates on Earth and their relationship with topography, earthquakes, and volcanoes. The strong relationship among Earth major features and plate boundaries shows that Plate Tectonics exerts a major control on Earth's Processes, which are rooted in the Structure and deep and shallow Dynamics of the Solid Earth (Modified from https://globalchange.umich.edu/globalchange1/current/lectures/evolving_earth/evolving_earth_ext.html)



Deep Earth's dynamic processes are so slow, exceeding historical times, that whole knowledge of internal processes and a robust test of thermomechanical models requires a reconstruction of the past through the tectonic, sedimentary, petrological, and geochemical study of ancient exhumed terranes. Reconstructing past Earth's dynamics involves many geological sub-disciplines (geological mapping, structural geology, sedimentology, and petrological studies, among others) that investigate the geological record of rocks exposed in the Earth's surface (exhumed deep crustal and mantle continental and oceanic terranes). Previously inaccessible rocks from the oceans and continents are now available thanks to international research initiatives such as the Integrated Ocean Drilling Program (IODP) and the International Continental Drilling Program (ICDP). Recent advances in paleomagnetism, seismology, geodesy, geodynamics plate reconstruction, thermodynamic modeling of fluids and melts, experimental petrology, sedimentology, and rheology, high-precision geochronology, and stable and radiogenic isotope geochemistry are developing new toolsets for decoding and understanding this geological record at unprecedented temporal and spatial resolution. These studies are not only unveiling the mechanisms driving Plate Tectonics but also the nature, structure, and dynamics of the deep crust and mantle and their evolution since the accretion of Planet Earth. They have been pivotal in unveiling the change from a stagnant lid to a Plate Tectonic driven Earth and the supercontinent cycle throughout Earth's history, which are now essential for understanding other terrestrial planets. Studies of the present and past geological record have also provided key observations to validate through increased physical and numerical models and analog models. Thanks to the advent of supercomputers, we are starting modeling the dynamics of the Earth's from the micro- to planetary-scale and times scales from seconds to billion years (earthquakes, magmatic differentiation, subduction and rifting, planetary convection) for process validation against the vast wealth of information of the present and past geological record.

We prioritize challenging points for which current and near future technology will allow CSIC scientists to thrive achieving significant advances. The potential in developing these key science priorities will have clear applications, although we expect they provide unanticipated positive benefits. A future more complete understanding of the structure and geodynamics of the Solid Earth must advance in multiple fronts in three key challenges:

1. Structure and Dynamics of the Solid Earth in four dimensions
2. Rheology of lithosphere and fault zone behavior
3. Dynamic interactions among Earth-surface processes and topography.

These three key challenges are research priorities in the most relevant international initiatives to develop a new long-term research plan research in Solid Earth Sciences[1].

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Addressing the challenge on the *Structure and Dynamics of the Solid Earth in four dimensions (Challenge 1)* will have a fundamental impact on four understanding of the planetary system evolution in four dimensions from nanoscale to the whole planet and throughout the Earth's history. This challenge will lead to a better understanding of the Earth's deep lithosphere and mantle interaction, composition and dynamics, the formation and differentiation of the continental crust, the structure and generation of the oceanic lithosphere, continental rifted margins, and subduction zones, the origin and evolution of plate tectonics and its impact in making Earth a habitable planet, as well as exploring the fourth dimension of time. The details of how plate tectonics, in terms of motion, forces and geochemistry, is linked to flow in the deep mantle remain unknown and this continues being the basic science core question that articulate the purpose of the study of the structure and geodynamics of the Solid Earth.

Tackling the challenge on the *Rheology of lithosphere and fault zone behavior (Challenge 2)* will improve our understanding of fault zone evolution, from earthquake cycle deformation to the cumulative effects of faulting on topography over millions of years. The combination of structural geology, geochemistry, and geochronology, seismic and aseismic fault-slip, surface kinematics and geodynamic modeling, will provide a comprehensive understanding of fault zone evolution and behavior through time and in three spatial dimensions, and the interactions and feedbacks between fluids, slip behavior, and the development of fault and crustal strength. New numerical

1. NASA Challenges and Opportunities for Research in Earth's Surface and Interior (https:// science.nasa.gov/earth-science/focus-areas/surface-and-interior); NSF Subduction Zones in 4D (https:// www.sz4d.org/); Integrated Ocean Drilling Project 2050 Science Framework (http://iodp.org/2050- science-framework-survey); NSF GeoPRISMS Implementation Plan (http://geoprisms.org/research/ science-plan/); Challenges and opportunities for research in tectonics (https:// sgtfuturedirections.wordpress.com/); Deep Carbon Observatory: a decade of discoveries and opportunities (https://deepcarbon.net/).

models that integrate the composition, microstructure, fluid content, and rates of processes in fault zones will bridge the gap between theory, the natural record, and experimental laboratory data. This challenge has important potential applications in the mitigation of risks related to earthquakes, landslides and economic resources commonly associated with fissures and fault zones.

Finally, one of the most fascinating contemporary developments in Earth's science is the notion that atmospheric, surficial and deep Earth processes are coupled processes with complex feedback relationships. This complex feedback processes addressed in the *Dynamic interactions among Earth-surface processes and topography (Challenge 3)* will have an important impact in understanding the links between rheology, deformation, and erosion, the evolution of landscapes and sedimentary basins, and the tectonic controls on weathering, the carbon cycle and Earth's habitability.

Critical issues influencing society, such as shaping Earth's landscapes where we live, natural hazards, essential geological resources, short and long-term climate change, water resources, biotic diversity and environmental risks, require a holistic knowledge of the Earth's dynamics and structure at different spatial and temporal scales. Earth's plate tectonics establishes the global cycling of energy and matter that controls the planetary scale environmental and climatic conditions, generates economic resources, governs earthquakes, tsunami, and volcanoes that pose grave hazards to society, and provides the key building blocks for life. We are only beginning to comprehend the full diversity of complex feedback processes and the role of plate tectonic cycle and head fluxes that strongly impacts society by regulating Earth's climate factory, generates critical energy and non-energy resources and poses natural hazards, among others. The quest for a fundamental understanding of the Earth's dynamic of the structure and dynamics of the solid Earths is essential to understand the long-term functioning of some of these Earth's complex natural phenomena relevant to society, increasing the access to natural resources, its resilience in the face of naturals hazards, and meeting the challenges associated with maintaining Earth's habitability.

Addressing Challenge 1 will lead to a better understanding of the underlying tectono- magmatic processes leading to critical resources improving exploration targets and access to new, more sustainable resources necessary for the energetic transition. It will also enhance our knowledge of carbon mass balances associate with plate tectonic recycling and the long-term climate change and planet habitability. The interaction between the lithosphere and hydrosphere (e.g., serpentinization of the oceanic lithosphere; Challenge 1) is essential to test feasible geological scenarios for early Earth prebiotic world and life emergence and evolution. Improving our knowledge of shallow and deep processes in subduction zones (Challenges 1 and 2) is critical for advancing in predicting volcanic and earthquake hazards. Conceptual advances integrating faults and shear zones in a model of fault zone evolution predicting the flow of fluids through faults and fractures is crucial for meeting society's needs for energy, economic, and groundwater resources, and for safely sequestering contaminants and potentially carbon sequestration and storage (Challenge 2). Understanding how deep processes shape Earth's landscape (Challenge 3) and form continental basins is essential for the access to water resources, and landslides and environmental risks.

3. KEY CHALLENGING POINTS

3.1. Structure and Dynamics of the Solid Earth in four dimensions

The exploration of the deeper interior of our planet has dramatically advanced thanks to seismic tomography, which enables us to link near-surface processes to the internal dynamics and structure the lithosphere and mantle. Seismic studies are complemented with petrological and geochemical studies of the volcanism and their deep-seated xenoliths, and studies of exhumed terranes exposing unique sections of continental rocks (metamorphic and plutonic), and continental mantle peridotite massifs. The Earth's continental crust is a first-order geochemical reservoir that evolved through billions of years. Extreme geochemical fractionation is a unique feature of Planet Earth; representing only a small mass fraction of the whole Earth (<0.4%), it contains more than 30% of elements of economic and strategic interest. The formation of new ocean crust at mid-ocean ridges, it's aging, and ultimate sink into subduction zones, constitute the Earth's cycle of matter and energy-driving plate tectonics, and controlling Earth's environment and life. Oceanic lithosphere meets its inevitable fate at subduction zones, where the majority of mature, hydrated ocean crust descends back into the mantle, recycling the serpentinized mantle lithosphere and altered oceanic crust and volatiles back into Earth's interior. Exploration of the early Earth dynamics takes us back to an era before plate tectonics, when accretionary processes and planetary differentiation were of paramount importance, and enables us to build an understanding of how plate tectonics can arise on rocky planets and how habitable worlds emerged. Some of the critical questions in this challenge are:

1. When and how the continental crust and lithosphere formed throughout Earth's history and how they persisted and evolved for billions of years? What are the essential processes involved in the extreme geochemical fractionation of the continental crust and the layered structure of continents?
2. When and how did Earth transition to plate tectonics, and what was the role of tectonic processes in the origin and development of Earth's atmosphere, cryosphere, hydrosphere, and biosphere? What is the relative importance of plume versus plate mantle convection during Earth cooling evolution?
3. What is the interplay of tectonics, magmatic and hydrothermal activity at variably spreading mid-ocean ridges, and at the onset of the oceanic spreading in continental-to-ocean transitions and margins and how is recorded in current active settings and in the geological record? How these processes affect the interaction between hydrosphere and lithosphere, leading to submarine hydrothermal vents, and what is the mass and energy balance exchange between these reservoirs and its implications for the development of a deep geobiosphere?
4. What is the mass balance of volatiles and other elements in subduction zones and their role in the deep cycle of carbon on Earth? How deep and shallow slab tectonic and magmatic processes contribute to the formation and accretion of continental and oceanic arcs across the Earth's history?
5. What is the relative importance of plume versus plate mantle convection during Earth cooling evolution? What are the physical and chemical properties of the melt generation region beneath hot spots? What are the mobility and time-scale dynamics of mantle plumes?
6. What processes and mechanical relations govern plate-like behavior of the lithosphere and the transition to geodynamics of the asthenosphere and deep Earth, how do plate interiors deform in both continental and oceanic lithosphere?
7. How do rates of geological processes vary through time and across time scales, and how can we obtain this information for different processes and timescales from the geological record?

3.2. Rheology of the lithosphere and fault zone behavior

The Earth-surface record of fault zone evolution, from earthquake cycle deformation to the cumulative effects of faulting on topography over millions of years, is increasingly known due to new developments in geodesy, geochronology, and modeling of the surface process. An increasing number of studies show that the geological record preserves a record of earthquake rupture and other slip behaviors linking fault zone complexity to earthquake processes. The main key questions in this challenge are:

1. How do crustal fault networks evolve at different spatial and temporal scales in 4D via propagation, linkage, abandonment, and reactivation of segments, and how is distributed and localized deformation from the surface to the upper mantle?
2. How in both the brittle and ductile domain do the strengths and other mechanical properties of fault zone materials evolve at different depths over the lifetime of a fault? How do strength and other mechanical properties of fault zone materials evolve at different depths, in both the brittle and ductile domain, over the lifetime of a fault?
3. How do landforms and structures within exhumed fault zones result from and record the processes observed in active fault systems?
4. How do fluids and chemical reactions affect fault zone evolution and fault slip behavior?
5. What controls the nucleation, rupture behavior, and slip arrest of regular earthquakes?

3.3. Dynamic interactions among Earth-surface processes and topography

Geophysical observations and modeling of mantle dynamics show the critical role of dynamic topography on the continents. New high-resolution paleoelevation reconstructions and geochronologic datasets are enabling geodynamic models on the unforeseen feedbacks between deep and superficial processes using observations from structural geology, petrology, thermochronology, geodesy, geophysics, and geomorphology. New LiDAR and photogrammetry tools are improving our ability to quantify and testing models. Fundamental advances in this challenge lie in the true integration of modeling and observational experiments. Key questions in this challenge include:

1. How does dynamic topography affect continental tectonics and surface processes and how deep mantle dynamic processes influence the surface topography recorded in the geologic record, and how do rheology, deformation, and orogenesis affect surface erosion, and vice versa?
2. How are tectonic and climate processes recorded in the sedimentary deposits and stratigraphy? How are they linked to erosion rates, rock uplift rates, and climate proxy records across various timescales?
3. How do bio-geomorphic feedbacks that link vegetation, slope stability, and weathering operate during orogenic evolution?
4. How surface mass loading dynamics affect (intra- and interplate) seismicity, mantle magma production and regional sea-level records over different time scales?

CHAPTER 2

ABSTRACT

The demand for geological resources is constantly increasing, a trend that will continue as the world's population grows and the standard of living increases. Thus, one of the most critical challenges facing our society is to ensure a sustainable and environmentally friendly supply of mineral raw materials and a secure surplus of green energy. To meet the growing demand imposed by society and to avoid adverse environmental impacts, cutting-edge research and especially knowledge of the subsoil with unprecedented resolution is needed. For economic and social change, it is therefore essential to explore new repositories and promote the education and training of researchers who can lead new discoveries and encourage innovation. The sustainable use of the subsoil requires the integration of different exploration methodologies and unique developments in the generation of 3D, static and dynamic models, limited by extremely large data sets. Managing large databases (Big-Data) and machine learning (Artificial Intelligence) will significantly reduce costs, increase success rates even to great depths, and reduce social and environmental stress. In other words, it's about going from asking "where is it" to asking "what if", looking for quick and accurate answers to complex situations. Push the simulation / prediction of behavior through numerical models at scale, "digital twins" of the natural reality of the subsoil is one of the main future challenges in geosciences.

KEYWORDS

mineral resources | energy resources | sustainability | exploration strategies | modelling

CHAPTER 2

SUSTAINABILITY OF GEOLOGICAL RESOURCES AND ENERGY TRANSITION

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1. INTRODUCTION AND GENERAL DESCRIPTION

One of the most critical challenges for our society, and especially for the European Union, is the assurance of a sustainable supply of mineral raw materials needed for the technological revolution and for a secure surplus of green energy (Lusty & Gunn, 2015). The exploitation of geo-resources has played a central role in the development of our civilization, from the earliest stone tools and arrow-heads to the hydrocarbons that fueled the industrial revolution and recently to the critical metals that enable electronic miniaturization or low-carbon energy generation. The economic, energy and technological transition that is taking place is producing a significant change in the supply and market of mineral raw materials and the disposal of its associated waste (Grandell *et al.,* 2016). Despite technological advances leading to more efficient use and recycling and substitution (Giurco *et al.,* 2014), the demand for geological resources is steadily increasing and is predicted to continue like that far into the next future as global population growths, demand for energy increases and standards of living raise (Rosenau-Tornow *et al.,* 2006; Tilton 2015). This unavoidable need is in open contrast with the increasing limitations, especially in the western world, to the exploration, opening and development of mines following the “Not in my Backyard” doctrine. This is changing the rules of mine exploration and industry is moving towards more predictive models that induce less social and environmental stress.

Our ability to develop our society on the geosphere in a sustained and equitable way is increasingly strategic and therein lie the relevance to address this challenge. Meeting the growing demand imposed by our technological societies while avoiding adverse environmental impacts requires leading-edge research. For such a big economic and social change, is critical to find new ore deposits and sources of energy and also to be able to recycle the materials already used in a more efficient way in order to reduce the amount of waste we are generating. Contribution of geosciences to this challenge is via:

(a) the exploration of new raw materials needed for the technological society and for the production and storage of renewable sources of energy; (b) exploration of hydrocarbons needed for a smooth energy transition from fossil to renewable sources of energy; (c) underground storage of natural gas and/or greenhouse gases; (d) the use of geothermal power as a renewable energy source; and (e) finding new ways of recycling "old materials".

Metals for the future are not only those traditionally used for most of our industrial development and mobility, the base and ferrous metals, but also there is a growing demand on those that are the base of telecommunications, nanotechnologies and data storage (e.g., Moss *et al.,* 2011). The new technologies of energy production, supply and storage and the exponential development of computer science, communications, mobility and data processing rely, on the use of minerals and metals that, until now, have been considered of secondary importance. These are currently added to the list of base metals (Fe, Cu, Zn) on which a significant part of our development rests. The need to substitute hydrocarbon as the main source of energy not only requires new engines, but new raw materials (e.g., Nb, Ta, Sn, W, REE), new energy storage schemes based on Li, V, Co or Ni and the promotion of low- and high-enthalpy geothermal power.

While the sources of base metals are generally diversified, many of these technological and green raw materials are currently regarded as critical ones, i.e., raw materials that are produced by a small number of sources, many of them in politically unstable or conflict areas[1]. Acknowledging that the excessive dependency on imports carries major economic and political risks, Europe is facing a renewed interest in the production of natural raw materials. The European Commission has realized that the current modern societies strongly depend on these materials and is systematically fostering exploration,

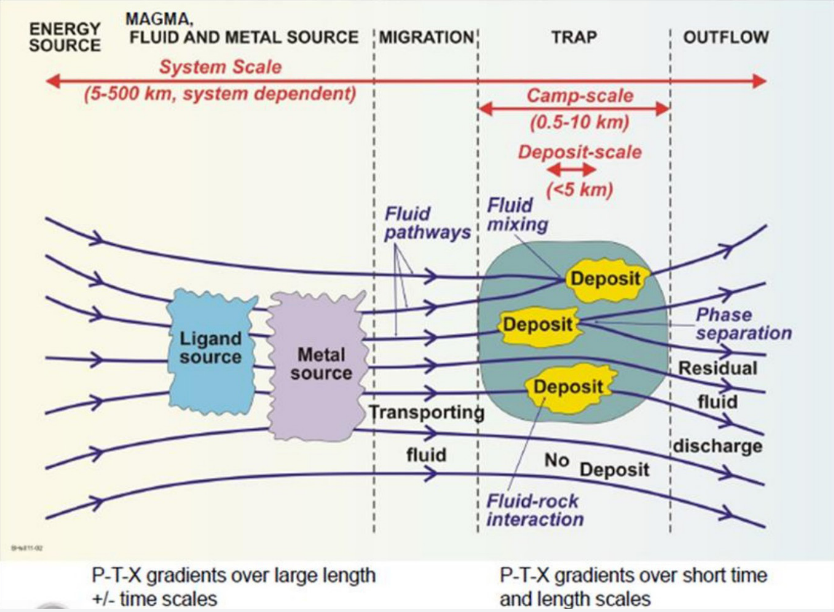
1. https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

mining, recycling and substitution via the 7th Framework Program, H2020, the EIT Raw Materials Initiative and, the different Lighthouse programs. This interest will continue at least for Horizon Europe but very likely, it will continue at least for some decades.

Exploration is the first step in the production of mineral raw materials and, thus, the basis for any increase in metal production that could remediate potential shortage. The main challenge to promote the finding of new areas, green fields exploration, is to open new areas to exploration and develop new sustainable exploration technologies able to find mineralization more accurately, at greater depths and, producing the less social and environmental stress. Exploration of ore deposits, both in brown field (explored camps) or green field (new areas) targets, need new predictive concepts and methodologies. In historical old and, densely populated areas, most outcropping ore deposits are already discovered and exploration must be focused to new areas, areas of difficult access such as seafloor (Dutkiewicz *et al.*, 2020; Hoagland *et al.*, 2010), and deeper levels where exploration costs increase significantly. Fundamental ingredients in the generation of mineral deposits are the circulation of melts and fluids at a global scale and the formation of highly effective ore traps by physical or chemical processes. Thus, the detailed study of modern, active ongoing analogs is mandatory. This includes a wide variety of settings including active geodynamic environments such as magmatic arcs or evolving basins.

Novel approaches for mineral exploration include the superposition of accurate geological maps and 3D models, structural geology, high resolution geophysical imaging, geochemical ore vectoring, 3D data integration and visualization and reliable conceptual mineral system models. The multidisciplinary integration of this techniques can predict the ore traps and the volumes with more chances of hosting an ore deposit (Barnicoat 2007; Cleverley 2007; Hagemann *et al.,* 2016; Korsch and Doublier 2016; Heinson *et al.,* 2018)., The sustainable exploration of the subsurface requires unique developments in the generation of 3D, static and dynamic, models that are constrained by extremely large datasets. The management of large databases (Geosciences-Big- Data) and machine learning allows to significantly reduce costs, increase success rates even at high depths and reduce social and environmental stress (Karpate *et al.,* 2018; Kingdon, 2018). In other words, moving from "where is it" questions to predictive models with questions like "what if" scenarios, trying to provide fast and accurate answers to complex situations (Spina 2018; Xiong *et al.*, 2018).

FIGURE 5. Sketch of a mineral system emphasizing the role of fluid and its interaction with the rock matrix. Furthermore, this diagram also emphasizes the complexity of this specific challenge as it involves a fully integrated approach combining static factors (the structure and nature of the subsurface) and dynamic processes (fluid flow, heat flow, stress and strain regimes). Ore deposits, in general mineral systems are a very small part of a much larger and complex system. Thus exploration need to understand the mineralization and focus on the overall system's drivers. The process of mineralization extract the commodity from larger to smaller volumes of rocks. Key roles are played by the heat source and the fluid flow. The foundation of the exploration processes needs to be based on the source of the heat and the fluid-pathways (fluid-flux) (Modified from Knox-Robinson and Wyborn, 1997).



Nowadays, examples of promising targets in Europe are the new exploration areas in the Carpathian belt of Eastern Europe, deposits in the arctic region of Scandinavia and Greenland, and the historical districts that continue providing new discoveries such as Iberia (with the Iberian Pyrite Belt, the largest concentration of massive sulphides in the world or the world-class Sn-W-(Ta) district of Western Iberia) or the Kupferschiefer between Germnay and Poland (GEODE project[2]; Nurmi and Molnar 2014). In addition, the concern about access to critical minerals boosted the European interest in the exploration under the sea and in the Arctic regions. However, in a global world,

2. http://archives.esf.org/coordinating-research/research-networking-programmes/life-earth-and- environmental-sciences-lee/completed-esf-research-networking-programmes-in-life-earth-and- environmental-sciences/geodynamics-and-ore-deposit-evolution-geode.html

Europe must not focus its supply just in its geographical domain. It is unlikely that Europe will attain self-supply and thus must encourage Europe-based exploration and mining companies to help with that secure supply in the way that Japan is doing.

The development of ore deposits and its relation to plate tectonics is by itself is a high profile basic science target which requires a multi-disciplinary team of scientist to design a research strategy that will involve indirect observations (subsurface characterization; e.g., Chauvet, 2019) and direct subsurface sampling (deep boreholes) of different terranes rich in ore deposits at national, European and global scales. Thus, aims of this Challenge will need the full support of Challenge 1.

The coming decades will see a gradual transition from fossil to renewable energy sources. At present, conventional fuels still account for ~90% of the primary energy trade, and a smooth transition demands new research towards the sustainable exploration and exploitation of hydrocarbons for the years to come. An example of the contribution of geoscientists on this front is the development of enhanced hydrocarbon recovery techniques in tandem with carbon capture and storage (CCS) through CO_2 sequestration, potentially an important mitigation and adaptation measure to face the challenges of climate change. Our ability to continue tapping the Earth's resources without disrupting the ecosystems relies heavily on a better knowledge of the subsurface and an improved understanding of its processes and interactions. The rapid expansion of the shale-gas sector globally – under consideration also in Europe – and the associated environmental issues are another topic requiring the contribution of geoscientists: urgent research and technological development for the environmentally sound extraction of this valuable resource is of paramount importance. Exploitation of shale gas reserves in Europe and globally will require careful geological and geophysical characterization of the underground to find and map potentially suitable areas, assess the commercially viable reserves and monitor for potential environmental problems including groundwater pollution and induced seismicity. The sheer potential economic significance of the sector will lead to extensive multi-disciplinary basic and applied Earth sciences research over the coming decades, requiring integrated access to data and facilities of many different types.

District heating and cooling represent around 10% of energy use in the EU. There is a vast untapped potential for the adoption of industrial-scale heat pumps in district heating and it is estimated that over 25% of the EU population live in areas suitable for geothermal district heating applications, enabling higher shares of renewable energy in the EU energy system. Europe has a large potential for medium- to high-enthalpy geothermal energy in a variety of geodynamic settings – sedimentary basins, crystalline rock, active volcanic regions – both for heating or cooling and for production of electricity. The optimization of production and the mitigation of environmental concerns require detailed monitoring and modeling of the reservoir environment.

Large-scale subsurface storage is a critical theme and, one of the best solution for resources (natural gas, energy, storage of green hose gases). In addition, several industries produce hazardous waste that requires safe long-term storage below the Earth's surface. The requirements are particularly strict for the nuclear industry, whose waste – spent fuel rods as well as mine tailings – must be disposed of in underground facilities with the highest standards of safety. Adequate planning of underground repositories to meet all potential long-term threats – a current concern in several countries – demands geological information with an unprecedented level of detail.

Geoscientists are tasked with providing the needed knowledge and expertise to access minerals and raw materials in Europe, adjusting industrial practice to evolving societal requirements. Public resistance to large open-pit mines is leading to the development of mining methods that have minimal impact, such as fully-mechanical underground mines or in-situ leaching. This requires the development of integrated monitoring systems, data capture from underground sensors, data assimilation and open exchange of knowledge with the public.

The increasing societal awareness on the rapid changing environment is fostering research in the integration of geosciences observations to assess the implications on the planet surface (at all scales) of the human activity related to underground activities. This target requires the integration of data from broad number of sources including satellites, land and oceans (including seafloor, Galsby, 2002; Rona, 2003). Despite being different, gas production, exploitation of geothermal energy and subsurface storage rely on the same basic concepts that mining exploration, that are, geological and structural infrastructure, conceptual models and, the geophysical characterization of subsurface conditions without harming the environment. Thus, there remains a strong role for the geosciences in addressing key problems for the future of mankind – in a middle term, geosciences will have to help to address some key challenges for the society. Therefore, the need for the promotion of education and training of technicians and researchers that can lead to new discoveries by fostering innovation. Addressing this challenge is a cornerstone to meet the energy and technological demands of future generations.

Most of these objectives involve direct social and economic implication and, very likely, need the integration of CSIC's scientific teams with other research organisms and, industry at national, European and international scale. In order to carry out the necessary research, funding must be mainly based on EU funding – mainly H2020 and its continuation (Horizon Europe) or the EIT Raw Materials- as well as direct collaboration with the industry via direct research contracts or through Research Agencies like AMIRA, CDTI, etc..

To tackle these challenges CSIC features access of a series of singular infrastructures, which are either part of CSIC or, it can have easy access via joint centers, collaborative research or co-funding. A singular and dedicated multi-hardware instrument pool platform should be developed in the style of the ICTS "Infraestructura Científico Técnica Singular" focused on the Observation of Earth's interior (comparable to the USA National Geophysical Observatory, NGO). Currently, Spain lacks such a large scale infrastructure. An infrastructure similar to the Super-Colliders, or the network of telescope observatories is needed. The available infrastructure needed to tackle this challenge is currently distributed among research institutes and Universities within Spain. CSIC owns some important part of this instrumentation for example downhole probes and, over 250 autonomous three-component data loggers (seismic stations).

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Up to status tackling this challenge has contributed to applied science and, also produced recognized contributions in the field of basic science. Most of the concepts and mineral system models used routinely today are based on scientific studies carried since the 1950's and that have strongly influenced all the way of thinking in the exploration of mineral deposits. Within the latter, is the understanding of how the mineral deposits work and evolve depending on their tectonic, magmatic and geologic scenarios. Clear societal impact can be envisage derived from exploration for new deposits and exploitation of mineral resources in new environments, such as deep Earth or under the ocean. Relevant impacts concerning methodological approaches will include the full integration of fundamentally different datasets from different origins which can will managed in an integrated form for producing innovative 3D models. Perhaps this will be the major milestone in exploration for the next decades. This integration is fostering research in big-data analytics in geo-science. The novel data storage and integration techniques will permit the optimal use of any available data, and thus allow gaining new information from re-interpretation of legacy data. This implies avoiding the need to repeat measurements, and therefore reduce cost as well as avoiding environmental and social disruptions. Model resulting from this integration constitute an important step towards a simplified, unified and efficient interpretation; a meaningful step towards the understanding of mineral systems. Innovations and new developments resulting of tackling this challenge will result in key contributions in a wider view of the sustainable use of the subsurface. New developments in wave-field tomography required in geophysics can benefit from the advanced imaging system that medical science and odontology have.

3. KEY CHALLENGING POINTS

Midterm strategy includes the focus on major and specific problems to address (Figs. 5 and 6). Some examples include:

1. Understanding the location of ore deposits at the district scale with special emphasis in the "Mineral System Approach", basic to predict the ore traps and, where the largest and richest deposits should form.
2. Understand the location and time scale of ore deposits at a crustal/lithospheric scale by targeting the lithospheric processes and discontinuities that give rise to such systems (Pirajno and Hoatson 2012; Korsch and Doublier 2016). This this target it would be interesting to align and focus projects with the International Continental Drilling Program and the Challenge 1.
3. The development of conceptual exploration and predictive models for ore deposits. New geophysical techniques for ore exploration.
4. Multidisciplinar and multitask integration in high resolution 3D models of geological, structural, geochemical and geophysical data and, conceptual modeling for targeting of ore deposits at great depths with the aid of machine learning and, intelligent prediction. This will orientate drillholes to increase the chances of finding ore bodies (decreasing costs and social stress).

5. Image and geochemical studies oriented to support the re-mining of mine wastes including the dumps and tailings in a circular economy model and decreasing their environmental impact.
6. Technological challenges associated to big-data analytics and the indirect determination of the structure and nature of the subsurface
7. The contribution of satellite monitoring and geophysics to ensure secure mining: detect and follow (monitor) anthropological induced tectonics in actively mining areas (anthropogenic subsurface activities).
8. Assessment of subsurface energy storage potential to support the energy transition.
9. Positively collaborate, as scientists, in activities related to wide society learning oriented to the importance of earth resources in our society and, especially, in the need of materials for the new society.

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CHAPTER 3

ABSTRACT

In the last centuries, the exposure of our society to natural hazards has notoriously augmented. Despite a given location on Earth may be threatened by more than one hazard happening simultaneously, cascadingly or cumulatively over time, most current scientific knowledge, and hazard assessment and risk management protocols focus on individual hazards and risk. In fact, due to the inherent complexity of multi-hazard scenarios, the scientific community is still far from fully understand the interrelations (cause/effect) between two or more hazards. As a consequence, it fails in correctly evaluating the related cascading effects and potential impacts, establishing effective monitoring and early warning systems, and implementing complete vulnerability and risk analyses. This challenge pursues providing the scientific knowledge required to develop innovative decision-making tools abandoning the 'traditional' single-hazard approach commonly considered in risk reduction strategies and move towards a multi-hazard risk management, and at last, towards a multi-risk approach. Mainly addressed to geohazards, of special interest for this challenge are the so-called 'extreme' events. These, characterized by their low-probability of occurrence, typically strike as sudden onset, but have long-term and high-impact consequences with the potential to generate global disasters, trigger severe disruption of economies, and bring society beyond the limits of sustainability.

KEYWORDS

Natural hazards | geohazards | multi-risk | extreme events | cascading effects

CHAPTER 3

MULTI-HAZARD APPROACH TO RISK REDUCTION

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1. INTRODUCTION AND GENERAL DESCRIPTION

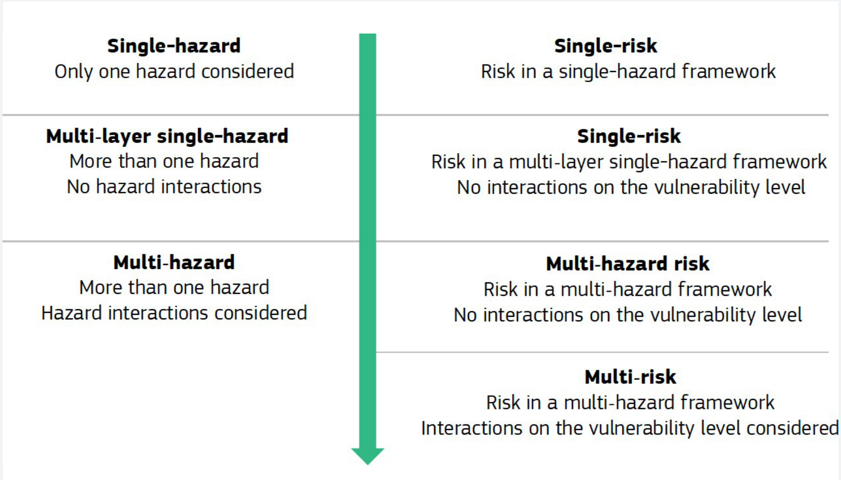
In the last centuries, demographic expansion, extensive urbanization, and the increased concentrations of infrastructure in spaces deemed as being at high risk from natural disasters have notoriously augmented the exposure of our society to natural hazards. According to the data collected by the United Nations Office for Disaster Risk Reduction (UNDRR), climate-related and geophysical disasters (mostly earthquakes and tsunamis) killed 1.3 million people and left a further 4.4 billion injured, homeless, displaced or in need of emergency assistance between 1998 and 2017 (UNDRR, 2018). In the same period, only the impact of earthquakes and tsunamis led to 661 and 656 billion US$ of economic losses, respectively (UNDRR, 2018). In particular, the impact on Europe of disaster events (mostly geological and hydro-meteorological) has been significant, causing 80,000 deaths and €95 billion in economic losses over the past decade (European Commission, 2014a). Within this context, national and international policies have become increasingly focused on the social, economic and cultural impacts of disasters and are now gradually spotlighting on preparing for them, mitigating risks, and building 'resilient communities'. In this sense, the main priorities for action of the Sendai Framework for Disaster Risk Reduction-SFDRR (2015-2030) include: (1) Understanding disaster risk in all its dimensions; (2) Strengthening disaster risk governance to manage disaster risk and for proper prevention, mitigation, preparedness, response, and recovery actions; (3) Investing in measures to enhance the economic, social, health and cultural resilience of persons, communities, countries and their assets, as well as the environment; and (4) Improving disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction.

Hence, securing the society, and strengthen its resilience and adaptive capacity against climate-related hazards and natural disasters should constitute one of the central elements of the functioning of any society and are unquestionably fundamental aspects of the UNESCO Sustainable Development Goals. In the European Union, natural disasters are addressed in a Commission Staff Working Document (European Commission, 2014b); while the EU strategy on adaptation to climate change (European Commission, 2013) aims at contributing to a more resilient Europe at national, regional and local levels.

To date, most of the scientific knowledge, and hazard assessment and risk management protocols focus on individual hazards and risk. However, a given location on Earth may be threatened by more than one hazard happening simultaneously, cascading or cumulatively over time. Thus, multi-hazard scenarios (Fig. 7) occur when one hazard triggers others forming a cascade or domino effect (e.g., offshore earthquake leading to a tsunami), or when specific hazard(s) increase the probability of occurrence of other natural phenomena by changing, for example, the landscape and/or the physical conditions (e.g., droughts enhancing the likelihood of forest fires) (United Nations Internal Strategy for Disaster Reduction-UNISDR, 2017). The chain of events can increase the total risk, and the secondary events may be more devastating than the original trigger. Additionally, compound multi-hazards, considered as those that may overlap in space and/or time because a primary hazard has triggered multiple secondary hazards within a given timeframe, or the coincidence of two (or more) independent hazards, may also generate greater loss than the sum of totally separated single events (UNISDR, 2017).

Due to the inherent complexity of multi-hazard scenarios, the scientific community is still far from: (i) fully understand the interrelations (cause/effect) between two or more hazards; (ii) correctly evaluate the related cascading effects and potential impacts, (iii) establishing effective combined monitoring and early warning systems; and (iv) developing and implementing complete vulnerability and risk analyses. Today, most research on natural hazards takes a single-hazard approach and multi-hazard assessment methodologies, often more qualitative than quantitative, do not incorporate, for example, temporal changes in the vulnerability of assets over time, such as during successive hazards (Ciurean *et al.,* 2018), or due to the impacts of climate change.

FIGURE 7. From 'single-hazard' to 'multi-risk' assessment (Modified from Zschau 2017)



While some progress has been made, due to the complexity of the different phenomena, planners and policy-makers, and the scientists who inform their judgements, still treat the hazards and risks related to such events separately from each other, neglecting interdependencies between the different types of phenomena, as well as the importance of risk comparability. This approach can lead to a distortion of management priorities, an increased vulnerability to other spatially relevant hazards, or an underestimation of risk (Ciurean *et al.*, 2018). Hence there is an urgent need for further development of a proper systematic and quantitative methodology for multi-hazard risk assessment and scenario definition; particularly with regard to potential indirect effects and chain-shaped propagations of damage into and within the socioeconomic system.

The present challenge seeks promoting a multidisciplinary investigation on the causes and effects of multi-hazards to be finally capable of properly evaluating the complex interactions and chain reactions among the different hazards and hence, to quantify their extend and potential impact. The final aim is to provide the scientific knowledge required to develop innovative decision-making tools that will help planners and policy- makers to abandon the 'traditional' single-hazard approach commonly considered in risk reduction strategies and move towards an effective multi-hazard risk management, and at last, towards a multi-risk approach (Fig. 7).

More specifically, we will concentrate on geohazards, referring to those natural phenomena of geological (e.g., landslides, earthquakes, volcanoes) as well as hydrometeorological origin (e.g., floods, freak tides). Of special interest for the present challenge are the so-called 'extreme' (rare but with very high impact) events, which account for most catastrophic events worldwide. At present, the increase in their potential is not only apparent but also greater than ever before, with some of these events being directly linked to climate change. Indeed, climate change has demonstrated to have an influence on extreme weather and climate events increasing their frequency and magnitude (IPCC, 2018). Extreme events, characterized by their low-probability of occurrence, usually strike as sudden onset, but have long-term and high-impact consequences with the potential to generate global disasters, cause severe disruption of economies, and bring society beyond the limits of sustainability (Casti, 2012; Plag *et al.*, 2015; Broska *et al.*, 2020). In general, extreme events may derive from: (i) the occurrence of a single, but unusually large natural process (e.g., the 2011 Great Tōhoku Earthquake of magnitude 9.0-9.1 (Mw) and related tsunamis or the 1815 Mount Tambora eruption and climate effects on 1816); (ii) the disastrous coincidence or concatenation of several single non-extreme processes leading to an abnormal extreme impact (e.g., the 1991 Mount Pinatubo eruption followed by Typhoon Yunga); and (iii) a moderate-to-large natural hazard producing high impact at local/regional scale due to unusual characteristics of the propagation and/or the affected site (e.g., the 2011 Christchurch Earthquake of magnitude 6.2 (Mw) and related liquefaction processes). The possible consequences of extreme events could expand at wide regional/national or global scales, including: economic crises; millions to tens of millions of fatalities; catastrophic destruction in megacities and possibly countrywide; disruption of critical infrastructures affecting food supplies, transport and communications; severe climate states; and environmental pollution (Huppert and Sparks, 2006).

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

The scientific knowledge on natural disasters from a multi-hazard perspective should become a fundamental pillar during the development of policy recommendations leading to improved assessment of best practices on disaster management, as well as to precise recommendations on how to better understand, prepare, respond, and recover from the serious social, economic and political consequences.

Scientific results emerging from the different key action points presented in the next section will expand our knowledge on how geohazards occur and interact, and help to develop methods and protocols that will provide a significant input to national and international policies, fundamentally on the area of civil protection, but also on societal and environmental management. The evaluation of the current state of assessment of multi-risk and resilience in front natural impacts on a quantitative basis, will certainly contribute to the definition of a new standard legislation on risk assessment and mitigation in populated regions threatened by natural hazards. More specifically, this challenge will help to:

- Provide a comprehensive framework to understand the link between Earth geodynamics and geohazards, focusing on the relationship between their triggering mechanisms and the global energy balance.
- Consolidate and complement the current knowledge about the triggering mechanisms, dynamics and impact of individual geohazards, especially those with the potential to generate extreme events.
- Investigate and understand the origin and potential interrelations (cause/effect) between two or more geohazards, with the final aim to correctly assess the resultant cascading effects and most likely impacts.
- Develop more accurate simulation models and probabilistic methodologies for multi- hazard risk assessment and multi-hazard forecasting, including a visualization system to represent probable multi-hazard scenarios and their potential extent.
- Establish the scientific basis of new early warning systems for the different multi- hazard scenarios and to define specific alert protocols able to inform, in a standardized way, on the new alert and current unrest situation.
- Contribute to educational and outreach programs focused on raising the awareness of the citizens concerning the need to launch local risk reduction and resilience activities and on improving the capacity of the population to fight against and face natural disasters.
- Advance in science communication knowledge in order to improve the quality and effectiveness of interactions between scientists, general media and the public.
- Establish efficient communication networks that will allow to exchange social or legal information, in addition to the data on natural hazards among the different community members and stakeholders.

All these actions should increase the effectiveness of research and innovation in responding to key societal challenges contributing to the overarching objective of a sustainable development. In this sense, this challenge looks for integrating society in science by showing how to anticipate and assess potential environmental, health and safety impacts derived from extreme geohazards. From this point of view, results obtained can actually represent an important trigger to raise public awareness at the regional, national, and international level and will certainly help in the definition of a mitigation policy aimed at risk reduction, including the risks of economic loss from unnecessary intervention. All these effects, directly or indirectly, will improve the quality of life and the safety level of millions of citizens and may also contribute to the spreading of a balanced and rational risk assessment and mitigation culture, not only at the decision level, but also in the people living in the territory. This, in its turn, should favour the development of long-term land-use planning within the high-risk regions, and the implementation of specific policies for hazard assessment, crisis management, vulnerability reduction and resilience management. The availability of conducting accurate risk assessment and management analysis is also the fundamental basis for cultivating natural disaster insurance. Hence, insurance companies are increasingly active in assessing the likelihood that a particular hazard will strike an area and combining hazard with vulnerability and value data.

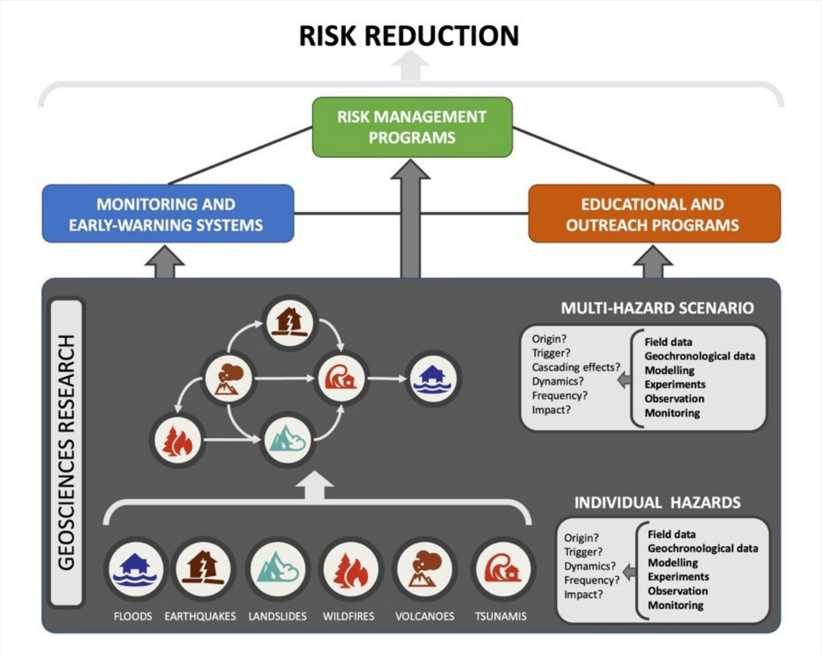
Finally, the reduction of natural risk level in densely populated areas will contribute to preserving and enhancing the environment and cultural heritage. A more accurate assessment and management of risk would directly favor a more rational planning and use of the territory.

3. KEY CHALLENGING POINTS

Extreme geohazards have the potential to inflict cascading effects, whose associated risks are difficult to predict and to prepare for. For that reason, they are not considered in standard hazard assessment and tend to be ignored in land-use planning, lifelines and other critical infrastructures, and socio-economic processes (Plag *et al.*, 2015). During the Holocene (i.e., the last 11,700 years), the Earth has experienced extreme events but these have dwarf those occurred during the last few thousands of years (Plag *et al.*, 2015). This lack of experience by modern civilization to such extreme events, together with a rise in population density, has driven an increase in exposure to geohazards, with megacities and industries located in hazardous areas. Nonetheless, there are evidences that natural events on the scale necessary for global catastrophe may happen in the future and our society will eventually have to face them (Huppert and Sparks, 2006).

During the last decades, important efforts have been made towards a full understanding of the origin and dynamics of individual geohazards with the final objective of quantitatively assess their potential impacts, as well as those conditions, and under which circumstances, they may lead to extreme events. However, there is still an urgent need for further investigate the potential interrelations (cause/effect) between two or more hazards, and to correctly predict the resultant their cascading effects and impacts under a multi-hazard scenario. Furthermore, geoscientific research aimed at fully understanding the triggering mechanisms and dynamics of the diverse natural processes is also crucial to: (i) support the design of an effective monitoring program; and (ii) help interpreting the recorded signals and parameters that may be determining the current state of activity or imminent occurrence of a potentially hazardous event.

FIGURE 8. Main components of a risk reduction program highlighting the importance of a complete and solid research program in geosciences. Individual listed natural phenomena are those more prone to lead to extreme events. An example of a multi-hazard scenario originated by a volcanic eruption is also illustrated.



Finally, a risk reduction strategy has guarantees of success only if it is founded on a solid scientific program, a robust and efficient monitoring network, an educational program in charge of teaching population on potential hazards and risks that may threat them, and an effective management program responsible of establishing emergency plans and resilience strategies (Fig. 8).

Considering all this, the key challenging to be addressed from the Geoscience perspective and within this challenge are:

3.1. The science of extreme geohazards: From understanding the Earth's interior to the elaboration of hazard maps

Earth system processes operate over a wide range of spatial and temporal scales, from microscopic grain boundaries to the thousands of kilometers involved in mantle convection and plate boundaries, and from fractions of a second to billions of years. Geohazards are not an exception and represent the culmination of a complex series of geological processes controlled by diverse factors that will finally influence, and in some cases determine, the nature and dynamics of the hazardous process. Therefore, although geohazards represent very short time periods at geological, or even at human, scale (from days to few thousand years), they may be the response or culmination of geological processes that last hundreds of thousands to millions of years (e.g., magma genesis). Hence, to fully understand the mechanisms triggering, for example, a volcanic eruption or an earthquake, fundamental aspects of the structure and functioning of the Earth's interior need to be better understood. The basic knowledge about the origin, triggering and dynamics of the individual geohazards is the cornerstone of further research focused on assessing their impact, as well as their capacity to generate extreme events and multi-hazard scenarios. The following key points, partially addressed by other challenges in this Strategic Theme 14, are issues of great relevance to understand the causes and effects of extreme multi-hazards and to properly assess the intricate interactions among the diverse natural phenomena and hence, to calculate their extent and possible impact.

1. Improve the general understanding on the dynamic processes that drive plate tectonics and result in natural hazards, such as earthquakes, tsunamis, and volcanic eruptions.
2. Extend the knowledge of the physical and chemical properties that make the lithosphere "plate-like" and its coupling with the convecting, weaker mantle below (asthenosphere), trying to better understand the

role of materials, fluids and gases in creating a weak asthenosphere through high-resolution geological, geophysical and geochemical models

3. Improving our understanding on how extreme hazardous processes are controlled by the internal and external stresses that deform the Earth, and on how this defines plate boundary dynamics and the volcanic and earthquake cycles, along with the mechanical properties of fault zones.
4. Gaining new insight on how variations in the style and degree of deformation in the crust and mantle lithosphere control magma production and ascent.
5. Imaging and understanding the Earth's interior by developing innovative geophysical instrumentation (including remote-sensing techniques), as well as analogue and numerical modeling tools.
6. Increase the acquisition of offshore observations to enhance our ability to identify, locate and define the spatial extent of hazardous geological structures (e.g., potential slope failures, seismogenic faults or active submarine volcanic areas). This requires performing dedicated geophysical surveys for seafloor and sub-seafloor mapping of potentially hazardous areas (e.g., continental margins) and deploying, for example, seismological networks at the seabed to monitor seismic activity for long time periods.
7. Developing a new generation of more sophisticated and realistic mathematical models on the triggering mechanisms and dynamics of the individual geohazards and their potential interactions with the final objective of accurately identifying and quantifying: (i) key controlling parameters; (ii) potential extent and impact; and (iii) those conditions leading to extreme single- or multi-hazard events. Current models focused on simulating on the individual geohazards suffer from serious limitations and scarce knowledge of the key source properties (e.g., amount of slip or rupture propagation velocity for earthquakes) are subject to large uncertainties hampering predictive assessments. To improve model prediction of these source properties, it is necessary to include realistic information on the spatial distribution of physical variables such as rock elasticity, porosity, fluid pressure, stresses, fault surface relief, etc. This information could also be extracted from offshore geophysical and geological data.
8. Completing the geologic record and geochronologic data for a thorough reconstruction of past occurrences of the expected hazards, evaluate their future impact and accurately estimate the recurrence periods of large

events. This information is key to develop probabilistic hazard analysis and starting point for hazard-zonation maps, and long-term probability forecasts.

9. Developing probabilistic and deterministic methods to perform accurate estimates of the timing, magnitude and impacts of single- and multi-hazard scenarios and define the most accurate way to estimate the associated uncertainties.
10. Understanding how to forecast future events that might happen (for instance, low- probability high-consequence disasters), and where there simply is not a distribution of previous events from which to extrapolate (e.g., eruption from a long-time dormant volcano).
11. Establishing integrative methodologies for multi-hazard assessment (probabilistic and deterministic) with the final aim of elaborating event trees and hazard maps, which will help decision-makers to define management plans during future crises.

3.2. Knowledge-based monitoring of (extreme) geohazards and early-warning systems

An important requirement of any risk reduction strategy is the deployment of a monitoring network for determining the current state of activity, or diagnose the imminent occurrence, of a potentially hazardous natural process. The longer the monitoring period prior to the occurrence of a certain geohazard, the earlier can be obtained a reliable detection of a measurable departure from a baseline or "normal" behavior. Scientific knowledge about the nature, triggering mechanisms and dynamics of the different geohazards is crucial to correctly interpret the recorded monitoring signals and parameters and their implications in terms of forecasting or "predicting" an impending geohazard, or of mid-course changes for an ongoing event. In this sense, the key challenging points for geoscientists are:

1. Contributing to the definition, for a specific threatened area, of the minimum monitoring requirements (and parameters to be monitored) for the correct surveillance of the individual geohazards but also considering the potential occurrence of a multi-hazard scenario.
2. Providing support to improve monitoring (e.g., quality, resolution, methodology, density, spatial distribution and number of monitoring devices), early-warning systems based on the scientific knowledge of these hazardous processes and considering multi-hazard scenarios, so

an earlier notice of unusual activity can be detected and more time is available to carry out the required mitigation actions.

3. Developing mathematical models and analogue experiments focused to understanding the monitoring signals generated by the different processes preceding the occurrence of a hazardous phenomenon and how these can be registered by the monitoring network.
4. Contributing, in collaboration with those in charge of monitoring activities and decision-makers, to improve alert protocols able to inform, in a standardized way, on the new alert, current unrest situation, multi-hazard forecast and probable scenarios, and evolution of the potential hazardous events, including also a visualization system to represent probable multi-hazard scenarios and their potential extent.

3.3. Educational programs: Enhancing risk perception and society awareness

Effective hazard mitigation is only achieved if communities directly threatened by the hazard are actively involved in mitigation measures. This active participation requires both awareness (i.e., knowledge and acceptance of existing hazards) and the willingness of taking individual actions to effectively reduce the risk. In this sense, educational and outreach activities, addressed to different kinds of public (including media, local and civil protection authorities and general public) have the triple function of disseminating scientific information, fostering the community awareness, and of creating a positive bond based on mutual confidence between population and scientific community. Hence, geoscientist play a fundamental role in the development and implementation of educational, outreach and dissemination activities with the following challenging and specific tasks:

1. Help determining the most appropriate content, effective format (e.g., 3D maps, visual reports, documentaries, etc.), and means (e.g., through campaigns, social media, etc.) to disseminate location-based disaster risk information, including risk maps, to decision makers, the general public and communities at risk of exposure to disaster. In this sense, the key challenging point is to adapt the content, format and means to the different audiences considering their cultural and educational background as well as their specific needs.
2. Contribute to the development of methodologies to conduct critical analysis or risk perception through the design of specific questionnaires

focused on evaluating for the threatened communities: (i) their background knowledge on the individual geohazards and their potential impacts; (ii) their degree of safety perception, and (iii) their confidence on the existing emergency plans and decision-makers.

3. Provide support to carry out efficient global and regional campaigns as tools for public awareness and education, to promote a culture of disaster prevention, resilience and responsible citizenship, grow understanding of disaster risk, support mutual learning and share experiences; and encourage public and private stakeholders to actively engage in such initiatives.
4. Expand the knowledge of government officials at all levels, civil society, communities and volunteers, as well as the private sector, through sharing experiences, lessons learned, good practices and training and education on disaster risk reduction, including the use of existing training and education mechanisms and peer learning and enhancing collaboration among people at the local level to disseminate disaster risk information through the involvement of community-based organizations and non-governmental organizations.
5. Finding the best ways to simulate and improve dialogue and collaboration among scientific and technological communities, other pertinent stakeholders and policymakers in order to facilitate a science-policy interface for efficient decision- making in disaster risk management.

3. Risk management programs: Vulnerability analysis, resilience planning and communication protocols

For an effective risk reduction, risk management programs should include a systematic physical and social vulnerability analysis, a proper resilience planning and satisfactory communication protocols. In this sense, geoscientific knowledge and geological evidence on the nature, dynamics, and duration of past events, with an emphasis on the exploration of first- and second order effects, is crucial for the management programs to succeed. Considering this, the present challenge seeks contributing to and assisting risk managers with the:

1. Definition of technological (e.g., building retrofitting, infrastructure protection) and non-technological (e.g., investment on education and communication) mitigation options and adaptation strategies at territorial and building scale, aimed at reducing the impact of multi-hazards.

2. Development of resilience strategies appropriate to deal with large-scale natural events that would exceed local coping strategies. These should contribute to the empowerment of local communities, and assist in rebuilding the social cohesion and restoring the self-confidence of affected communities. Particular attention should be paid on how to address social differentiation in vulnerability to disasters.
3. Design of specific methodologies to conduct effective quantitative physical vulnerability analysis for multi-hazard scenarios considering, not only the direct impact of a disaster, but also its indirect consequences. Such analyses have to concentrate on population, property, infrastructure and land uses, giving special emphasis on the assessment of potential impacts on cultural and architectural heritage, as well as on transport networks and critical infrastructures like hospitals.
4. Review the existing forms of communication on natural risks, both formal (e.g., education programs; outreach and public relations; structured communications between stake-holders including risk maps; emergency communications; and early warning and alert systems), and informal (e.g., social media, the role of social networks).
5. Design of communication programs and protocols able to build trust between the different communities and to effectively convey, complex, uncertain and dynamic information in a timely fashion. Such protocols shall be implemented at the core of social research (Strategic Theme #1).
6. Promotion of the mainstreaming of disaster risk assessments into land-use policy.
7. Development and implementation, including urban planning, and land degradation assessments, and the use of guidelines and follow-up tools informed by anticipating demographic and environmental changes.
8. Encouragement of the revision of existing or in development of new building codes and standards and rehabilitation and reconstruction practices with a view to fostering disaster-resistant structures.
9. Development of user-friendly systems and services for the exchange of information on good practices, cost-effective and easy-to-use disaster risk reduction technologies and lessons learned on policies, plans and measures for disaster risk reduction.

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CHAPTER 4

ABSTRACT

Humankind is facing unprecedented climate and environmental crises with economic and social consequences that may compromise our development. Therefore, to design science-based policies for our fair and sustainable development we need to consider the long-term, natural evolution of Earth ecosystems and biogeochemical cycles. Characterizing the temporal context for environmental changes is necessary to understand the impacts at a planetary scale of the current climate change and increased human pressure. The concept of "safe planetary boundaries" for humankind development critically frames the drivers, dynamics and challenges, like the present global warming, the biodiversity crisis, and the alteration of geochemical cycles that are currently affecting us. However, the definition of boundaries for our "safe" development and the "natural" Planet dynamics can only be properly carried out if a larger temporal scale than the last few decades when instrumental records are available is taken into account. The three objectives in this challenge are related to understand i) the short and long-term climate variability, the dynamics of past abrupt climate changes and the main forcing and their impacts on Earth dynamics and human populations, ii) past changes in ecosystems, landscapes and surface processes and their feedbacks and finally, iii) the long-term changes in the biogeochemical cycles.

KEYWORDS

global warming | great acceleration | paleoenvironments | paleoclimate modelling | biogeochemical cycles | rapid climate changes

CHAPTER 4

UNDERSTANDING PAST GLOBAL CHANGES TO FACE FUTURE CHALLENGES

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1. INTRODUCTION AND GENERAL DESCRIPTION

Humankind is facing unprecedented climate and environmental crises with economic and social consequences that may compromise the development of our societies on Planet Earth. Changes in our Planet dynamics have played a determinant role in the evolution, migration and extinction of hominids and controlled the onset of sedentary societies, the development of agriculture and the Neolithic revolution, and the rise and fall of civilizations and empires. The history of the Homo genus is linked to the natural evolution of the Planet, although the detailed interplays of environment-climate-humans remain unclear in crucial milestones as the origin of bipedalism in the first hominids. the fate of Neanderthals, the onset of agriculture, the first cities and the Neolithic revolution, and the recent impact of humankind in the Planet owing to complex and often non-linear relationships. To design science-based policies for a fair and sustainable development of the societies we need to consider the long-term, natural evolution of Earth ecosystems and biogeochemical cycles and to understand the impacts at a planetary scale of the current climate change (Global Warming) and increased human pressure (Great Acceleration). To prepare as species and humankind to the planetary-scale challenges we need a complete knowledge and comprehension of our planet, an Earth-System strategy and vision and a time perspective that only geological records can provide.

We have entered a new phase (so called the Anthropocene) characterized by abundant empirical evidence of the unprecedented rate and global scale of impact of human influence on the Earth System since the Industrial Era (Steffen *et al.*, 2016). The concept of "safe planetary boundaries" for humankind development critically frames the drivers, dynamics and specific challenges, such as the present global warming, the crisis in biodiversity, the alteration of geochemical cycles and other environmental threats that are currently affecting Earth's population. However, the definition of boundaries for the "safe" development of our societies and the "natural" Planet dynamics can only be properly carried out if a larger temporal scale than the last few decades when instrumental records are available is taken into account. Hence, past global changes provide the only possible analogs of Earth scenarios and the only validation for forecasting models for climate and environmental evolution at the end of the 21st century. Geological records hold the key to our understanding of what lies ahead. Besides, to understand the uniqueness of the rapid nature of the changes we are witnessing in the Planet in recent decades, we need to identify other periods in Earth History when abrupt changes happened. Fortunately, geological records provide such opportunities, mainly related to the Precambrian Snowball episodes, the regional glaciations recorded at the end of the Hirnantian (Ordovician), the Carboniferous, the Permian crisis and along the Quaternary Period (last 2.58 Ma), when our species (*Homo sapiens sapiens*) begun and developed, as well as generalized greenhouse episodes, such as those recognized in the Early Palaeozoic and Early Mesozoic. Therefore, to better define the natural boundaries of a safe Planet for humankind and set in a context for the recent trends we will focus on three main but complementary perspectives: climate, biodiversity and biogeochemical cycles. The recent biodiversity crisis and its relationship with previous ones and the Biosphere dynamics will be dealt with in Challenge # 7, although Geoscience teams will also contribute with paleoecological strategies. Similarly, climate change as a main driver of the Global Change dynamics is considered in other Challenges but limited to its instrumental and documentary range, not with the full needed temporal range of its variability provided by the geological record.

The three main objectives in this challenge will be related to climate, environmental and biogeochemical cycles, particularly understanding i) the short and long-term climate variability, the dynamics of past abrupt climate changes and the main forcing (insolation, volcanics, ocean-atmosphere-hydrosphere-biosphere interactions) and their impacts on Earth dynamics and human populations, ii) past changes in ecosystems, landscapes and surface processes and their feedbacks iii), the long-term changes in the biogeochemical cycles (C, N, P, S...). Although Quaternary records are more likely to have the chronological resolution and sensitivity to address these objectives, deeper time archives (since Archean to Neogene times) will also be used to constrain climate, environment and biogeochemical cycles.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Understanding the impacts of the undergoing global warming, the increasing human pressure on the Planet and their consequences in the different Earth domains is of paramount importance to correctly design both sustainable and environmental friendly strategies and to establish long-term policies that might allow reducing the negative impacts that the current rise of carbon dioxide might have on our development. Our strategy aligns with the Sustainable Development Goal 13 (Take urgent action to combat climate change and its impacts) defined by the United Nations.

2.1. Past constrains to our future climate

Reliability of future global warming projections depends on how well climate models reproduce the observed climate change over the twentieth century (Kravtson *et al.*, 2018). At present, climate models reproduce with a significant degree of confidence the seasonal, annual, and multi-annual climate variability owing to both the excellent availability of instrumental meteorological datasets and the large computational capacity that allows the use of sophisticated climate models. However, decadal climate variability present in the instrumental meteorological datasets is poorly modeled in terms of its magnitude, spatial patterns and its sequential time development. Longer data series are clearly needed to improve the models predictability.

Decadal-scale climate variability is crucial for understanding present and future climate as it allows us to contextualize the response to anthropogenic forcing with natural changes due to internal climate dynamics (Cane, 2010). The modes of variability affect global, hemispheric and regional climates on different spatiotemporal scales and can therefore have important societal impacts. They are often associated with severe climate events such as droughts, floods, heat waves and cold spells affecting agriculture, water resources and blue economies, which, in turn, modulate air quality, fire risk, energy availability and human health (Zubiate *et al.*, 2017).

Geological records are the best archives for studying this decadal-scale climate variability as it is their most often temporal-scale resolution. Therefore, the main efforts of the CSIC researchers will be focused on obtaining the control of long-term climate reconstructions in the replacement of microbial and shelly, benthic and pelagic ecosystems, although shorter (i.e., seasonal, annual) and longer (i.e., centennial, millennial) temporal scales will not be disregarded.

2.2. Abrupt and Rapid climate changes

Long-term climate changes might be led by variations in the dominance, intensity and relationship among the modes of climate variability as can clearly be seen during the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA). These rapid changes have proven to be responsible of many of the migrations that societies have faced through time, especially when living in areas vulnerable to drought, flood, and abrupt and significant temperature changes (Kaczan and Orgill-Meyer, 2020). The Mediterranean area in general, and the Iberian Peninsula in particular is a high vulnerable area (IPCC, 2013). There are evidences of increase in the frequency and intensity of some extreme climate events as a consequence of global warming and it is expected to continue to increase under medium and high emission scenarios, strongly affecting ecosystems as well as economic goods. In fact, the projected changes for the end of the 21st century under high-warming scenarios are greater than those under historic climate change. The scientific efforts will be focused to determine the periodicity and recurrences of these abrupt climate changes further analyzing the available geological archives, such as lake and marine sediments, speleothems, peatbogs, ice, and corals. Although some efforts have been carried out to perform this task they have always been done from the qualitative perspective and not from the quantitative one. The qualitative reconstructions are very useful to describe past climate and environmental evolutions. However, these reconstructions can be really useful when incorporated in global climate models as quantitative reconstructions since they can be then employed to validate climate variability when testing the performance of these models. This cutting-edge research field, between the climate modelers and the paleoclimatologists, who work in climatic models from Archaean-Proterozoic- Phanerozoic to the Quaternary, is currently being developed and it will become a significant hot topic in the next few years since both research communities have already agreed that, if global climate models must be employed to forecast future challenges that society will face, they should perfectly simulate well-known past climate and environmental conditions (Phipps *et al*., 2013).

The coupling (uncoupling) of the modes of climate variability might enhance (reduce) the intensity and periodicity of these abrupt climate changes. In fact, the main climate chronozones of the last 2,000 years in the Iberian Peninsula can be explained by changes in the coupling/uncoupling of the North Atlantic Oscillation and the Easter Atlantic climate modes (Sánchez-López *et al.*, 2016). Despite the large effort carried out to characterize in detail the decadal climate evolution of a given climate chronozone, like the LIA (Oliva *et al.*, 2018) and the MCA (Moreno *et al.*, 2012) there is still a scarce knowledge of the forcing mechanisms responsible of their evolution. The correct assessment of the intensity and frequency of these abrupt climate events as well as of their most probably forcing mechanisms can only be performed if longer than instrumental meteorological datasets are available.

One side effect of the present global warming is linked to the significant modification of the ice mass balance. The ice mass balances of Antarctic and Greenland ice sheets represent the largest uncertainty for predicting future sea-level rise worldwide (Dowdeswell, 2006). The mass balance is determined by the ratio between the snow accumulated inland of the ice sheet and the ice removed in the coastal zone. However, the mechanisms controlling the flow of ice flow in polar ice sheets are not yet understood. It is therefore crucial that these mechanisms must be understood in detail in order to predict the volume of polar ice that arrives to the oceans thus controlling sea level evolution (Kopp *et al.*, 2017). According to the Intergovernmental Panel on Climate Change (IPCC, 2014), the current climate change is expected to directly impact ecosystems and human societies by enhancing processes like sea level rise. The prediction of ice-sheet discharge is highly relevant in times of intensive warming in polar regions.

2.3. The current Biodiversity crisis and previous extinctions

Five mass extinctions are known in the past, some of them related to sharp paleoclimatic shifts. These are the Ordovician, Devonian, Permian, Triassic-Jurassic and Cretaceous-Tertiary (or the K-T) Mass Extinctions. Climate change and increasing anthropogenic impacts on the environment are projected to become the leading drivers of biodiversity loss, eroding the natural capital that sustains human wellbeing and prosperity. The challenge of understanding these large-scale changes and their consequences for human wellbeing have led to the development of a set of planetary boundaries to guide Earth system governance. These boundaries identify key biophysical limits which, by staying within these limits, humankind may reduce the risk of crossing thresholds that could lead to devastating and potentially irreversible environmental change, ensuring the maintenance of critical ecosystem services (Nash *et al.*, 2017). However, it is not clear when during this 21st century ecological assemblages might suffer such losses, and whether the process will be gradual or abrupt.

Most of the existing biodiversity forecasts lack the temporal perspective needed to answer these questions because they indicate the number and locations of species threatened by climate change for just a snapshot of the future, often around the end of the century (Trisos *et al.*, 2020). Usually, these biodiversity forecasts focus at the level of several target species rather than ecological assemblages. However, many of the most sudden and severe ecological effects of climate change can occur when conditions become unsuitable for several co-occurring species simultaneously, causing catastrophic die-offs and abrupt 'regime shifts' in ecological assemblages.

Therefore, a holistic and long-term characterization must be carried out in order to characterize how these biodiversity losses are initiated, which are their evolution and main driving mechanisms, and which are the thresholds that led to these abrupt 'ecological shifts' (i.e., long-term climate fluctuations, anthropogenic exploitation of natural resources). The geological record offers a unique opportunity to reconstruct and characterize the onset, evolution and offer clues about the main drivers of past global diversity crises. These reconstructions of past global crises in biodiversity, including extinctions, help to frame the current biodiversity trends in a longer time-scale context and to understand how life responds to environmental perturbations, such as climate loss of habitats, in order to provide the boundary conditions for engineers and policymakers working to mitigate impacts and hazards. Reconstructions of past global crises evolution show, in addition, the potential role of resilience, if exits, and how usually is the post-crisis scenario.

The recent biodiversity crisis and its relationship with previous ones and the Biosphere dynamics will be dealt with in Challenge # 7, although Geoscience teams will also contribute with paleoecological strategies.

2.4. Anthropogenic impacts

Concern about the anthropogenic impact on climate has led to predictions of how people living in areas vulnerable to drought, flood and temperature extremes will respond to such events. Although some recent studies have focused on observed climate events and trends to document how migration flows vary as a function of both the severity of the event and the ability of people to migrate, among other factors, most of these studies lack a long-term perspective that might help to design and implement more effective environmental and political measures to mitigate the adverse effects of these climate events. Indeed, hydrology, surface processes, biological dynamics and even socio-economic evolution are particularly sensitive to both climate and environmental changes at varied temporal scales (http://www.ipcc.ch/). Short- and long-term Pleistocene and Holocene climate and environmental fluctuations have influenced human migrations and territory occupations as well as agricultural productivity, food security, health risk, and conflict level of preindustrial societies. However, discrimination between climate, environmental and anthropogenic impacts on past humankind evolution remains difficult because of the complex and often non-linear interactions between multiple driving mechanisms.

Therefore, the use of a new transdisciplinary and cutting-edge approach employing historical, archaeological, paleoenvironmental and paleoclimate data is strongly encouraged since it will provide access to long-term perspectives on human ecodynamics (interaction between human social and cultural systems, and climate and environment) and offer a unique basis for counteracting the recent political and fiscal reluctance to mitigate projected climate change (Büntgen *et al*., 2011). In this context, high-resolution temporal-scale, multi-disciplinary, and robust paleoclimate and paleoenvironmental reconstructions are of paramount importance since they provide key information on this long-term human ecodynamics evolution.

Human activities now rival the great forces of nature in driving changes to the Earth System and this fact has led to the proposal that Earth has entered a new geological epoch called the Anthropocene (Gaffney and Steffen, 2017). Although there is a lack of consensus on the spatiotemporal onset of the Anthropocene, otherwise called “Age of Humans”, which will be the main indicators that will define this geological period, and how this geological epoch will be formally defined, human action is undoubtedly the main driver in the origin of many current landscape configurations and their recent evolution. Therefore, its definition and characterization is key to determine from when the Earth System might have been functioning beyond the natural climate and environmental Earth variability for the last millennia or even millions of years.

The nature and dynamics of environmental changes can only be approached throughout long-term studies of landscape evolution using a multiproxy and multidisciplinary methodology, evaluating independently both climate and human action through robust and well-dated evidences.

2.5. A longer term perspective of recent and future biogeochemical cycles

The third complementary perspective of reconstructing past global changes is related to the long-term characterization of the biogeochemical cycles. The onset of the intensive agriculture in the 1950s has strongly increased the N/P (nitrogen/phosphorous) ratio in the atmosphere and thus in natural, semi-natural and managed ecosystems. This ratio increase, together with high levels of carbon dioxide in the atmosphere due to anthropogenic emissions, has a profound and yet uncertain consequences on the phosphorus cycle and N:P stoichiometry for the structure, functioning and diversity of terrestrial and aquatic organisms and ecosystems as well as threats biodiversity, ecosystem productivity, food security, and human health (Peñuelas *et al*., 2020). This abrupt modification of the biogeochemical cycles, among other factors, served to define the term 'Great Acceleration' in order to capture the holistic, comprehensive and interlinked nature of the post-1950 changes simultaneously sweeping across the socio- economic and biophysical spheres of the Earth System, encompassing far more than climate change. This Great Acceleration has become an iconic symbol of the Anthropocene and it is being used as an indicator of the trajectory of this new geological epoch.

Biogeochemical processes are of particular interest in the 'critical zone' defined as Earth's outermost surface, from the vegetation canopy to the zone of groundwater (Brantley *et al*., 2006), and thus encompasses the nexus amongst all earth systems. Most terrestrial life resides in the critical zone, and it is rapidly undergoing transformation by anthropogenic changes. As ICDP stated in its Science Plan in 2019, "the critical zone is, indeed, the key record of the emerging Anthropocene".

Paleoenvironmental records from geological sequences may provide the longer perspective in biogeochemical cycles and a better understanding of current processes.

3. KEY CHALLENGING POINTS

Reconstructing past global changes face a number of challenges that hampered the achievement of the aforementioned goals. The major challenges are:

1. The limited temporal and spatial coverage of the needed geological records to obtain reliable and robust spatiotemporal short and long term evolution of key climate/ environment parameters (i.e., precipitation, temperature, chemical element cycling, ...)

2. The proxy quantification to obtain the availability of long and highly-resolved temporal records that might allow to capture decadal climate variations.The only way to overcome these two major limitations is to combine a large variety of sedimentary records (such as espeleothems, lake and marine sedimentary records and peatbogs, archeological sites, etc., at short-term chronological intervals, and climatically sensitive facies and minerals associated with fluctuations in biodiversity and evolutionary patterns at long-term chronological intervals) in order to ensure the best spatiotemporal coverage as well as to use a large array of techniques at high-temporal resolution to obtain the best information of the studied records. Also, it is of paramount importance to establish close collaborations between the different research groups to ensure that a real multidisciplinary approach is applied and that a sufficient temporal and spatial coverage is attained. To this end, the use of indirect climate indicators (also known as proxies) from natural archives becomes of paramount importance. Proxies generally respond to environmental parameters such as temperature and precipitation, and in turn may be indirectly linked to certain modes of climate variability, through for example their response to the atmospheric circulation (Bradley, 2015). Over the last decades, several studies have attempted to reconstruct a number of modes of climate variability at different time scales using historical documents and natural archives (proxy records). Major findings show evidence of the spatiotemporal variability of these modes, their impacts, interactions and possible links to external forcing since the early Holocene and especially for the last millennium (Dätwyler *et al.*, 2018).
3. More accurate and robust chronological models by integrating several absolute (AMS ^{14}C, ^{210}Pb/^{137}Cs, ^{234}U/^{230}Th, Optical Stimulated Luminiscence, tephrochronology) and relative (paleomagnetism, orbital tuning) techniques, depending on the type of record and its temporal scale.
4. Model- Data integration. The decadal characterization can only be carried out when working together climate modelers and paleoclimatologists and this is one of the main goals that we CSIC researchers' should focus rooting the new research in the previous expertise we have.
5. Accessible and FAIR databases. Results must be independently checked by other researchers in order to validate them. This implies that datasets employed in research should be accessible following

standardized protocols. Although, there are some public databases (i.e., NOAA Paleoclimatology: https://www.ncdc.noaa.gov/data-access/paleoclimatology-data) in which researchers can make publicly available their datasets and scientific journals begin to compel authors to submit the employed datasets prior to the final acceptance of a given manuscript, these initiatives must be generalized.

6. Understanding ice flow in polar ice sheets. The goal to understand how ice flows from the accumulation to the ablation zone is crucial for correctly estimating the changing mass in polar ice sheets. To achieve this objective, the balance between i), the internal deformation of the ice itself, driven by gravity flow, and ii), the ice-sheet basal motion, which takes place only where the ice bed is at the pressure melting point (temperate ice) should be characterized in detail.
7. Monitoring Networks. The main challenge that might hamper the acquisition of quantitative past global reconstructions is the lack of long and continuous monitoring datasets that allow to characterize in detail how the climate and other environmental signals are transferred to the sediments. Implementing and maintaining this monitoring network is costly both in instrumentation and personnel but, without investing the required funds to conduct it, we will not be able to obtain these quantitative past global reconstructions.
8. Repositories of geological archives. Only a large and coordinated effort between all research groups involved in this task can overcome this limitation and CSIC researchers are already working in this direction.

There are also specific challenges for each dimension of the past global changes:

3.1. Climate

- How did the Earth's climate system behave during warmer / high-CO_2 worlds?
- How did the Earth's climate system behave during glacial / interglacial cycling in cold and warmer worlds, and during icehouse greenhouse transitions?
- What are the fundamental processes and feedbacks forcing climate transitions, at timescales from decadal to million years and beyond?
- How fast did permafrost and gas hydrate stability react on changing climate and vice versa?
- How does ice rheology control ice-sheet motion?

- What is the influence of temperate ice in deeper parts of the ice-sheets on the ice flow properties?
- How is the ice sheet discharge enhanced due ice-sheet basal motion?

3.2. Environment/Biodiversity

- What were the biotic responses to major environmental changes (e.g., climatic, super-eruptions, impacts), at timescales from decadal to million-year and beyond?
- What were the impact of abrupt climatic / biogeochemical events at decadal to millennial timescales, and how are these propagated through the atmosphere– hydrosphere–biosphere systems?
- Calibrating the palaeoclimatic influence in the replacement and disappearance of microbial and shelly ecosystems in deep time
- High-resolution, near-time targets are also needed to fully probe questions regarding the sensitivity of land surface processes to anthropogenic perturbations.
- Lakes can enable a vastly improved understanding of phylogenies through the combined study of body and molecular fossil information in such self-contained ecosystems.

3.3. Biogeochemical cycles

- What are the key processes characterizing Earth's Critical Zone?
- How the carbon, oxygen, sulphur and phosphorous cycles were affected by biotic crisis in the past?

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CHAPTER 5

ABSTRACT

Human society is expanding and globalising at an unprecedented accelerating rate, pushing the planetary boundaries. High-quality, solid and reliable science is key in the fight to resolve 21st century environmental problems. Increased water usage and severe scarcity, especially in arid and semi-arid areas, are a global risk. In the Mediterranean region, global change endangers water resources which are intensely used in irrigated plains and densely inhabited littoral areas, increasing the risks already associated to pollution and salinization. Similarly, projections envisage ever growing urban agglomerations, creating environmental challenges that are hard to imagine. Populations living in cities are increasingly exposed to polluted air. While in Europe the main threat to air quality is road traffic, in the developing world this source adds to industrial and domestic emissions and poor infrastructures to create what is a global danger to human health. Furthermore, natural air pollutant sources such as desert dust and wildfires, with growing impacts due to global change, affect air quality in both high- and low-income countries. New approaches are required. To tackle all these issues, the Environmental Quality Assessment challenge comprises topics related to atmospheric science, surface waters, groundwater and hydrogeochemistry.

KEYWORDS

atmospheric science | surface waters | groundwater | hydrogeochemistry | human and planetary health

CHAPTER 5

ENVIRONMENTAL QUALITY ASSESSMENT

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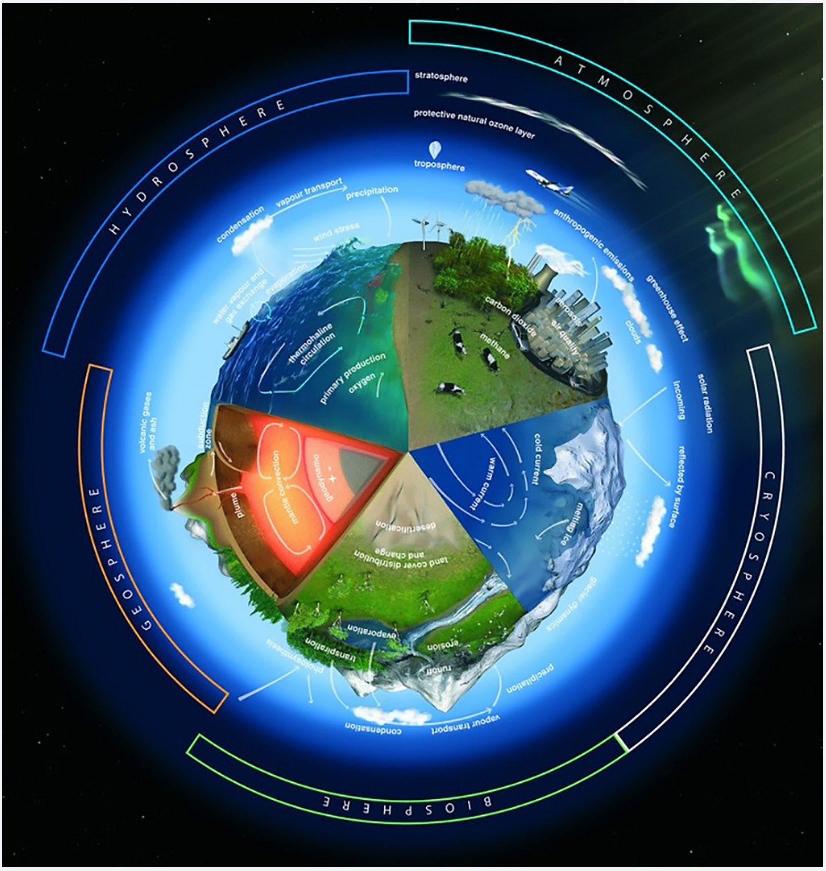
1. INTRODUCTION AND GENERAL DESCRIPTION

It is difficult to overemphasize the potential value of high quality, hard-science-based research disseminated on an international stage in the fight to help resolve, or at least ameliorate, 21st century environmental problems as extreme as hydrologic sustainability, megacity air quality, and the ongoing global extinction affecting so many species in our ecosystems. And these are only some of the individual aspects of an interconnected global system (Fig. 9).

Details of our plans and efforts to extend the CSIC international profile and outreach as a leading scientific research institution are detailed below in this section, but are first preceded here by a brief overview on some of the water- and air-related environmental problems facing us, and how we view these issues as positioned in the centre of this growing storm.

Human society is expanding and globalizing at an unprecedented, accelerating rate, pushing the limits of what our ecosystems can sustain. Increased water use and severe scarcity, especially in arid and semi-arid regions, have been highlighted by the World Economic Forum as a global risk. In the Mediterranean, water resources are mainly generated in mountain areas and are intensely used in irrigated plains and densely inhabited littoral areas. The generation of resources is threatened by Global Change, the needs for irrigation and supply are expected to increase and water quality in the coastal areas suffers from pollution and salinization. Water engineers have traditionally overcome the problem using reservoirs, water transfers, desalination and

FIGURE 9. Main elements that build up the complex Earth System (https://www.esa.int/Applications/Observing_the_Earth/New_scientific_challenges_and_goals_for_ESA_s_Living_Planet_Programme)



New approaches are required. In the case of water supplies Integrated Land and Water Resources Management is emerging as the way to address water scarcity from a 21st Century perspective. This means taking into account the water needs of forests and pastures in the headwaters, managing not only flowing waters but the whole land water cycle. New and renewed existing techniques are necessary to reconcile the demands of people, agriculture, industry and the environment. Water re-use is increasingly considered as an alternative for the whole water cycle management and to support the circular economy as society recognizes that it no longer has the luxury of using water only once. Concerning water quality, pollution caused by human activity (agriculture, industry, mining, poor waste management) has as strong impact on the available water resources. The current trend is to reduce the amount of residues generated and to increase the implementation of water treatment technologies, especially passive treatments subject to low cost and energy demands. Artificial recharge of aquifers is positioned as an increasingly realistic option because it increases available groundwater resources.

Finally, all of us living in cities are increasingly aware of the fact that we breathe air contaminated with toxic particles and gases. Many people with pulmonary and cardiovascular systems already compromised by decades of breathing contaminated city air will figure among those made more vulnerable to the consequences of being infected with Covid-19. In Europe the main air quality problem is road traffic, but in the developing world this combines with industrial and domestic emissions and poor infrastructure to create what is a global insult to human health and results in millions of premature deaths. Furthermore, natural sources such as desert dust and wild fires have been proved to affect air quality in developed and developing countries. These two sources and levels of secondary pollutants, such as ozone (O_3), are highly influenced by climate trends. In this context, although aerosols are well known to have a major impact on the Earth's radiative balance and thus on climate change, we still face large uncertainties in our understanding of these processes, as has been highlighted in all IPCC reports. We need to understand the phenomenology of the air pollutants in present and future scenarios and develop more efficient and accurate methods of measuring our daily dosage of these pollutants, draw up legislative controls that really make a difference, tell people exactly what they are breathing and why, and accurately assess pollution abatement strategies to lessen impact on climate and health (WIN WIN).

The Environmental Quality Assessment challenge focuses on issues related to atmospheric science, surface waters, groundwater and hydrogeochemistry. Given their subject breadth and complexity, these issues are discussed separately in successive subsections.

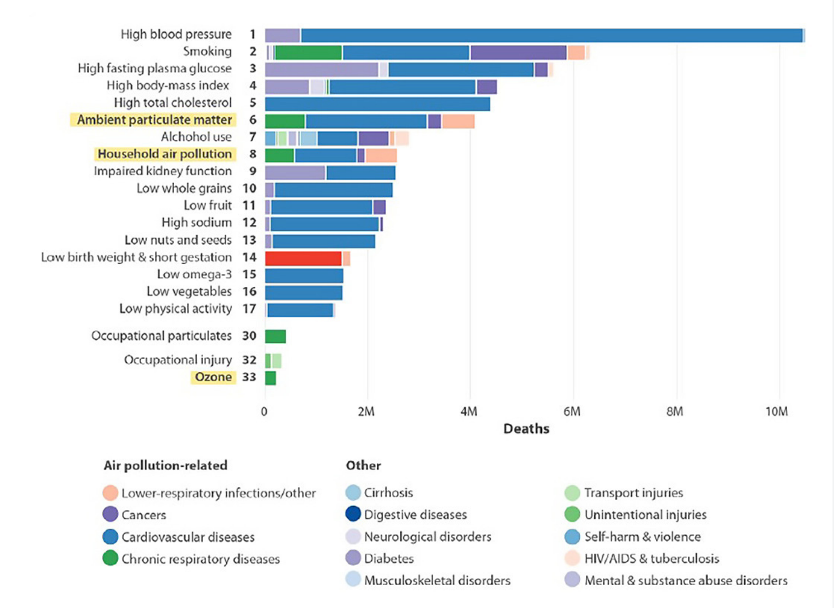
1.1. Atmospheric geochemistry

The atmosphere is a key component of the environment, acting as a dynamic link between the hydrosphere, the lithosphere and the biosphere, and impacted by the anthroposphere. As a result, atmospheric research has direct inputs into multiple fields that encompass a broad range of key topics such as air quality, climate change and human health and ecosystems, with impacts in societal issues such as human behavioural patterns, urban planning and environmental health. This raises the need for robust cross-cutting collaborations to respond to increasing demands within an increasingly complex multidisciplinary Earth system. Key pillars of atmospheric geochemical research performed in CSIC include air pollutant source apportionment in both outdoor and indoor air, the study of atmospheric processes driving levels of contaminants such as O_3 and ultrafine particles (UFP), the chemical and mineralogical characterization of complex aerosols, the impact of transport use on urban air quality, and the effect of particulate matter on global climate change. The fruits of CSIC research in these fields have direct practical applications, for example in guiding scientific and legal air quality policy from local administrations right up to a multinational level involving the United Nations and World Health Organization.

Air quality problems are diverse and greatly depend on regional climate and economic development. In developed regions, transport, industry, power generation, agriculture- farming and domestic sources are the key emission sources contributing to air quality impairment, whereas in developing countries industry, agriculture and domestic sources are the major emitters. Across large swathes of the planet desert dust and forest fires impact seriously on population exposure to air pollutants, including deeply inhalable UFP, a problem that is being exacerbated by current and predicted climatic trends.

The field of air quality faces a daunting environmental problem. Indoor and outdoor air pollution are responsible globally for at least 7 million premature deaths per year (Lelieveld *et al.*, 2015), being the 6th and 8th causes contributing globally to the burden of mortality (Fig. 10, HEI, 2018). The impact on current urban life style is already evident in the form of unhealthy levels of particulate matter (PM) and toxic gases, which in Europe alone results in >400,000 premature deaths/year due to ambient air pollution (EEA, 2019). The impact of several key air pollutant emission sources and atmospheric processes on climate and meteorology is driving trends in the wrong direction, for example in the cases of O_3, secondary organic aerosols, desert dust and forest fire PM. Accordingly there is a need to better understand the emission sources and atmospheric processes to devise cost/effective measures to improve air quality throughout the world. Furthermore, sources of human exposure are widely variable between regions, homes, schools, workplaces and different types of transportation. Thus, there is a pressing need to develop more efficient and accurate methods to estimate the daily doses of air pollutants received by populations in outdoor and indoor air, design and verify the effectiveness of improvement strategies that are able to make a difference, communicate the relevance of these strategies to the population, and find multidisciplinary solutions in greener cities.

FIGURE 10. Global ranking of risk factors by total number of deaths from all causes for all ages and both sexes in 2016. Source: Health Effects Institute (HEI, 2018).



At regional and global scales, atmospheric composition impacts upon climate and terrestrial ecosystems, in addition to air quality and human health issues. Understanding the sources and processes involved in controlling atmospheric composition is essential in any prediction of the changing environment and in the application of win-win strategies for climate and air quality. Long- and short-lived pollutants, such as O_3, halogens, aerosols and their precursors, influence both climate change and air pollution, and therefore their long-term monitoring is paramount to assess global change especially in view of the increasing impact of certain key environmental stressors such as wildfires. Integrated interpretations of both long- and short-term time series constitute the tools to gain insight into sources and processes affecting both air quality and climate.

Similarly, soil dust aerosols created by wind erosion of arid and semi-arid surfaces are among the largest contributors to the global aerosol mass load and dominate climate effects over large areas of the Earth. Dust mineralogy however continues to provide a key uncertainty in the overall physical and chemical contributions of aerosols to radiative forcing (IPCC, 2016, 2014). In addition to inorganic aerosol mineralogy, special attention also needs to be paid to the study of organic aerosols, composed of a huge variety of components with different sources that, despite (or in some cases due to) the abatement measures, have been increasing their contribution to atmospheric particulate matter in recent years. Given the complexity of organic aerosols, groundbreaking characterization and source apportionment techniques are needed to underpin adequate policies for climate and air quality. Once again, this research requires combining efforts from diverse teams with complementary expertise, requiring in this case the use of state-of-the-art instrumentations for continuous in-situ speciation of organic aerosols and measurement of precursors such as volatile organic compounds (VOCs). Of especial relevance here is the increase in the prevalence of biogenic secondary organic aerosols (eBSOA) and biomass burning aerosols (BBOA). eBSOA are particles of secondary origin generated from the oxidation of terpenes and isoprenes emitted by forests, relative concentrations of which are enhanced due to the oxidising atmosphere created by anthropogenic pollution (Hoyle *et al.*, 2011). Persistent droughts in many places around the world have increased the intensity and frequency of forest fires, with already obvious negative impact on air quality and increase of premature mortality. Such large scale climatic effects of air pollution require the investigation of radiative forcing of aerosols due to their scattering and absorbtive properties and of the sources and physic chemical properties of aerosols, using measurements from regional background and remote supersites integrated into the GAW (Global Atmospheric Watch Program (UN-WMO) and the EU ESFRI- ACTRIS program.

With regard to human health impacts, research on population exposure aims to investigate the pathways of human exposure to air pollutants in outdoor and indoor environments, and to understand and quantify the contribution of different emission sources on health. Examples of environments studied are urban air, primary schools, commuting (by metro, bus, etc.), and workplaces (occupational exposure). Target metrics assessed in this field of research are UFP and nanoparticles (incidental and engineered), particle mass concentrations and chemical composition, particle surface area, black carbon concentrations, and particle morphology and toxicity.

Linking particle characteristics with their emission sources will set the framework to facilitate risk assessment and hazard identification, with the ultimate goal to influence policy-makers in the design of effective and realistic mitigation measures. Integrated policies to improve the lives of urban dwellers are needed to ensure economic, social and environmental protection, which will be supported by solid, multi-disciplinary science underpinning decisions and policy making across the urban management – environmental quality – health axis.

Finally, a major impact of the anthroposphere on the atmosphere occurs through management of urban and industrial waste. Pollutant emissions and management of by- products and waste from different industrial activities must be assessed, especially those from coal power generation, to meet the current EU legislation on decarbonization of the EU energy mix. Other examples of industrial research refer to the recovery of valuable metals and rare-earth elements, e.g. from copper production by-products. Similarly, research should improve mechanistic knowledge on the processes controlling the contaminants-soil-water-air interactions in urban settings, which is crucial to reduce the exposure of environmental receptors. Major goals are to holistically address urban pressures such as water security/quality and public health issues, and to enhance our ability to predict and effectively mitigate the impact of climate change on urban resources.

1.2. Surface waters

The main scientific objectives for the coming years on surface hydrology are twofold: i) to improve our understanding of water fluxes in the *critical zone*, the thin dynamic "skin" of the Earth that extends from the top of the vegetation canopy, through the soil, down to groundwater; and ii) to update the knowledge of the response of Mediterranean headwater catchments to climate forcing in terms of water flow, age and sediment loads. Subsequent objectives are the advance in the identification of the pathways of precipitation water to the streams, the knowledge of the hydrology of temporary rivers and of the connectivity of the sediment fluxes from the plot to the hillslope, stream and drainage net scales.

How and when precipitation water is partitioned into the diverse hydrological compartments has been a core research concern since the beginning of hydrology as a modern science. Current research results suggest that the traditional assumption that rain water was rapidly evaporated or mixed with soil water is inadequate in seasonal climates, as different soil pore size ranges may store water of different ages. New rainfall water may be directly drained to ground or stream waters whereas vegetation continues to transpire months-old water retained in small soil pores (Brooks *et al.*, 2015; Sprenger *et al.*, 2020). On the other hand, newly developed methods (Kirchner, 2016; von Freyberg *et al.*, 2018; Gallart *et al.*, 2020) allow the assessment of the fraction of young stream water, which bypasses storage, whereas a new generation of models (Botter *et al.*, 2011) allow the simulation of the ages of stored and released waters in the catchments, *i.e.*, the description of how catchments retain and release water and solutes in response to rainfall forcing.

In this context, the scientific questions about the hydrological role of vegetation as well as the hypotheses and methods for elucidating water paths, stores and turnover rates at the hillslope and small catchment scale have changed significantly, offering new opportunities for advances in these fields. Achieving and maximizing such advances will require joint utilization of updated hydrological processes monitoring, experimentation and modeling. Newly developed models will be able to simulate the age of the diverse stores and outputs at the hillslope and small catchment scales, but such approaches need tailored observations and experiments for their implementation and validation in order to test and "groundtruth" theoretically model-based working hypotheses.

Although they cover about 50% of the global drainage net, non-perennial rivers have been largely disregarded by the scientific community because of their assumed low ecological and economic value. Nevertheless, new insights under more interdisciplinary water management rules such as those emerged from the European Water Framework Directive and the threats of climate change, a new research and management awareness of the hydrology of temporary rivers is emerging (Skoulikidis *et al.*, 2017).

Finally, connectivity has emerged as a useful concept for studying the movement and transference of surface water and water-borne materials (e.g., sediments, nutrients, seeds) between landscape locations or scales. This concept is particularly advantageous for investigating and managing sediment processes in semi-natural environments as it overcomes the classical concepts conceived in agricultural settings (Keesstra *et al.,* 2018).

1.3. Groundwater and hydrogeochemistry

The access to and contamination of groundwater resources, together with the management and underground disposal of different types of waste (e.g., CO_2 or radioactive waste) are key global topics that need to be addressed to guarantee the sustainability of our society as a whole (see e.g., Cole and Oelkers, 2008; Adelana, 2014; NEA, 2014; Jakeman *et al.*, 2016; Vishal and Singh, 2016). Understanding the complex coupling of fluid flow, heat and solute transport, deformation, and chemical reactions taking place underground requires the study of the hydraulic, chemical, thermal and mechanical processes operating in the subsurface. To this end, laboratory, mathematical, numerical and field methods are used. Specific topics include, for instance, the development of numerical modeling techniques coupled to visualization and processing tools, the management of urban aquifers, and the study of the processes controlling the behavior of newly-detectable emerging pollutants, artificial recharge facilities, marine intrusion in coastal aquifers, groundwater interaction with civil works and mining operations, storage of waste and/or its recovery, water decontamination methodologies, the unsaturated zone and the circulation of fluids at great depth (storage of CO_2, storage of nuclear waste, geothermal energy, shale gas, induced seismicity).

Concerning some of the impacts of human activity on the environment (related e.g., to CO_2 emissions, generation of acid mine drainage from old abandoned mines, the off- shore disposal of mine wastes, or the geological disposal of toxic or radioactive waste), there is a need to improve the understanding of the mineralogical alteration of rocks (e.g., reservoir and cap rocks in CO_2 sequestration systems, host rocks for geological disposal systems), anthropogenic sediments (mine waste disposal) and engineering materials (e.g., Portland cement and concrete structures used in the cementation of boreholes for CO_2 sequestration and in the treatment of acid mine waters). Mineralogical alteration has a strong impact on flow (permeability) and solute transport (porosity, diffusivity, sorption) properties. In addition, a new avenue in this line of research is the study of the effect of microorganisms (e.g., sulfate-reducing bacteria) which accelerate these alteration processes. A large effort is being devoted to this new topic combining geochemistry and microbiology and requiring a whole new body of expertise.

Research related to urban water management confronts the challenge of combining the whole hydrological cycle and the life cycle of the involved contaminants in a single management tool to optimize and integrate urban planning and the management of the urban water cycle, considering water supply, public health and environment. To this end, it is imperative to understand which processes define the chemical and biological quality of water resources, the quantification of the water balance (especially groundwater recharge mechanisms), as well as processes that affect the transformation of pollutants. Civil works in both urban contexts and mining areas result in highly complex hydrogeological and hydrogeochemical environments. This generates groundwater management uncertainties that include key issues such as the definition of uses, complex drainage system design, reserve estimations, and water quality degradation induced by mixing and pumping. The increasing demands for mining and civil works, combined with rising public concern, demands a clearer assessment of groundwater environmental impacts.

2. IMPACT ON BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Internationalization, international standing and a demonstrated ability to commit to and help solve the great environmental challenges of our time lie at the strategic heart of research taking place in CSIC. Other, more pragmatic, factors lie behind the need to enhance our recognition and reputation, the most important being strong competition for both human and financial resources and the globalization of the economy that has such an influence on research and development in research institutes worldwide.

2.1. Atmospheric geochemistry

The scientific impacts of environmental quality assessment in the field of air pollution will be driven by innovation, by integrating air quality research with climate studies and environmental pollution targeting the interlinkages with the lithosphere, hydrosphere, biosphere and anthroposphere. The basic science of such investigation rests upon empirical research of complex pollutants and atmospheric processes such as the formation of new particles, the phenomenology of desert dust episodes in origin and receptor sites, and the mechanisms causing O_3 and secondary aerosol pollution. The potential applications of such studies of air quality impairment include allowing us to assess impacts of air pollution in relation to other spheres of interaction, investigating the co-benefits, trade-offs and conflicts of traditional and innovative measures to combat air pollution. This will fill a major research gap at international scale, especially from a structural point of view due to the lack of such multidisciplinary and cross- cutting research.

In addition, social and economic impacts will derive from knowledge transfer towards policy-makers, to support the design and implementation of effective air pollution mitigation strategies for cleaner and greener cities. One of the main strengths of CSIC researchers is their role as consultant and external advisors for local, regional, national and international policy bodies in terms of air quality and climate, e.g. with regard to abatement strategies for tropospheric ozone, ultrafine particles, and occupational and indoor air pollution. Furthermore, interactions with the private sector will drive technological innovation and co-design of solutions to achieve air pollution mitigation and carbon neutrality. Collaboration with global organizations such as UN Environment, WHO and WMO will enhance the visibility of this research challenge, with impacts on Sustainable Development Goals Nr. 3 (Good Health and Well-being), 5 (Gender Equality), 7 (Affordable and Clean Energy), 9 (Industry, Innovation and Infrastructure), 11 (Sustainable Cities and Communities), and 13 (Climate Action).

2.2. Surface Waters

A more detailed mechanistic understanding of water fluxes in the critical zone will enable hydrological and climate models to better predict changes in green (water moving upwards to the atmosphere) and blue (water moving downwards to groundwater, lakes and streams) -water fluxes (Penna *et al.*, 2018). The first supports terrestrial ecosystems as well as forest, pasture and dry crop resources, whereas the second sustains freshwater aquatic habitats and provide the traditionally so-called water resources (Falkenmark, 2000). This knowledge also would support headwaters management and conservation strategies that promote long-term sustainability of water resources and related ecosystem functions and services as adaptation measures in a Global Change context.

Although experimental research results in the early twentieth century have already clearly demonstrated that afforestation decreases water resources (Engler, 1919, Bates & Henry, 1928, Bosch and Hewlett, 1982), the application of this realization to land and catchment management has been largely delayed due to the difficulties involved in changing accepted theory as well as the conciliation of the needs and potential drawbacks affecting diverse forest ecological services. Nowadays, this new paradigm is mostly accepted by the land and catchment managers, but the design of a new generation of management plans needs a renewed effort from the scientific community especially given the considerable uncertainties generated by ongoing climate change (FAO, 2006; Birot *et al.*, 2011).

The launch of the European Water Framework Directive has led to a change of the water management from a use-oriented paradigm to an environment-oriented one as the only way to ensure a future availability of adequate quantity and quality water resources. Among the diverse difficulties encountered for the implementation of this Directive, the fact that many 'water bodies' may be temporarily dry, particularly but not only in Mediterranean countries, was one of the most relevant from the hydrological point of view. This is because the usual methods in hydrology, i. e., the recording, simulation and analysis of hydrographs, is not sufficient for dealing with the needs for understanding and managing the ecology of temporary rivers. New hydrological concepts, methods and information are necessary to link the hydrology and ecology of this, expected to increase, type of rivers.

Under climate change perspectives in Mediterranean areas, water resources are expected to be threatened, many permanent rivers are expected to become temporary and changes in rainfall patterns or intensities may activate sediment sources, increasing soil erosion and sediment loads in the drainage nets.

Ensuring access to water and sanitation for all is the Goal 6 of the UN Sustainable Development Goals, whereas sustainably manage forests, combat desertification, halt and reverse land degradation and biodiversity loss is the Goal 15. A major scientific effort is necessary for attaining and conciliating these goals under climate change.

2.3. Groundwater and Hydrogeochemistry

From the scientific point of view, addressing the challenges related to groundwater and hydrogeochemistry involves the study and understanding of the different flow, transport and reaction processes from a mechanistic nanometric scale, through typical laboratory centimeter to decimeter scales, and up to the field scale (meters to kilometers). Fundamental investigations at the nanometer scale, linked usually with experimental observations using modern spectrometric (synchrotron based) and imaging techniques (electron microscopy, X-ray micro-computed tomography, autoradiography), are gradually providing a mechanistic understanding of the different flow, solute transport and chemical reaction processes. The coupling with microbiology (impact of microorganisms on chemical reactions) is also proving to be a key factor influencing the rates at which many of these reactions occur, and requiring also a whole new body of expertise.

Parametrization of the processes, according to the appropriate constitutive laws, is usually performed by means of small-scale laboratory experiments, with reactive transport modeling aiding typically in the interpretation of results. A big challenge results from the need to upscale these types of results obtained at the small scale to the field scale. Numerical modeling will play a fundamental role here, especially in terms of how to deal with spatial heterogeneity, which affects all these processes.

In terms of societal impacts, the research proposed will address a number of sustainable development goals (SDG):

SDG6. Clean Water and Sanitation

- 6.3. By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe re-use globally.
- 6.4. By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.
- 6.5. By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.
- 6.6. By 2030, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.

SDG7. Affordable and Clean Energy

- 7.2. By 2030, increase substantially the share of renewable energy in the global energy mix.

SDG12. Responsible Consumption and Production

- 12.2. By 2030, achieve the sustainable management and efficient use of natural resources.
- 12.4. By 2030, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment.

3. KEY CHALLENGES

CSIC strategic objectives should be predicated on the intention to harness and foster our current strengths in order to maximize our already strong competitive advantage and thus reinforce our position at the forefront of environmental science research. These key challenges have been formulated to connect our mission to aim high with our overall vision for the future, which is to support research especially focused on the global challenges of air and water contamination within the anthroposphere.

3.1. Atmospheric geochemistry

Key challenges ahead for atmospheric geochemistry are:

1. Understanding the links between air pollution and climate change, in view of identifying co-benefits and maximizing the potential of mitigation strategies.
2. Understanding the impact of air pollution exposures on human health, in ambient, indoor and workplace air, from epidemiological and toxicological perspectives.
3. Understanding the nature and the role of emerging pollutants, and novel metrics and tools to monitor them, on our health and our environment.
4. Understanding the impacts of urban and industrial waste, their potential as high- value resources at global scale, and the role of urban pressures on water security/ quality and public health issues.

In spite of its relevance and timeliness, environmental quality assessment in the field of atmospheric pollution is burdened by 3 major drawbacks:

- Lack of integration of research fields dealing with climate, air quality, waste
- management and health. Impacts of pollutants in each of these compartments are frequently assessed following a silo approach, thus failing to identify interlinkages and impacts and missing out on potential co-benefits of co-designed mitigation strategies.
- Highly specialized and costly research instrumentation required, which in turn
- requires highly trained technical staff. Major investments are necessary in terms of infrastructure and technical staff.
- Lack of dedicated funding mechanisms, which currently have currently shifted
- focus towards urban actions and climate services, and away from the different facets of atmospheric research.

3.2. Surface waters

Hydrological processes in the Mediterranean are more intricate than those in the temperate regions where most recent developments have been made. From the research point of view, this has the disadvantage that the application of new hypotheses and methods to Mediterranean headwater catchments is more difficult, but, on the other hand, these catchments provide valuable demanding test benches for their validation and development (Gallart *et al.*, 2020; Sprenger *et al.*, 2019). From the application side, research on the hydrological role of vegetation in the Mediterranean headwaters are of major relevance, as both water resources (Jiménez-Cisneros *et al.*, 2014) and forest masses (Keenan *et al.*, 2011) are highly threatened in Mediterranean areas under climate change. Under these premises, the current key challenges in surface hydrology can be summarized as:

1. Understanding the role of vegetation type, structure and spatial distribution on the partitioning of water into green (evapotranspiration) and blue (usable water) from the tree to the catchment scales and for diverse meteorological forcings.
2. Improving our knowledge on the paths and timing how catchments store and release (blue) water at different time scales.
3. Improving our knowledge on the hydrology of temporary rivers and developing methods for their characterization, adequate for establishing relationships with aquatic ecology.
4. Developing methods for characterizing and understanding the connectivity of water and sediments at the catchment scale.

3.3. Groundwater and hydrogeochemistry

Major global challenges, besides the continuous improvement in the fundamental understanding of the multiple processes involved, include:

1. The upscaling and meaningful application of newly acquired mechanistic understanding of flow, transport and chemical reactions at the nanometre/ micrometre scale (pore scale for flow and transport processes, mineral-surface scale for biogeochemical reactions) to larger scales, especially the field scale.
2. The coupling in interpretative and predictive models of mechanical (deformation) and biogeochemical processes.
3. The integration in computational models of heterogeneity at different spatial scales affecting all processes.

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CHAPTER 6

ABSTRACT

The study of extraterrestrial planetary bodies provides a unique opportunity for the understanding of the origin, present and future of the Earth. The progress in extraterrestrial exploration will allow Earth scientists to go beyond the present limitations in planetary research, finding new opportunities to match our geological and geodynamic evolution models. By the combination of multiple science disciplines, such as field geology, geomorphology, petrology, mineral physics, glaciology, geophysics and process modeling, among many others, this scientific challenge focuses on quantitatively linking our Earth System knowledge to the exponentially growing data acquired by rovers in other planetary bodies, exoplanetary search and other missions. Understanding the Earth structure formation, its relief history, the effects of volcanism on its environment, its long-term heat balance or the future evolution of our ice sheets and glaciers, and the feedbacks between geosphere and biosphere will also benefit from the analysis of meteorites, Martian outburst floods and ice caps and volcanism in planetary bodies. The multidisciplinary character inherent to this challenge requires a truly transverse approach that cross the borders of well-established "classical" fields of research.

KEYWORDS

earth analogues | extraterrestrial bodies | core-mantle differentiation | system earth | planetary evolution

CHAPTER 6

EXTRATERRESTRIAL ANALOGUES FOR EARTH SYSTEM DYNAMICS

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1. INTRODUCTION AND GENERAL DESCRIPTION

As extraterrestrial exploration advances, Earth scientists find new opportunities to match our models of geological and geodynamic evolution with increasingly known extraterrestrial planetary bodies. By the comparison between processes and structures on Earth with those found on extraterrestrial bodies, we will be able to find the answers of fundamental scientific questions about the origin, present and the future of the Earth. Inversely, as seen in section *12.2.5 Solar System exploration* in Volume 12 of this collection, Solid Earth Science becomes crucial to understand the origins of other planetary bodies, their composition and internal structure, and their volcanism and surface processes. Earth- Science will benefit from the better understanding of the dynamics of other planetary bodies with different boundary conditions such as the age of the hosting stars (in the case of exoplanets) or the orbiting distance to them. One of the main common future challenges in Earth and Space Science is the exploration of the resources available and understanding inhabitability. Planetary geology is a strongly multidisciplinary field of research involving disciplines as diverse as field geology, petrology, mineral physics, glaciology, seismic wave propagation and modeling, among many others. A significant part of planetary research is achieved by analyzing materials and processes from specific environments on Earth that exhibit similar conditions as planets and moons in our Solar System (i.e., planetary field analogues), by means of field-work, laboratory analyses and experiments (using set-ups that reproduce planetary and deep space conditions) and also including an important theoretical component that involves numerical simulations. To test these models, we can also use differentiated meteorites arrived from other rocky planetary bodies like e.g. the Moon, 4 Vesta or Mars. These “free-delivered” samples can guide us in the future robotic or manned exploratory missions to these planets and moons. Therefore, we can consider the Earth as a natural laboratory to study planetary processes that, together with meteorites, will allow us to go beyond the actual limitations in planetary research.

The key open scientific question limiting the achievement of these challenges is: what are the geodynamic, structural and geomorphic conditions indicative for life development, environmental conditions and potential habitability? The Earth’s evolution provides key constraints as to what mechanisms are key to sustain an inhabitable planet accumulating and preserving substantial amounts of liquid water. And yet we still ignore when precisely life appeared on Earth and what mechanisms allowed the accumulation of liquid water at that time. The development of an inner/outer core boundary and a magnetic field is essential in impeding the loss of volatiles from the upper atmosphere over geological timescales. By studying the formation of meteorites, combining description of natural samples, deformation experiments and numerical simulations, we can obtain fundamental information about the differentiation of the planetary core-mantle boundary in the Earth.

The development of plate tectonics is essential in order to regulate the surface temperature via buffering the carbon and calcium cycles. Average planetary heat flow and seismicity are not only important to sustain life conditions, but they are also key parameters compromising human inhabitability and exploration. Thus, there is a strong need to learn how to estimate these mechanisms remotely based on Earth-based knowledge, analogues and models.

Our understanding of what planetary structural and geodynamic conditions have determined the habitability of the Earth has significantly improved in the last decades. We have today a quantitative knowledge of the role of plate tectonics in the long-term carbon cycle as a key regulator of greenhouse temperature and for maintaining liquid water oceans on planets. However, the presence of plate tectonics itself may depend on climate according to geodynamical studies. Planets in the supply-limited weathering regime may become inhospitable for life and could experience significant water loss. However, on plate tectonic planets where high erosion occurs there is a greater supply of bedrock to the surface, which reduce the water loss. We do understand the planetary structural, geomorphic, and water conditions required for both the development of an earth-like chemistry, atmosphere and temperature regime. However, much effort is still going on to understand the mechanisms governing these phenomena and conditions. Univocally interpreting the sedimentary record recently found in Mars has been proved a challenge, in spite of the important implications regarding the amount of liquid water available in the past in that planet. The advance in exploration of Mars by the InSight and Curiosity missions, have provided a new horizon in geophysical and geological data, as well as surface images. The comparison between observed extraterrestrial geological features with terrestrial geological processes, will allow us to unravel the Earth geodynamic history. One example is the Mars north polar ice layered deposits (NPLD) which represent the largest reservoir of Martian water ice. Terrestrial ice sheets are natural laboratories for the study ice rheology, where research based on natural data, ice deformation experiments and numerical simulations is providing us an accurate understanding on water ice rheology on Earth conditions. Despite from all these advances in research, the response of polar ice sheets on Earth (Antarctica and Greenland) to the atmospheric increment of greenhouse gases is still unknown. The history and dynamics of the Martian ice deposits are of great interest because Mars is the only planet in our solar system that has a dynamic climate like Earth, but with an atmosphere strongly dominated by CO_2.

On the other hand, a dwarf planet orbiting around Neptune, Ceres, and has a heterogeneous crust, formed by ice, salt and silicates that dome structures originally attributed to cryovolcanism. However, the formation of these domes can be explained by ice flow, as observed in salt domes in the Earth and more especially in deep parts of Antarctica and Greenland ice-sheets. Unfortunately, no surface evidences of diapirism in ice have been described on Earth ice-sheets. The assumption that an ice tectonics exists, is highly controversial and implies that paleoclimate records in ice-sheets would be altered and disturbed. By the comparison with these extraterrestrial ice planet features we could potentially demonstrate that tectonic processes indeed occur in terrestrial ice.

Such an understanding is essential in order to unravel the past, understand the present and predict the future of our planet Earth.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

"Extraterrestrial Analogues for Earth System Dynamics" is a scientific challenge that aims to identify and improve our knowledge of geological processes that occur in both terrestrial and extraterrestrial environments. By the comparison between processes and structures of the Earth with those found on extraterrestrial bodies, we will be able to find the answers of fundamental scientific questions about the origin, present and the future of the Earth. Can meteorites reveal the origin of our planet? How did mantle-core differentiation occur? Can extraterrestrial outburst floods shed some light about the Earth's relief history? Can paleoclimate interpretations from ice cores drilled in Antarctica and Greenland be altered and disturbed by ice tectonics? What will ice caps on Mars tell us about our glaciers and ice-sheets on the Earth in a long-term future? How are terrestrial ice sheets going to react to the alarming increase of atmospheric CO_2? These are examples of many highly relevant questions that geoscientists are not currently able to answer. However, as extraterrestrial exploration advances, Earth scientists find new opportunities to match our models of geological and geodynamic evolution with increasingly known extraterrestrial planetary bodies.

3. KEY CHALLENGING POINTS

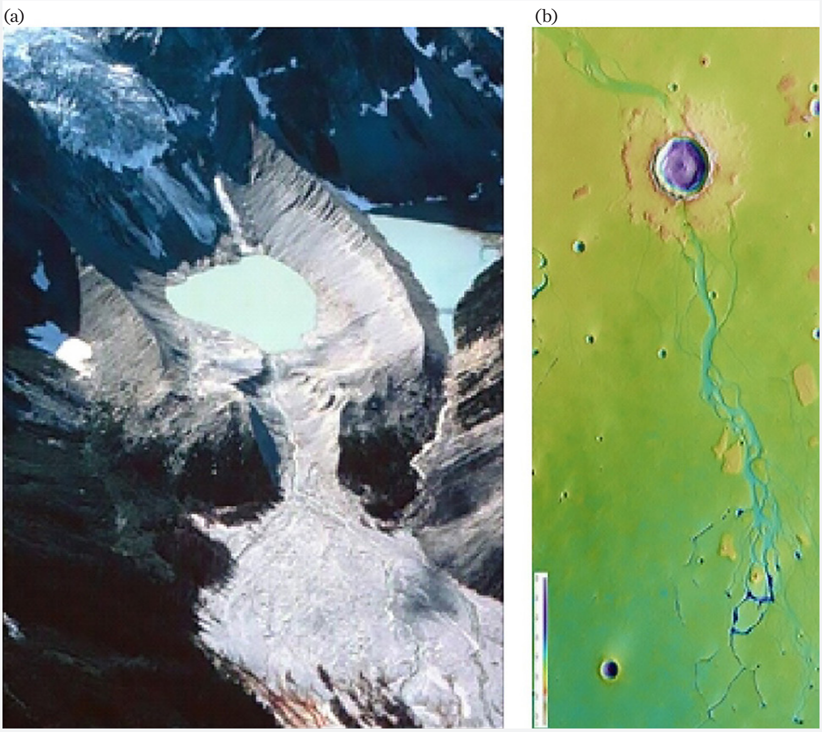
The proposed scientific challenge will focus on the following key questions, which will be developed according to a specific plan (see chapter 5):

1. Can extraterrestrial outburst floods shed some light on Earth's relief history?

Outburst floods are abrupt, often catastrophic releases of water that exceed in discharge meteorological flood events, lasting typically between days and weeks and leaving a recognisable signature in the landscape, usually in the form of erosion channels or large sedimentary deposits. The first recognition of one of such events in the Scablands (Washington State, USA) lead in the middle of the 20th century to one of the main paradigm changes in Earth Science. The idea that the sedimentary record is gradual and

at rates similar to our historical record (uniformitarianism) started to yield pass to a scenario where unknown catastrophic events contribute to landscape evolution and topographic relief, thus continuing with the old

FIGURE 11. (a) In 1983 Lake Nostetuko, British Columbia, overtopped and drained catastrophically 6 million m³ of water (Clague and Evans, 2000). (b) Craters and megaflooding channels in Hephaestus Fossae, Mars. Credit: ESA



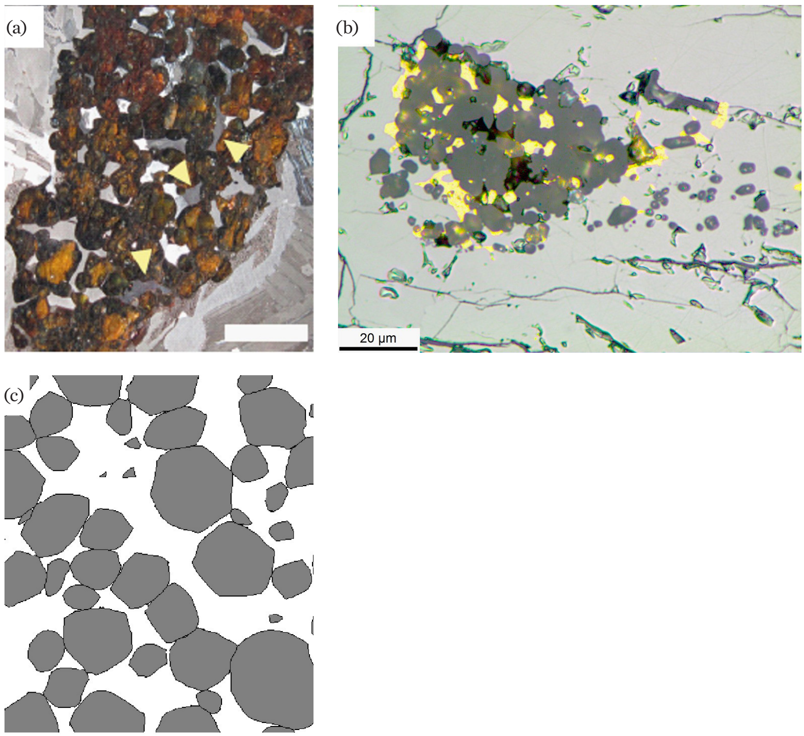
discussion between catastrophism and uniformitarianism. Tens of other scenarios have been described ever since on Earth, including the breaching of numerous moraine lakes (see Fig. 11). Over the last 3 decades, many such scenarios have also been identified in Mars, mostly attributed to the first half of the planet's life. For example, the circum-Chryse outflow channel systems are the largest known fluvially eroded planetary landscapes in the Solar System, resulting from catastrophic floods released from groundwater aquifers (Baker, 1982). Understanding the water discharges responsible is important in reconstructing the hydrological past of Mars, but also offers the opportunity to answer common questions about out relief: how were these enormous erosion channels initiated and then evolve through time? Were they carved by multiple flood episodes? When were they carved? Addressing these questions is of great significance to reconstructing the evolution of the Martian hydrologic cycle because these channels record the largest movements of surface water on the planet (Carr and Head, 2009). There is today a wide record of these type of events on Earth (O'Connor *et al.*, 2009), where the relict channels are not as well preserved as in Mars. A common modeling approach to both scenarios may allow estimating the quantitative contribution of such episodic catastrophic events in sculpting the surface of our planet.

The most extreme such event has been recently proposed to put an end to the Messinian Salinity Crisis, a period where the entire Mediterranean Sea entered a hypersaline condition, undergoing widespread salt precipitation and purportedly a kilometric-scale sea level drawdown by evaporation (Garcia-Castellanos *et al.*, 2020, ESR). This megaflood is supported by evidence showing a 400 km-long and >200 m deep erosion trough along the Alboran Sea (E of the Strait of Gibraltar) in combination with large deposits of chaotic sediment in the lower areas of the Alboran Sea and the Malta escarpment, all dating back to the Miocene/Pliocene time boundary. Similar features have been described in Mars with even larger proposed geomorphic features and peak water discharges. These martian and terrestrial features must be jointly modelled and understood.

2. How did the Earth form? How did the core-mantle differentiation occur? How is the rheology of the current core mantle boundary?

Planetary bodies formed by accretion from the early solar nebula. After the stage of accretion, the majority of planetary bodies in the solar system passed through a stage of internal differentiation, reaching a final stage of tectonic activity. Differentiated meteorites, achondrites and rocky-iron meteorites, come from planetary bodies and provide very valuable information about the formation conditions of igneous bodies. However, undifferentiated meteorites, mostly the so-called *chondrites*, come from much smaller bodies (few hundreds of km in diameter) that escaped differentiation and preserved primordial information. They provide us with a highly valuable information about the origin of our solar system, because they contain the primordial material that formed the protoplanetary disk and even contain stellar grains arrived from nearby stars. One example of materials arrived from large differentiated bodies are the stony-iron meteorites, called pallasites, which contain similar amounts of sillicates and nickel-iron alloys (Wahl, 1965) (Fig. 12). Although the formation of pallasites is still controversial, the most accepted theory is that they form in the limit between the silicate solid

FIGURE 12. (a) Symchan pallasite formed by olivine in a metallic melt (from Solferino *et al.*, 2015). Large melt pockets (equilibrated by anealing) co-exist with thin olivine fractures (not equilibrated). Hece, two-stage processes can be observed. (b) Experiment SA 171 (courtesy from Nico Walte. Walte *et al.*, 2020). The olivine mass contains “old” gold melt that displays a well-defined local solid-melt equilibrium attained by pre-deformation annealing. The olivine mass is subsequently dismembered by deformation, which injected new FeS melt (light grey). The gold melt pockets are preserved after deformation. (c) Numerical simulation of crystal plastic deformation including dynamic recrystallisation (by intracrystalline recovery and grain boundary migration) of a solid-melt aggregate. The percentage of melt is relatively high (>40%) and it is initially nucleated at grain triple junctions. After deformation melt pockets merge forming large melt pools. Such pools can accommodate most of the subsequent deformation, while the solid mineral grains preserve their facets (from Llorens *et al.*, 2019).



(olivine) mantle and the molten metal (Fe-Ni) core of a differentiated asteroid (Boesenberg *et al.*, 2012). By studying the formation of these meteorites, we can obtain key information about core-mantle differentiation and the formation of the boundary between these two planetary layers. The study of these meteorites is particularly relevant to understand the early stages of the Earth core-mantle differentiation.

3. What can glaciers and ice caps on Mars tell us about the long-term future of glaciers and ice-sheets of the Earth?

The systematic study of ice on Earth allows reconstructing and predicting Antarctic and Greenland ice dynamics and therefore understand what mechanisms determine ice flow (e.g., temperature, presence of impurities, boundary conditions, water content, etc. Terrestrial ice sheets are natural laboratories for the study ice rheology. By the combination of natural data acquisition and analysis (Weikusat *et al.,* 2017), numerical modeling of ice-viscoplastic deformation and recrystallization (Llorens *et al.,* 2016a; 2016b; 2017) and ice laboratory experiments (Qi *et al.,* 2017) water ice rheology can be accurately studied. By the combination of these studies, we can predict how is ice going to behave according to the current environmental conditions. Despite the response of Antarctic and Greenland ice to the atmospheric increment of greenhouse gases is still unknown, recent studies show that the Antarctic ice-sheet is more vulnerable to greenhouse gas than expected (Levy *et al.,* 2016).

Mars is the only planet in our solar system that has a dynamic climate like Earth, but with an atmosphere composed mostly of CO_2. Due to low pressure and temperature, water can only be stable on Mars' surface in the form of ice. The Mars north polar layered deposits (NPLD) represent the largest reservoir of Martian water ice, which actively interacts with the atmosphere (Hofstadter and Murray, 1990). The history and dynamics of these deposits are of great interest because their layers, as in Earth ice- sheets, potentially store the recent Martian climate record (Thomas *et al.,* 1992). The absence of impact craters on this part of Mars' surface is an evidence of the ice-flow activity of the Martian north pole (Herkenhoff and Plaut, 2000). As in the Earth's case, we must understand how ice flows in Martian conditions if we want to be able to unravel the evolution of the Martian climate recorded within ice layers. But in the other way, the study of the ice deposits on Mars will help us predict the present and future responses of the Earth's ice-sheets to atmospheric CO_2 increments Ice flows following the Glen's flow law (Glen, 1955), where the strain rate ($\dot{\varepsilon}$) is proportional to the effective stress (σ) to the power of the exponential stress (n). However, the stress exponent that determines the behavior of ice depends on different deformation mechanisms and recrystallization processes, where grain size has a remarkable influence. Another interesting site to study in future expeditions to Mars is the exposed underlying ice beneath recently excavated impact craters (Byrne *et al.,* 2009, Science). When did these sub-surface ice layers form? Can they provide clues about past climatic changes? We should remark that we needed to invoke an atmospheric greenhouse effect to fit the evidence for liquid water in ancient Mars. Early Mars atmospheric composition is not well constrained, but was probably mostly composed of CO_2 with a surface pressure between a few hundreds of millibars to a few bars. Large amounts of CO_2 and H_2O were probably released by the substantial Tharsis volcanism during the mid-Noachian. In any case, other greenhouse gases like e.g. NH_3, CH_4, or SO_2 could have promoted a global warming, but they are photochemically unstable and rapidly exhausted require continuous volcanic outgassing. In such sense, the recent discovery of sulfate salts deposits by NASA rovers probably suggests that SO_2 is also a relevant greenhouse in this system.

The future Mars Sample Return mission will provide valuable rocks to get additional clues in regard to the ancient Mars' climate. In fact, the current study of aqueous alteration minerals in some ancient meteorites, like e.g. Allan Hills 84001, has provided relevant clues on a complex and changing climatic environment (Moyano-Cambero *et al.*, 2017). Carbonate globules in the interior of ALH 84001 fractures were formed by the precipitation of Mg- and Fe-rich carbonates from an aqueous solution while that ~4.1 Ga old meteorite was forming part of Mars crust. Distinctive accretion layers suggest that the globules growth occurred in several flooding stages having distinctive chemical solutes, perhaps related with transient volcanic activity (Trigo-Rodríguez *et al.*, 2018).

4. Have the large perturbations in ice-sheets been formed by diapiric rise of ice? Does ice flow in the same way as salt? And therefore, can the terrestrial paleoclimate record from ice cores be altered and disturbed?

Antarctica and Greenland are formed by stratigraphically ordered compacted ice layers originally formed of buried snow. Ice cores drilled in Antarctic and Greenland ice sheets are unique archives that record the Earth's climate evolution. By analyzing gas bubbles, molecules and particles trapped in ice layers, scientists can reconstruct the levels of greenhouse gases and the temperature of the Earth's ancient atmosphere (EPICA, 2004). But paleoclimate reconstruction requires firstly the study of ice flow, as ice-sheet dynamics can disturb and alter ice layering (Llorens *et al.*, 2016b; Faria *et al.*, 2017; Bons *et al.*, 2016). Recent radargrams of improved resolution (Rodriguez-Morales *et al.*, 2013) have shown that the stratigraphy of ice is altered, and ice layers appear folded in deep parts of ice-sheets. Understanding these structures is highly important, as they directly impact the interpretation of ice climate records from ice drill cores. However, the mechanisms that result in the formation of these large perturbations remain unknown. Current explanations, which are focused on bedrock-ice interactions, like bedrock bumps, variations of basal friction, or simply lateral shortening, fail to explain the formation of large and overturned folds in ice-sheets. One hypothesis that can explain the formation of large ice folds is the amplification of pre-exiting small perturbations by diapiric rise, as it occurs in subsurface salt rock bodies.

Diapir and dome formation in the Earth due to salt tectonics is common in areas with evaporite deposits (i.e., generally termed salt) (Hudec and Jackson, 2007). This is a process where low-viscosity, low-density (LVLD) salt rocks flow relative to higher- viscosity, higher-density (HDHV) sedimentary rocks, when they are affected by differential loading (Jackson and Vendeville, 1994). The assumption that ice flows like salt rocks do is highly relevant, as it implies that the paleoclimate record in ice-sheets can have been altered by ice tectonic processes. However, to date only evidences in radargram profiles have been found and no surface evidences of ice tectonics have been described.

The differentiation of planetary bodies depends on the initial rock to ice ratio. Most asteroids have been disrupted or excavated to a large extent due to the impact energy of projectiles (Beitz *et al.*, 2016). The current population of large asteroids is probably dominated by rocky-metal differentiated bodies, such as 4 Vesta or 2 Pallas. In any case, Ceres is the only unambiguous dwarf planet inside Neptune's orbit, and has a heterogeneous crust formed by ice, salt and silicates. The large number of domes on Ceres' surface indicates geological activity, where the formation of these domes has been attributed to cryovolcanism. However, this theory is not consistent with the small size of Ceres and the absence of heat sources. Recently, some authors (Bland *et al.*, 2019) have proposed that the formation of these domes is due to ice flow within a heterogeneous crust, a process directly analogous to the formation of salt domes in the Earth. According to this, the LVLD water-ice rich layers could flow relative to HDHV salt and silicate layers, driven by differential gravitational loading (Bland *et al.*, 2019). Different scenarios can be assumed as the cause of the differential loading, such as the lateral thickness variation of the water-ice layer or simply by impact craters.

5. What are the mechanisms behind both the delivery of large celestial bodies to the Earth and crater formation?

Impact cratering is a key mechanism shaping the evolution of planets, the surface of the terrestrial planets and smaller rocky bodies, and the evolution of life on Earth. The impact process is fundamental for the search for potential habitats for extraterrestrial life in the solar system (e.g., deeply fractures crust, long-lived energy source from melt sheets). The coincidence in time of the Cretaceous-Paleogene (K/Pg) boundary mass extinction and the 200-km Chicxulub impact crater in Mexico points to the importance of impact events on biological evolution and the geological record (Alvarez *et al*., 1980; Lowery *et al.,* 2019). This crater is now a reference for global climate change studies due to its fast input of contaminants to the atmosphere (e.g., Brugger *et al.,* 2017, Bardeen *et al.,* 2017, Vellekoop *et al.,* 2014).

Despite their obvious significance, the majority of known craters on Earth (~200) are still poorly studied. The mechanisms behind both the delivery of large celestial bodies to Earth and crater formation are not well understood, particularly for craters formed in aquatic environments (at least 70% of our planet's surface). It is especially critical as those are prone to trigger global consequences due to widespread tsunami propagation reaching faraway coasts and higher load to the atmosphere of both water vapor (a strong greenhouse gas) and chemicals from marine sediments (e.g., sulphates, CO_2) (e.g., Artemieva *et al.,* 2017). Smaller events may pose a potential hazard to human society since they are much more frequent. This became obvious with the 1908 Tunguska airburst over Siberia, and yet again with the 2013 bolide and meteorite fall over Chelyabinsk city where more than 1500 people were injured.

But cosmic impacts are not only destructive. In addition to creating habitats for thermophilic life that can persist over geologic time, they can also provide a useful tool in the studies of other planets: Impacts can deeply fracture the target and facilitate the escape of trapped volatiles as well as offer conduits for magma, which can tell about the properties of the deeper parts of the crust. Cratering follows certain physical mechanisms and the ejected material at various distances from the crater can be traced back to certain depths in the crust, thus offering a "peep hole" to the interior of the crust. There is also an increased awareness of the value of impact craters as indicators for the properties of the target in which they form, which is important for the hazard mitigation of Earth-threatening asteroids.

Geological/geophysical studies and core drilling enterprises will lead to important developments in the field of impact cratering in the next decades.

6. How is the feedback between the Geosphere and Biosphere of the Earth?

About 300 mineral species have been described in Mars, whereas the Earth evolved from about 250 minerals at the time of its formation to more than 5,000 recognized today. This remarkable difference between two similar planets might be explained by life and by plate tectonic processes, both unique processes to our planet. The Geosphere and Biosphere have co-evolved during planetary history giving rise to both biological and mineral diversity. Biological evolution on our planet began more than 3.8 billion years ago, whereas mineral evolution began long earlier, shortly after the Big Bang, as stars began producing the elements of the Periodic Table. Inversely, some minerals (e.g., metal sulfides, clays, quartz, calcite) have probably had a fundamental role as catalysts for the formation of biopolymers, for the operation of a proto-metabolism or as enantiomer selectors, all of them essential reactions to understand the origins of life. Understanding the feedbacks between both Geosphere and Biosphere will be a key challenge for both Earth and Space science.

7. How can volcanoes and their environmental effects be better understood?

Volcanic activity is a common feature of most of the rocky bodies of our Solar System and has been directly responsible for forming at least three quarters of the surface rocks of Earth and Venus, all of the surface materials of Jupiter's satellite Io, and extensive parts of the surfaces of Mars, Earth's Moon, and Mercury (Wilson, 2014). Indeed, some of the most prominent volcanic features on the Earth, Mars, and Venus are large (>50 km diameter) shield volcanoes and associated calderas (e.g., Greely *et al.,* 2000).

Main knowledge on planetary volcanism resides in looking for analogs on Earth with present-day terrestrial volcanism or our understanding of past terrestrial volcanic activity (e.g., Kaltenegger *et al.,* 2010). Morphological features observed on the different rocky bodies are compared to terrestrial ones and related to different styles of volcanic activity (e.g. explosive or effusive) due to, for example, composition and gas content of the magma. Additionally, morphological evidences of magma-ice interactions have been found on Mars thanks to our knowledge of volcano-ice interaction occurring on Earth in alpine environments or beneath broad continental-scale glaciers or ice sheets (e.g., Chapman *et al.,* 2000). In fact, there are Martian geomorphic features that have been interpreted to be analogous to those terrestrial edifices that form from diverse types of sub-ice eruptions such as tuyas, hyaloclastitic ridges, or mudflows (e.g., Chapman *et al.,* 2000; Gilichinsky *et al.,* 2015). Also, magma-water interaction on Mars is assumed based on detailed morphometrical analyses and overall appearance of some morphometries analogue to terrestrial tuff cones and rings, and possibly maars (Brož and Hauber, 2013; Hemmi and Miyamoto, 2017).

Being Mars ~1.5 times more distant from the Sun than the Earth, the solar energy available on Mars then was only 1/3 of what gets the Earth today. Mars' volcanic activity can help us to understand early global warming, by invoking an atmospheric greenhouse effect to solve the early- Sun paradox. Early Mars atmospheric composition requires significant amount of greenhouse gases to answer that paradox. They were probably released by the substantial Tharsis volcanism that might explain the mid- Noachian Ancient shorelines and 3 Gyr-old (late Noachian and early Hesperian) debris deposits in Arabia Terra by a tsunami. This evidence has renewed questions about the stability of ocean in early Mars (Costard *et al.*, 2017).

In the same way, morphological features on Venus surface have been compared applying analogues from the Earth's seafloor (e.g., Grosfils *et al.,* 2000). The surface of Venus, obscured by dense cloud cover, is similar in many ways to the seafloor of the Earth's oceans dominated primarily by basaltic volcanism. Even though Earth's seafloor and Venus are dissimilar in many ways, both environments are characterized by significantly elevated pressure at the surface resulting, respectively, from the burden imposed by the overlying ocean water and the weight of the dense atmosphere. This provides volcanologists with an excellent opportunity to examine how elevated surface pressure affects the development and behavior of volcanic systems (cf. Grosfils *et al.,* 2000).

Sulfur dioxide on Earth atmosphere is used as a chemical proxy to assess volcanism. Estimating the SO_2 concentration on exoplanets atmospheres, we can study the large- scale explosive volcanism on them (Kaltenegger *et al.,* 2010). Our knowledge on diversity and prevalence of volcanism can be greatly increased by the remote observation of volcanic activity on exoplanets.

8. What can we learn from the lithospheric strength of terrestrial planets about the long-term heat balance of the Earth?

Temperature determines both life and plate tectonics development, but little is known about the quantitative importance of radiogenic versus primordial heat inherited from the accretion phase. Matching Earth models with future heat flow measurements in other planetary bodies should provide a better knowledge of what governs the thermal regime of the lithosphere and the Earth's interior.

The structure and evolution of the terrestrial planets, including the temperature distribution with depth, is key for understanding the Earth's origin as well as the evolution of the solar system. The lithosphere is the outer rigid layer of solid-surface planets, and its mechanical behavior reflects the thermal regime, a key factor controlling global geodynamics, heat transfer between the deep planetary interior and surface, and potentially the existence and nature of plate tectonics, seismicity, and a magnetic field (Watters and Schultz, 2010; Artemieva, 2011; Turcotte and Schubert, 2014).

The analysis of gravity and topography data provides useful constraints to address science questions regarding the interior structure of the terrestrial planets, probing the structure and mechanical behavior of their lithospheres, for example how they respond to loading and unloading (Audet, 2014; Wieczorek, 2015). In particular, a useful parameter that describes this behavior is the effective elastic thickness (T_e) of the lithosphere, which, in turn, can be used to constrain the thermal structure and evolution of a planetary body (Ruiz *et al.*, 2011).

Recent advances in joint spectral analysis of gravity and topography and improvements in lithospheric modeling of the Earth have led to mapping of T_e at an unprecedented resolution (Audet, 2014; Kirby, 2014). Given these recent methods developed for the Earth, it is a natural step to make a reliable T_e map for most terrestrial planets with high- resolution gravity and topography models (Audet, 2014). Limitations due to resolution of the available data emphasize the importance of future missions to map out the gravity and topography with sufficiently high resolution in order to produce regional lithospheric models and solve key gaps in the understanding of the lithospheric structure and evolution of Mercury, Venus, or Mars.

Comparing the results from these techniques to Earth studies will provide key hints on the past structure of the Earth.

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CHAPTER 7

ABSTRACT

The geological heritage is made up of all those places or points of geological interest that have a particular value, which makes them stand out from the surrounding environment. This value is of particular scientific and / or educational relevance in explaining the history of the Earth, so its conservation and management must be a priority of the global society. In today's society, there has been a significant increase in concern about the problems related to the conservation of our natural heritage and our biodiversity. In this sense, the study of geological heritage is among the most recent areas of research incorporated in the field of Geology and Nature Conservation. Over time, this new perception has crept into society, which already considers it a right, a need and a duty to protect the environment, promote sustainable development and leave for future generations a well-preserved environment, including geological elements of exceptional interest. In order to highlight the geological heritage, a non-renewable asset, it is necessary to develop a communication strategy capable of conveying to the population and the authorities the importance of its conservation. In addition, geological heritage can be an important resource for sustainable development in rural areas and boost the local economy through eco-tourism activities (geotourism). However, the dissemination and conservation of geological heritage cannot be done efficiently without relying on solid scientific knowledge. This is crucial to identify those unique geological elements that tell us the history of our geological past and help to understand the present and future of our planet. Therefore, it is in scientific knowledge where we must lay the foundations for the dissemination and conservation of geological heritage.

KEYWORDS

geoheritage | conservation | dissemination | scientific knowledge | earth's history

CHAPTER 7

GEOHERITAGE KNOWLEDGE AND PRESERVATION

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1. INTRODUCTION AND GENERAL DESCRIPTION

Geodiversity has been defined as "the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features. It includes their assemblages, structures, systems and contributions to landscapes" (Gray, 2013). Society benefits from three aspects of geodiversity – topographies, geological materials and physical processes. Society also benefits from geoconservation of the planet's geoheritage, according to the criteria for designating UNESCO World Heritage Sites, UNESCO Global Geoparks and national protected areas, the public interest in visiting spectacular geological places, and the economic benefits this geotourism brings (Gray, 2019).

The World Heritage sites listed by UNESCO include a wide variety of sites where both the natural / geological and cultural heritage are intertwined, as occurs in the Vall del Boi in Lleida, as well as in the geoparks that cover a territory where there is a cultural heritage that has used geological resources for its construction (geomaterials) and therefore also shows the geodiversity of the region. Both types of heritage, geological and cultural, suffer the same conservation problems, produced by natural weathering agents (physico-chemical), and others by anthropogenic agents, but both are enriched by the tourist interest of the regions that preserve the cultural heritage

Therefore, improving knowledge and preservation of geoheritage must be also a basic challenge for geosciencies, and should constitute one of their main contributions to build a modern sustainable society.

Geoconservation involves the protection of those elements of geodiversity that have geoheritage value principally for scientific reasons, but also for supporting educational, cultural, aesthetic, spiritual and ecological values (Crofts and Gordon, 2015; Gray, 2013). While there has been significant progress in the identification of terrestrial geosites, especially in Europe (Wimbledon and Smith-Meyer, 2012), there has been less emphasis on practical site management and the application of best-practice based on sound geoconservation principles. This is now a priority in the face of a wide range of threats to geoheritage, including urbanization, infrastructure development, mineral extraction, changes in land use and coastal protection (Crofts and Gordon, 2015).

The principal steps in the development of an effective geoconservation strategy for an area or a country involve: 1) inventory of geoheritage interests and sites; 2) assessment of their values; 3) conservation management; 4) monitoring; and, where appropriate, 5) promotion through interpretation (Brilha, 2016). In addition, the elaboration and diffusion of knowledge on these areas of geological interest to the general public, through different type of documentaries (broadcasting, virtual reality, apps, etc) and other outreach material, is an effective way to increase awareness about them and of the need to be protected.

Site inventory and assessment methodologies across a range of scales from local to national must be based on the scientific knowledge and constitute the most important part of any geoconservation strategy (e.g., Brilha, 2018). Also, a management plan providing a structured approach for the management of a protected area, requires solid scientific basis. Geoheritage is important for reconstructing Earth history. The case for society conserving geoheritage sites is similar to that for conserving historic or archaeological sites. But rather than conserving the evidence for reconstructing human history, we are dealing here with the history and evolution of the planet. There is a strong case for knowing and conserving the important sites that either have allowed, or have the potential to allow, scientists to reconstruct Earth's history and the evolution of life on the planet. And since humans have evolved during geological time and bynatural selection from ancestor species, it follows that human history is part of Earth history, reason why its preservation is necessary for its scientific and social interest. So, an important reason for conserving geoheritage is that it gives us an understanding of the history of the planet and our place in it (Gray, 2019).

One of the most important weaknesses in the current management and conservation of the geological heritage is still the little disclosure and marketing of geosites. The terminology used is sometimes difficult to understand and is nor properly known and used in the media. In addition, there are few informative books for non-specialists and for the general public and the language used is not very inclusive. There are difficulties in making geology relevant, since geological processes are not very tangible and not very visible. It is difficult to structure the information to attract the interest of general public and, once in the geosite, there is a risk of wandering, as it is an inanimate resource that draws less attention than others (like animals, plants, etc.). This is why geosciences have to contribute to the geoheritage knowledge and preservation, not only identifying those sites that are interesting for being known, but also making their basic knowledge accessible to the general public. Moreover, geological heritage (non- renewable element) is highly vulnerable against natural (e.g., erosion) and anthropogenic risks (e.g., bad practices) when it is not properly preserved and managed, as there is still a lack of interest on the part of society due to the lack of understanding about the value of geological heritage.

Therefore there is an urgent need to use the scientific knowledge to increase interest of the society due to the singularity and rarity of the geological elements, in some places also converging with other heritage values (natural, historical, etc.), which translates into a greater demand for rural tourism. Being this a field still rather unexplored, it offers a new approach to conservation and awareness of climate change from geological records. The recognition of geology makes it possible to raise awareness of nature conservation globally, since geology is a key piece for the conservation of ecosystems (geodiversity conditions biodiversity, habitats and landscape).

The UN 2030 Agenda for Sustainable Development defines 17 sustainable development goals to be universally applied in all countries. Many of these goals require proper management of the natural environment, including the two things: geodiversity and biodiversity. Geoconservation helps in the following objectives:

- increasing the quality of education (objective # 4)
- ensure that everyone has access to clean water (objective # 6)
- promote decent work and economic growth (objective # 8)
- organizing sustainable cities and communities (objective # 11)
- understand climate change (objective # 13)
- protect, restore and promote sustainable ecosystem use, combat desertification and stop biodiversity loss (objective # 15).

Geological heritage is a non-renewable resource. The distinguishing feature of geological elements as part of natural heritage is their low resilience. It is an irreplaceable resource, the destruction of which implies its disappearance because most of the impacts are irreversible, so prevention is of particular importance. The main normative of reference is the law 42/2007, of the natural heritage and of the biodiversity and the law 45/2007, for the sustainable development of the rural environment. International recommendations and guidelines should also be considered. The inventories of geological sites are the main instrument for developing the precepts of these laws. These inventories can be very varied, but in each case they must include diagnostic information that makes it possible to apply management measures to guarantee the conservation of the geological heritage, as well as its valuation and use.

Preservation of geological heritage and investments brings social and economic benefits to the area. Different studies in the National Parks of the USA like Yellowstone and in Catalonia as the Volcanic Zone of the Garrotxa assure that for each Euro invested the territory receives 9 from visitors, better image for the local industry, and a mitigation of the risk by raising the awareness of the population living there.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Spain is a privileged area in terms of its geological heritage and its geodiversity. In the I Spanish Geology Congress (Segovia, April 1984) hundreds of publications from all branches of geology were presented; for economic reasons then, two mining and hydrogeological resource groups stand out. In addition there was a shocking phrase for us, when they said: "From a geological point of view, Spain is a small Australia, referring to the enormous variety of different geological outcrops and geosites". The geological configuration of the territory, as a result of the geodynamic evolution of the Mediterranean region, the convergence between Africa and Europe and the opening of the Atlantic (not necessarily in this order), are responsible for it. The Spanish territory includes plutonic, alkaline, basic and ultrabasic massifs, Precambrian metamorphic areas, karstic morphologies and complex tobaceous buildings, mobile dunes, sediment deposits from tsunamis, active glaciers, the largest accumulation of mercury on Earth, pyrite mining pits sized one cubic kilometer, hot springs, volcanic activity, etc. Many of such elements are especially relevant to geological heritage are currently unprotected from the constant anthropization of the environment. Aggression to the geological environment is often due to ignorance of the existence of elements of special heritage value. There are many elements of geological interest that are found together with other elements of natural interest, forming a set to be conserved or already protected as a natural space, although often they do not have any specific protection features in addition to possible basic protection of the area.

In Spain, the autonomous communities have developed various measures for the conservation of geological heritage: some are classified as geological sites of interest or EIGs, and internationally as sites or geosites. It also includes those points or areas of geological interest that are related to mining activity and which are currently abandoned or in disuse. In many cases, mining and geological heritage are closely linked to historical and architectural heritage, to the traditions, beliefs, and folklore of some places, and may even have significant religious significance or become a sign of local identity.

The conservation of the geological and cultural heritage plays an essential role for the achievement of the Sustainable Development Goals. Objective 17 of the UN 2030 Agenda for Sustainable Development promotes that involving different people and groups in the elaboration of projects fosters social cohesion, thus contributing to the achievement of the one that advocates the creation of alliances between multiple stakeholders to achieve the goals of sustainable development. Likewise, in objective 8, where a proper management of a country's heritage attracts long-lasting and sustainable tourism investments, involves local communities and preserves sites of historical value from their degradation.

This awareness of timid but growing trends in geological values has become permissible on the socio-economic side, both in Spain and the World, and the Global Geoparks and the European Geoparks Network, sponsored by UNESCO, are the highest exponent. There are currently 12 geoparcks in Spain. The European network of geoparks has 75 geoparks in 26 countries, which theoretically belongs three geoparks each, however Spain has 12 and could have more due to its great geological diversity. Currently, there are various initiatives to value geological heritage and geology as a Science. In Spain, the Geoloday has become consolidated as a celebration of geology for the general public, the Olympics of geology in education, and the Science in Action awards in the field of scientific dissemination and a reduced number of local interpretation centers, signs and panels on geosites together with local guides and some web pages with advertising and visiting conditions for the geoparks, examples could be Villuercas (Cáceres), Sobrarbe-Pirineos; Molina-alto Tajo (Guadalajara), Aigüestortes (Lleida); Cabo de Gata Nijar (Almería); Las Loras (Burgos-Palencia), etc...

In many of these areas of general interest, true research is still lacking because most of them are protected by its beauty or cultural value, but the geological processes that shaped them are unknown in detail. For this reason, conducting geological heritage research has four main purposes: i) knowing better the places that are already inventoried and / or cataloged for their conservation and dissemination, ii) have the opportunity to incorporate to the existing catalogues new sites due to their relevant scientific value and potential pedagogical use, iii) avoiding some points of geological interest being lost by ignorance, and iv) spread to the Society the intrinsic beauty of geological forms and geological processes using two powerful tools: 1) internet and 2) the huge intrinsic geological complexity of almost all the territories of Spain.

3. KEY CHALLENGING POINTS

The scientific contribution to the knowledge and preservation of our geological heritage should include the following key challenging points:

1. Assess the geodiversity of our country. This is an urgent task that should include the valuation and assignment of the advantages of abiotic components of the natural environment, as well as the appraisal of the relationships determining their dynamics and even the satisfaction of human needs. Assessment of geodiversity should consider as main factors: 1) the purpose of the assessment; 2) the type of landscape in the study area and its spatial dimension; 3) and the availability of spatial data in an appropriate scale, including in its digital form (that will be used to build up the VR documentaries or apps).
2. Improve the knowledge of our geodiversity. This fundamental to be able toconserve the most valuable aspects of each particular place. In order to be able to carry out inventories and apply legal measures beforehand, we must know what is there. Sometimes, the implementation of new land colonization plans destroys poorly studied geosites, which may be of high geological interest to understand the history of the land or the landscape of the area.

3. Identify targets and objectives to be managed. Development of management objectives includes: evaluation of actual and potential uses (e.g., for science, education, geotourism); identification of opportunities for interpretation, promotion and geotourism; and setting site condition targets. Management objectives should reflect the vision and purpose of the site, the different types of geoheritage interest present and the potential values and uses of the site. Protection of geoheritage interests will normally be the primary management objective. Complementary objectives may recognize the wider instrumental and relational values of geoheritage (e.g., cultural and aesthetic values, value for geotourism and conservation of biodiversity and other ecosystem service values) where they do not conflict with geoheritage protection.
4. Assessing risk and vulnerability to pressures and threats of the different geosites that may be caused by human activity, including urbanization; commercial, industrial and infrastructure developments; mineral extraction; land use changes; coastal defences; river engineering for flood and fisheries management; and loss of moveable geoheritage (e.g., fossil and mineral specimens). The vulnerability in front of adverse effects will depend on their sensitivity (i.e., the degree at which they will respond or will be affected by these adverse effects) and ability to adapt. Sensitivity is the degree to which a system is affected or will respond.
5. Enhancing site condition monitoring in order to establish whether conservation objectives and targets are being met. Protocols for monitoring need to be set, including a baseline, the key attributes to be assessed against the targets and the frequency of monitoring. Attributes will generally include the integrity of the physical attributes of the site (extent, structure and composition of the features), their visibility and access, and the integrity of geomorphological processes where these form part of the interest. The frequency of monitoring is determined by the degradation potential of the site and the risk assessment.
6. Recognizing the interactions and interdependencies of geodiversity and biodiversity to enhance protected area planning. The characteristics of the substrate geology, landforms, soils and geomorphological, hydrological and biogeochemical processes, interacting with climate, provide the foundation for biodiversity. While species and communities may change, conserving geodiversity and making space for natural processes that enhance landscape heterogeneity improves opportunities for biodiversity to adapt or relocate under both current and future climates. Conserving nature's stage is central to recent guidance that

highlights the value of environmental heterogeneity in building climate resilience and adaptive capacity since geodiverse, heterogeneous landscapes support high biodiversity and provide future habitat space, evolutionary potential, refuge and connectivity corridors. Protected area planning that incorporates geodiversity as well as biodiversity should therefore enhance resilience and adaptive capacity, sustain key abiotic processes and result in a system of protected areas that is more representative of a region's natural diversity. Particularly relevant to this key challenge pint is the definition of conservation strategies of natural subterranean ecosystems.

7. Learning from the past and applying understanding of physical processes and landscape evolution to inform restoration and adaptive management interventions Conservation management of active systems should be based on a sound understanding of the underlying physical processes and landscape evolution. Therefore, from a management perspective, the aim of learning from the past is not to provide static baselines, but to help understand past ranges of natural variability, landscape sensitivity and future trajectories of change. Conservation of geosites with records of past environmental changes can ensure that such temporal records remain accessible for study and help to inform restoration and adaptive management.
8. Bringing geological heritage closer to society in order increase its value and to recognize its benefits, as well as to generate sufficient influence on policy makers to understand the importance of conserving geological heritage as a tool for sustainable development. Geoheritage conservation is also an ideal way for developing citizen science, involving volunteers in the search for information and data, and for keeping geoheritage sites save and in good shape. Other excellent system of bringing geological heritage closer to society is to create geology classes on YouTube with cinematographic, scientific and teaching quality, using many Spanish geosites as natural scenarios. The enormous benefits of using cinematographic systems have been proven by the zoology thanks to Rodriguez de la Fuente, marine oceanography by Jacques Costeau or astronomy by Carl Sagan. The beautiful Spanish Geological sites have the same future, but unfortunately, we are in the present.
9. Innovating and developing methodologies between multidisciplinary teams of geological heritage inventories that take into account geology but also the society that coexists with this heritage.

10. Proposing suitable and sustainable solution to ensure access to geosites but also preserving them. The conservation of geological heritage involves infrastructures that are different from other heritage sites, since they are very often open-air outcrops and have to highlight those elements that are of most interest. In volcanic cones, for example, erosion is a risk to the visitor and a degradation by geological heritage, where to locate the path, what points of interest, what type of path should be laid. An interesting example is an Icelandic volcano (Saxhöll) that they have set up on a steel ladder to access.

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Every day human activities involve interaction with our planet Earth. Everything around us is built upon the Earth, grows on the Earth, or depends on the environments and internal dynamics of the Earth to some degree. Indeed, Earth's dynamic processes have strong influence on our society today as they have had at any time in human history, providing both major opportunities as well as challenges. Therefore, the knowledge about the Earth is the key to develop an informed citizenry and a global awareness of a common Planet and a common future. For example, dynamic processes during interaction between the tectonic plates that make up the outer "skin" of Earth provide us with the valuable mineral deposits we need to develop our society, or the arable land and fertile soils needed to sustain it. Likewise, plate boundaries are the locus of hazards such as earthquakes, tsunamis, and volcanic eruptions that can cause large-scale disruption to, and displacement of, communities and economies. Just as one example, the March 11th, 2011 Tohoku earthquake offshore Japan, shows how a single-event natural disaster caused by one of the dynamic processes of the Earth (plate subduction) can have important socio-economic impacts that range from large-scale infrastructure damage to local and regional population relocation. Understanding the full range of Earth's dynamic processes will not stop natural disasters like the Tohoku earthquake, but it will provide important information for developing models for their mitigation.

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